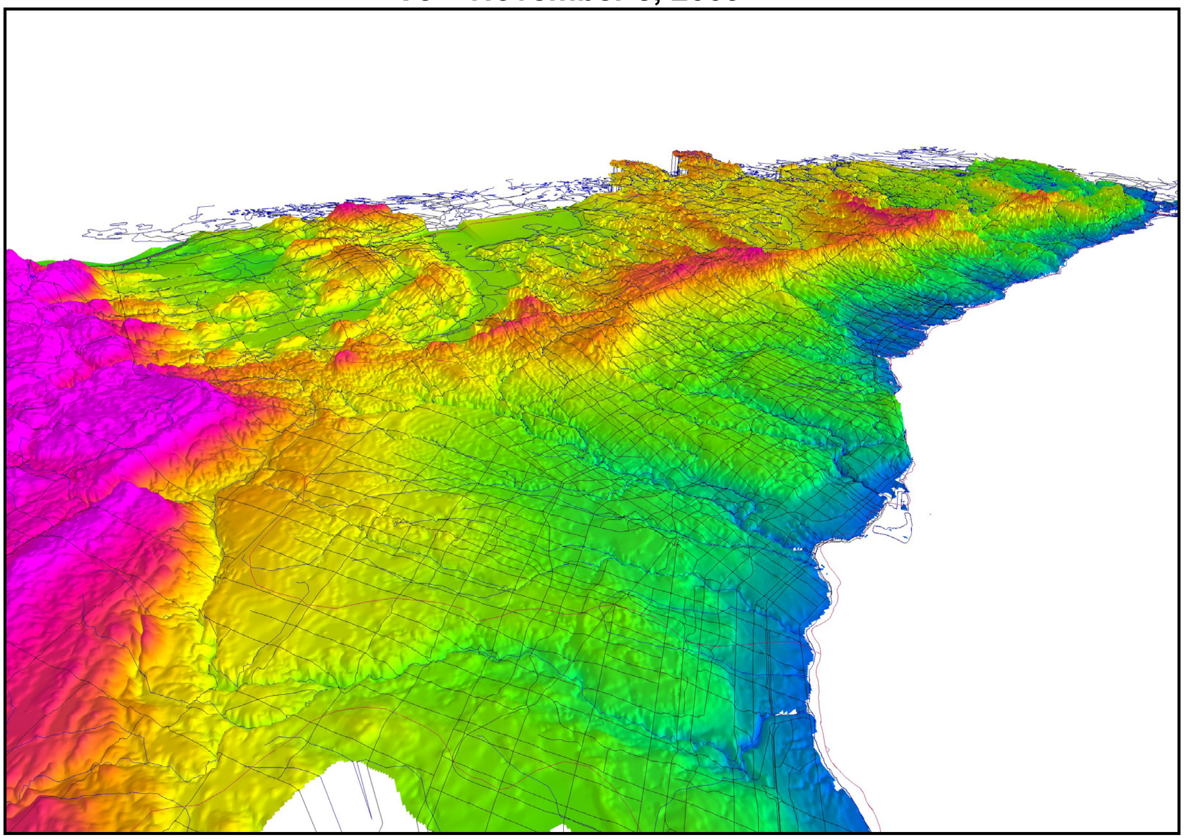
YPDT-CAMC Oak Ridges Moraine Hydrogeology Program

York-Peel-Durham-Toronto (YPDT) &
Conservation Authorities Moraine Coalition (CAMC)

Application of the Numerical Groundwater Flow Model - Considerations

V3 – November 8, 2009



Conservation Authorities Moraine Coalition

Credit Valley Conservation
Nottawasaga Valley Conservation
Toronto and Region Conservation
Lake Simcoe Region Conservation
Central Lake Ontario Conservation
Kawartha Conservation
Ganaraska Region Conservation
Otonabee Conservation
Lower Trent Conservation

FORWARD

Three dimensional numerical groundwater flow models have been developed for the York Peel Durham Toronto (YPDT) Groundwater Management program. This report provides a description of the considerations that must be made in applying the regionally constructed numerical groundwater flow models, particularly to local scale problems that arise at the partner agencies on a day to day basis. Numerical groundwater flow modelling is one of three principal technical components of the groundwater management program and is more fully described in YPDT-CAMC Technical Report #01-06 (Earthfx Inc., 2006). Further information is available at the program web site at www.ypdt-camc.ca.

The York Peel Durham Toronto (YPDT) Groundwater Management Study, initiated in 1999, is being carried out under the umbrella of the Conservation Authorities Moraine Coalition (CAMC). The project reflects the interests of nine Conservation Authorities and four municipalities that are working together to better understand groundwater issues across south-central Ontario.

An important theme of the YPDT initiative is that the major technical components assembled for the program, specifically: i) the database; ii) the hydrogeological interpretation; and iii) the numerical groundwater flow models have been designed as a comprehensive analysis system, and further, that each of the component parts is to be refined and updated on a continual basis. It is the goal of the partnered agencies that the program be maintained as a long term initiative in order to continually build on the early development work that has now largely been completed. It is recognized, that despite the high quality of the work undertaken to date, new data and new ideas will come along that will foster constructive improvements to the existing work. Appropriate cautions must therefore be taken when considering the results.

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The following people provided comments on earlier versions of this document:

- Rodney Bouchard, Regional Municipality of Peel;
- Wendy Kemp, Regional Municipality of York;
- Don Ford, Toronto and Region Conservation Authority; and
- Christopher J. Neville, S.S. Papadopulos & Associates, Inc. Waterloo, Ontario, Canada.

The constructive criticism received from the above people greatly improved this document and is gratefully acknowledged. Christopher Neville provides on-going expert Peer Review of modeling products emanating from the YPDT-CAMC program and also acts as an advisor to the program. His expertise, experience, opinions and comments are invaluable to the program.

General discussions with Muin Hussain and Tabitha Lee of Genivar Ontario Inc. (Markham, Ontario), Phil Smart of Conestoga Rovers & Associates (Mississauga, Ontario) and Ken Howard (University of Toronto at Scarborough) regarding numerical model use are greatly appreciated.

DOCUMENT HISTORY

Version	***Date***	***Comments***
V1	April 30,2007	Draft distributed to YPDT-CAMC partners for comment.
V2	Sept 5, 2007	Incorporate/edit based on comments from Wendy Kemp (York), Rodney Bouchard (Peel) and Don Ford (TRCA).
V3 - final	Nov 8, 2009	Incorporate comments from Chris Neville (S.S. Papadopolus) dated April 16 2008 on V2. Note – appendix A removed from final version (V3).

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1. INTRODUCTION

1.1 YPDT-CAMC Groundwater Management Study

The YPDT-CAMC Groundwater Management Program objectives are to provide a hydrogeological analysis suitable for water resources management encompassing the watersheds emanating from the Oak Ridges Moraine (ORM). The foundation for this flow system analysis consists of three main technical components including:

1) A database of all available water related information for the study area;
2) A geologic and hydrogeologic interpretation of the subsurface stratigraphy including development and refinement of a conceptual model; and
3) The construction of a numerical groundwater flow model.

It is important to keep in mind all three components when determining whether numerical groundwater model output can assist with formulating a solution to the problem being investigated. Together, these technical components of the program comprise an analysis system. Any or all of the components can be drawn upon to assist in decision making. An ongoing goal of the program is to refine all three components as more information becomes available. The current extents of the study area for the program are shown on **Figure 1**.

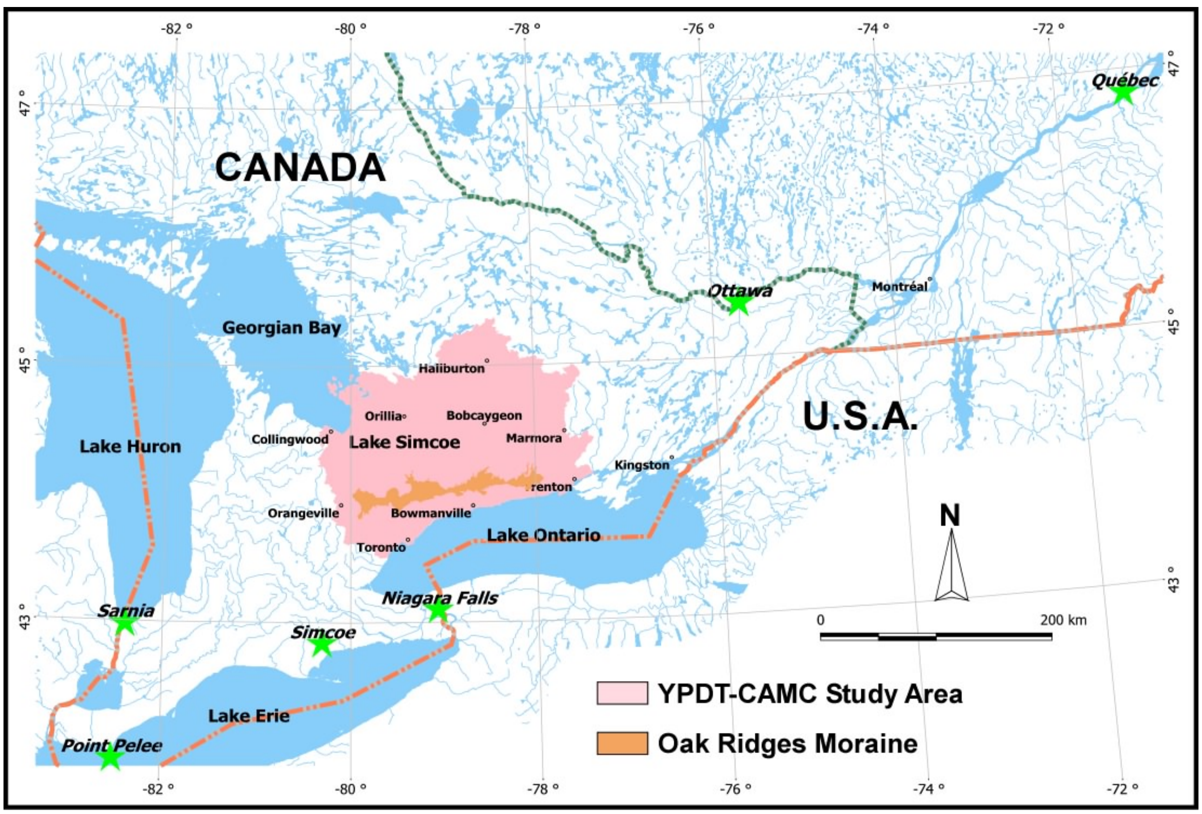

Figure 1: YPDT-CAMC Groundwater Management Program study area.

1.2 Background

The initial thinking behind the construction of the numerical model was to produce a watershed scale groundwater management tool that could be used to assist in making a number of day-to-day groundwater related decisions. The focus on York Region's Yonge Street Aquifer by the Ministry of the Environment (MOE) as well as by residents of York Region played a key role in focusing initial detailed efforts in that area. Another key issue that arose as the model was being constructed included the requirements of the Oak Ridges Moraine Conservation Plan (ORMCP) to produce water budgets (with the assistance of modeling) for watersheds originating on the Oak Ridges Moraine (Ontario Ministry of Municipal Affairs and Housing, 2002). Ancillary objectives of the model were envisioned to include:

- To assist in understanding the regional scale groundwater flow system – this would provide a context and setting for local scale groundwater issues;
- To provide a tool that would assist in assessing potential impacts from changes to the flow system such as those resulting from evolving land use and climate change;
- To provide further understanding of the spatial distribution of groundwater recharge and discharge; and
- To provide a tool to assist with evaluating gaps in the geological and hydrogeological understanding of the groundwater flow systems associated with the ORM.

In addition to providing a better overall understanding of the regional groundwater flow systems across the study area, to date, the steady-state numerical groundwater flow model has been used for several technical projects and assessments at the various partnered agencies including:

- Delineating Wellhead Protection Areas (WHPAs) based on time-of-travel analysis for municipal supply wells in Peel and York Regions;
- Assisting with water budget estimations for watersheds within the TRCA, LSRCA and CLOCA jurisdictions as part of Source Water Protection and ORMCP projects; and
- Predicting potential impacts to groundwater levels and groundwater discharge to streams from dewatering associated with sewer construction in York Region.

A description of the numerical groundwater flow modelling details including construction, calibration and sensitivity are included in CAMC/YPDT Technical Report #01-06 (Earthfx Inc., 2006). This report is available at http://www.ypdt-camc.ca/. **Figure 2** shows the model extents described in YPDT-CAMC Technical Report #01-06. The "Regional Model" was an initial exercise to work out logistics related to numerically modelling such a large area. This model incorporated 240m x 240m plan view cells with vertical discretization into a five-layer hydrostratigraphic sequence based on the initial geologic layers provided by the Geological Survey of Canada (GSC). The subsequent and current base model, initially termed the "Core Model", incorporates more model layers with a horizontal discretization into 100m x 100m cells. The "Core Model" was extended to the west in 2006 to encompass the Region of Peel, and to the east in 2008 to encompass the Region of Durham.

1.3 Purpose of Report

This document has been created to provide users with information and guidance on potential applications of the YPDT-CAMC numerical groundwater flow model to various issues that crop up at the partnered agencies on a day-to-day basis.

