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Coralie Charland

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

M.Sc. (Earth Sciences)

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FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

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the Vars-Winchester Esker System, South Nation River Basin, Eastern Ontario**

TITRE DE LA THÈSE / TITLE OF THESIS

Michel Robin

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Ian Clark

Fred Michel

Gary W. Slater

Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

VARIS-WINCHESTER ESKER CHARACTERIZATION STUDY:

**Conceptual and numerical hydrogeological model of the Vars-Winchester
esker system, South Nation River basin, Eastern Ontario**

Coralie Charland

Thesis submitted to the Faculty of Graduate and Postdoctoral Studies
in partial fulfillment of the requirements
for the M.Sc. degree in Earth Sciences

Ottawa-Carleton Geoscience Centre
and
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ABSTRACT

Buried esker systems are a major source of potable water in Eastern Ontario. Ever since the Clean Water Act was passed in 2006, efforts have been placed on understanding aquifers and characterizing watersheds in order to protect source water. This thesis focuses on one esker, extending from Vars to Winchester in the South Nation River watershed, which provides municipal water for seven villages – an estimated population of 17,000. The esker complex is conceptualized as a 50-km long deposit of glaciofluvial outwash high-permeability material that is generally surrounded by fine, low permeability materials, except in a number of locations where the esker outcrops at ground surface. The complex recharges at its northern- and southern-most areas, which correspond to topographic highs; it discharges in a topographically low area at its center near the village of Embrun. Regional stratigraphy was simplified for modeling purposes and brought down to six hydrostratigraphic units, two of which represent the esker: a coarser core, composed of a mixture of coarse sand and gravel, and sandy fan deposits.

A three-dimensional hydrogeological model was developed using a finite element groundwater flow system, FEFLOW. Recharge and hydraulic conductivities were adjusted during calibration. Calibration was assessed using the mean error of residuals, standard deviation of residuals and normalized Root Mean Square calculations; correlation was estimated using the determination coefficient and Pearson's coefficient. Results favour the conceptualization of the esker as a continuous, heterogeneous deposit comprising a gravelly core and sandy fans (ME=-4.33m, RMS=5.67m, n=18 wells in close proximity of esker); however, mean residuals are not significantly different when testing the discontinuous and homogeneous esker hypotheses. Sensitivity analyses testing the model's response to recharge and pumping showed that the system is relatively resilient; however, our better judgement tells us that this is an artefact due to boundary conditions and not an adequate prediction of what may happen. Nevertheless, we hope this model will be a facilitating tool for understanding, managing and protecting the aquifer's resource.

RÉSUMÉ

Les systèmes d'eskers enfouis sont d'importantes sources d'eau potable dans l'est ontarien. Depuis 2006, en Ontario, de nombreuses démarches visant à caractériser les bassins versants et les aquifères d'eau souterraine ont été lancées dans un souci de conformité avec la Loi sur l'eau saine, en vue de protéger les sources d'eau potable. Cette étude se penche sur un esker situé au sud du bassin-versant de la rivière Nation Sud, s'étendant sur 50 km de Vars à Winchester. C'est un réservoir d'eau potable desservant sept municipalités, soit environ dix-sept mille personnes. Le système a été sondé et conceptualisé comme un épandage fluvio-glaciaire hautement perméable enfoui dans des dépôts fins et peu perméables, sauf à quelques endroits où l'esker apparaît à la surface du sol. Les zones de recharge de l'aquifère sont situées à des hauts topographiques dans les extrémités nord et sud de l'esker; l'esker contribue un débit aux rivières près d'Embrun. La stratigraphie régionale a été simplifiée en six couches ou unités hydrostratigraphiques, dont deux représentent l'esker : le centre grossier, composé de sable et de gravier, et les dépôts sablonneux du cône de déjection.

Un modèle hydrogéologique numérique en trois dimensions a été créé grâce à un logiciel de formulation par éléments finis, FEFLOW. L'infiltration et la conductivité hydraulique ont été ajustées lors de la calibration. Les critères de calibration rapportés sont les suivants : l'erreur moyenne des résidus, l'écart-type des résidus, la moyenne quadratique normalisée, ainsi que le coefficient de détermination et le coefficient de corrélation de Pearson. Le scénario présentant l'esker comme un dépôt continu et hétérogène a généré les meilleurs résultats (EM=-4.33m, MQ=5.67m, n=18 puits à proximité de l'esker); cependant, les erreurs moyennes n'étaient pas significativement différentes entre ce scénario et les hypothèses de discontinuité et d'homogénéité. Lors des analyses de sensibilité visant à évaluer comment le modèle réagit à la sécheresse et à un stress de pompage accru, le système s'est montré beaucoup moins sensible que prévu. Nous interprétons ce résultat comme une conséquence des conditions aux limites et non comme une prédiction plausible de ce qui pourrait advenir. Nous espérons néanmoins que ce modèle servira d'outil de facilitation pour la compréhension, la gestion et la protection des ressources de l'aquifère.

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CHAPTER 1: INTRODUCTION

1.1 Background

Water and human health have always been and continue to be a primary concern to people. The vulnerability of communities to water supply, even in water-rich areas, was tragically exemplified in 2001 at Walkerton, Ontario, when people died as a result of the municipal water supply being contaminated by *E.coli* bacteria. This unfortunate incident prompted the Government of Ontario to enact source water protection measures. As a result, new regulatory measures about water supply management and practices were enacted (Source Water Protection regulations, fall 2005; Clean Water Act, 2006), and regional studies were initiated by conservation authorities across Ontario under the direction of the Ministry of the Environment (MOE) and the Ministry of Natural Resources (MNR). Since then, municipalities and their collaborators have been active in implementing the plans for overall technical assessment of Ontarian watersheds, which will ultimately result in safeguarding human health by protecting source water.

Ontario's Clean Water Act regrouped the 36 Conservation Authorities across the province into 19 Source Water Protection Regions (SWPR). The region of interest for this study is the Raisin-South Nation SWPR in Eastern Ontario. The overall watershed assessment started with a detailed characterization of the physical system (RRCA-SNC, 2006; WESA, 2006), and was followed by the development of a regional-scale Tier 1 water budget (RRCA-SNC, 2007a). Tier 2 and 3 are presently underway to provide local assessments of municipal water sources in terms of potential risks to both water quantity and water quality. The culmination of the process will be 5-year source water protection plans across the province.

In Eastern Ontario, water is provided by a number of regional aquifers of varying areal extent. Of particular importance are three major esker systems that are partially buried in relatively low permeability sediments. These long glaciofluvial features were first mapped in the region by Gorrell in 1991 (Figure 1). These eskers were deposited in a roughly north-south orientation by the Laurentide Ice Sheet during its retreat, near the end of the

Wisconsinian glaciation, about 10,000 years ago. They were subsequently buried by sediments of the Champlain Sea. Today, they are significant municipal water sources extending up to 50 km in length – which makes them some of the longest esker systems in the world. With the realization of their importance as potable water reservoirs and the knowledge gaps with respect to their size, location and flow dynamics, the Eastern Ontario Esker Characterization Project (ECP) was born. The ECP, initiated by the Raisin-South Nation Source Protection Region, is a joint project involving the South Nation Conservation (SNC), the Geological Survey of Canada (GSC) and the University of Ottawa (UO). Project funding was provided by the Ministry of the Environment (MOE), the Ontario Geological Survey (OGS) and the Eastern Ontario Water Resources Committee (EOWRC). The project also benefitted from many in-kind contributions from SNC, GSC and UO.

The focus of this study is one esker system in particular that extends from Vars to Winchester, south-east of Ottawa, in the South Nation River watershed (Figure 1). The esker is a seemingly continuous, sinuous deposit of highly permeable sand and gravel, stretching over a distance of approximately 50 km, and mostly buried under fine, low-permeability marine deposits.

The Vars-Winchester (VW) esker provides a reliable potable water supply for seven municipalities sharing the resource. It is therefore of utmost importance to gain a better understanding of the VW system, its geology, as well as groundwater flow dynamics within and around it. To this end, the objective of this thesis was to construct a three-dimensional numerical hydrogeological model of the esker complex, to calibrate it and to perform sensitivity analyses on model parameters. The model is a useful visualization and prediction tool to support decision making for general water resource planning and source water protection plans for municipal and residential water supplies. It will provide a basis for further Tier 2 and 3 water supply assessment work.

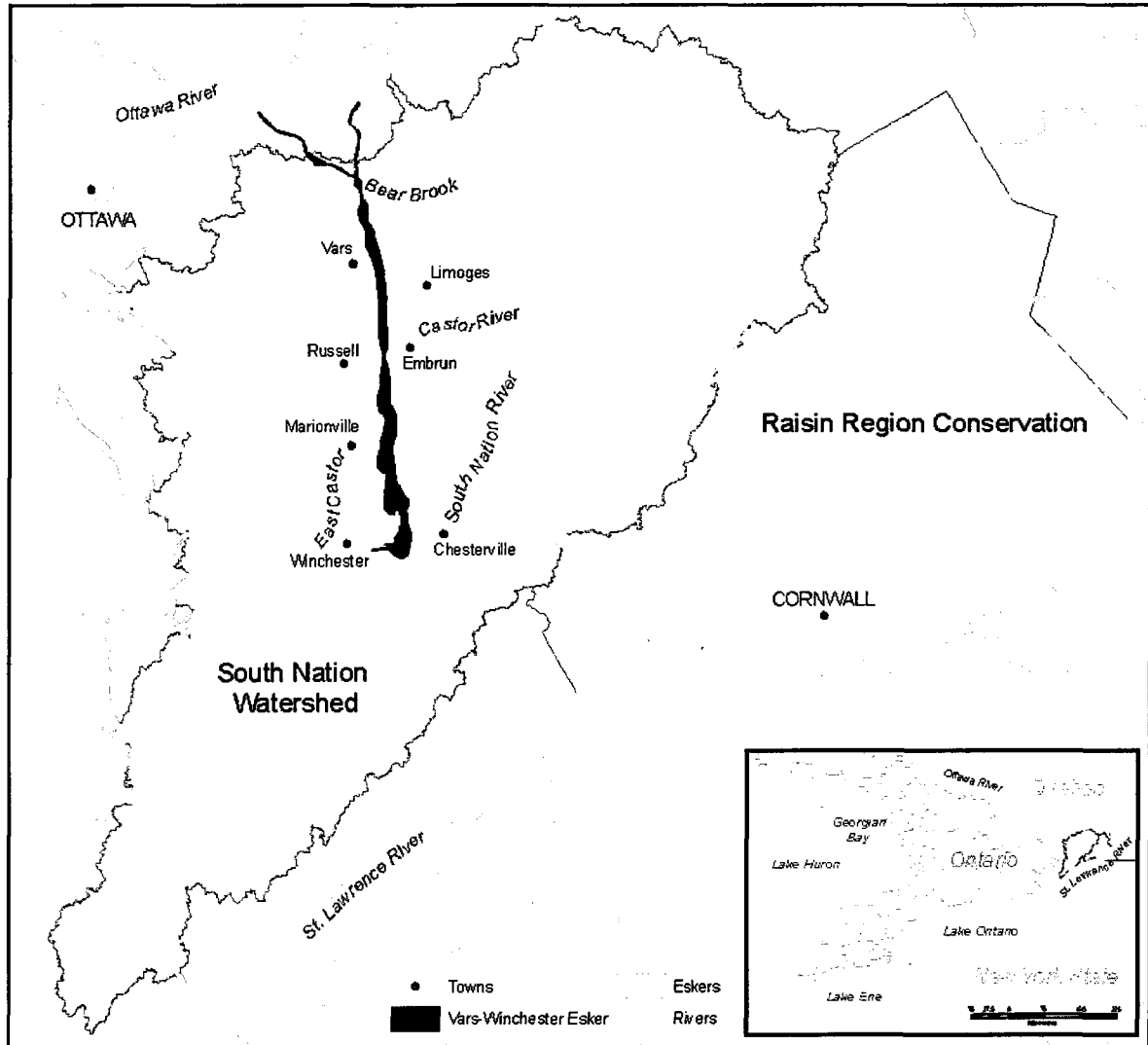


Figure 1: Esker distribution in the South Nation River watershed (Gorrell, 1991 adapted by GSC, 2007).

1.2 Objectives

The objective of the ECP is to gain a better understanding of the buried esker systems of Eastern Ontario, in terms of their geology (geomorphology, stratigraphy, and depositional history) and their hydrogeology (capacity to store and transmit water, flow dynamics of the system). This study, which is part of the ECP, focuses on the Vars-Winchester esker system in particular, because it is the largest esker South-East of Ottawa and because it is a potable water supply for the municipalities of Vars, Limoges, Russell, Embrun, Marionville, Winchester and Chesterville.

The secondary objective of this study was to create a numerical hydrogeological model which approximated groundwater behaviour within and around the VW esker system. This objective was met by using a “new” finite element tool called FEFLOW, which is a finite element subsurface flow and transport simulation system. This program was developed by the Institute for Water Resources Planning and Systems Research (WASY), the German branch of the research and consultancy organization, Danish Hydraulic Institute (DHI). The specifications and reasons for selecting this particular computer program are described in section 3.1.