This document outlines, and provides critical discussion on, the key points that must be considered in bridging the use of the numerical flow model across different scales of application. **The main goal is to foster responsible use of model outputs when making decisions on various hydrogeological issues.**

Three key considerations must be front and foremost when utilizing numerical models:

- **The first question to be considered in using the YPDT Model in any hydrogeological investigation is whether numerical modelling is even necessary to address the issue under consideration.** For example, at a recent Ontario Municipal Board hearing (Gerber, 2005) only the information from the CAMC/YPDT database as well as the CAMC/YPDT interpreted hydrostratigraphic layers were used in support of an argument. It was determined that numerical groundwater flow modelling was not necessary to assist with providing a solution to the proposed land use change problem under contention;
- **Another key message that must be emphasized is that numerical models do not provide "*the answer*", but only provide simulated estimates of possibilities that must then be further considered in the context of providing solutions to the problem at hand.** Numerical model output should always be subject to further analysis and verification testing based on field-based observations. Models are best used to evaluate relative changes between alternatives, rather than provision of absolute results;
- **Model output quality is directly related to the quality of information that is input to the numerical model.** In this document, model generated results are herein referred to as simulated estimates or output; and
- **Local-scale analyses should start with an evaluation of the consistency between the regional interpretations and high-quality local data.** Where high-quality data are not available, the results of any analyses should be treated with caution.

1.4 Access to the Model

Currently the Regional Model and Core Model reside with the project's prime consultant, Earthfx Inc., at their Toronto offices and at the YPDT-CAMC Groundwater Management Program Downsview office. The model is available for use by any of the partner agencies, or their designated representatives, for any type of groundwater related projects. The model is quite large and takes both expertise and computer power to run. Distribution of any components of the model (*e.g.* interpreted geological layer surfaces, interpreted hydraulic conductivity distribution) beyond the partner agencies will be undertaken in accordance with procedures outlined in a data sharing document that is currently being signed by the Partner Agencies. Other recommendations with respect to the distribution of interpretations and model results include:

- When distributing model interpretations and results, data sources used to constrain the interpretations and analyses should be indicated clearly;
- Data source points should be superimposed on interpretive product maps showing data distribution. For example, water levels reported from various sources (e.g. MOE water well records) should be included and superimposed over regional water level surfaces; and
- Under no circumstances should the regional interpretations be regarded as a substitute for detailed local-scale investigations.

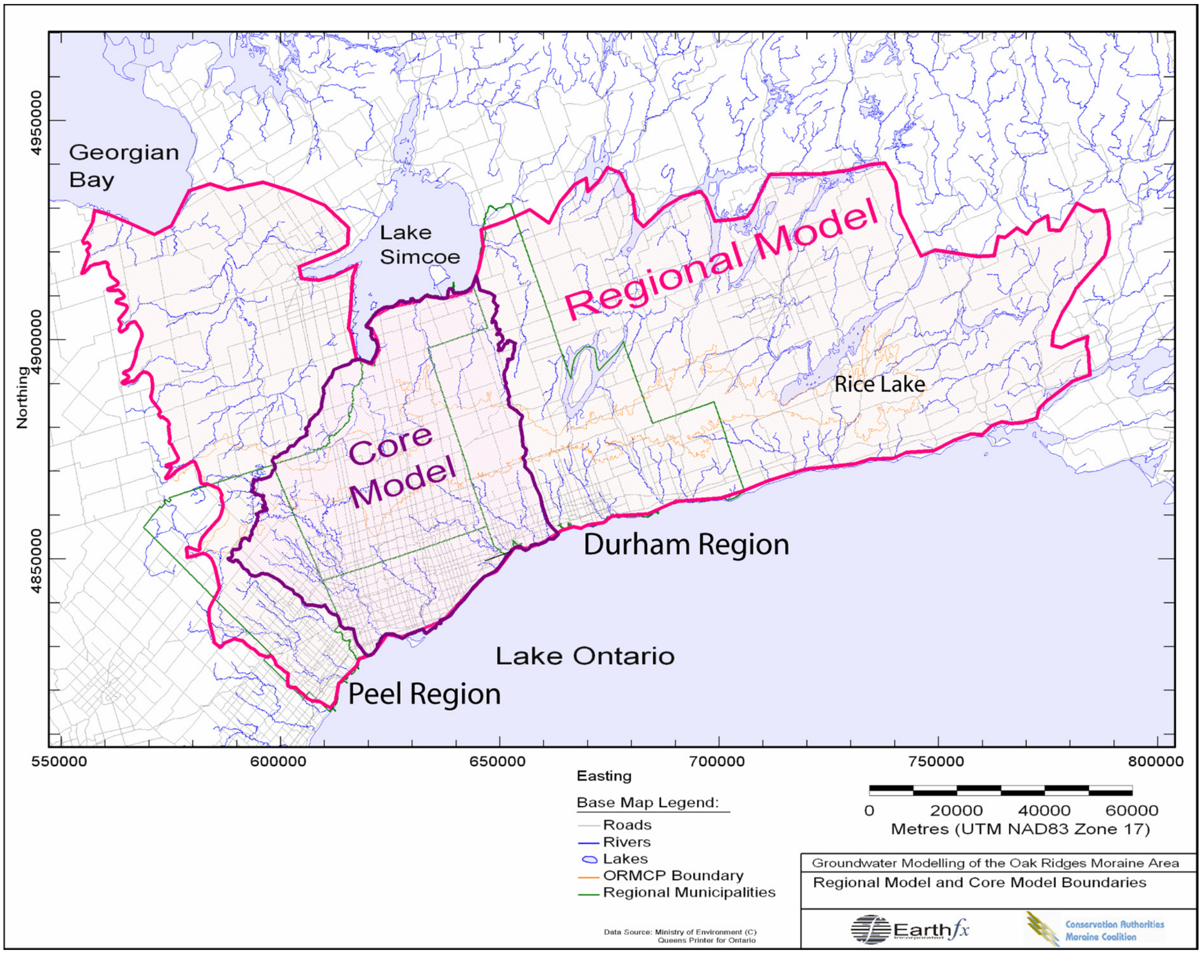

Figure 2: Numerical groundwater flow model extents.
Figure slightly modified from CAMC-YPDT Technical Report #01-06 (Earthfx Inc., 2006).

2. THE YPDT NUMERICAL MODEL

2.1 Assumptions and Limitations

Assumptions and limitations relating to groundwater modeling in general are discussed in other existing publications (*e.g*. Wang and Anderson, 1982; Anderson and Woessner, 1992; Hill and Tiedeman, 2007). Details, assumptions and limitations relating to the YPDT-CAMC numerical groundwater flow model are discussed in CAMC/YPDT Technical Report #01-06 (Earthfx Inc., 2006). Therefore, only a brief discussion is provided here. Key considerations in assessing the limitations of a model's output are: i) an understanding of the objectives of the study for which the model was constructed, and ii) an understanding of the information that was used to construct and calibrate the model. For example, a regional model constructed for water budget estimates may not be adequate for local area contaminant transport applications without considerable refinement. The terms "regional scale" and "local scale" are not well defined, and are subjective; however there is no question that the YPDT-CAMC models are, by any interpretation of these terms, "regional scale" models. Local scale models would be developed to encompass one well field or one contaminated site. Typically, regional scale models have a coarser grid discretization but extend out to natural hydrologic boundaries (*e.g*. lakes, streams, groundwater divides), whereas local scale models tend to have finer grid discretization but may not extend out to natural hydrologic boundaries. It is important to note that the relatively fine discretization (Regional Model - 240m; Core Model - 100m) of the YPDT models indicates the precision of the calculations, not the accuracy.

<u>Data Density & Geological Uncertainty</u>

Numerical groundwater flow models can provide considerable insight into flow system function and dynamics. However, it should be noted that all numerical models are simplifications of reality. Since the subsurface is not homogeneous, data must be collected and interpreted at known locations and extrapolated through areas of lower quality data or even areas of no data. As a result, assumptions must be made when constructing numerical groundwater flow models at any scale.

One of the main inputs to the YPDT-CAMC model is the interpreted three-dimensional architecture of the subsurface geology, which has been further interpreted into hydrostratigraphic units (i.e. aquifers and aquitards). The geological and hydrostratigraphic interpretations utilize data sets of variable quality. For example, geological information is included in the Ontario Ministry of the Environment (MOE) water well record (WWR) database. Given that the purpose of these MOE boreholes is largely to provide wells for water supply, the detailing of the geologic units encountered is often a secondary consideration. In addition, the drillers reporting on the intersected geological strata have different levels of geological training and expertise so that the MOE dataset is not consistent. On the other hand, boreholes constructed by the Ontario Geological Survey (OGS), the GSC or the YPDT-CAMC group (often termed "golden spikes") are drilled for the specific purpose of determining subsurface stratigraphy and these boreholes have been logged by qualified geologists and have better spatial and elevation control. Geologic descriptions from these "golden spikes" are considered more reliable than those descriptions contained within the MOE database; however, there are far fewer "golden spikes". Therefore the subsurface geology and hydrostratigraphy is interpreted between relatively sparse “golden spikes” (including outcrops) in combination with an interpretation of the many lower quality MOE WWR data points between the “golden spikes”.

Also considered in interpreting the stratigraphy is the depositional environment which controlled the distribution of the subsurface sediments. As an example, where tunnel channels are interpreted to occur north of the Oak Ridges Moraine, based on the available data, these features have been extended southwards beneath the moraine. It should be noted that the depositional infill characteristics of the tunnel channels vary significantly from fine grained silt deposits to coarser grained gravel deposits. It is also important to point out that the geological interpretation is being refined on an ongoing basis as localized site specific issues arise and are explored and as more data becomes available. Hydraulic response data also provide valuable information regarding subsurface stratigraphy (e.g. extent and integrity of aquitards; extent and infill of tunnel channels) and has been used where appropriate in interpreting geological and hydrostratigraphic surfaces. Long term pumping response data are available for the tunnel channel areas in the Bradford-Aurora-Newmarket area that help constrain channel infill characteristics. An example of channel aquifer hydraulics from western Canada is provided in van der Kamp and Maathuis (2002).

<u>Hydraulic Property Uncertainty</u>

Aquifer and aquitard properties such as hydraulic conductivity and porosity also vary considerably between measurement locations; therefore there is also considerable interpretation between known data points for these parameters. Given the difficulties of measuring aquitard properties directly (*e.g.* response times are often quite lengthy); there are even less direct measurements of aquitard properties than aquifer properties within the study area. In the model, aquitards are generally considered to have uniform hydraulic conductivity on a regional basis. The aquifer hydraulic properties were determined from local scale tests (*e.g.* pumping tests, piezometer slug tests, specific capacity estimates, etc.) and interpolated between known test locations utilizing geologic descriptions as contained for wells in the database. As with the geology, the hydraulic properties for the various hydrostratigraphic units are also refined as new data is made available.

<u>Water Level Uncertainty</u>

Groundwater and surface water levels (e.g. large lakes and streams) are initially used as inputs to set model boundaries and are also used in the calibration process which involves comparing model generated or simulated estimates of water levels to those measured in the field. The observed water levels used for the model are from many data sets and suffer the same limitations as data related to geology and hydraulic properties described above, namely variable quality and inadequate spatial coverage. An added complication is that the water levels have been collected over a wide ranging time period, over which the water levels in the groundwater system rise and fall. Groundwater level data within the YPDT-CAMC database include: i) MOE WWR water levels, which generally represent static water levels (provided the driller waited a sufficient length of time prior to obtaining the reading), ii) higher quality, but more sparse, PGMN monitoring network and municipal groundwater monitoring program data. In some locations the groundwater levels measured in these programs may not represent true static conditions due to local groundwater pumping effects. These factors must be considered when assessing the quality of the model calibration. YPDT-CAMC Technical Report #01-06 (Earthfx Inc., 2006) reports that the uncertainty or inherent error in the water levels, as interpreted from geostatistical analyses of the available data, could be on the order of 4.5 m for the Oak Ridges Aquifer and higher for deeper aquifers.

Uncertainty in Flux to Surface Water System

Simulated groundwater discharge to the surface (mainly streams) in the numerical groundwater flow model is partially determined by specifying various properties along stream reaches such as stream width and the hydraulic properties associated with the streambed materials. These are rarely field-measured and are often estimated based on underlying quaternary geological materials, stream stage or size and position of the stream reach within the flow system. In calibrating the model, simulated discharge is compared to estimates of the groundwater discharge (i.e. baseflow) component of total streamflow as measured at HYDAT (Water Survey of Canada) and conservation authority continuous stream gauges. These gauges are widely distributed but the overall coverage is largely considered to be inadequate to fully calibrate the regional groundwater model. To assist with calibration, the spatial distribution of model simulated discharge is also compared to low streamflow survey results which provide a snapshot of assumed groundwater discharge to stream reaches mainly in summer months remote from storm influences. These latter surveys are better aimed at delineating the spatial distribution of groundwater discharge and only provide a "ballpark" estimate of the average annual discharge (baseflow) since the magnitude of groundwater discharge on an annual basis can only be determined from continuous gauges. For local scale analyses, the stream gauging network may need to be enhanced.

Steady State versus Transient

The YPDT-CAMC model utilizes MODFLOW (Harbaugh and McDonald, 1996) to simulate groundwater flow. The model is currently steady-state although MODFLOW is capable of simulating transient (time-varying) groundwater flow. In natural flow systems, many processes such as recharge, pumping rates, groundwater discharge to streams and groundwater levels vary over many different time scales (hourly, seasonal, drought, etc). Steady-state flow modelling utilizes long-term or annual average inputs for variables such as pumping and recharge rates. As output, the model provides long-term average estimates of other variables, such as the groundwater discharge to streams or groundwater levels. In steady-state models, storage is neglected and the predictions provided for some output parameters (such as drawdown or change in discharge to streams) should be considered as being extremely conservative. Model outputs of hydraulic head results would represent the average annual condition. Also with steady-state models, estimates of the time frame required for predicted impacts to occur at various distances from, say a pumping well, are not provided.

In general, all modeling efforts require simplifications, assumptions and extrapolations because data and observation coverage are rarely considered ideal. Regardless, it is stressed at this point, that much can be learned about groundwater flow systems through the use of groundwater flow models. Care should be taken in explaining and utilizing the estimates that are derived from any model and modeling should not be considered an alternative to the collection of field-based observations. It is very important that model input and output, and the assumptions inherent in the process, are adequately documented (Zheng *et al*., 2006 and associated papers, particularly Olsthoorn and Kamps; McDonald and Reilly, 2007).

2.2 Addressing Uncertainty

As mentioned previously, the YPDT-CAMC Oak Ridges Moraine Hydrogeology Program consists of three main components:

a) Database;
b) Hydrogeological Understanding/Conceptual Model development; and
c) Construction of a numerical groundwater flow model.

Each of these components is subject to continual refinement as more information becomes available and more testing is conducted. The testing or calibration of the numerical groundwater flow model is also an on-going process where results are continually compared to observations. This means that the more observations that the model can match (i.e. historical trends in water levels from a sequence of steady-state analyses, groundwater discharge, pumping tests, etc.) then the more confidence a user may have in using model estimates to assist in the prediction of flow system responses. It is planned that these three components will be made available on a wider basis to increase the number of qualified individuals testing the interpretations generated. At a minimum, these three components (collectively or individually) are seen to provide a starting point for any regional or local scale groundwater analysis. It should be noted that a conceptual model (component 'b' above), and ultimately a numerical flow model (component 'c' above), reflects the interpretation of the information available. The interpretation incorporated into the conceptual and numerical models should always be checked with the original input information (part 'a' above), preferably utilizing multiple analysis methodologies.

As an example, **Figure 3** shows locations of simulated changes in groundwater discharge to streams within the Holland River watershed as a result of pumping of the "Yonge Street Aquifer" municipal wells. The 1950 scenario assumes no municipal groundwater pumping within the watershed. The 2002 scenario includes municipal pumping values representative of that year. The difference in simulated discharge to streams for both scenarios represents the estimated historical change in groundwater discharge to streams induced by municipal supply groundwater pumping since all other factors (*e.g.* recharge, hydraulic conductivity, etc.) were kept constant in both scenarios. This figure does not show the change that actually occurred, but represents an estimate of the change, given the understanding of the subsurface environment as replicated in the groundwater flow model. This model result is of course subject to further evaluation utilizing many lines of historical evidence including both qualitative and quantitative observations. Should model predictions be shown to be inaccurate when compared to field observations, then the model needs to be refined such that the model output compares favorably to the field observations. This refinement process often yields insight into flow system dynamics and processes. In summary, the chief way of addressing uncertainty is to continually improve the model (by collecting new field information, drilling new boreholes, re-assessing the conceptual model and the depositional environment, etc.) so that it increasingly reflects observed conditions.

Another consideration that warrants mention here is whether simulated predicted changes are actually measurable. This is especially true when considering modeled groundwater flux estimates to a stream, for several reasons including:

- there is inherent error in the ability to measure stream flows both from an equipment and technique perspective;

- in the case of steady state models, the model provides an annual average estimate of the groundwater discharge, which is difficult to “measure” given the lack of long term gauges across the model area; in addition, the fluctuation in streamflow in response to short duration storm events and seasonal changes inhibits the use of spotflows as an accurate surrogate; and
- the groundwater contribution to a given stream reach might be so low that the change predicted is not significant in terms of the overall streamflow – again detecting or “measuring” such small changes is problematic.

In all cases where reliable field-based observations are available, these measurements supersede numerical model simulated output. In other words, the model needs to be able to simulate the reliable field-based measurements or else model refinement is necessary.

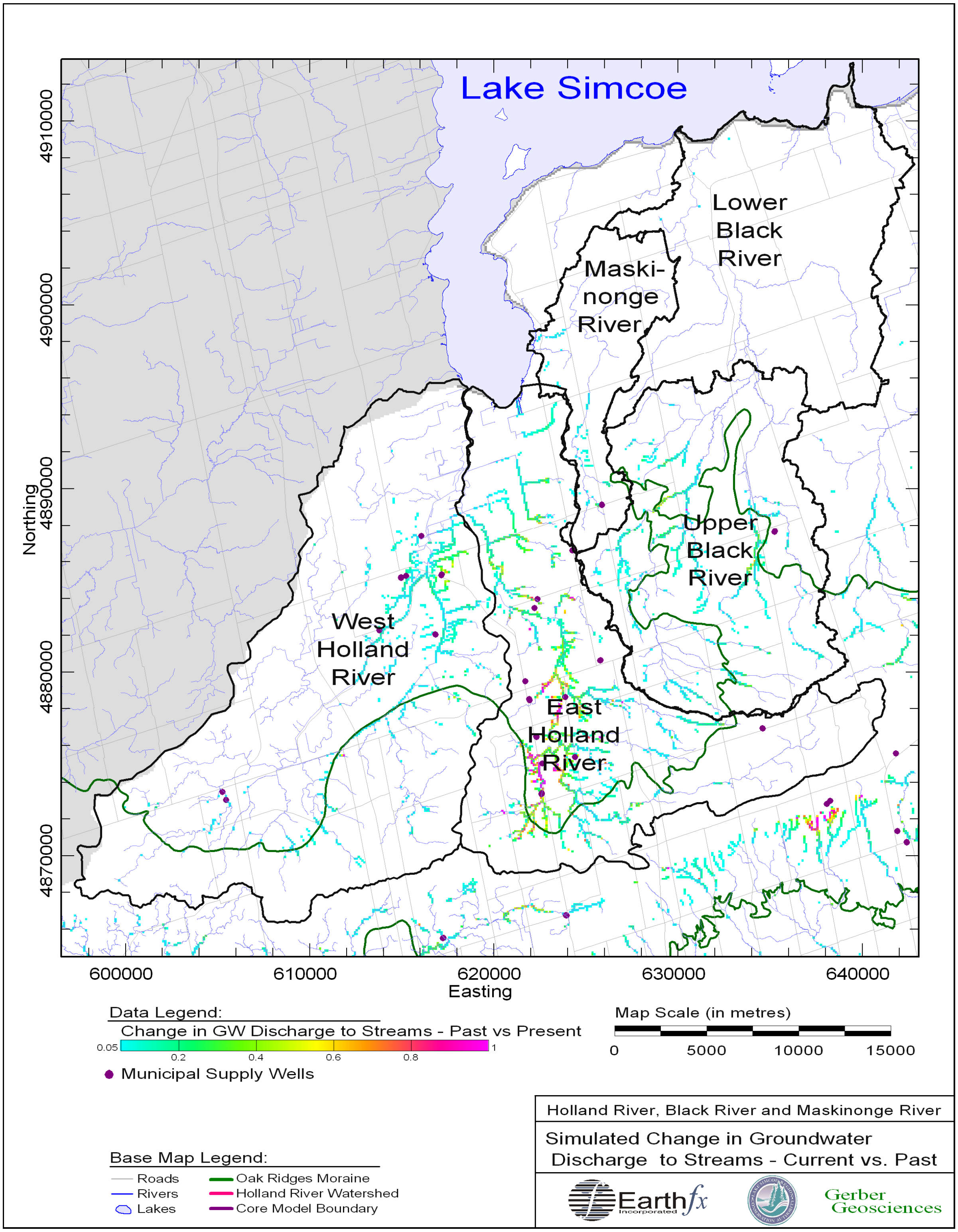

Figure 3: Simulated estimates of change (%) in groundwater discharge to streams - 2002 versus 1950 conditions. No precision is inferred with the scale bar for the estimated change in groundwater discharge to streams.
Figure from Earthfx Inc. and Gerber Geosciences Inc., 2005.

3. APPLYING THE REGIONAL MODEL TO LOCAL SCALE

To begin the discussion on the use of the model, a key point to keep in mind is that the database, geological interpretation and numerical model developed under the YPDT-CAMC program are to be considered as an analysis system, recognizing that some or all of the components may be applied to a problem to assist in generating a solution. The philosophy inherent in the YPDT-CAMC analysis system is that all data/information/observations are available to be utilized for any scale application. In this way, future refinement can benefit both the regional and local scale analysis of problems. This section provides a discussion on various aspects that should be considered in applying either the geological interpretation or the numerical model, both having been generated on a regional basis, to more local scale problems. The issue of refinement is a key theme of this section and is really the pathway that allows for a regional model to be used locally. Refinement in this case refers to refinement of the data control and interpretations, and not necessarily to refinement of the numerical model finite-difference grid.

This issue of using a regionally constructed model to address local scale problems will become more prevalent under the current Ontario Source Water Protection (SWP) water budgeting exercise where watershed-scale models will potentially be used for further local area analyses within "stressed areas" from a water quantity perspective (Ontario Ministry of the Environment, 2006). With respect to the YPDT-CAMC groundwater flow model, questions have been raised with respect to the use of the regional steady state model to delineate wellhead capture zones and to address localized groundwater/surface water interaction issues. This reduces to the fundamental question of utilizing a regional model for local area analyses which can be addressed if it can be demonstrated that the model is adequately constrained by high-quality local data.

Is a Numerical Flow Model Necessary?
The first question to ask in analysing any hydrogeological problem is whether estimates from a numerical groundwater flow model are even necessary to solve the problem. For example, an area may have suitable monitoring information readily available such that a numerical model is not necessary to assist with formulating a solution to the problem. As mentioned above, if a regional numerical flow model exists, the model output should match the observation information in order to develop greater confidence in model estimates for areas without a suitable observation network. Whether a numerical model is necessary or not can only be decided by qualified individuals considering the problem at hand, the objectives, and the results needed to address the problem.

As mentioned in the introduction, the YPDT-CAMC numerical groundwater flow model (Core Model) is currently a steady-state, 100m x 100m cell model covering much of the western part of the Oak Ridges Moraine (**Figure 2**). It was developed to assist with an overall understanding of the groundwater flow system across the area and along with the accompanying database and hydrogeologic interpretation, was envisioned to also assist with:

- water allocation decisions;
- assessing large scale construction projects;
- development review commenting;
- planning decisions; and
- groundwater - surface water interaction analyses.

The main point to highlight here is that the regional model, if it is to be used for looking at local scale issues, should not be used without careful thought, and likely some additional work. This additional work is framed under the general term “refinement”. The following sections discuss the issue of refinement with respect to various aspects of groundwater modeling. The regional model provides a solid framework within which to work, however it is not a panacea for all groundwater problems within the area. Assuming that a decision has been made that a particular local scale problem requires a numerical modeling component, the following sections discuss recommended considerations before utilizing estimates derived from the model to inform the decision-making process.

3.1 Geology/Hydrostratigraphy

Current Model

The current rendering of the geological layers involves a number of processing steps that are linked together resulting in the final geological construction. These steps include:

1. Background review of existing reports and papers to derive an understanding of the conceptual depositional processes that shaped the subsurface sediments;
2. Evaluation of key high quality geological boreholes and outcrops (“golden spikes”) that can be used to mark the tops of key geological units;
3. Picking of the geological formation tops at borehole and outcrop locations along numerous cross sections with the picks going to a centralized database;
4. Initial interpolation (kriging) of the geological surfaces using a set of rules that prioritize certain surfaces (*e.g.* bedrock surface, ground surface) as being more reliable than other surfaces;
5. Refinement of the layers through the use of polylines (user-defined lines of geologic contact constrained by geologic and geophysical information) that allow features such as channels to be merged into the geological construction; and
6. Migration of the geological units to modeling (hydrostratigraphic) units through another set of rules which allow each layer to be continuous throughout the model domain, necessary in this case for a model based on the finite difference method.

The geologic interpretation methodology is discussed further in Appendix D of Earthfx Inc., 2006.

Refinement Considerations for Local Scale Application

As mentioned throughout this document, the geologic/hydrogeologic interpretation is continually refined as more information becomes available. In general there is a three step process for incorporating new data into the analysis system:

- the database is updated as the new local scale data (new drill holes or outcrops) are logged and information is passed to the project;
- the geologic surface interpretation is then checked and refined if necessary to be consistent with the new data; and
- the numerical model is updated by re-interpolating the hydrostratigraphic model surfaces to reflect the new data.

There is usually a time lag between these steps. When initiating a local scale analysis, the interpreted geologic and hydrogeologic surfaces must be checked against the local data (which should be put into the database as per step one above) to ensure consistency. The numerical model should also be checked to ensure that the version of the model to be utilized incorporates and reflects the new data. It should be noted that hydraulic observations (*e.g*. water levels, response to pumping) may inform the geologic interpretation therefore, the hydraulic data also need to be checked for the local area as well. It should also be pointed out that in the absence of new data; the geological layers should still be reviewed using local sections to ensure that the geological setting is consistent with local understanding from pre-existing reports and local conditions. This review might result in some refinement of the geological layers.

3.2 Hydraulic Properties

Heterogeneity exists at all scales. Hydraulic properties, for example hydraulic conductivity, can and do vary over short distances due to facies changes. The hydraulic properties used for an investigation depend on the application or objectives. For example, contaminant transport studies within the Borden aquifer by the University of Waterloo have documented heterogeneity within a sand aquifer at a very fine scale (see Sudicky 1986 for example). Although this type of heterogeneity is important in determining the movement of contaminants within the aquifer, from a water budget or physical flow perspective (*e.g*. analysing drawdown from a pumping well), this same sand aquifer may be viewed as being relatively homogeneous.

<u>Current Model</u>

The hydraulic conductivity distribution for the YPDT-CAMC model was initially established regionally based on the geological material codes contained in the database. This was undertaken for the intervals that were associated with aquifers. Aquitards were assigned a uniform hydraulic conductivity based on values from a literature review. Within the hydrostratigraphic layers, refinement of the hydraulic conductivity was then undertaken based on pump or slug test information or based on geological interpretation (*i.e*. channel delineation). Further refinement occurs during the numerical model calibration process. Again, locations where physical testing allows refinement are limited and therefore interpretation between higher quality test locations relies upon the lower quality geological information (specifically the Mat1 and Mat2 material codes representing primary and secondary geologic materials).