The final outcome of this study is a useful visualization and predictive tool, which can be used by the conservation authority to help in their efforts to manage the esker’s water resources and develop Source Water Protection plans.

1.3 Literature review on esker modelling

Eskers are deposits that can manifest themselves in the landscape as sand ridges or be totally inconspicuous when buried. They are a type of ice-contact glaciofluvial deposit. When glaciers melt, meltwater and sediments are washed out from within or underneath the glacier, forming either enclosed (sub- or intraglacial) tunnels or open channels (crevasses) in the ice (Drewry, 1986; Fard et al., 2007; Cummings et al., 2007). They leave a trail of sediments in the channels, which are usually in the same axis as the direction of glacier retreat, perpendicular to the ice margin. In the case of subglacial tunnels, called R-channels, a peculiar situation arises where meltwater erodes the ice upwards instead of the glacier bed (in most instances, bedrock), sometimes to the point of roof collapse (Cummings et al., 2007).

Eskers are typically described as “sinuous, narrow, steep-sided ridge[s] composed of irregular stratified sediment” (Drewry, 1986), mostly sand and gravel. In fact, their geometry can vary widely and result in simple ridges, beads, networks, fan complexes, and hummocky deposits (Gorrell and Shaw, 1991; Brennand, 1994). The geometry of a particular esker depends on its depositional environment: tunnel fills may result in either continuous or

segmented (long-beaded) ridges, while subaqueous fans result in highly segmented (short-beaded) ridges (Warren and Ashley, 1994).

There is no universally applicable model for the origin of esker deposits (Fard and Gruszka, 2007). For this reason, deposition models and three-dimensional geological modelling are typically the primary goal of esker studies, as these features often reveal complex internal geometries and surrounding glacial, glaciofluvial and glaciolacustrine deposits. These geological models integrate a variety of sedimentological techniques used to investigate esker structure: lithofacies, sedimentary structures, and outcrop descriptions, core sampling and drilling profiles, paleocurrent data, and ground penetrating radar surveys (Artimo et al., 2003; Fard and Gruszka, 2007; Aspridon and Aigner, 1999; Warren and Ashley, 1994; Gorrell and Shaw, 1991; Makinen and Artimo, 2007; Bolduc et al., 2005).

Inferring the deglacial environment of eskers is beside the scope of this study (see Cummings, 2007); however, a sound understanding of the geology of the system is a key component to hydrogeological conceptualization. Although hydrogeological models in general are present in scientific literature and common in consultancy work, hydrogeological esker models are rare if at all present in reference databases. The completion of esker geological models and the development of flow analysis programs for eskers are presently active areas of research, which will meet the increasing need for groundwater management of these important resources.

1.4 Study methodology and general approach

The present study is based on a number of previous and concurrent studies that provided the building blocks to the conceptual and numerical models. Some focused on the geomorphology and geological origin, while others aimed at determining specific parameters that are required in the numerical model (e.g. hydraulic conductivity).

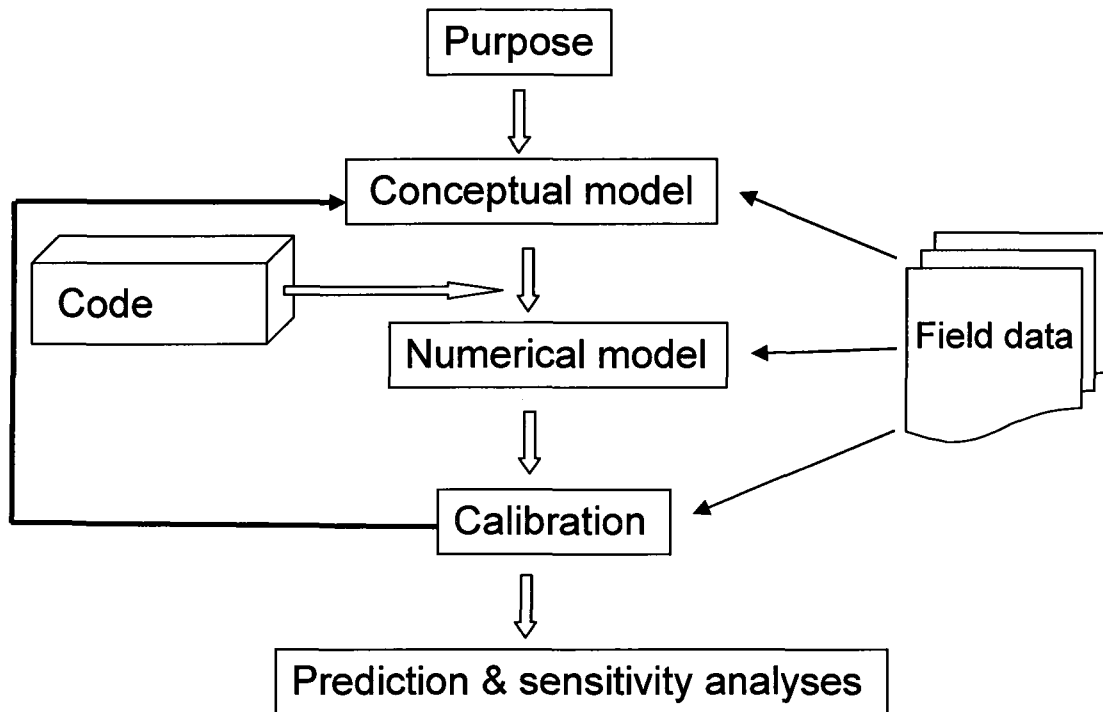
The geological aspect of the ECP was investigated by the GSC through traditional 2-D geological mapping, sedimentological studies, outcrops and core log descriptions, geophysical surveys (Cummings, unpublished, 2008; Pullan et al., 2007). Results of these

studies are described in more detail in section 2.2. This work was critical to make educated decisions about the structure and hydrogeological parameters of the system.

The hydrogeological aspect of the ECP was developed by the SNC and students at the University of Ottawa. In particular, the interaction between the esker groundwater and the surface water of streams and rivers crossing the buried esker was examined. Areas of groundwater discharge were identified using an electrical conductivity and temperature probe that was dragged along the bottom of rivers crossing the esker (Bustros-Lussier, 2008). Piezometers, open-top and closed-top seepage meters were installed in rivers and ditches to try to quantify the interactions between surface- and groundwater (Sargent, 2007; Cooper, 2008; Charland, unpublished data, 2007-2008). Water budgets were calculated for the region (RRCA-SNC, 2007a) and the Maple Ridge fan complex (Cooper, 2008) in an attempt to establish the relative importance of lateral influx into the esker. Previous governmental and consultant reports and maps were also compiled into a database (SNC), extrapolated to create surface maps, and to carry out statistical analyses that ultimately served in the modelling process. Methods used in these studies are presented in Appendix A; pertinent results are presented in section 2.3.

The results of these studies have either been integrated into the numerical model of this study or compared to simulation runs to assess their quality. Field data are a crucial component of all steps of model construction, from its conceptualization to its calibration. For this reason, as more information becomes available and as higher quality data are obtained, the model should be updated accordingly.

The typical protocol for building a numerical model can be simplified into five main steps which are represented in the flowchart below:



This thesis is structured based on this simple design. It begins with defining the purpose of the study (defined above in section 1.2), and draws the conceptual model of the system (Chapter 2), including details of the geology (topography and stratigraphy) and hydrogeology (hydrostratigraphic layers, the model boundaries and boundary conditions). The construction of the numerical model (Chapter 3) is then explained. Model calibration is the process by which the model input parameters are adjusted to produce water levels that reproduce reality as closely as possible; it is addressed in Chapter 4. The thesis continues with sensitivity analyses (Chapter 5) which identify the parameter that impact the model results the most, in order to help focus future research efforts. Finally, the thesis closes with concluding remarks (Chapter 6) that include recommendations for future work.

CHAPTER 2: CONCEPTUAL MODEL FORMULATION

2.1 Regional setting

The Raisin-South Nation SWPR is comprised of the Raisin and South Nation watersheds as well as several small watersheds that drain directly into the Ottawa and St. Lawrence Rivers (Figure 1). The region extends over approximately 661,000 hectares (6610 km²) and presents a generally flat landscape, with some exceptional topographic surges from bedrock outcrops and the occasional rolling hill (which can be, in some cases, an esker ridge). The land is dominantly used for agriculture, such as cattle production and farming of hay and cereals, with some minor forested and wetland areas (Figure 2). More information about land use can be obtained from the 2006 Census of the Agriculture and Economic Development Policy Branch for the Eastern Ontario Region, available online.

Groundwater is the major source of potable water in the SWPR. Local farmers, residents and municipal water supplies depend on good quality groundwater. The eskers (indicated in orange in Figures 2 and 3) constitute a significant resource of drinking water for local communities; the VW esker in particular is the municipal water source for seven communities with a combined population of approximately 17,000 (Di Iorio and Chapman, 2007). The eskers are also exploited by a number of sand, gravel and aggregate companies.

A number of rivers and streams make their way through the area. The ground is poorly drained, due to the geology and shallow overburden (less than 80 meters thick), and the water table is typically close to the surface. Topography ranges from approximately 35 to 120 meters above sea level (Figure 3).

Precipitation varies seasonally with a regional annual mean ranging between 800-1000 mm. Runoff, which is the water that goes directly to lakes, rivers and wetlands, is estimated at 200-400 mm. Evapotranspiration, the water which returns to the atmosphere through plant and sun interactions, estimated at an actual annual average of 500-600 mm (MNR, 1984;

RRCA-SNC, 2007). The remaining 0-300 mm enters the ground as infiltration or groundwater recharge.

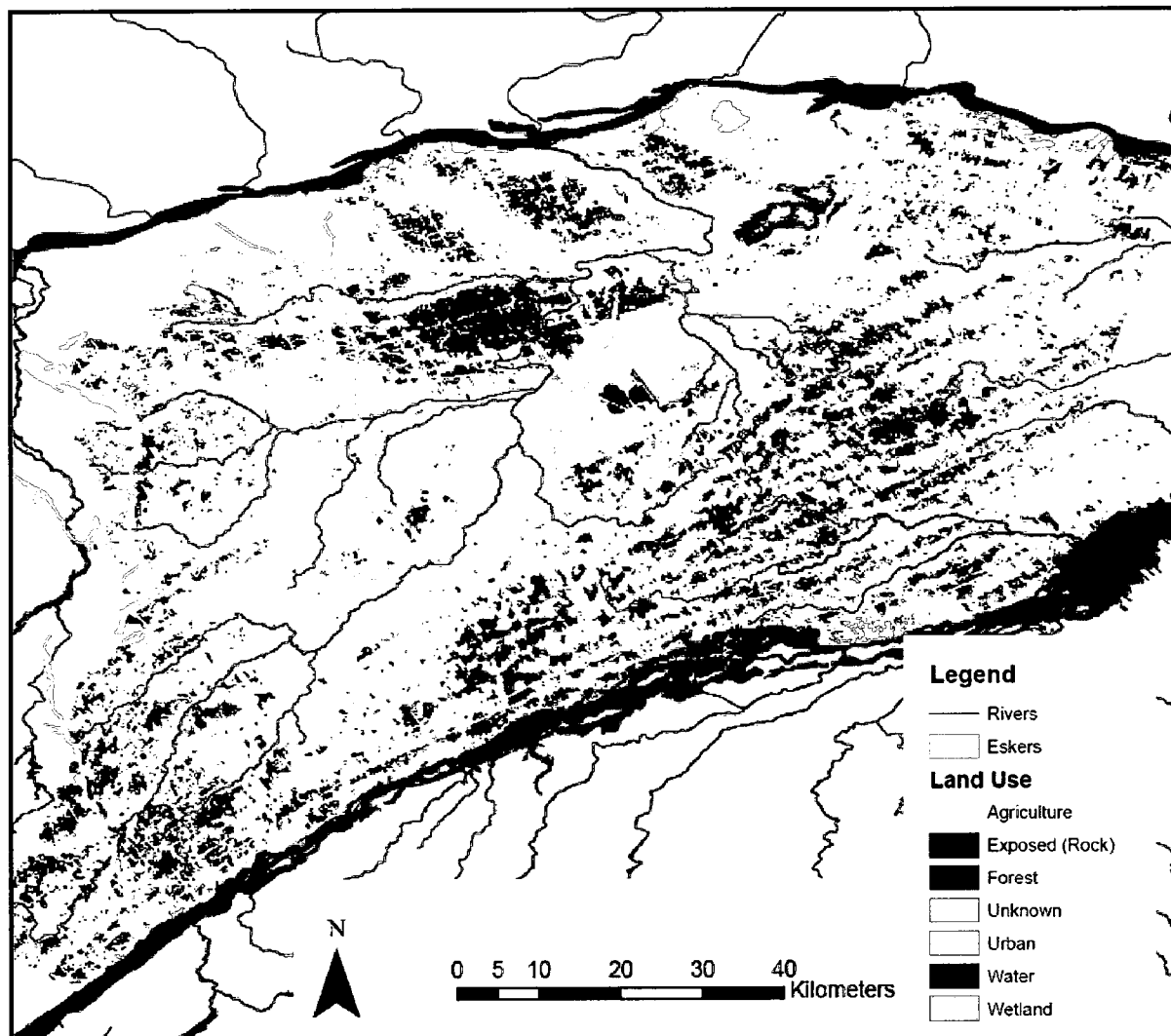


Figure 2: Land use classification in Eastern Ontario.