Hydrostratigraphic units are interpreted as one unit vertically within the model; that is each aquifer and aquitard is represented as one model layer. In reality, model units such as the Thorncliffe aquifer complex are not all aquifer material. There are also diamict, and silt and clay rhythmites occurring within this unit. As one transitions from the regional to the local scale, horizontal and vertical heterogeneity and facies changes might become more important to the local scale problem and further refinement of media properties may be necessary. With the current model framework, lateral facies changes can be accommodated by adjusting hydraulic conductivity assignments; however there is no ability to discretely account for vertical facies changes within a single unit unless further layers are added to the model. It should be noted that no numerical model can incorporate heterogeneity to the fullest extent because it can’t actually be measured in a practical manner.

The problem of selecting representative hydraulic properties for a hydrogeologic analysis is illustrated by looking at hydraulic conductivity estimates for the Northern or Newmarket Till (**Figure 4**). The Newmarket Till can be considered a dual-porosity medium, meaning that the sandy silt till has a relatively low permeability matrix with an increased secondary permeability provided by fractures and sand seams. This is illustrated by the fact that for small scale laboratory analyses of till cores (<0.3m) the hydraulic conductivity is consistently measured at < 10^{-10} m/s (triaxial tests on **Figure 4**). Field based physical testing including pump and slug tests sample a larger volume of the till and yield higher estimates of hydraulic conductivity, up to several orders of magnitude higher. These larger volume tests incorporate the influence of the fractures and sand seams resulting in higher estimated hydraulic conductivity values for the unit. Numerical model derived estimates represent the bulk hydraulic conductivity of the till incorporating both matrix and secondary permeability structure (e.g. sand seams, fractures) effects. For a regional analysis, such as watershed water budget estimation (tens to hundreds of km^2), the larger scale bulk hydraulic conductivity estimates are considered to reasonably represent the behaviour of the unit with respect to the problem being addressed. For a local scale analysis such as the potential migration of contaminants emanating from a landfill, the secondary permeability structures such as fractures may need to be more fully incorporated into a model. These structures can lead to groundwater velocities exceeding several metres per day within the fractures (Harrison *et al*., 1992). Contaminant transport calculations would also have to incorporate the important attenuating effects of matrix diffusion.

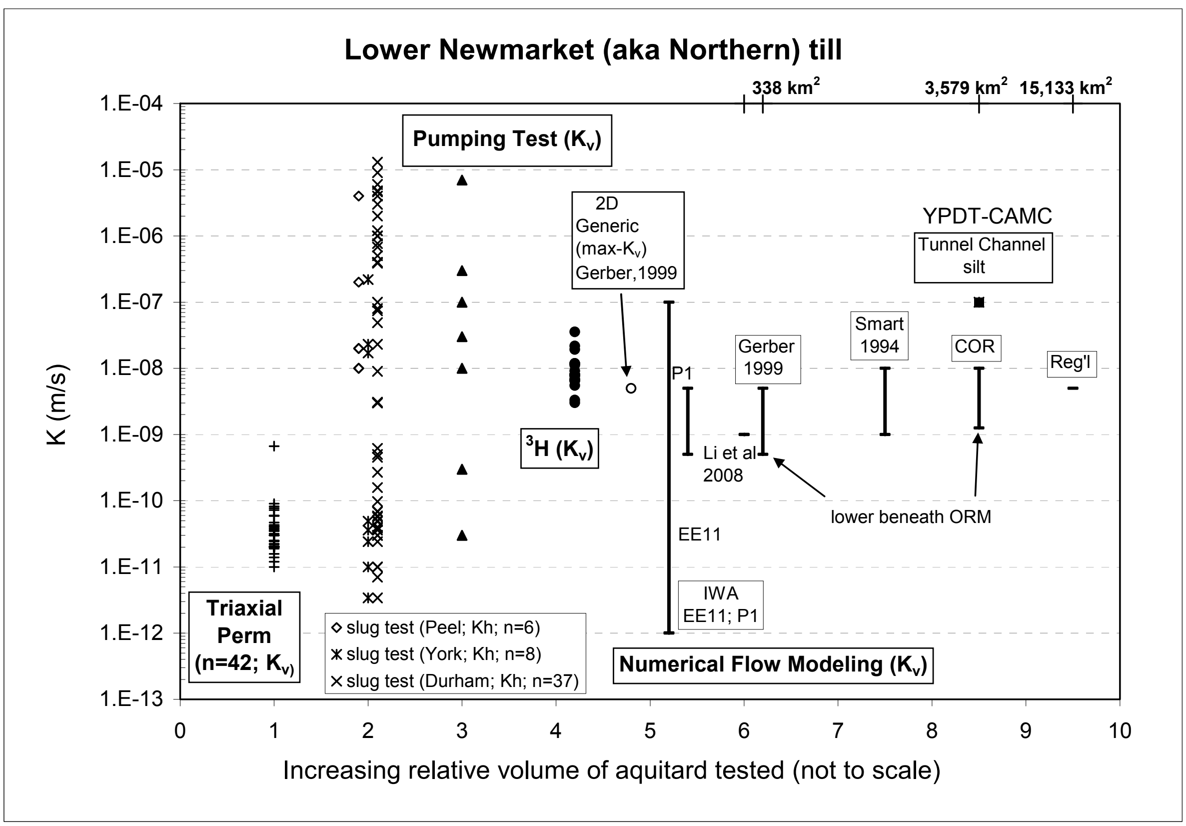

Figure 4: Hydraulic conductivity estimates for the Lower Newmarket/Northern Till. K_h = horizontal hydraulic conductivity, K_v = vertical hydraulic conductivity.
Figure modified from Gerber and Howard, 2000 (who estimate bulk K_v ~ $1x10^{-9}$ m/s)

Refinement Considerations for Local Scale Application

The hydraulic conductivity distribution within the model can be adjusted as new information becomes available. Prior to determining if this is necessary, one must consider whether there is sufficient data to drive such a refinement. Consideration must be given to the fact that for each of the three main aquifers in the model (Oak Ridges, Thorncliffe and Scarborough) the hydraulic conductivity at any one location is represented by only one value. There is currently no opportunity to account for hydraulic conductivity differences in the vertical direction, unless more model layers are added. Given the fact that the hydraulic conductivity distribution can be quite variable, it likely only makes sense to adjust the hydraulic conductivity field (or hydraulic conductivity anisotropy) for an aquifer where:

- a large pumping test with several observation wells has been undertaken and results show that the hydraulic conductivity of an aquifer unit is different from that in the model; and/or
- several slug tests have been undertaken in an area, they are considered representative of the entire vertical distribution of the aquifer, and they consistently show hydraulic conductivity values that differ from the value represented in the model. It should be noted that hydraulic conductivity estimates derived from slug tests are particularly sensitive to the properties in the immediate vicinity of the well.

In cases where new drilling has shown considerable variability within one of the three regionally delineated aquifer complexes, and it is considered that additional model layers are required to provide a solution to the problem being investigated, then a new local model might be needed. This localized model should be informed by the regional model.

3.3 Recharge

Current Model

The recharge rates in the current model have been estimated largely based on the surficial quaternary soils as mapped by the Geological Survey of Canada (Sharpe *et al*., 1997) and the Ontario Geological Survey (Ontario Geological Survey, 2000). Adjustments to the original values were made to account for urbanization in developed areas, whereby the recharge rates were reduced by 40% within these areas. The specific effects of urbanization on groundwater recharge are uncertain and undoubtedly variable depending on local conditions. For example, leakage from urban infrastructure may even increase recharge rates above background or natural fluxes (Lerner, 2002). For specific watersheds in the model area further work has been undertaken to adjust the recharge rates using near surface modeling of precipitation, climate and land use to partition precipitation between runoff and recharge (e.g. PRMS model, Leavesley *et al*., 1983).

Refinement Considerations for Local Scale Application

Adjusting the recharge rates for a local application of the model is difficult since recharge is typically not a measured parameter but is only estimated. Generally speaking, adjustments to hydraulic conductivity should be attempted first in order to better calibrate the regional model to local observations. We do note that recharge generally has well-defined physical bounds (0 < Recharge < Average Precipitation) whereas hydraulic conductivity may vary over orders-of-magnitude. Where evidence suggests that recharge rates could be adjusted in order to better calibrate the model to local collected field data (*e.g*. water levels), then adjustments might be required. Examples of circumstances which might support local adjustments to recharge rates include:

- where more detailed mapping of surficial soils indicates a difference from the regional mapping;
- where slope or topography that hasn't been considered in the regional model appears to play a significant role in recharge (*e.g*. hummocky topography; sloping low permeability soils adjacent to coarse soils)
- where development (i.e. increase in impervious surface covering) has occurred that has not been taken into account in the regional model; and/or
- running of a model such as PRMS which use climate data, land use, vegetation and slope to partition precipitation into recharge and runoff.

3.4 Pumping Stresses

Current Model

The YPDT-CAMC model has considered all of the larger water takings within the model area. These have been derived from the MOE's Permit to Take Water (PTTW) Database. For municipal takings the average actual pumping rates from the past ten years were incorporated into the model. For other large water takers the pumping rates were estimated based on data provided in the permit database.

Refinement Considerations for Local Scale Application

Given that the municipal takings in the regional model reflect the true actual takings, there is likely not much refinement needed to the municipal pumping rates that are in the model. However, if the pumping schedule or regime for a given community changes, then adjustments to municipal pumping rates might be required. For the other large takers and for takers that are not reflected within the PTTW database, adjustments to pumping stresses could be used to assist in refining the model for local purposes. Surveys of local water users and adjustments to permitted rates to account for seasonal, actual and consumptive water use are two ways in which pumping stresses could be adjusted. We note that seasonal and actual water takings may not be reflected within the historical PTTW database. This may be reconciled in the future as more actual water use measurements are a requirement of many recent permits. If local water taking (e.g. private domestic water wells), below the rate necessary for a permit, is deemed to influence the local groundwater flow system then these takings may need to be added to the model at some point in the future.

3.5 Discretization

Numerical model discretization is the process of splitting up the study area into horizontal blocks (for the finite difference method) and vertically into layers representing aquifers and aquitards, or stratigraphic units having different hydraulic properties. It should be noted that multiple model layers may be used to represent a single hydrostratigraphic unit if variable hydraulic properties within a unit dictate such refinement (Neville *et al*., 1998).

Current Model

The YPDT-CAMC model has horizontally split the study area into 100m x 100m cells. This cell size was chosen to provide a grid on a regional basis that was fine enough to handle flow patterns between headwater streams. It is recognized that rarely is the distribution of subsurface hydrostratigraphy and associated hydraulic properties known at this fine a scale. However, increasingly more detailed DEM information is accessible, the latest version in parts of Ontario available at 5 m resolution. This detailed information is averaged to provide values on a 100m x 100m grid; however, stream elevations incorporated into the model files are derived from the more detailed DEM (Earthfx, 2006).

Vertically the study area has been split into layers representing aquifers and aquitards as shown on **Figure 5** and **Figure 6**. The regional model currently contains 8 layers. Above the escarpment the Lower Amabel/Reynales/Clinton-Cataract group functions as a single aquitard and is represented as a single model layer that controls interaction between the overlying Amabel Production Zone and the underlying Whirlpool/Weathered Queenston Formations.

Closer inspection of **Figure 6** shows that the uppermost model layers are draped over the escarpment which may incorrectly suggest that there is continuous groundwater flow over the crest and down the east slope of the Niagara Escarpment. Observations suggest that seepage faces form at the base of the Quaternary sediments and the Amabel Formation (Amabel Production Zone in **Figure 5**) near the crest of the escarpment. Numerical flow modeling must properly incorporate this physical system. One way would be to truncate the uppermost model layers at the escarpment face by deactivating the corresponding grid blocks and adding drain boundary conditions. Further discussion can be found in Rulon and Freeze (1985) and Rulon *et al*. (1985).

Layer	Above Escarpment	Below Escarpment
1 Top	Recent Deposits - Weathered Till	Recent Deposits - Weathered Till
2 Top	Halton/Wenthworth Till	Halton Till
3 Top	Outwash	ORAC
4 Top	Port Stanley Till	Newmarket
5 Top	Weathered Rock/Guelph/Valley Fill	Thorncliffe
6 Top	Eramosa/Upper Amabel	Sunnybrook
7 Top	Amabel Production Zone	Scarborough
7 Bottom	(Lower Amabel/Reynales/Clinton-Cataract)	
8 Top	Whirlpool/Weathered Queenston	Weathered Bedrock
8 Bottom	Top of Queenston	Unweathered Bedrock

Figure 5: Hydrostratigraphic layers incorporated into the YPDT-CAMC model.
Figure provided by Earthfx Inc.