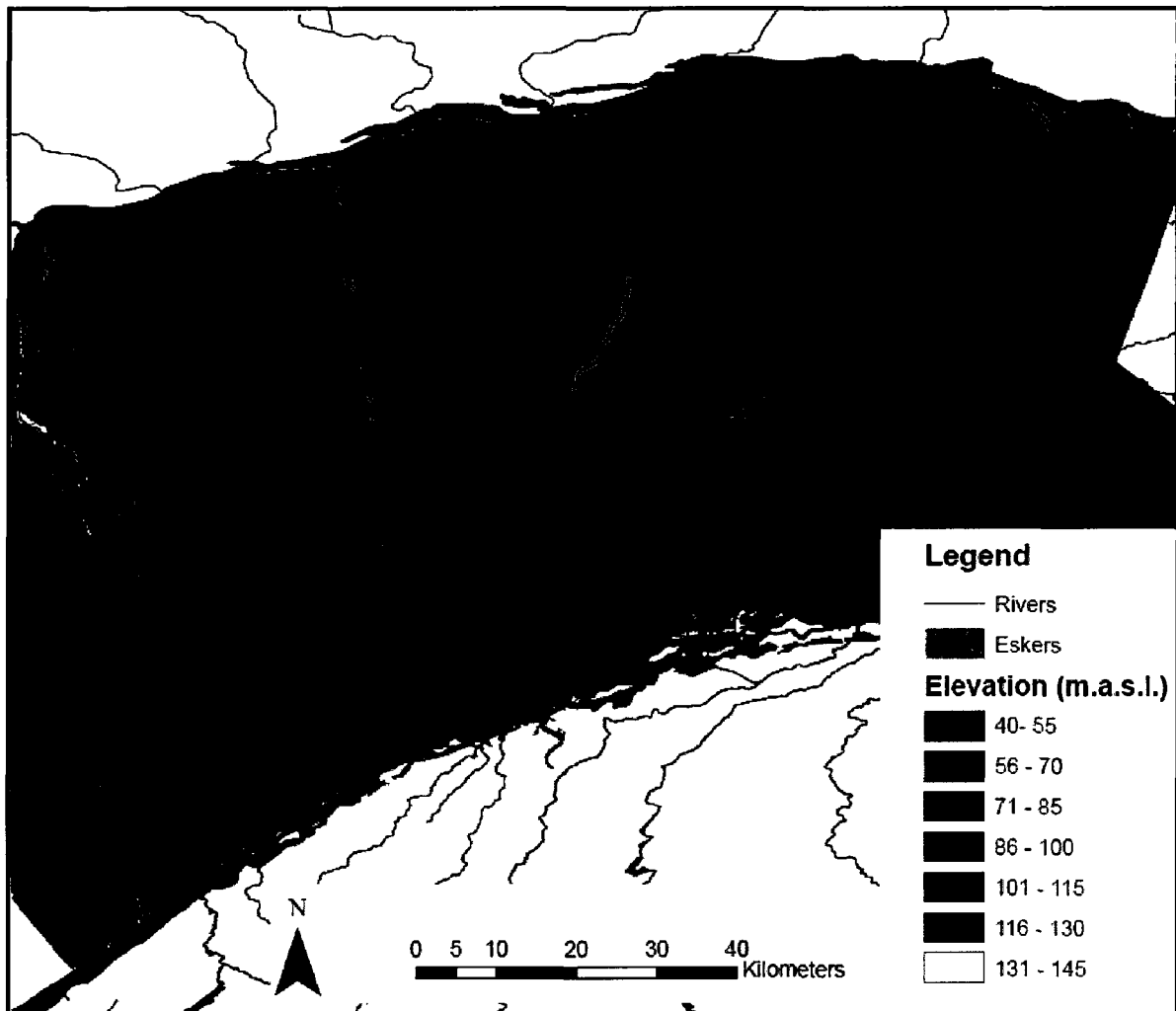


Figure 3: Topography in Eastern Ontario. Elevation in meters above sea level (m.a.s.l.).

The region is located in a physiographic area known as the Ottawa-St. Lawrence Lowlands. The bedrock is highly deformed metasedimentary rocks of the Grenville Province (Precambrian and Palaeozoic in age), overlain by Quaternary (Pleistocene and recent) unconsolidated deposits. The Quaternary geology is a result of the advancement and retreat of the Laurentide ice-sheet during the Wisconsinian stage (Late Pleistocene).

A regional conceptual geological and hydrogeological model was first proposed in a consultant report (Draft Watershed Characterization, WESA, 2006). The data used to generate this model are compiled in an extensive hydrological and hydrogeological

information database created using SiteFX, an Environmental Data Management System developed by Toronto-based consulting firm EarthFX. This database has been populated since 2005 by WESA and SNC. It will be referred to in this thesis as the “SNC database”. For more detailed descriptions of the units of the stratigraphic framework of this regional model, the reader is directed to the Preliminary Watershed Characterization for the Water Budget Conceptual Model, May 2006 final report (RRCA-SNC, 2006) and the Draft Report Watershed Characterization: geologic Model and conceptual hydrogeological model, November 2006 (WESA, 2006). Pertinent excerpts of the latter report and examples of cross-sections can be found in Appendix B of this thesis.

After simplification of the geological conceptual model, the following six units were retained, listed from oldest to youngest (Logan *et al.*, 2006):

- 1) Bedrock; Precambrian igneous and metamorphic rocks overlain by Paleozoic sedimentary carbonate rocks (limestone, siltstone, mudstone and dolostone),
- 2) Sub-till sediment; basal gravel, wide-spread regionally but discontinuous,
- 3) Regional till; consolidated mixture of sand, silt and clay, with occasional gravel, clasts or angular boulders, wide-spread but locally discontinuous,
- 4) Glaciofluvial outwash deposits; sand and gravel esker material, localized
- 5) Champlain Sea offshore marine deposits; silt and clay, widespread in some parts of the region, and
- 6) Post-glacial sediment; consisting primarily of sandy interlayers.

The regional stratigraphy described above was used for the development of a regional-scale water budget and groundwater flow analyses that was then used to determine boundary conditions for the sub-regional scale numerical model in this study. In addition, the regional geologic model was used to support the understanding of the depositional environment of the VW esker through an analysis of the complete basin, which was needed to conceptualize and construct the sub-regional geologic model.

2.2 Sub-regional geological model and numerical model domain

A sub-regional conceptual model was necessary to allow for the incorporation of local detail (esker geometry) and to properly describe the groundwater flow field within and adjacent to the esker. This conceptualization is also necessary to properly account for surface-groundwater interactions. The model domain, delineated in red in Figure 4, was constructed by establishing a wide buffer zone around the estimated extent of the sand and gravel of the VW esker – approximately 1000 km² (rationale in section 3.3). The local geologic setting was simplified as not all the geologic lithologies mapped at the regional scale are present at the sub-regional scale. For instance, the sub-till deposits have not been found to date around or under the esker, and were therefore omitted from the sub-regional geologic model. If this unit is encountered at a later date, it could be grouped with the fractured bedrock because it is expected to have a similar range of hydraulic conductivity and hence, the same effect on groundwater flow. Thin surficial deposits or local heterogeneities were neglected due to their limited thickness; it is assumed that these thin units have minimal to no effect on groundwater flow at the sub-regional scale. However, this assumption may be questionable as sand lenses found in the silt and clay unit or at ground surface may have some impact on groundwater recharge into the esker.

The resulting sub-regional conceptual geological model is described as follows and assumes each layer to be homogeneous and continuous, but of varying thickness (from bottom to top):

- 1) Fractured weathered bedrock,
- 2) Regional glacial till (sandy/silty),
- 3) The esker glaciofluvial deposits, which consist of
 - (3a) Gravel and coarse sand, forming the central ridge, and
 - (3b) Fine sand, forming the broad overlying fans, and
- 4) Champlain Sea silt and marine clay deposits.

Each geological material can be classified according to its capacity to transmit and store water. In this case, the low permeability unit (unit 4 on the list above) will be considered as an aquitard; units 1 and 2, also commonly called the Contact Zone Aquifer, are moderately

permeable units, while the esker aquifer (units 3a and 3b) is highly permeable. The esker geometry is described in detail in the following section. The permeability contrast between the esker and the encasing low-permeability materials (underlying till and overlying clay and silt) is such that the esker can be considered as a conduit with a preferential flow path with semi-impermeable margins. The detailed distribution of hydraulic conductivities is described in section 3.4 and was adjusted during calibration (section 4.3).

The underlying bedrock is weathered and fractured. A thickness of ten meters of bedrock is considered in the model (consultant reports vary on the most appropriate number, ranging from 3 m (Robinson Consultants, 2004; Gorrell, personal communication, 2007) to 10 m (WESA, 2008)). Interaction with deeper bedrock is considered negligible (Gorrell, personal communication, 2007), as the vertical hydraulic conductivity value for the lower bedrock aquifer is estimated at 1/100 of the value of the upper fractured bedrock aquifer.

Following the development of the sub-regional conceptual model, was the development of a sub-regional geological digital model. The sub-regional geological model is based on Gorrell's esker map (1991), geological interpretation and a three-dimensional structural model obtained through collaboration with the Geological Survey of Canada Groundwater Mapping Program (Logan, personal communication, 2007). The model is bounded at the top by ground surface, as defined by a 10-metre Digital Elevation Model (DEM Version 2.0.0, MNR, 2006). The elevations of the overburden layers were refined locally from the regional geologic model and updated with information from recent seismic analyses (Appendix A of the VW Characterization Study Report, 2007), borehole information (Appendix B of the VW Characterization Study Report, 2007) and field observations. The top surface of each unit was interpolated using a Natural Neighbour algorithm, and was influenced by water well data and surfaces geology (OGS "seamless" mapping) (Logan, personal communication, 2007). The interpolated surfaces will be used to define the hydrostratigraphy within the numerical model.

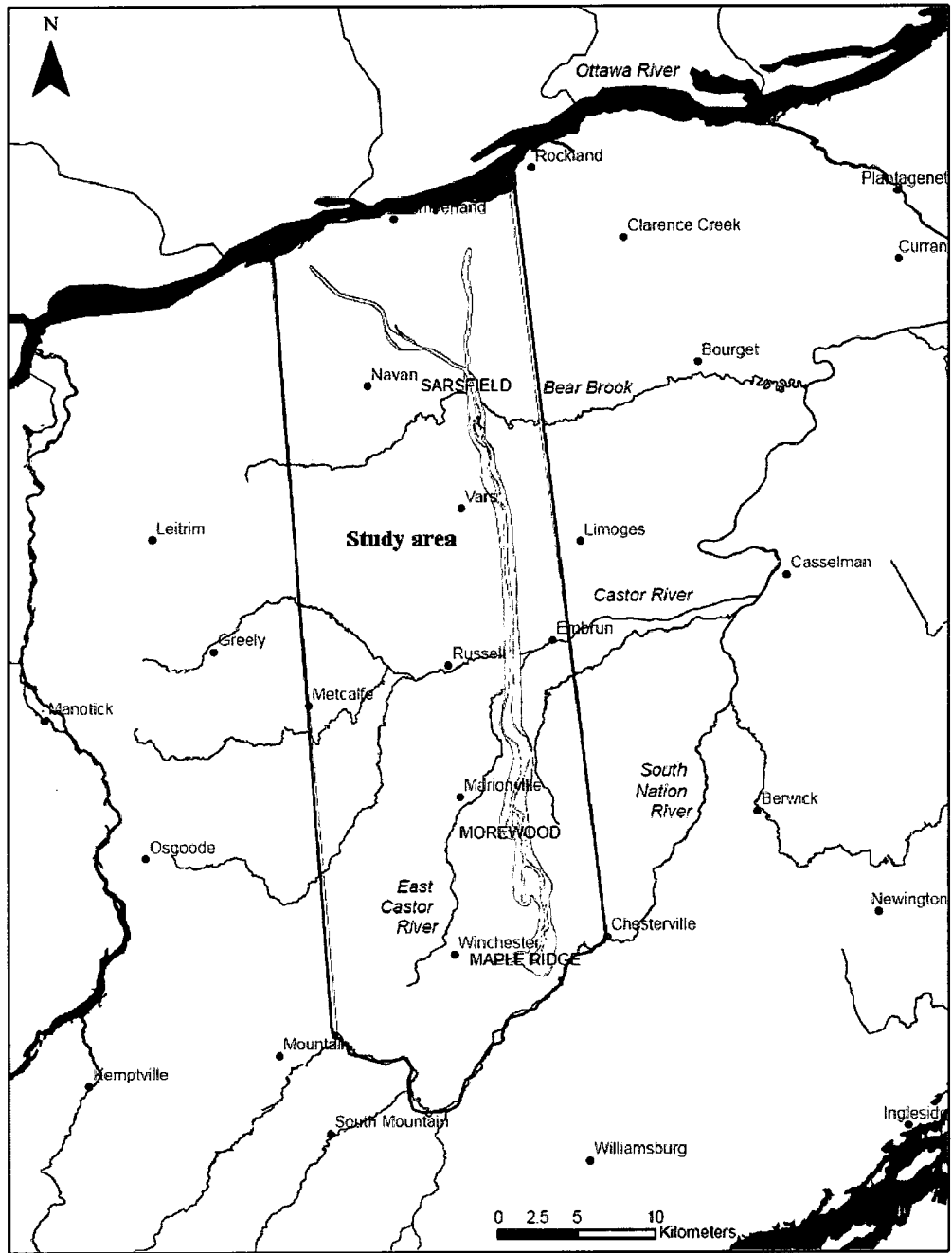


Figure 4: The Vars-Winchester model domain (red line) is defined by a large buffer zone surrounding the estimated outline of the esker (purple area). The central esker outline represents the gravel core whereas the outer esker outline represents the sandy flanks of the esker.