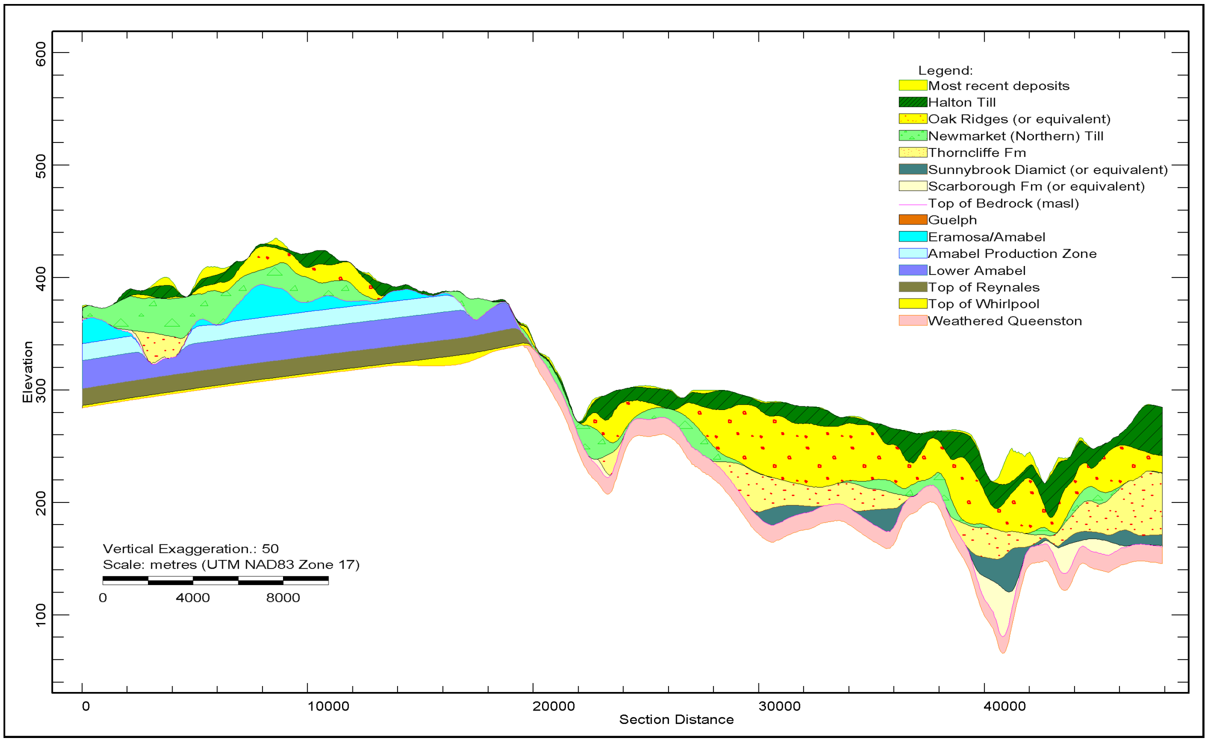

Figure 6: West-east cross section through west part of the model showing model layers. Figure provided by Earthfx Inc. (Section distance in metres and elevation in metres above sea level.)

Refinement Considerations for Local Scale Application

The question has arisen as to whether the regional model has a sufficiently fine resolution to predict capture zones for the municipal supply wells or to address other similar local scale issues.

To answer this question, a comparison of the effects of the grid size on the simulated WHPA for the deep (Thorncliffe aquifer complex) Stouffville municipal supply wells (PW#1 and PW#2) was undertaken and is illustrated on **Figure 7** and **Figure 8**. The predicted WHPA using the 100m grid is compared to the predicted WHPA using a grid refined to 12.5m cells for the affected area (see **Figure 7**). In this example all parameters were held constant except for the grid spacing so that any changes in the predicted WHPA delineation can be attributed to the discretization change. In both cases (**Figure 8**), the simulated WHPAs are very similar so in this case, at the scale of the analysis, the affects of grid spacing are considered negligible.

As discussed in YPDT-CAMC Technical Report #01-06 (Earthfx Inc., 2006), the 100m x 100m model will underestimate drawdown in pumping wells and in areas close to the pumping well. In the unlikely event that the model is used to predict drawdown at or near the pumping well then the simulated estimates will need to be corrected. There are several corrections that may be required. For example, the correction methodology of Pricket and Lonnquist (1971) corrects for converging head losses in the grid block containing the well; however, this method does not account for potential head losses across a skin zone or nonlinear head losses within the wellbore itself.

As mentioned above, the need to enhance the vertical discretization of the regional model might arise in isolated instances. In cases where new drilling has shown considerable variability within one of the three regionally delineated aquifer complexes or adjacent aquitards, and it is considered that additional model layers are required to provide a solution to the problem being investigated, then a new local model might be needed. This localized model should be informed by the regional model as a platform or starting point.

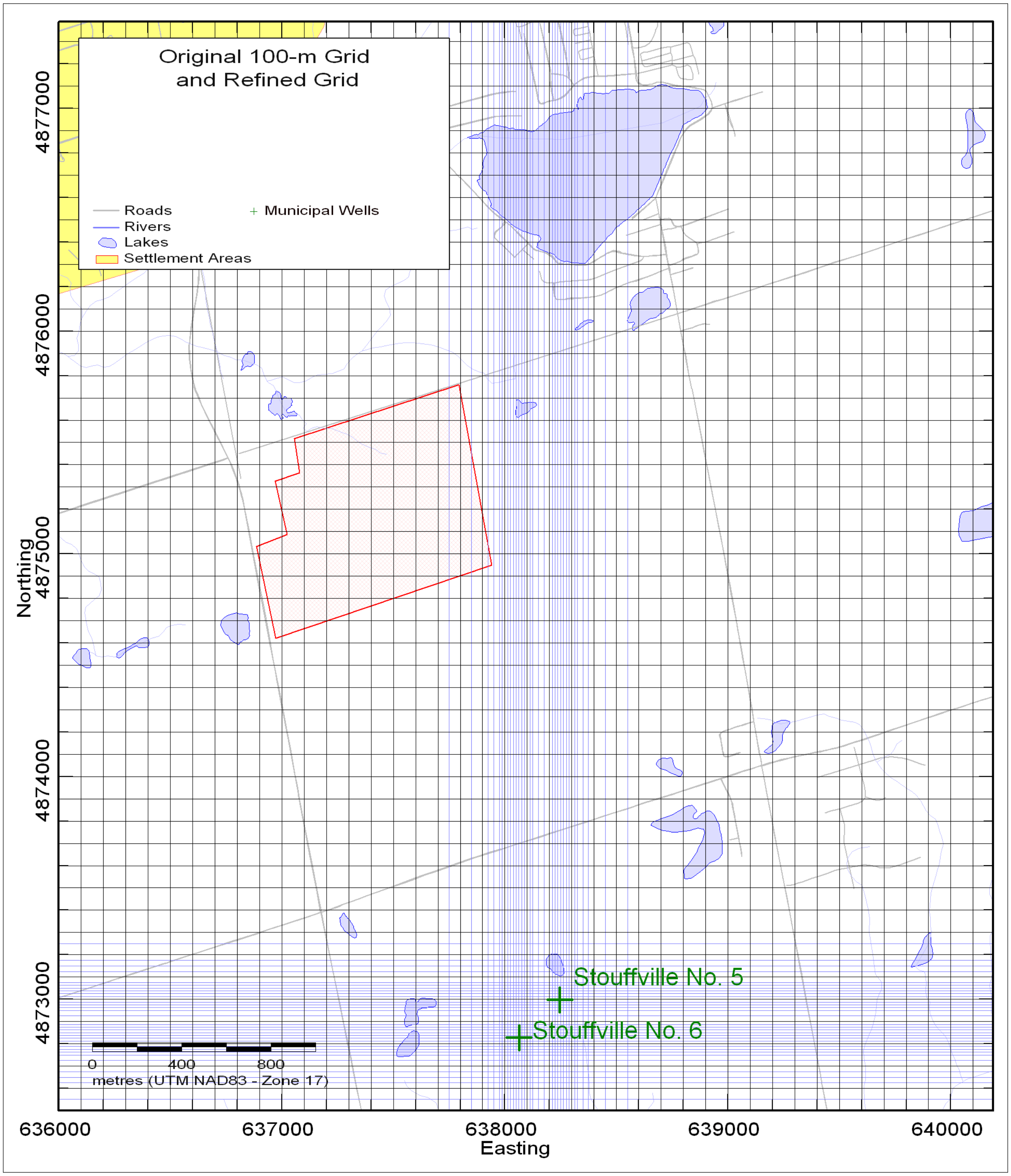

Figure 7: Stouffville area numerical model grid. Grid size ranges from 100m x 100m to 12.5m x 12.5m.
Figure from Wexler, 2007 personal communication.

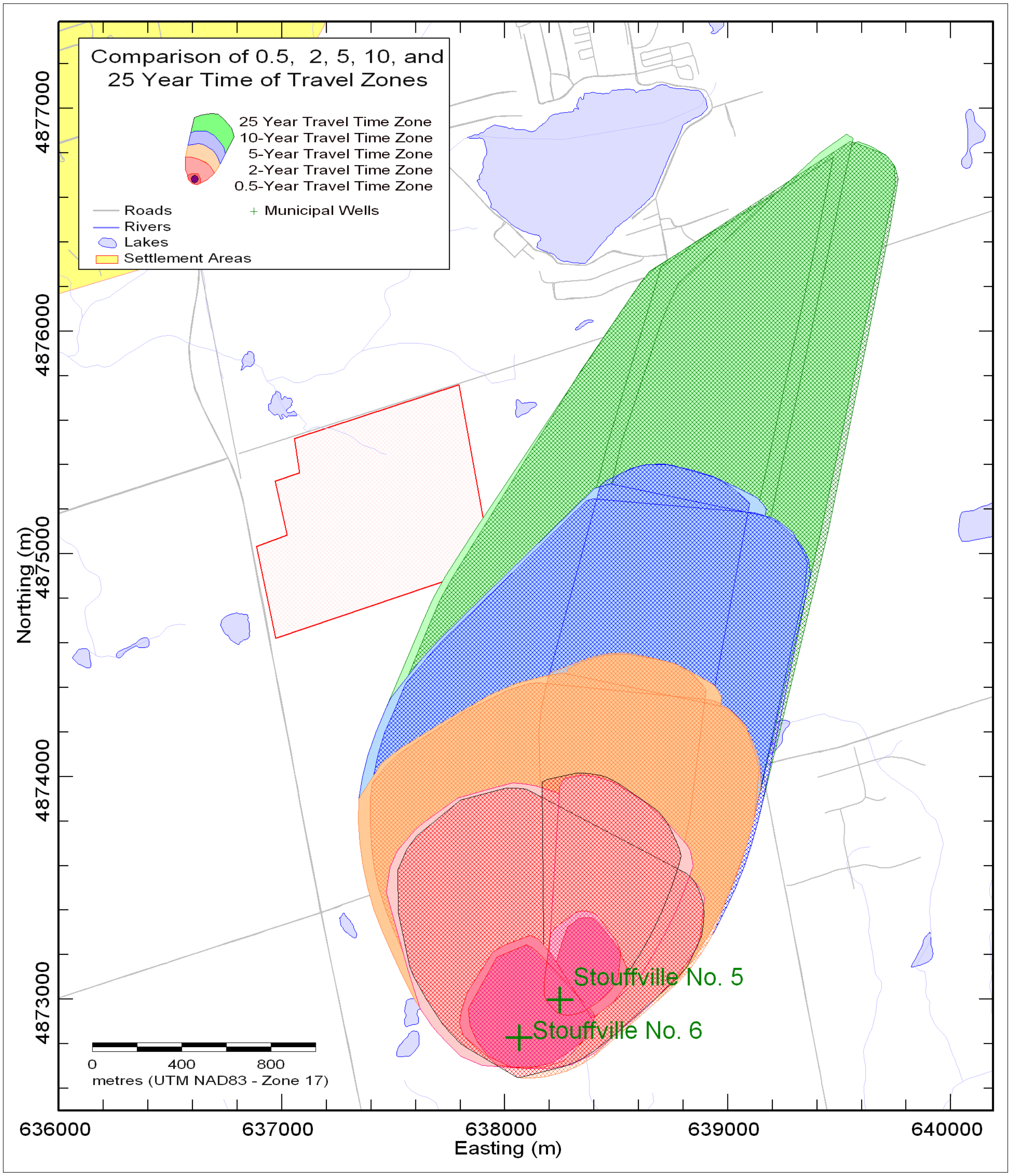

Figure 8: Comparison of Stouffville WHPA delineating using a 100m grid (light colors) and a 12.5m grid (dark colors).
Figure from Earthfx Inc., 2006.

For the vertical discretization into single layers representing interpreted hydrostratigraphic units, the YPDT-CAMC model recognizes that material properties vary within layers, and for aquifers this variability has been estimated as discussed previously in Section 2.1. In MODFLOW, properties and flow between vertically adjacent cells are averaged such that the generalized pattern of near horizontal flow in aquifers and near vertical flow in aquitards, as illustrated in **Figure 9,** may not be strictly achieved by discretizing aquifers and aquitards into single units. This will have implications to the simulated flow nets.

One way of modifying the simulated flow net would be to construct more model layers near hydraulic conductivity contrast interfaces. **Figure 10** illustrates a generic 4 layer (2 aquitards and 2 aquifers) system for consideration that has been horizontally discretized into 100m x 100m cells, similar to the YPDT-CAMC model. **Figure 11**a shows simulated flow vectors using MODFLOW for the four layer system, given the properties summarized on **Figure 10**. Note that because of averaging vertically between cell nodes that the flow vectors within the aquitards deviate from near vertical while flow vectors within aquifers deviate from near horizontal. **Figure 11**b illustrates flow vectors simulated by adding 1m thick model layers at aquifer-aquitard boundaries. In this system the upper aquitard is represented as 2 layers, an upper layer 9m thick and a lower layer 1m thick. The upper aquifer is represented as 3 layers (upper and lower 1 m thick layers and a middle 8 m thick layer), as is the lower aquitard (upper and lower 1 m thick layers and a middle 18 m layer). The lower aquifer is represented as 2 layers, the upper one being 1m thick and the bottom layer 9m thick. In this 10 layer system the flow net simulated using MODFLOW approaches the direction of flow lines expected and similar to the pattern exhibited in **Figure 9**.

It is important to note that the water budget for the both 4-layer and the 10-layer systems is the same. In other words, simulated flow in, out and through the two representations of the flow system are the same. The simulated movement of water particles or conservative contaminants through the two systems can also be investigated. To explore this, a particle was inserted into a cell within the upper aquitard (layer 1) near the centre of the 10,000m square domain. For both representations, the expected time of travel paths for transport of a conservative contaminant are shown on **Figure 12**a for the 4 layer model and **Figure 12**b for the 10 layer model. For both scenarios the particle traces are similar except that in the 4 layer model the simulated particle has traveled 300 metres further than the 10 layer model over the 450 year simulation period. Given that these are simulated estimates, the simulated difference in travel distances may or may not be significant depending on the scale of the problem being analysed.

Figure 12b also compares the simulated travel of a particle through the 10 layer system with a 100m grid (horizontal cells equal to 100m x 100m) and a 25m grid. Again there are differences in the simulated travel distances over the 450 year simulation period. In the 25m grid model, the particle enters the lower aquitard at a location 200m upgradient from the 100m simulated particle. Breakthrough to the lower aquifer occurs sooner and the particle is simulated to travel 600m further within the lower aquifer. Again, given that these are simulated estimates, the simulated difference in travel distances may or may not be significant depending on the scale of the application. The significance of these differences needs to be determined by the hydrogeologist charged with providing a solution to the problem at hand. As mentioned previously, considerations include making sure that any modeling efforts are consistent with local field-based observations and the objectives of the analyses.

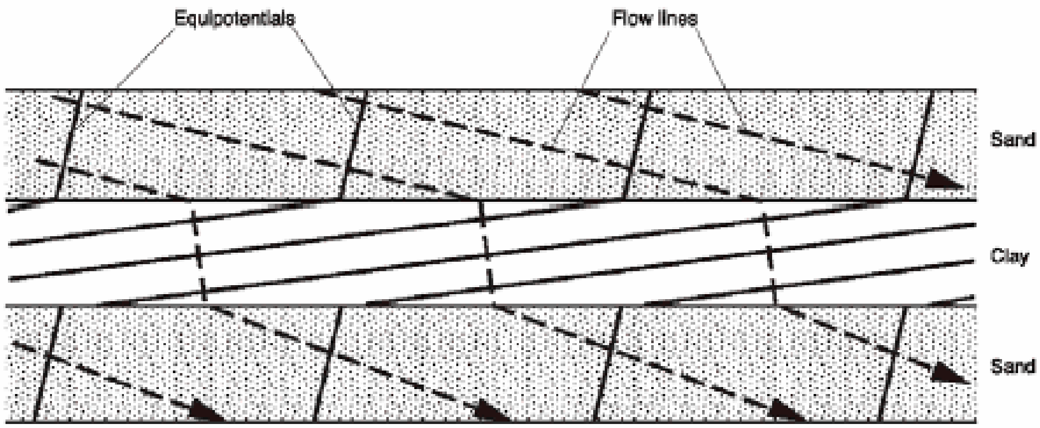

Figure 2-9. Possible pattern of flow in a cross section consisting of two high-conductivity units separated by a low-conductivity unit. (From McDonald and Harbaugh, 1988.)

Figure 9: Possible pattern of flow in a cross section.

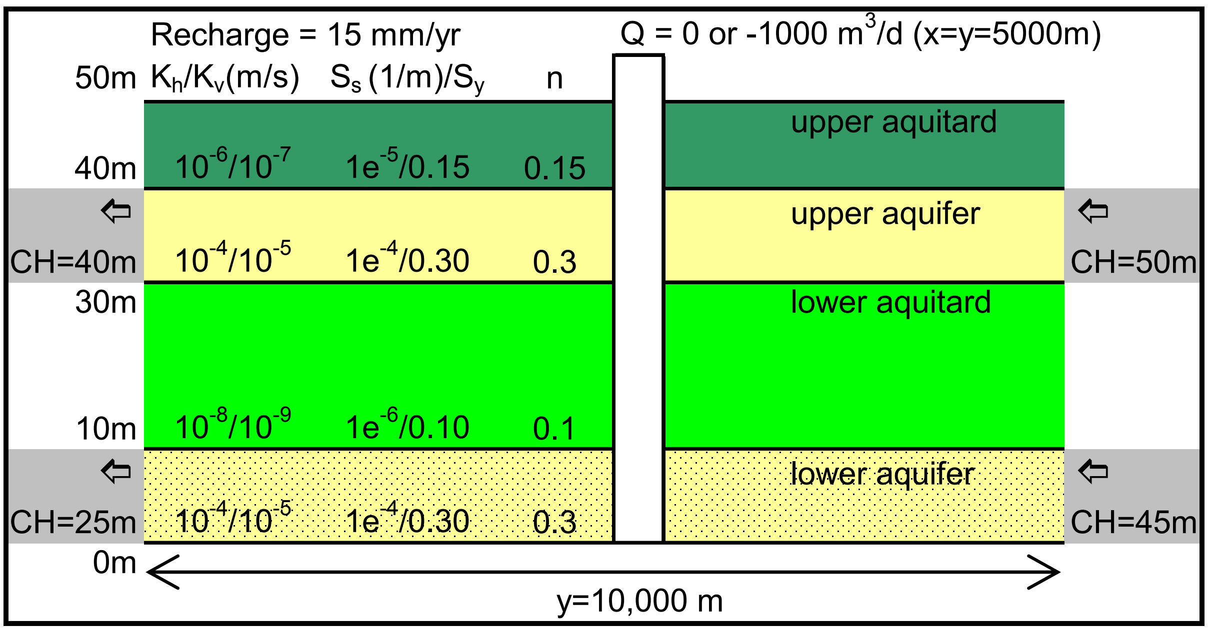

Figure 10: Generic 2 aquitard - 2 aquifer flow system.

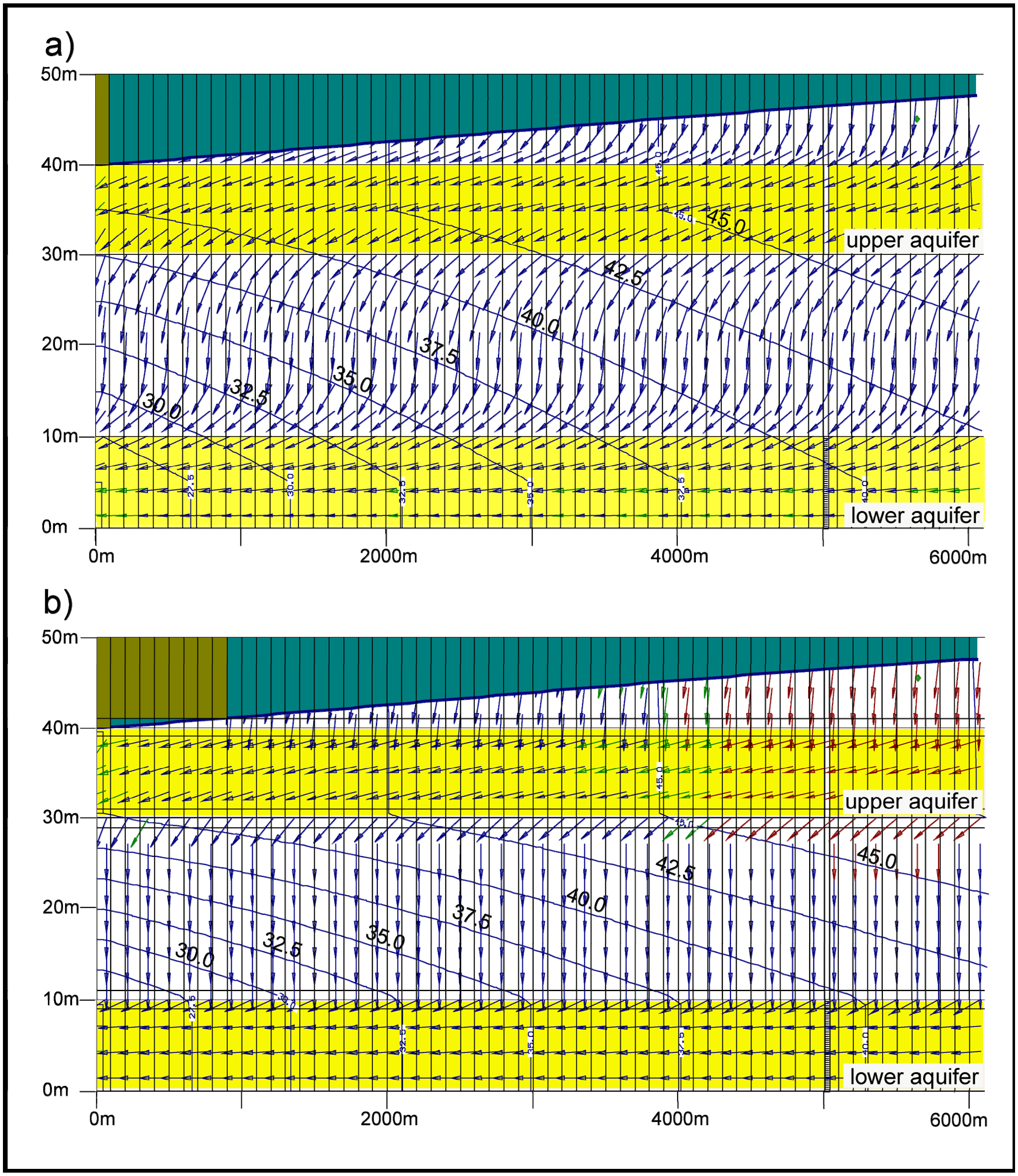

Figure 11: Simulated velocity vectors for generic 2 aquifer - 2 aquitard system for a) 4 layers and b) 10 layers. Velocity vectors not to scale.

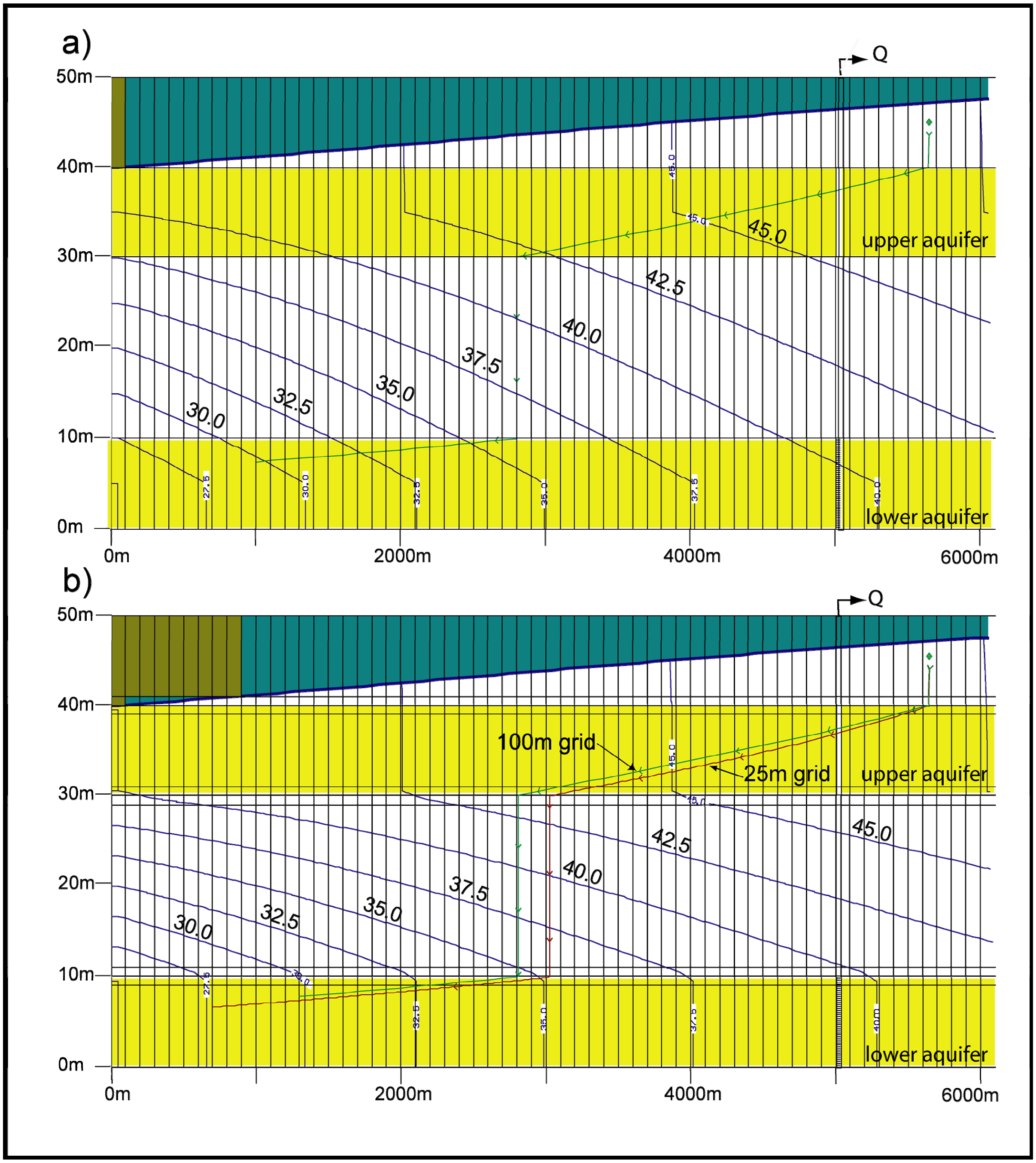

Figure 12: Particle traces for generic 4 layer system with a) 4 layers and 100m cells, b) 10 layers and 100m cells with particle trace for both 100m grid (green) and 25m grid (red) as labeled. Arrows represent simulated 50-year time of travel intervals for a total travel time of 450 years. No pumping (Q = 0).

3.6 Calibration

Current Model

The YPDT-CAMC numerical groundwater flow model is calibrated to measurements of hydraulic head from numerous data sets that have variable quality as discussed previously (*e.g*. MOE wells, conservation authority & municipal observation wells, consultant wells, etc.). Head calibration is undertaken for aquifer units only. A problem with the calibration head targets is that the water levels used to derive the potentiometric surface maps are taken from wells measured at different times of year and during different years (wet vs. dry) and therefore only represent an approximation of the true hydraulic head distribution. Measurement error and groundwater pumping can also contribute to water level variation. A variogram analysis indicates that there is an intrinsic variation in the water level data within the MOE water well database on the order of 4.5 to 8.4 m, depending upon which aquifer unit is being considered (Earthfx Inc., 2006)). The variogram analysis suggests that water level patterns can be correlated over large distances; however, the intrinsic error in the data must be recognized when using some of the datasets (e.g. MOE water well record information). In addition to hydraulic head calibration, model simulated groundwater discharge is calibrated to estimates of groundwater discharge made from continuous streamflow daily hydrographs and results from low streamflow surveys.