2.3 Conceptual model of the Vars-Winchester esker complex

Refining the regional model to meet the needs of this project required integration of detailed data about the feature of interest, namely, the Vars-Winchester (VW) esker. The conceptualization of the VW esker system is a result of how raw geological information can be understood and interpreted in light of knowledge of glacial geologic processes. This section addresses a key element of the conceptual model: esker geometry, which refers to shape, extent, and structure.

An esker is typically made of two fundamental elements: a central ridge composed of gravel and coarse sand, and overlying fan-shaped sediment bodies composed of fining-upwards sand, with some minor silt and clay (Saunderson, 1975; Banerjee and McDonald, 1975). Based on recent field studies, the VW esker abides by the typical structure. Seismic profiles transverse to the esker were conducted by Pullan and others in 2006, and brought light to the dimensions, extent, and internal composition of the buried VW esker (Pullan *et al.*, 2007). An example of a seismic transect is presented in Figure 5. These results were further supported by visual inspection of outcrops and cores (Cummings, 2007). The coarse sediments forming the esker are interpreted as deposits that were left by a subglacial meltwater stream. Sandy fans are interpreted to have been deposited where the conduit widened or flow decelerated, at the ice front or in sub-glacial cavities (Cummings, 2007).

Over its 50 km length, the VW esker meanders, splits up in a few places and varies in width (Figure 4). Based on seismic reflection profiles, the esker core is approximately 200 m wide at its base, and is flanked by sand deposits that extend more than 200 m on each side (Pullan *et al.*, 2007; Appendix A of the VW Esker Characterization Study Report, 2007). Including core and fans, the VW esker is typically 1 to 2 km wide. Figure 5 shows a typical cross-section perpendicular to the length of the esker. Fan deposits can be very significant, like at Maple Ridge where they reach up to six kilometres in width; at Morewood; at Sarsfield; and close to Navan. The esker complex is mostly buried beneath Champlain Sea sediments but is exposed in a number of places: close to Bear Brook, North of Vars, at Morewood, and at Maple Ridge. The esker core is commonly directly atop the bedrock, but in some areas it rests on top of till.

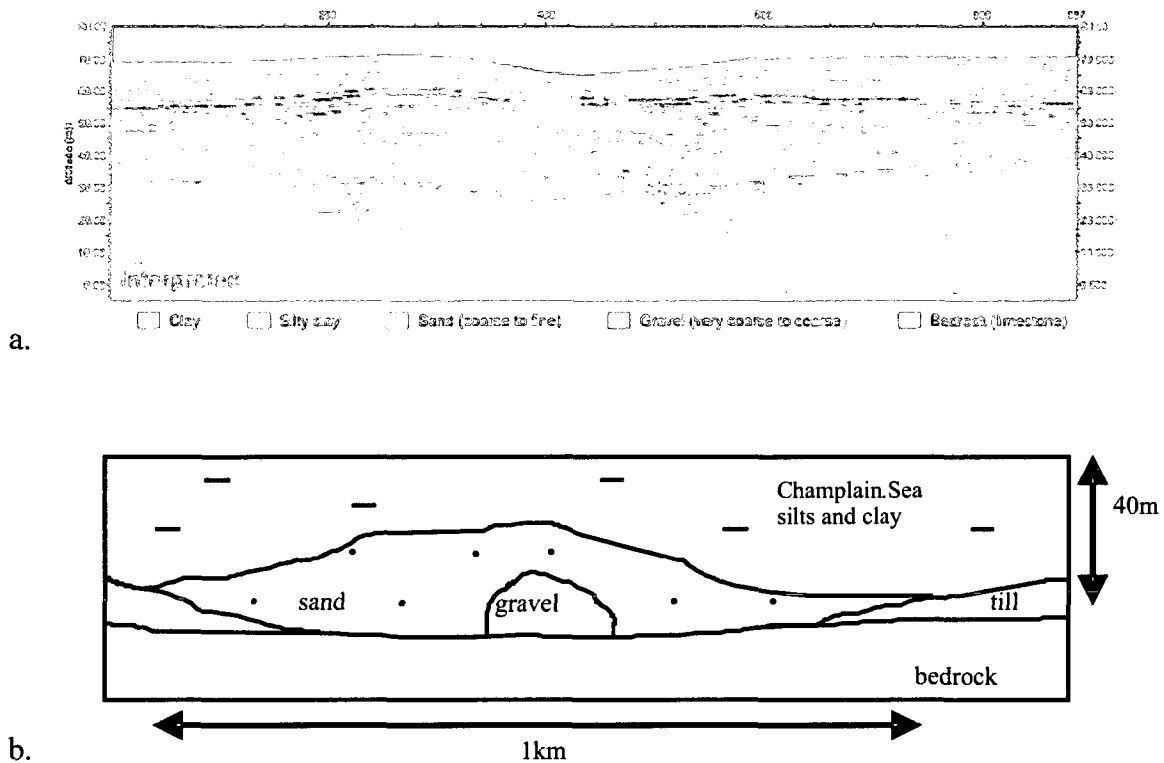


Figure 5: Cross-section view of the buried esker as (a) interpreted from an SH-wave seismic reflection section (from Pullan *et al.*, 2007) and (b) schematically drawn (based on Cummings, 2007).

Eskers can vary in their degree of continuity; they can be continuous or segmented, the gaps being a consequence of non-deposition or post-depositional erosion (Banerjee and McDonald, 1975). The continuity of the VW esker has a direct effect on the ability of the system to transmit water along its length. Since the VW esker is mostly buried, its lateral and longitudinal continuity is uncertain. Conceptually, the esker is assumed to be continuous; however, potential gaps have been identified (Cummings, 2006), such as one over a 100-200 m distance near Vars.

Delineating the VW esker complex in shape, extent and depth, was based largely on Gorrell's work (1991) and updated with archival and new water well records, borehole log information, hydrogeological and engineering reports, seismic profiles and other geophysical

work, general knowledge, and expert judgement. Although the best information possible was utilized, conceptualization always relies to some extent on interpretation, resulting in some uncertainty. Consequently, the geological and hydrogeological model should be under constant revision and updated as more information is obtained.

2.4 Hydrogeological setting: groundwater flow dynamics

At the outset, prior to formulating a numerical model, it is extremely useful to have an approximate idea of groundwater flow, regionally and locally within the esker. This information is used to help determine and set boundary conditions around the numerical model. In this study, approximate flow patterns were inferred from a piezometric surface generated by interpolation (kriging) of water levels, from water well records (RRCA-SNC, 2007a). As shown in Figure 6, groundwater flow in the overburden and in the shallow bedrock within the model domain is inferred to be in a general north-easterly direction, towards the Ottawa River. As is often the case, it closely follows ground surface when bedrock topography is flat and horizontal, but it preferentially follows bedrock topography otherwise (RRCA-SNC, 2007a).

Groundwater flow within the VW esker is difficult to measure due to heterogeneity of sediments within the esker deposits and the overall uncertainty of the subsurface distribution of sediment. In general, the gravelly core of the VW esker has a higher permeability than its surroundings, offering a preferential pathway for groundwater flow. Hence flow within the system occurs preferentially along the length of the esker instead of following regional gradients. As indicated in Figure 6, the longitudinal groundwater flow within the esker is not unidirectional. Based on several consultant reports, groundwater flow within the esker has been documented to converge towards the Castor River and diverge at the local topographic high of Maple Ridge in the south, with the groundwater divide located 500 metres north of Country Road 3 (Intera, 2006; Golder Associates, 1996; WESA, 1992). Another groundwater divide is believed to be located in the north near Vars, based on bedrock relief. Areas of groundwater discharge and recharge correspond, respectively, to topographic lows and highs, suggesting that groundwater flow within the esker and the surrounding

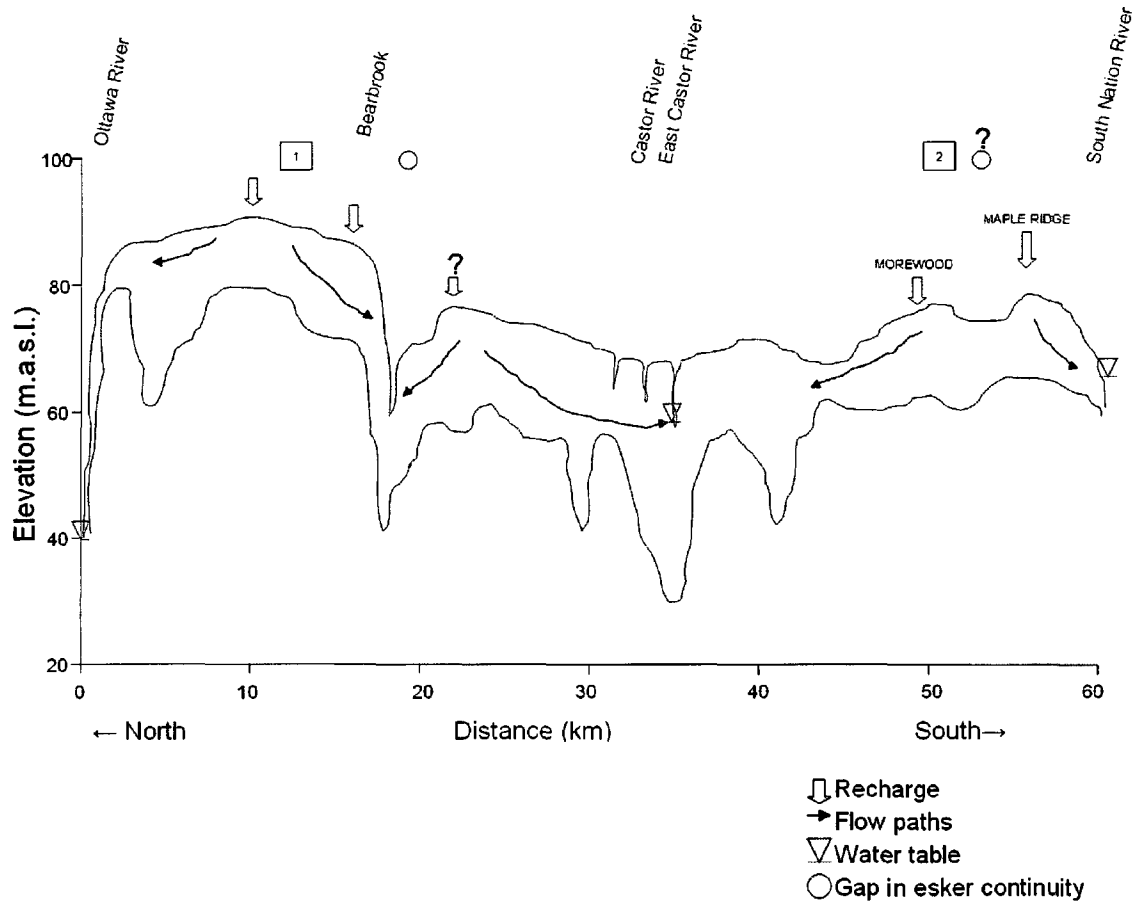
overburden is intimately linked to topography, even though topography varies less than 20 metres over the 50 km length of the esker. The topographic gradient is estimated at less than 0.1 %.

Several potential mechanisms for groundwater recharge to the VW esker have been identified. The esker primarily recharges from precipitation, with additional contributions from rivers and streams, and possibly from the bedrock (Cummings, 2007) (Figure 6b). A semi-quantitative, small-scale water budget was calculated for the Maple Ridge fan deposits (MRFD) and resulted in an estimated infiltration rate of 751,850 m³/year (approximately 250 mm/yr) over the area, which accounts for less than 500,000 m³/year (less than 150 mm/yr) to recharge the esker aquifer, assuming it is hydraulically linked with the MRFD (Cooper, 2007). Cooper's assessment supports the assumption that the MRFD is connected to the esker and discharges into the South Nation River. The volume of contribution of other recharge sources and the seasonal variability of groundwater recharge requires further investigation.