The comparison of model simulated output to observed data are then expressed as a series of statistics to illustrate the degree of fit (Earthfx Inc., 2006, p. 161-170). In general three calibration statistics are usually reported to illustrate goodness-of-fit: the mean error (ME), the mean absolute error (MAE), and the root mean squared error (RMSE). In an ideal world, all simulated values match observed values. In reality, residuals between simulated and observed values exist. Acceptable calibration statistics and simulated values depend on the objectives of the modeling exercise, the accuracy of the calibration targets, and the physical characteristics of the system being modelled. Further discussion of model calibration can be found in ASTM International Standards (ASTM, 2004; 2008a; 2008b).

Refinement Considerations for Local Scale Application

Checking and if necessary refining the model calibration to replicate locally observed field data is perhaps one of the most important exercises in applying the regional model to a local scale problem. Alternately, if may be more appropriate to consider a smaller local model with boundary conditions that are informed by results of the regional analysis, an informal conception of telescopic mesh refinement. As an example, consider **Figure 13** which illustrates a cross section through Richmond Hill, a typical ORM south slope area. Along the south slope of the ORM, groundwater discharges from the Oak Ridges aquifer complex leading to the formation of headwater streams. This discharge occurs where the water table or potentiometric surface intersects the ground surface. The regional YPDT-CAMC numerical model, for the ORM aquifer hydraulic head distribution, is calibrated to about +/- 7m, according to calibration statistics (Earthfx Inc., 2006). This means that overall, the averaged modeled heads are within 7 m of the targeted heads throughout the regional model area. When looking at the local area, this error may be significant. For example, on **Figure 13**, if the simulated potentiometric surface is 5m above the observed condition then the model generated groundwater discharge will occur further north and at higher quantities than observed. Similarly, if the simulated potentiometric surface is 5m lower than observed values, then the model generated groundwater discharge will occur further south than observed. For a regional numerical flow model, the groundwater discharge is often compared to streamflow hydrograph generated estimates at gauges remote from this headwater area. While the overall quantity may compare to that observed, the spatial distribution between the modeled flux estimates and observed values in the field may be different. This difference may be compounded as the size of the study area is reduced when considering more local problems.

Of course, the implicit consideration behind the above discussion is that there are local water level measurements, ideally collected at the same time that can be used to better calibrate the model locally. Alternatively, if local water level measurements are not available, perhaps due to an insufficient number and distribution of suitable observation wells, then there is the possibility that the headwaters of local streams could be used as a surrogate to determine a water elevation target. Care must be taken when using such indicators as a representative measure of the hydraulic head. Calibration of the model will involve adjusting some or all of the parameters discussed above including the geology, the hydraulic conductivity and the recharge. Considerable caution should be exercised before considering local revisions to the model structure. Any changes that are made will have to be introduced carefully to ensure a gradual transition between regional model versions.

In summary, when utilizing the regional YPDT-CAMC numerical model to address local scale problems, the simulated regional model output needs to be carefully compared to local observed information including groundwater discharge measurements (low streamflow survey results), groundwater level measurements, and any influences induced by pumping to determine the suitability of the calibration for the local area. This field observation information is critical to the process and should be collected and added to the database as part of the local study. The regional model should then be recalibrated to reproduce the field observations. By refining the model calibration for the local area, the regional calibration should also benefit.

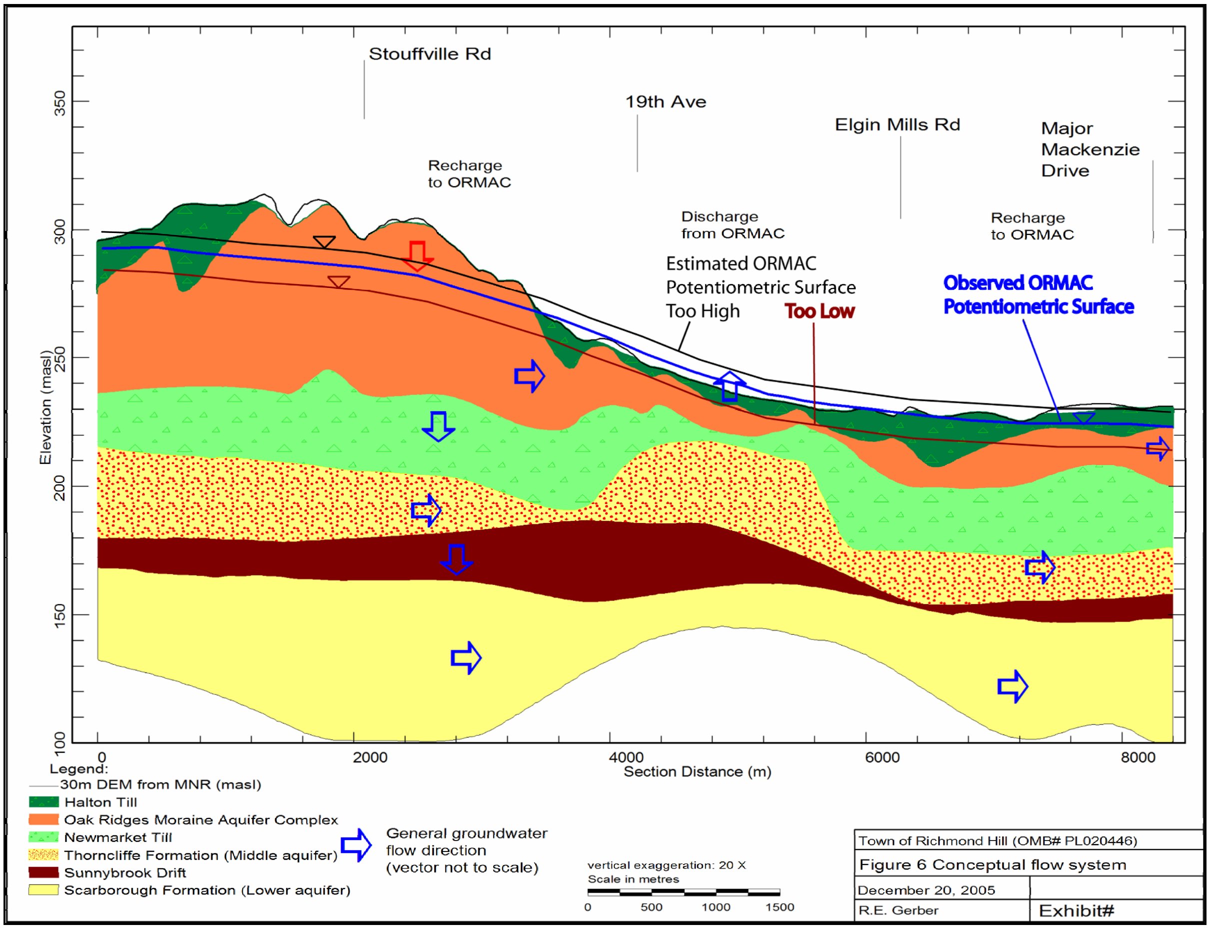

Figure 13: North-south cross section along Bayview Avenue, Richmond Hill.
Figure modified from Gerber (2005).

3.7 Steady-State versus Transient

The consideration of steady state versus transient modeling is not so much a regional versus a local scale consideration as have been the other topics addressed above. Never-the-less, in addressing local scale problems the question as to whether a steady state model is sufficient should be contemplated.

Current Model

As stated in Section 2, the current YPDT-CAMC model has been built as a steady state model, although for several projects in York Region it has been run in a transient mode to estimate the time-frame for potential flow system changes stemming from different groundwater pumping schedules at numerous locations. Natural flow systems exhibit variability on a range of temporal scales (*e.g.* hourly, daily, annually, long-term response to drought or water taking, etc.). Steady-state numerical models are designed to look at long-term average flow system conditions, albeit they can be adjusted to simulate average conditions, low saturation state conditions (*e.g.* drought), or high saturation state conditions (*e.g.* spring snow melt period in southern Ontario). A practitioner may utilize a steady-state numerical model to simulate the possible impacts of a pumping well by looking at the

estimated change in groundwater levels and the model estimated change in groundwater discharge to streams.
A very important point when considering simulated steady-state output is that time and storage are ignored. Any model estimated changes should therefore be considered as conservative in that the prediction is the ultimate change that may be expected, even though it might take many years for the groundwater system to fully respond to the changes that are being investigated. For example, numerous projects use steady state numerical models to estimate drawdown and change in groundwater discharge to streams as a result of a pumping scenario. When considering the model predictions one should be fully aware that these changes represent the estimated ultimate long term condition. It may be some time before any response is initially observed, and similarly it might take many years for the response to actually stabilize or reach the predicted steady state condition. Steady state estimates are useful to see where predicted changes may occur and what the ultimate response in the groundwater system might be. An important point that must be highlighted is that when evaluating the significance of predicted changes in the groundwater discharge to streams, it is important to assess the magnitude of the response with respect to the actual measured flow within the stream. It is also important to note that seasonal fluctuations of groundwater levels and discharge to streams occur. In many instances it may be completely appropriate to simulate long-term average conditions that ignore seasonal changes. The key is to recognize when they might be important. Haitjema (2006) has presented a simple criterion for assessing when steady-state approximations of transient flow are appropriate. Haitjema has shown that for a transient forcing function with period *P*, it is appropriate to use time-averaged boundary conditions and recharge rates when the following is satisfied:

$$\tau = \frac{SL^2}{4T}\frac{1}{P} > 1.0$$

Here *L* is the average distance between surface waters, *T* is the average transmissivity, and *S* is the storage coefficient. For seasonal fluctuations, the period *P* is one year.

In many circumstances, the predicted change in groundwater discharge and total streamflow may not be measurable and might not even be within the accuracy of the measurement instruments or techniques used. We do not need a numerical model to evaluate the gross change that a stress such as groundwater pumping will cause to streamflow. At the large scale, streamflow will be reduced by exactly the pumping rate.

Considerations for Local Scale Application

Refinement of the model is not the appropriate term to use in the case of considering whether a steady-state versus a transient model is the most appropriate. However if a transient analysis is required, it is again important that the model is calibrated to transient field observations before using the model to predict water level or discharge changes at unmonitored locations. This will provide some assurance that the model is reasonably predicting the groundwater system in a transient fashion. The main consideration in determining whether a transient model should be used is whether time is an issue. If the problem requires a temporal analysis, such as knowing how long it will take for a drawdown cone to fully develop, then a transient analysis is recommended.

To explore this further, the 4 layer generic flow system example summarized on **Figure 10** can be used to look at the simulated effects of pumping the lower aquifer at a rate of 1000 m^3/d from both a steady state and transient perspective. In this example the pumping well has been placed in the lower aquifer at the centre of the domain at x=y=5000 m. An observation well has been placed at the same location within the upper aquifer. Other observation wells shown on **Figure 14** are in the upper and lower aquifers at x=5000m and y=6000, 7000 and 8000m, or 1, 2 and 3 km upgradient from the pumping well. The figure shows the simulated transient responses of predicted drawdown at the observation locations for both aquifers. In a steady state simulation, drawdown is predicted at all locations. For the transient simulation, it is obvious in the figure that it takes some time for the predicted drawdown to stabilize, or to reach the predicted steady state drawdown (slope = 0). For example, pumping of the lower aquifer is predicted to induce a drawdown in the upper aquifer (5000A – upper aquifer) of 0.7m. The simulated transient response shown suggests that this drawdown won't be reached until approximately 75 years have elapsed. This time frame is similar for all other upper aquifer locations. The steady state predicted drawdown in the lower aquifer is approached much sooner, within 10 years in this case.

The evolution of the response to pumping therefore depends on where that response is being monitored. The evolution of the response will also depend strongly on whether the pumping is taking place in an aquifer that is confined or unconfined, and on the properties of confining units.

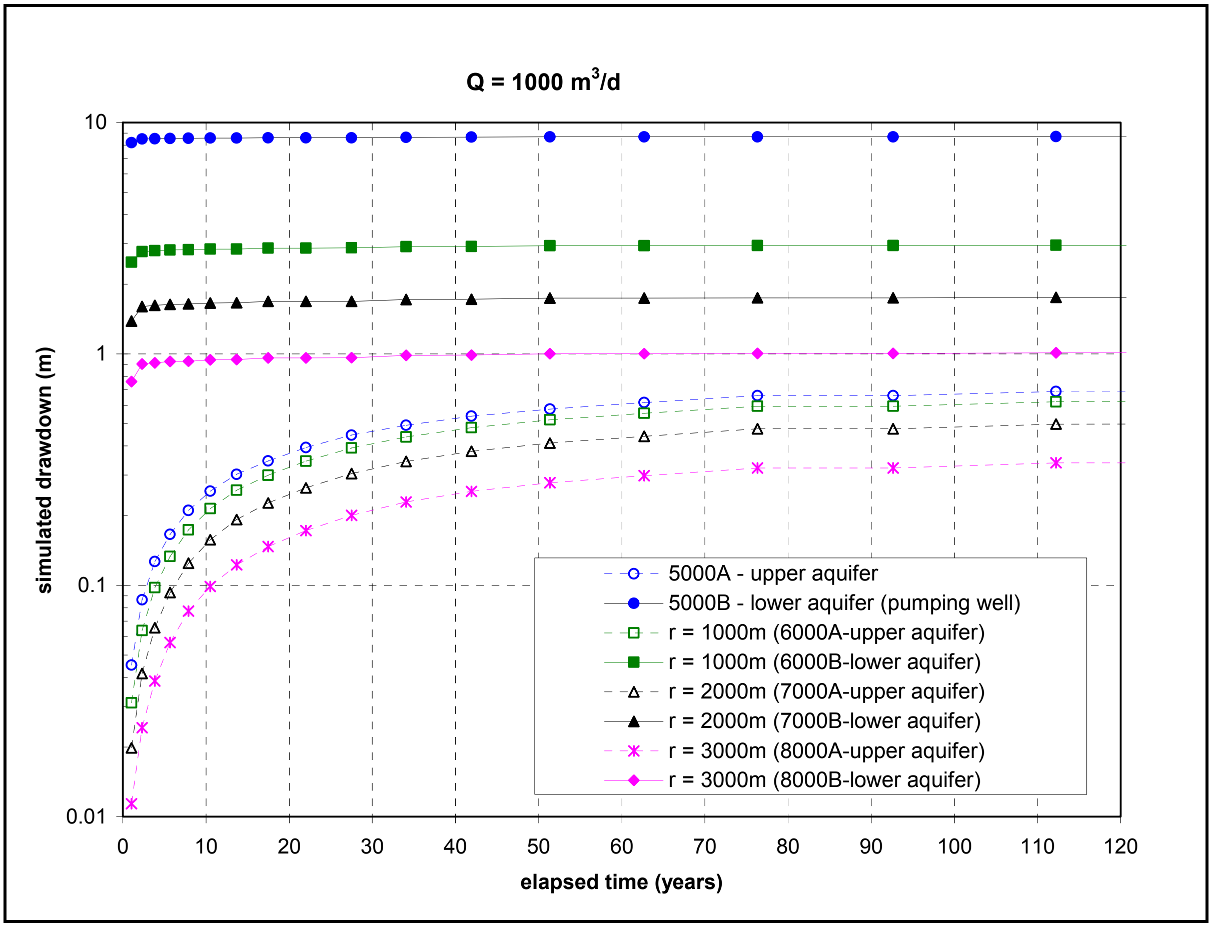

Figure 14: Simulated drawdown – 4 layer generic transient system.