Field investigations using Electrical Conductivity (EC) and direct seepage measurements have revealed that groundwater interacts with surface water where the esker intersects rivers in the South Nation Watershed. The locations investigated for groundwater seepage were the South Nation, Castor, and East Castor Rivers (Bustros-Lussier, 2007; Cooper, 2007; Sargent, 2007; Cummings, 2007). Results suggest the esker discharges into these rivers (See Appendix E of the VW Esker Characterization Study, 2007). Results were conclusive with EC in the Castor and East Castor rivers, pointing out anomalous areas which appear to be related to the esker (Bustros-Lussier, 2007). It may be of interest to point out however that we found a discrepancy between the anomaly area in the Castor and the location the esker is thought to cross under the river according to the geological model. Results were inconclusive in the South Nation River because of a lack of contrast in EC between the river water and groundwater; however, another study estimated a seepage rate of 11,370 m³/year into the river (Cooper, 2007). We attempted to re-assess actual seepage using shallow piezometres and open top seepage metres (OTSMs) in the Castor, East Castor and South Nation Rivers, but results were highly variable and not conclusive. OTSM measurements

showed little difference in fluxes measured in what we considered to be within or outside of the anomaly areas – flux values were in the same order of magnitude, except in the Castor where the difference was of one order of magnitude.

Having formulated the conceptual model, by completing a summary of our understanding of the esker's structure and of groundwater flow dynamics, we are ready to move to the next level: digital formulation of the system. The various pieces of information from the conceptualization phase will be incorporated into a numerical model, aiming at reproducing observed water levels and dynamics. The following chapter addresses the choice of the modeling software and the construction of the three-dimensional numerical groundwater flow model.



b.

Figure 6: (a) Direction of conceptual groundwater flow in the overburden, from an interpolated potentiometric based on water well records (RRCA-SNC, 2007a). As a preferential permeable conduit, the esker alters groundwater flow paths, although it is likely that there is flow across the esker as well. Groundwater flow in the esker is shown as bold black arrows, with approximate location of flow divides at the dashed lines. (b) North to South cross-section following esker, showing approximate conceptual ground surface and bedrock topography (with possible bedrock valleys and faults), water levels in main rivers, anticipated recharge zones and flow paths. At 1 and 2, the esker branches in two; the longer western branch is drawn in the first case, and the longer eastern branch linked to Maple Ridge in the second. Suspected gaps in esker continuity are marked by circles. Vertical exaggeration is x358.

CHAPTER 3: THE NUMERICAL MODEL

3.1 Groundwater flow equations

“A mathematical model simulates groundwater flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model” (Anderson and Woessner, 1992). The governing equation of our numerical model is a mathematical expression describing transient groundwater flow. It is a second order partial differential equation which, when combined with initial conditions and boundary conditions, can be solved for hydraulic head as a function of space and time, as $h(x,y,z,t)$. The partial differential equation, with its initial and boundary conditions, is known as an initial and boundary value problem. These problems can be solved analytically for very simple geometries; but in the vast majority of cases the geometry of the problem warrants the use of numerical approximations. The choice of the numerical approximation is explained in detail in the next section.

The equation for transient groundwater flow in a confined aquifer, through a saturated, anisotropic and heterogeneous porous medium, is (Fetter, 1994):

$$\vec{\nabla} \cdot ([K] \vec{\nabla} h) = S_s \frac{\partial h}{\partial t}$$

where the left hand side of the equation is known as the divergence of the flux;

$\vec{\nabla}$ is the “del operator”, essentially a three-dimensional spatial derivative, such as

$$\vec{\nabla} = \vec{i} \frac{\partial}{\partial x} + \vec{j} \frac{\partial}{\partial y} + \vec{k} \frac{\partial}{\partial z}, \text{ and } \vec{i}, \vec{j}, \vec{k} \text{ are unit vectors in the } x, y, z \text{ directions}$$

respectively;

[K] is the hydraulic conductivity tensor [LT⁻¹],

$$[K] = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{xy} & K_{yy} & K_{yz} \\ K_{xz} & K_{yz} & K_{zz} \end{bmatrix}$$

h is the hydraulic head [L], and the specific storage is given by $S_s = \rho g(\alpha + \eta\beta)$ [], with ρ the fluid density, g gravity, α aquifer compressibility, η porosity and β fluid compressibility.

If the hydraulic conductivity is homogeneous and isotropic, $[K]=K$ and the above equation reduces to:

$$\nabla^2 h = \frac{S}{T} \frac{\partial h}{\partial t}$$

where $S = b * S_s = b(\rho g \alpha + \rho g \eta \beta)$ is storativity [m], and $T = Kb$ is the transmissivity [m], and b is the thickness of the aquifer.

In many cases, however, the hydraulic conductivity is heterogeneous and anisotropic, but with the anisotropy aligned with the coordinate axes, then:

$$[K] = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix}$$

and the groundwater flow equation reduces to:

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t}$$

This partial differential equation is based on Darcy's Law and the principle of mass conservation (which states that a change of mass of the fluid in a small unit of volume has to be equal to the difference between the flux entering and the flux leaving the small volume), at the scale of a small representative elemental volume (REV) where properties are constant.

Therefore the following assumptions are implied:

- flow is laminar and slow (Reynolds number R_e between 1 and 10);
- the water is incompressible at the REV scale (but not at the aquifer scale);
- the system is isothermal;

- the external loads on the aquifer are constant.

In order to simplify this equation, we have assumed that the VW esker system can be considered at steady-state, i.e. with no change in hydraulic head with time (and therefore

there is no change in storage): $0 = \frac{\partial h}{\partial t}$

This was deemed appropriate for two main reasons: first, because of the regional scale of the model, and second, because we are interested in the long-term average behaviour of the aquifer. However, because the aquifer is considered confined and the system heterogeneous (due to its layered configuration), the set of equations are still highly complex, explaining the need for a numerical solution. The general equation for flow in a confined aquifer, in three-dimensions, for a steady-state, anisotropic, heterogeneous porous medium becomes:

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = 0$$

Despite all its assumptions, this steady-state partial differential groundwater flow equation is a good means of generating a temporally averaged spatial distribution of hydraulic heads in modelled aquifers.

In order to solve the steady-state groundwater flow equation, the model requires boundary conditions. These can be of three types (I, II or III). When a hydraulic head is specified at a given location, the model calculates the water fluxes needed to maintain the fixed potential value; this is called a Type I boundary (or Dirichlet, [m]). At least one Type I boundary is required to solve the partial differential equation; hydraulic heads can easily be measured in the field with high accuracy, but need to be referenced to a geodetic point or to a GPS-approximated ground elevation measurement with as much vertical accuracy as possible. Alternatively, if the hydraulic heads are unknown at the boundaries, fluxes can be specified (Type II boundaries, or Neumann boundaries, [m/d]); these can only be measured directly with tracers or inferred from piezometric surfaces. Type III boundaries (Cauchy, [m]) are controlled Type I boundaries in the sense that a reference hydraulic head is specified, as well as a vertical conductance (defined as $\frac{K_z}{b}$, with K_z the vertical hydraulic conductivity and b

the thickness of the hydrostratigraphic unit). They can be applied to lakes or rivers; the conductance constrains the leakage occurring between the aquifer and the fixed head.

The numerical model generally produces a set of linear equations that must be solved in a number of possible ways; the most common of which are iterative, repeating computation until the solution converges. We must then define a convergence criterion, e.g. the preset value constraining “the maximum difference in head values from one iteration to the next” (Fetter, 1994).

3.2 Numerical code selection

Numerical approximations fall into two main families: finite differences and finite elements.

Finite difference schemes approximate derivatives with finite differences; they are intuitive, and consequently popular, but they can be unstable. Examples of rectangular grid finite-difference model are MODFLOW and HYDROTHERM, developed by the USGS.

Finite element formulations, on the other hand, are based on interpolations between nodal values using user-specified basis functions (for instance, linear first order basis functions are used in FEFLOW triangular elements). The basis functions are subjected to the differentiations in the partial differential equations and the resulting elemental values are forced to converge over the entire domain in a least-squares sense, much like functions fitted by regression. Finite element models are generally more stable, more flexible and arguably more accurate, although inaccuracies can develop locally because of the inherent solution scheme. The inaccuracies can easily be detected by vigilance and corrected by refinement of the finite element mesh. Examples of finite-element modeling software include SVFlux (developed by SoilVision Systems Ltd.), 3DFEMFAT (Scientific Software Group) and FEFLOW (WASY, Institute for Water Resources Planning and Systems Research).

Geographical Information Systems (ArcGIS software products, by ESRI) models also use finite differences and have grown in popularity in the past couple of years due to new hydrogeological functions. ArcView’s integrated water modeling offers practical, user-

friendly and intuitive ways of manipulating data, and requires regular 2-D GIS shapefiles and point files. It is particularly well adapted to calculate and view things such as vulnerability indices and advection times. Despite these new options, which can be easily integrated with previous mapping, data management and spatial analyses efforts, GIS models can only handle relatively simple hydrostratigraphies.

A finite element code was selected for this particular project because of the heterogeneous nature of the flow system and because of the need for mesh refinement near municipal wells. Indeed, finite element coding has advantages over finite difference schemes with how it deals with irregular meshes, boundary conditions and anisotropic media. For example, for finer resolution in any given location, finite difference models would need to refine the mesh over entire rows or columns while respecting aspect-ratio constraints, whereas a finite element mesh can be locally refined for specific applications, resulting in a mesh with fewer nodes and less computation effort.

The choice of the software, FEFLOW (version 5.3), was based mainly on the good reputation of the company that developed it and on the existence of support through Schlumberger Water Services in Waterloo, Ontario. But FEFLOW has many aspects to make it desirable and preferable compared to other software. It is best known for its efficient pre- and post-processors, GIS/CAD compatibility, and modern visualization tools. For the expert modeller, it has flexible mesh-generation algorithms and user-defined options, highly sophisticated solvers, and an open programming interface. Additional information on this software can be found online on the FEFLOW website (www.feflow.info).

3.3 Development of the finite element (FE) mesh

Considerations for model domain design

During the system's early conceptualization phase, it was necessary to decide where to set the model boundaries. Ideally, model boundaries should reflect real natural boundaries. That is why the Ottawa River and South Nation River were chosen as northern and southern boundaries, respectively. It was considerably more difficult to find natural boundaries along the sides of the esker. Consequently, these boundaries are arbitrarily-drawn straight lines,

along which it was possible to determine likely flow magnitudes for the shallow bedrock unit based on a comparison of bedrock topography (GSC), the potentiometric surface of the shallow bedrock (WESA), and ground surface topography (DEM).

Another consideration in designing the model domain was inclusion of all municipal wells serving the population of the area and of their capture zones. A capture zone is defined by the areal boundary within which all groundwater flows towards a well; the higher the pumping rate, the larger the capture zone. Zones of 25 years of time of travel were therefore calculated for the municipal well located furthest from the esker: Winchester Well no. 6 and Russell WTP. These bedrock wells are located to the West of the esker, making their capture zones even more crucial relative to the boundaries since regional flow is generally from South-West to North-East. Plant capacity (based on Permits-To-Take-Water records) are approximately 400 000 m³/year (358 500 m³/year for Winchester no.6 and 430 700 m³/year for Russell). Capture zone were calculated analytically following the method for uniform flow in a confined aquifer (Todd, 1980; Grubb, 1993; in Fetter, 1994). Details of the method and a sample calculation are presented in Appendix C. Conservative parameter values for capture zone calculations were chosen to overestimate probable conditions:

Bedrock porosity = 0.3 (range 0.05-0.3)

Thickness (of the contact zone aquifer or fractured shallow bedrock) = 5 m

Hydraulic conductivity = 10⁻⁴ m/s = 3153.6 m/yr (range 10⁻³ to 10⁻⁸ m/s)

Regional hydraulic horizontal gradient = 0.01 (range 0.001 - 0.01)

Results indicate that the minimal distance up-gradient from the wells should be close to 2.6 km in order to include 25-year times of travel (TOT). The model domain was therefore constructed large enough to include 25-year TOTs of all pumping wells, so that stresses imposed to the esker are not propagated to the model boundaries.

Considerations for mesh creation

The construction of the finite element grid is an important step in the development of the numerical model. The location of nodes (where hydraulic head is calculated) and discretization of the grid determine the resulting resolution of the model.

Finite element nodes are set at locations where boundary conditions and calibration points are located, including the boundaries of the domain, municipal wells, streams and rivers, as well as material discontinuities (in this case, the esker's outline). The grid has an approximate element length of 100 to 300 metres, with finer grid discretization in areas where there is an expected variation in hydraulic head: around wellheads (5 to 10 metres) and along the length of the esker (50 to 100 metres), as shown in Figure 7a.

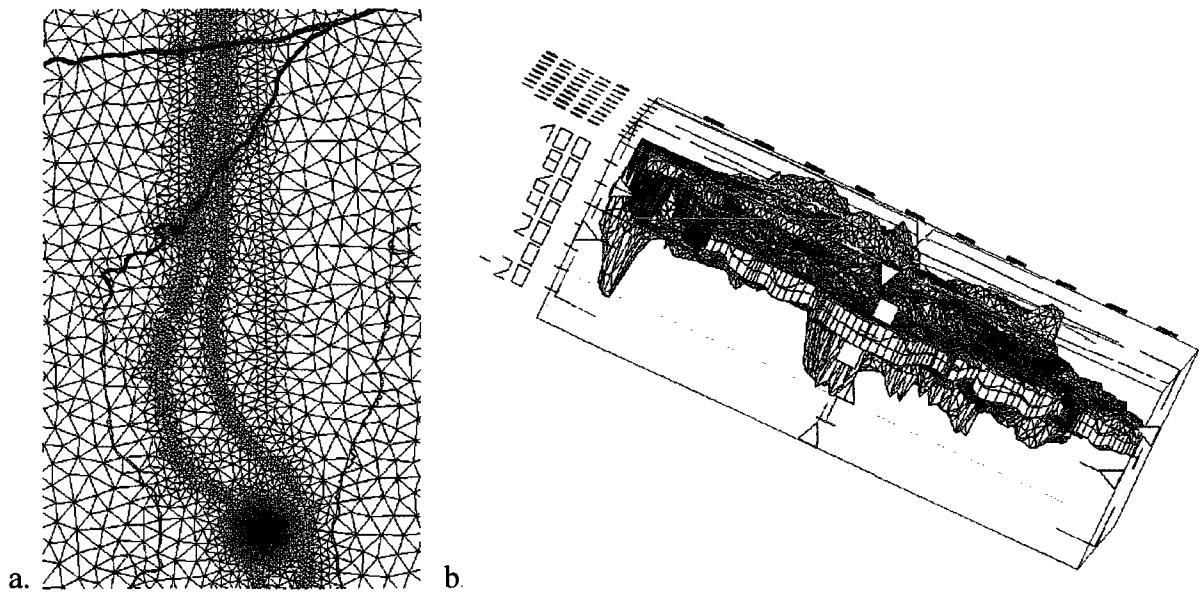


Figure 7: Picture of the grid, showing (a) triangular elements in 2-D with mesh refinement at the borders of the esker and the Embrun-Marionville well, and (b) resulting triangular prisms in 3-D (vertical exaggeration x42).

The three-dimensional grid is made up of 6-noded triangular prism elements (as shown in Figure 7b), giving increased flexibility for the model geometry to represent the complex hydrostratigraphy. The geometry of the domain can be visualized as an irregularly shaped, elongated, six-sided box. Vertically, the domain extends from ground surface down to ten metres below the highly weathered bedrock interface; areally, the domain comprises the esker plus a large buffer zone (Figure 4). The model does not address the unsaturated zone. It is therefore a saturated, steady-state flow model. Its structure is based on sub-regional geology: it is composed of 6 layers (7 slices).

In FEFLOW, slice elevations were inputted from the top down, with a minimum thickness of 0.01 m. The subsurface layers were therefore pushed down below the fixed surface (DEM), in which we have best confidence, thus correcting any abnormal interpolation-related issues using slice elevation. All interpolations used Inverse Distance Weighting (IDW) with four neighbouring points. These layer elevations are the work of Charles Logan, GSC, as described in section 2.2. Surface topography (Figure 8) has an estimated vertical error of +/- 5 m; other layer elevations have been interpolated with unknown accuracy.

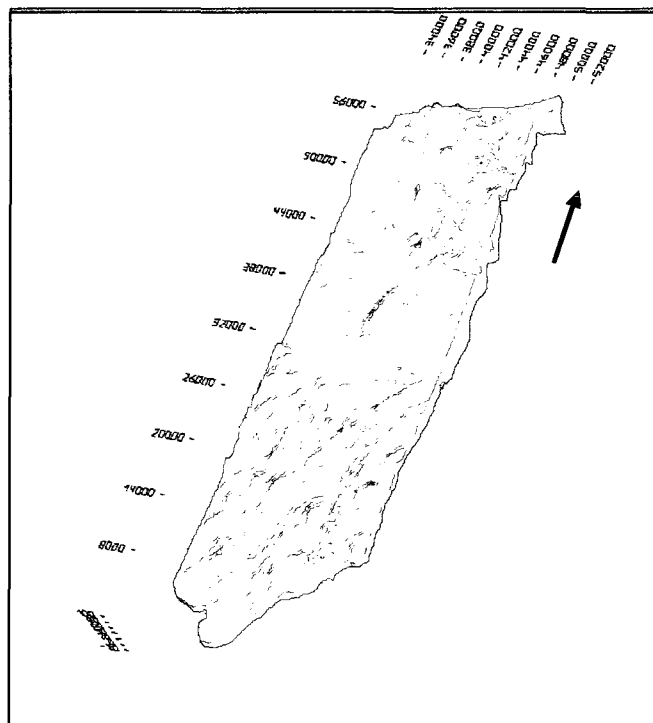


Figure 8: Visualization of topography of numerical model using FEFLOW Tricycler tool. Scale units are metres. See North arrow for direction.

The finite element mesh created has a total of 1,062,750 mesh elements and 621,880 mesh nodes. It covers an area of 893,920,000 m² and a total volume of 21,806,000,000 m³. The mesh properties indicate there are 155 triangles (0.1 %) which violate the Delaunay criterion; this happens when the circumcircle of the finite element includes a node which does not belong to the finite element. Additionally, there are 26,059 (14.7 %) obtuse-angled triangles, which were minimized as they may produce numerical problems along material discontinuities, but were inevitable in some highly refined areas.

Other model settings include the formulation and convergence criteria. FEFLOW's default best-accurate Galerkin-based formulation was used. The convergence criterion was set to an error tolerance of 0.02, applied to Euclidian L2 integral (RMS) norm, and the adaptive mesh error was set at 0.01 with the Onate-Bugeda posteriori estimator.

3.4 Hydrostratigraphy

Since the model is at steady-state there is no storage component considered, which simplifies the number of parameters to define. As a matter of fact, the only parameter which has to be quantified for each geological unit is hydraulic conductivity (referred to as K). Hydraulic conductivity is a function of the permeability of the porous medium, and the viscosity and density of water. It expresses the ease with which water is transmitted through the media, as a volume of water that will move per unit time across a unit cross-sectional area, given a unit gradient of potential.

Reasonable hydraulic conductivity (K) ranges were estimated based on all available descriptions, expertise, literature and tests. Ranges of values for these various sources are given in Table 1 for the six hydrostratigraphic units. Hydraulic conductivities were an important calibration target, and conductivity values selected for the base case scenario are presented in Table 2; the topic is addressed in detail in section 4.2.

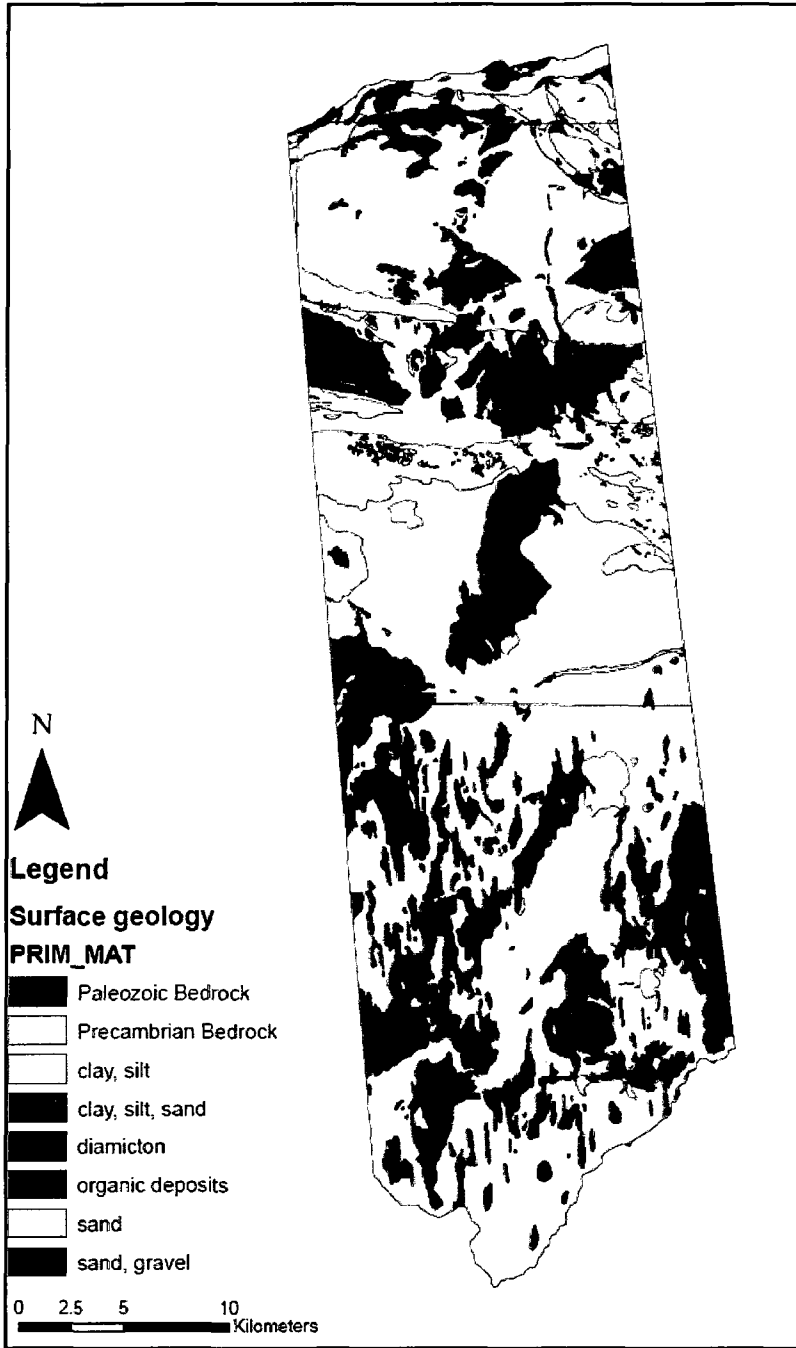
Layer	Hydrostrata	K (m/s)				
		i	ii	iii	iv	v
1	Surficial deposits	variable				
2	Champlain Sea deposits	1e-12 to 1e-9	1e-12 to 1e-8	8.8e-7	1e-9 to 1e-5	1e-10 to 1e-6
3	Esker sand	1e-6 to 1e-2	1e-6 to 1e-4		1e-3	1e-6 to 1e-3
4	Esker gravel	1e-3 to 1	1e-3	1e-3	1e-7 to 1e-5	1e-4 to >1e-3
5	Till	1e-12 to 1e-6	1e-12 to 1e-8	1e-8	1e-7 to 1e-3	1e-8 to 1e-5
6	Upper bedrock	1e-8 to 1e-3	1e-6 to 1e-3	1.2e-4	1e-4 to 1e-3	1e-8 to 1e-3
		(i) Textbook values (Freeze and Cherry, 1979)				
		(ii) Textbook and visual estimations (Cummings, 2007)				
		(iii) Geometric Mean of K from database (SNC-RRCA, 2007)				
		(iv) QSC and M.Robin judgement (2008)				
		(v) Cummings (2008)				

Table 1: Compilation of estimated reasonable ranges for hydraulic conductivity values for the different model layers, in m/s.

Layer	Hydrostrata	K (m/s)
1	Surficial deposits	variable
2	Champlain Sea deposits	1e-6
3	Esker sand	5e-3
4	Esker gravel	1e-2
5	Till	2e-4
6	Upper bedrock	1e-4

Table 2: Hydraulic conductivity values (in m/s) assigned to units in the base case scenario.

It would not have been realistic to represent the system as six superposed continuous homogeneous stratigraphic units. For this reason, based on surficial geology distribution (Figure 9a), hydraulic conductivities were assigned by stratigraphic unit material but not uniformly by numerical model layer. In other words, a given model layer could encounter a number of stratigraphic units, and a given hydrostratigraphic unit could span a number of model layers. This results from the numerical model constraint that all layers must be present throughout the domain. The Champlain Sea deposit for instance is defined in slices 1 to 4, for parts of the domain and is absent elsewhere. Esker gravel is only a sliver in slice 4, whereas esker sand is on slice 3, and partly on slices 1 and 2 (where esker sand outcrops).