A transient response is illustrated within the YPDT-CAMC study area at a long-term monitoring site (2/94) situated near Claremont (**Figure 15**). This location shows a long term response to regional pumping in the area. A piezometer nest was installed at this site with details of the monitoring intervals illustrated on **Figure 16**. Inspection of the groundwater level data in the various hydrostratigraphic units (**Figure 17**) shows a long-term drawdown trend within the Thorncliffe aquifer complex (2/94-2) overprinted on top of seasonal trends. To date, only the vertically adjacent piezometer (2/95-5b) shows a similar, although dampened, drawdown response. The shallow aquifer, the Oak Ridges Aquifer Complex, has yet to show any obvious response other than seasonal fluctuations during the thirteen years of monitoring. This is consistent with the generic case discussed previously in that predicted drawdown in a shallow aquifer from deeper aquifer pumping may take years to actually occur, obviously controlled by local hydraulic properties and conditions. Such long-term trends are impossible to fully capture in the context of a steady-state analysis. Long-term observation records are invaluable for assessing the sustainability of groundwater resources.

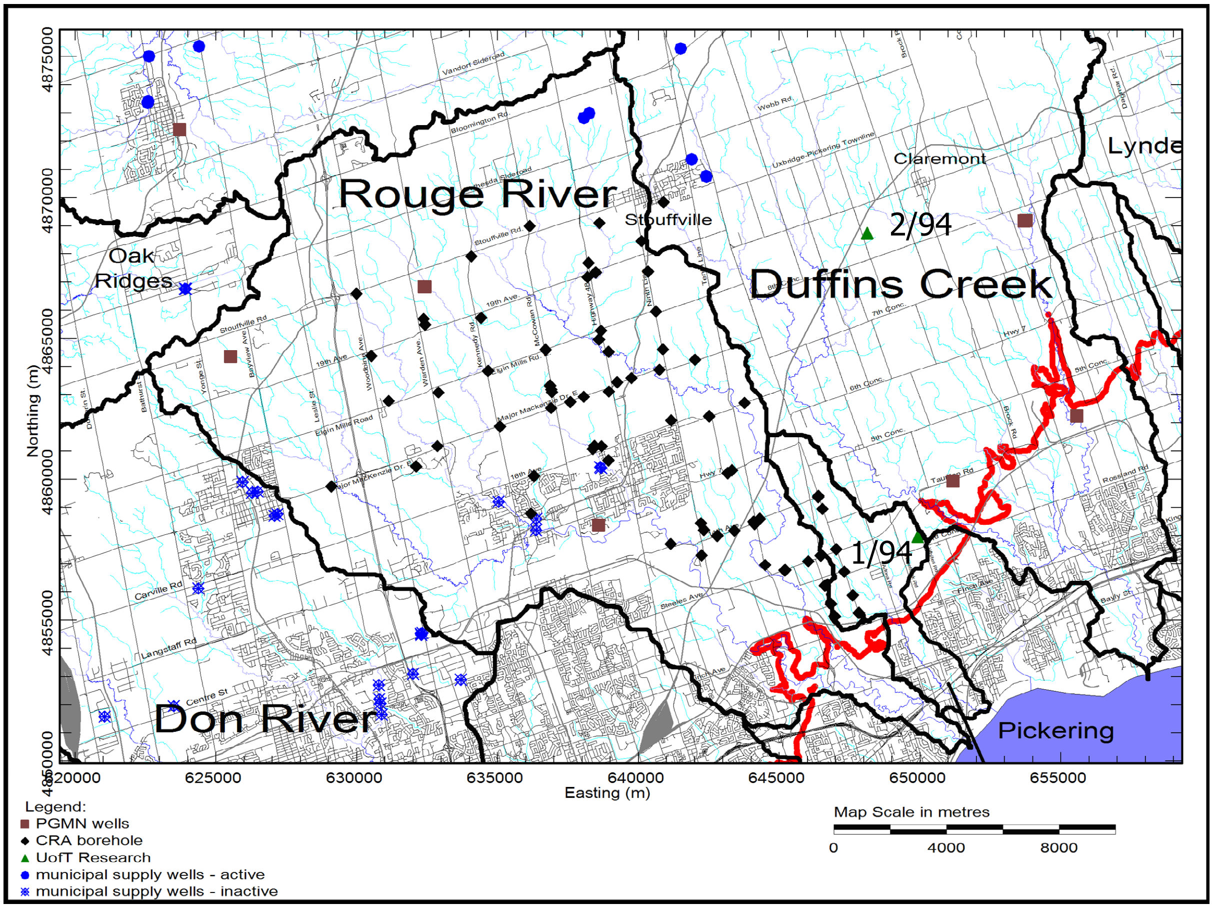

Figure 15: Monitoring well locations.

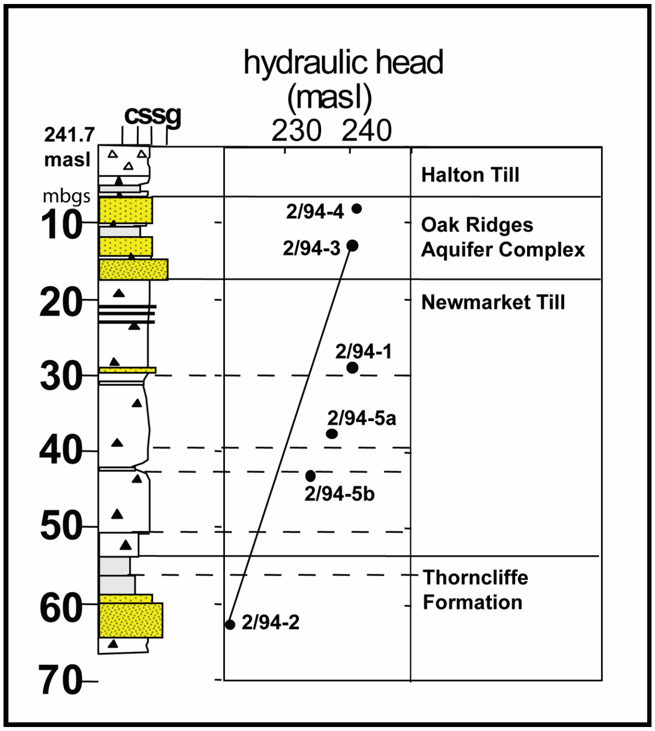

Figure 16: Geologic profile at monitoring site 2/94. Non-uniform hydraulic head profile through Newmarket till suggests variable hydraulic conductivity with depth within aquitard.

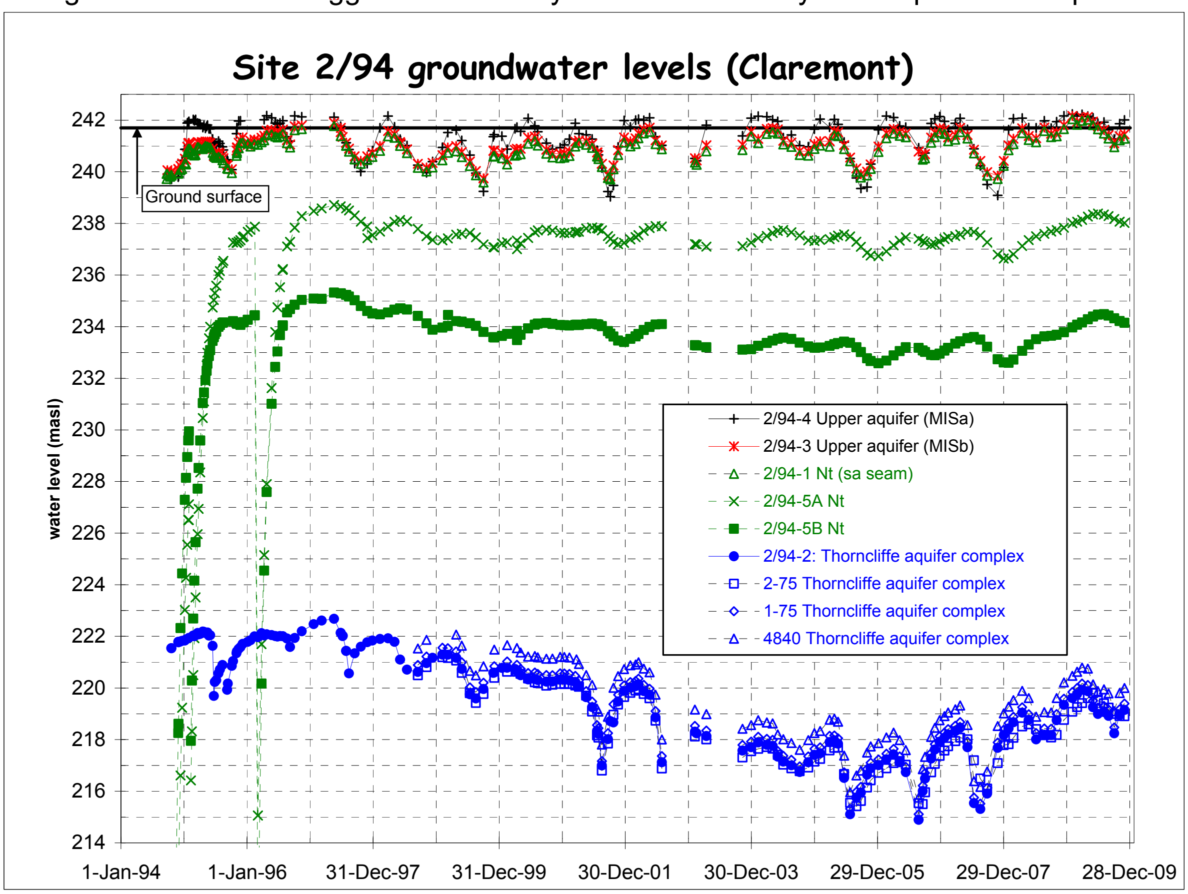

Figure 17: Groundwater levels at monitoring site 2/94.

4. SUMMARY & MOVING FORWARD

From the above discussions it is evident that the regional model can be used to address local scale problems, should modelling be necessary. The key is that the model can not be applied blindly without making adjustments or refinements to account for more locally derived field data and local understanding of the geology and the groundwater system. The goal is, through the use of accurate and well documented field data, to address and lower the uncertainty that is inherent in the groundwater flow model. Such refinements can be made to many different model parameters including the geological layer geometry, the hydraulic conductivity distribution, recharge rates and the vertical discretization of the layers. Discretization in the horizontal plane beyond the current 100 m x 100 m grid size does not appear to be warranted.

When using estimates derived from groundwater flow models two key points should be kept in mind:

- Models don’t make decisions – people do. The final decision on any hydrogeological problem is made by the practicing hydrogeologist. The model is only a tool that can assist the hydrogeologist in making decisions.
- Models don’t provide the answer – they may provide input to the answer. Given the inherent uncertainty in any groundwater flow model, it is dangerous to use phrases such as “The model says…” or “It has to be because the model said so.” The output from a model should still be subject to critical thinking before a final decision is made. When looking at model output always ask

    - Does the result make sense?
    - Is the result consistent with measured observations?

This document is part of a strategic approach to assist in moving forward to make good use of the YPDT-CAMC groundwater flow model(s). In addition, a modeling subcommittee of the Technical Steering Committee has been established to review and provide direction or comments to agencies wishing to use the model for different projects. This would ensure:

- That all agencies are kept abreast of different projects that are using the model. This would provide ideas on how the model could be applied by other agencies in the partnership;
- To assist various parties with the decisions on whether the use of the model is appropriate or not for various projects. That projects where the model was considered to be inappropriate for use would obtain impartial advice from the group so that they could reconsider whether the use of the model was the most appropriate path forward; and
- To attempt to ensure that all parties utilizing the model and output are aware of the limitations, assumptions, accuracy, etc regarding model input and output. In other words to attempt to foster responsible model use.

And finally, the first step that should be taken when applying the Oak Ridges Moraine regional groundwater model(s) for site-specific analyses is a careful checking of the results of the regional analysis against water levels from nearby dedicated observations for which time series data are available. In areas where these data are not available, the reporting of the analyses should indicate that model calculations are not constrained by observations and that data collected subsequently may be used to adjust local areas in the regional models.

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