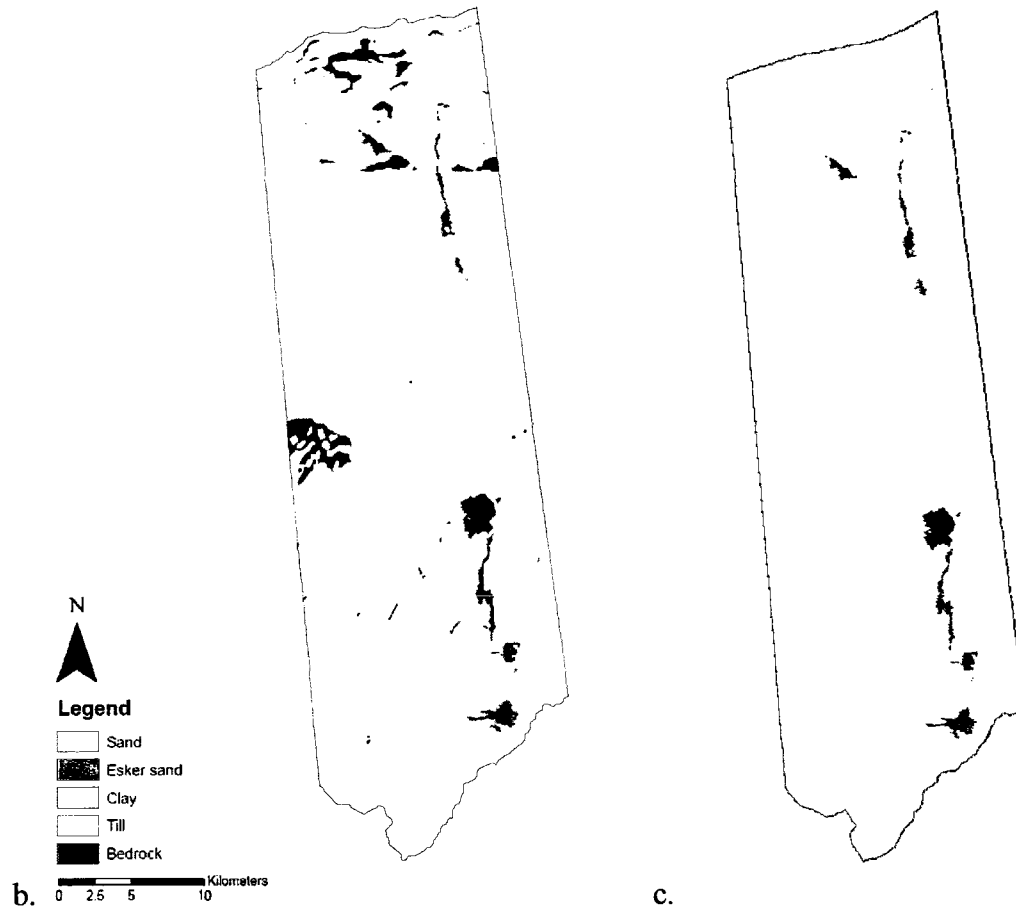


Figure 9: Map of surface geology (a) official distribution (GSC, 1994); (b) simplification for modelling purposes; (c) FEFLOW input by specifying K (slice 1).

3.5 Initial and boundary conditions

Once the geological framework and hydrostatic parameters have been established, initial conditions for the water table and boundary conditions all around the flow domain (at the top, bottom and sides of the model) need to be specified. Anthropogenic stresses such as water extraction are also considered among the flow boundaries.

Initial hydraulic head values

Steady-state models do not require initial conditions, but the rapidity of convergence is vastly improved if a relatively good initial set of hydraulic heads is provided to the model.

Two sets of initial values were used for the steady-state model. A first set of initial values was selected for the upper strata, from till to surface. These values were taken from a water table surface, calculated as being two metres below surface elevation, with linear interpolation at rivers and streams to bring the water table level up to DEM level (Daneshfar and Robin, 2008, unpublished data). The second set of initial data was for the confined bedrock aquifer; these values were obtained from bedrock potentiometric maps (WESA, 2006) produced for the Tier 1 hydrogeologic characterization.

Domain boundaries

It is preferable to set lateral boundary conditions using natural hydrogeological boundaries; however, in order to limit the extent of the model domain around the esker, boundary conditions were determined from interpretation of potentiometric information at the watershed scale (from overburden and shallow bedrock maps (WESA, 2006)). On this basis, the lateral boundaries to the north and south at the Ottawa and South Nation rivers, respectively, are considered surface water bodies above groundwater divides. Consequently, they are represented as Type I boundaries for the surface layer and no-flow boundaries for deeper layers. The lateral boundaries for the east and west sides of the model were represented as specified lateral fluxes (Type II) and were estimated from topographic gradients from layer elevation maps (GSC or Logan, 2007), in the upper layers; and from the gradients obtained from regional potentiometric maps (WESA, 2006) for lower layers. As such, lateral fluxes are highly uncertain, and are one of the major calibration parameters.

Layer elevation and potentiometric maps are somewhat uncertain, in spite of having been developed by interpolation with the best available data set. The reason for this is the sparse distribution of wells and the inconsistent time frame; measurements were taken at various times of the year at individual wells and over several years. In addition, domestic wells may intersect a number of water-bearing zones by design, and consequently there is some uncertainty as to which stratigraphic unit the water level represents where it is obtained from a domestic well. The most significant methodology problem associated with the development of these potentiometric surface maps was the way the data were divided between overburden and shallow bedrock, assuming them to be internally connected and

homogeneous when this may not be the case, as shown by the stratigraphic model presented in this report.

The bottom boundary of the model is represented as a no flow boundary: i.e., the vertical water exchange between the lowest layer or gravel/till/bedrock contact zone aquifer and the deeper bedrock aquifer is assumed to be negligible. The potential effect of faulting in bedrock is also assumed to be negligible; because of insufficient information on the location of faults and their effect on groundwater flow, the fractures are assumed to be infilled (Allen, 1996).

Buried bedrock valleys are other geological features that have potential importance on groundwater flow since they may control the deeper flow system and their effect may be translated to the shallow groundwater flow system and the surface water network. One potential bedrock valley crosses the area in a south-west to north-east direction, following an axis passing through Marionville and Limoges (RRCA-SNC, 2007a). This requires further investigation, but is beyond the scope of this project.

Recharge

The boundary condition along the top of the model in areas other than open water bodies was represented as a specified flux (Type II) to take into account recharge from precipitation. At the regional scale, preliminary investigations indicated average overburden recharge to be in the vicinity of 285 mm/yr. MOE methodology yielded an annual recharge distribution (ranging between 45-360 mm/yr with a mean for the model domain of 156 mm/yr = 4.3×10^{-4} m/d) offering complete coverage of the model domain (except for marsh areas). These values were obtained from a regional-scale recharge calculation completed for the water budget, based on maps of precipitation, soils, land use and topography (RRCA-SNC, 2007a). However, calibration proved unsuccessful using this recharge distribution, so a new distribution had to be created. (See section 4.3)

Surface water bodies

Open water bodies include the Ottawa River, marshes (e.g. Mer Bleue) and gravel pit excavations. Water levels approximated from DEM and Google Earth in these features were used as additional Type I conditions (specified hydraulic heads). In the case of quarries, we assumed that the pits' activities maintain the hydraulic head more or less constant. These values are crucial for the model, which requires at least one Type I boundary condition.

Rivers at boundaries (namely the Ottawa and South Nation rivers) were given specified hydraulic heads (Type I) set equal to the DEM. Other rivers are set as Type III boundaries, defined in FEFLOW using specified hydraulic heads, and using estimated transfer rates (conductance) through the sediment veneer at the bottom of the rivers (Table 3). A conductance of 0.15 d^{-1} was used globally in the model. The hydraulic heads that were specified at Type III boundary condition locations were estimated using a third order polynomial functions, with the hydraulic head (h) as a function of the cumulative distance (d) from the most up-gradient point of the river in the model domain, such as $h=A+Bd+Cd^2+Dd^3$, where capital letters are user-defined empirical constants. Depending on the choice of the constants the estimated h below the sediments may fall below surface elevation along the river.

River	Estimation of hydraulic conductivity [m/s] from field / lab	Lab Conductivity [m/d]	Estimated bottom sediment thickness [m]	Transfer rate or Vertical conductance = K/d [d^{-1}] with d =sediment thickness [m]		
				$d=2$	$d=1$	$d=0.5$
Castor	$10^{-7} / 10^{-8}$	$8.64 \cdot 10^{-4}$	1-2m	0.000432	0.00086	0.00173
East Castor	$10^{-4} / 10^{-7}$	$8.64 \cdot 10^{-3}$	1-2m	0.00432	0.00864	0.01728
South Nation	$10^{-6} / 10^{-6}$	$8.64 \cdot 10^{-2}$	0.5-1m	0.0432	0.0864	0.1728

Table 3: Transfer rates calculated from lab-determined conductivity values of cores from three rivers in the model domain. Falling-head tests were done on open-top seepage meters in situ and on cores ex situ (Hall, 2008) to estimate the hydraulic conductivity values of the sediments.

Stresses

There are three types of stresses to the regional aquifers: 1) municipal water extraction, 2) industrial and agricultural extraction, and 3) private domestic well extraction. At the scale of the VW esker, only the first will be taken into account explicitly by the model (see Figure 10 for map of municipal wells). The domestic wells are likely to have a minor impact because the water withdrawn at depth is simply returned to the ground surface via the septic system. Industrial and agricultural uses were identified by the Permits To Take Water (PTTW) based on 2007 data available. Surprisingly, PTTW data indicates that most permits are now terminated and that only one remains active (François Richard, WESA, personal communication 2008). This permit (code 03-P-4069) allows a total volume of 157.73 m³/d from two adjacent wells and is located in the vicinity of Vars (See Appendix D). This PTTW was included in the model. For lack of precise information on well depth we have assumed this well draws its water from the bedrock aquifer, because overburden is only 7 m thick at that location. However, this permit is for ponds used to mix concrete and wash trucks; water is taken from shallow groundwater, and quickly makes its way back. It may have been wiser to use 50 % or less of the permitted use as an approximation for actual taking.

With no industrial use PTTW being recorded for extraction of water at aggregate pits in the area at the moment, pits were represented as Type I boundary conditions based on the assumption that the operator needs to maintain a specific water level to operate and that the observed water level will represent the natural water table. Because of their small extent, only pits which did not cause bulls' eye features or which were not too closely located to a well were kept as Type I boundary conditions. In the future, aggregate resource pits should be monitored more closely, as their direct contact with the esker material poses a significant threat to the aquifer.

Municipal permitted extraction from the esker aquifer is substantial and amounts to 22,156 m³/day (Table 4). Nine of the active municipal wells are screened in the esker or regional till, and four are screened in bedrock. Pumping data were first extracted from compliance reports and engineering reports (RRCA-SNC, 2007b), then updated and confirmed by consulting municipalities. Considerable discrepancies have been identified between

permitted water takings as regulated by the PTTW and the actual water takings; therefore average daily usages have been used in the model (Table 5). The average actual takings amount to 6,089 m³/day.

Drinking Water System Name	Wells in overburden aquifer	Wells in contact zone or bedrock aquifers	MOE Reference Number	PTTW (m ³ /day)	Average daily usage (m ³ /day)	Maximum daily usage (m ³ /day)
Chesterville Waterworks	5, 6	1*	210000728	4575	604	1235.0
Limoges WTP	1, 2**		260006841	2080	564	935.0
Russell - Russell WTP		1, 2*	220008060	1180	864	2052.5
Russell - Embrun/Marionville WTP	1, 2		220004297	5419	2025	3572.5
Vars Well Supply	1, 2**		210002263	4600	228	990.0
Winchester Waterworks	7(a,b,c)	1, 4, 5, 6	210000586	4302	1804	2502.4

* off-line (i.e. currently inactive) or ** standby well (not operated on a regular basis)

Table 4: Permitted and actual amounts of water pumped by municipal wells (in bedrock and overburden combined) in the study area (RRCA-SNC, 2007b).

X	Y	Well name	Pumping rate (m ³ /d)	Slice
470275	5024430	PTTW no. 03-P-4069	145	6
470225	5024360	PTTW no. 03-P-4070	12	6
472834	4992119	Winchester Well no.1	235	6
470322	4992931	Winchester Well no.5	235	6
467211	4992425	Winchester Well no.6	415	6
471013	5008976	UNK-RUSL-????-PW1 (Russell Well)	864	6
476602	5000426	GLD-WINC-1994-94-2 (Winchester Well no.7A)	460	4
476609	5000483	MOE-WINC-1996-Well7B (Winchester Well no.7B)	460	4
476618	5000489	MOE-WINC-1996-Well7C (Winchester Well no.7C)	0	4
474953	5022389	WES-VARS-1991-VARS-WELL-NO.1 (Vars Well no.1)	228	4
474942	5022417	WES-VARS-1994-VARS-WELL-NO.2 (Vars Well no.2)	0	4
476416	5006558	GEL-RUSL-1982-PW1 (Embrun/Marionville 1)	1923	4
476397	5006557	GEL-RUSL-1982-PW2 (Embrun/Marionville 2)	101	4
475425	5021088	GLD-LIMO-1994-WELL1 (Limoges Well no.1)	564	4
475425	5021088	GLD-LIMO-1994-WELL2 (Limoges Well no.2)	0	4
477866	4994078	MBL-CHST-1989-PW5 (Chesterville Well no.5)	302	4
477950	4994175	GLD-CHST-2003-BH03-1 (Chesterville Well no.6)	302	4

Table 5: Pumping rates as inputted into the model of the 15 municipal wells, 2 of which are standby wells, and 2 industrial well records (same permit). X,Y coordinates are expressed as Easting and Northing using UTM NAD1983 (zone 18N). Limoges Well no.1 and 2 have slightly different location despite coordinates indicated here; since Limoges well 2 is kept on standby it was not relevant. Slice number indicates that pumping is assigned to the bedrock aquifer (6) or esker gravel (4) (RRCA-SNC estimates, 2008). Total municipal takings amount to 6,089 m³/d; 6,246 m³/d including PTTW no.03-P-4069.

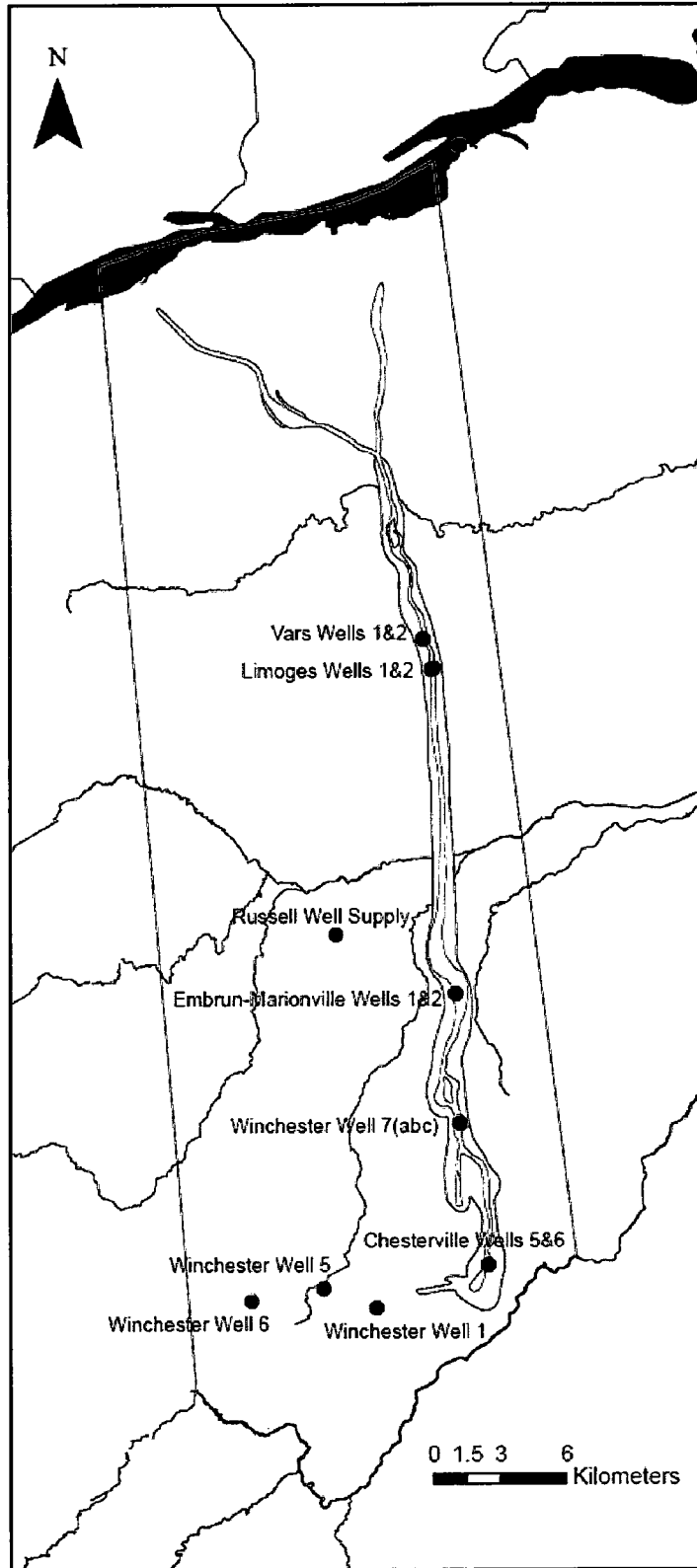


Figure 10: Location of municipal wells within the model domain.

Once the mesh for the numerical model has been constructed, and once the hydrostratigraphy, important features, boundary conditions, and ranges of values of unknown variables have been defined, calibration may begin. Calibration is the process of finding the best match between model simulations and observed field data (calibration targets). It is performed by adjusting parameters that are least certain and that have the most impact on results (calibration parameters), within their possible range. The impact of parameters on the simulation results is referred to as a sensitivity analysis, and in the context of this study model calibration and sensitivity analyses were carried out simultaneously and interactively. Because of the nature and complexity of the system, the parameters were adjusted manually by trial and error. The process is described in the following chapter.

CHAPTER 4: CALIBRATION

4.1 Calibration criteria

According to Neville (S.S. Papadopoulos internal memo, 2008) a number of calibration criteria may be utilized to quantify how closely a modelled simulation resembles a real situation. All of these criteria are based on the residuals (R), defined as the calculated hydraulic head at a calibration location minus the observed hydraulic head at the same location. Two commonly used criteria are the mean error (ME), or average of the residuals, and the root mean square (RMS) residual, which is the quadratic mean of the residuals:

$$ME = \frac{1}{n} \sum_{i=1}^n R_i \text{ where } R_i = \text{calculated } h_i - \text{observed } h_i, \text{ and}$$

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^n R_i^2}$$

The RMS can be normalized (nRMS) by dividing by (a) the total head loss in the system (Woessner and Anderson, 1992) which will be referred to in this thesis as nRMS_s; or (b) the range of observed heads at the calibration points (max (observed h) – min (observed h)) which we will call nRMS_o; or (c) the range of calculated heads at the calibration points (max (calculated h) – min (calculated h)) (Maric, 2008).

Neville (2008) briefly stated the advantages and disadvantages of each method, noting that the disadvantage of the ME is that large negative and positive residuals cancel out, such that the ME may be small while the localized residuals may be large (positive and negative). The quadratic averaging in the RMS eliminates the issue of the sign but imparts a bias towards large residuals; while, by the same token, it will fail to detect whether a model consistently over- or under-estimates the observed hydraulic heads. A compromise, adopted here, is to report the mean (ME) and the standard deviation (SD) of the residuals:

$$SD = \sqrt{\frac{1}{n} \sum (R_i - m_r)^2}$$

where $m_r = ME$. SD is different from the RMS as it takes into account the distribution of the residuals compared to the ME of the residuals.

To evaluate how strong the relationship between observed and calculated hydraulic head values is, two correlation coefficients were calculated: Pearson's correlation coefficient and the coefficient of determination. Both parameter results are interpreted the same way: the closer r^2 is to 1, the more the model accounts for observed variability. These coefficients require the residuals to be normally distributed (which can be determined with the Kolmogorov-Smirnov normality test).

The correlation coefficient represents the normalized covariance between two variables. It is typically defined as the ratio of the covariance to the product of standard deviations:

$$r = \frac{S_{xy}}{S_x S_y} \text{ such that } -1 \leq r \leq +1$$

This coefficient, called Pearson's linear correlation (unbiased) coefficient, can be developed as follows:

$$r = \frac{(\sum (\text{observed } h_i - m_o)(\text{calculated } h_i - m_c))}{\sqrt{\sum (\text{observed } h_i - m_o)^2} * \sqrt{\sum (\text{calculated } h_i - m_c)^2}}$$

where m_o is the mean of observed head measurements and m_c is the mean of calculated heads for the set of data. Pearson's coefficient r can give both magnitude and direction; its value can be squared (r^2) to compare to the coefficient of determination coefficient (R^2), which is calculated with the following equation:

$$R^2 = SS_{res} / (SS_{res} + SS_{mod})$$

Where SS stands for sum of squares of either residuals (SS_{res}) or the model (SS_{mod}), such that

$SS_{res} = \sum (R_i)^2$ and $SS_{mod} = \sum (\text{calculated } h_i - m_o)^2$. It is highly biased because it only gives a magnitude (the sum of squares is always positive), and the squaring magnifies

the largest gaps; however, it may be interpreted as the fraction of the total variability that is explained by the model.

4.2 Calibration targets

Water levels used as calibration targets were taken from the 18 monitoring wells drilled by the GSC in February 2007 (Appendix B of the VW Characterization Study Report, 2007; Appendix Table A of this report), which were monitored for static water levels, surveyed, and equipped with data loggers for continuous water level measurements.

Additional independent water levels were extracted from the SNC database (which includes extensive coverage of domestic, industrial, and commercial wells). Significant seasonal, temporal variability arose in the latter case, with levels dating back from the 1950s to recently, at all times of the year (dry and wet periods). To resolve this issue, several sets of calibration targets were extracted from the database for a specific aquifer (in this case: bedrock and diamicton till):

- water levels of a small number of wells for a specific year, and
- water levels of as many wells as available, for better coverage of the model domain.

Confidence is highest in the DEM (RMS=1.3 m for 18 calibration points – the DEM underestimates survey values) and surface geology map. The level of confidence in the geological conceptual model and the hydrostratigraphy is high since they were based on the best available data, and were developed in collaboration with numerous experts from the Conservation Authorities, the Geological Survey of Canada, the University of Ottawa, and Water and Earth Science Associates. Nevertheless there were a few minor discrepancies between the various inputs into the model; for instance, the surface deposits map only partially corresponds to the layer thicknesses in the geological model in particular in some areas where esker sand outcrops the thicknesses had to be adjusted by hand. As a further consequence, since features defining hydraulic conductivity distribution were derived from surface geology mapping, there may be some error in the model due to overestimation of recharge areas based on the map and estimated layer thicknesses. The only elevation data

that were modified were peaks in the DEM within the bed of the Ottawa River that were physically implausible.

4.3 Calibration parameters

The following model parameters, which will be addressed one by one in the following paragraphs, were modified during calibration:

- i. hydraulic conductivity of layers and anisotropy assumption,
- ii. groundwater recharge,
- iii. lateral boundary conditions, and
- iv. to a lesser extent, water levels in rivers, and river bottom conductance.

Hydraulic conductivity

Through calibration, a combination of hydraulic conductivities for the different units was chosen based on ranges presented in Table 1 (section 3.4).

A vertical to horizontal anisotropy ratio of 0.1 was initially assumed within each hydrostratigraphic unit to account for layering. The Champlain Sea layer was later changed to isotropic, as it yielded better calibration results and could be justified by the fact that water flow is likely to be weak in all directions in these semi-impermeable deposits. The distributions of hydraulic conductivities tested for the various calibration runs are presented in Table 6. ME and SD statistics are not reported because the simulations gave unacceptable flooding areas or very large depth to water table (more notes in Appendix E). The K distribution that led to the best calibration at this time in all respects is given in the last column (vii) of Table 6.

Layer	Hydrostrata	K (m/s)						
		i	ii	iii	iv	v	vi	vii
1	Surficial deposits	variable	variable	variable	variable	variable	variable	variable
2	Champlain Sea deposits	1.E-09	1.E-08	1.E-08	1.E-07	1.E-06	2.5E-05	1.E-06
3	Esker sand	1.E-06	1.E-05	1.E-04	1.E-03	5.E-03	5.E-03	5.E-03
4	Esker gravel	1.E-04	1.E-03	1.E-03	1.E-02	1.E-02	1.E-02	1.E-02
5	Till	1.E-08	1.E-07	1.E-07	1.E-06	5.E-05	5.E-05	2.E-04
6	Upper bedrock	1.E-04	1.E-05	1.E-05	1.E-04	5.E-04	5.E-04	1.E-04

Table 6: Combination of hydraulic conductivity values (in m/s) tested during calibration. Best distribution of hydraulic conductivities (in m/s) assigned to the model layers is shown in column vii. Surficial deposits were assigned based on outcrops as shown on the surface geology map (Figure 9). Surficial fluvial sand unrelated to the esker was assigned 1e-3 m/s conductivity.

Groundwater recharge

Recharge distribution was perhaps one of the most difficult parameters to establish. Initially, the MOE methodology was used to estimate the infiltration distribution. This distribution forced water into permeable fluvial surface deposits, which are not very thick and which are overlying impermeable fine sediment, resulting in huge mounds of water at implausible locations. Although 100-250 mm/yr were used at a wider regional scale in the EOWRMS (2001), this range was much too high for the model to deal with at the scale of the domain. The more recent Tier 1 water budget work of Igor Iskar (2008) suggests that infiltration should be about 3 % of total precipitation, which corresponds to 30 mm/yr of infiltration (assuming precipitation is approximately 1000 mm/yr). However, following discussions with the Raisin - South Nation Source Water Protection Technical Advisory Team and with Hydrogeologists at the Geological Survey of Canada, (GSC meeting, July 3, 2008) it was agreed that a more plausible range of infiltration values would be 0-10 mm/year in most places and 0-150 mm/yr in areas where the esker outcrops (Morewood, Maple Ridge...) and in highlands. Within these ranges, the spatial distribution of infiltration was based largely on soil type and slope, according to the recharge distribution from Robin and Daneshfar's uncalibrated model (2008), scaled down by a factor of 120. In addition, the thickness of the Champlain Sea deposit layer was taken into account: where it was thinner (less than 5 m), recharge values were increased by a factor of 1.5. Any higher recharge values resulted in extensive flooding at surface layer. Bedrock outcrops and esker outcrops in topographic highs, based on how they are mapped on the surface material map (GSC, 1994), were added in as higher recharge areas (up to 219 and 438 mm/yr, respectively – which is more than was

suggested, but which was necessary to produce reasonable water levels). A buffer zone of intermediate recharge rate was added around the high infiltration areas. The buffer zone was 200 m in most areas but wider if the adjacent surficial deposit was till. It is fair to say, based on the above, that recharge distribution is arguably the single most influential parameter in the calibration of the model. The final distribution is presented in Figure 11. Future effort at filling this knowledge gap should focus on infiltration estimates.

Lateral boundary conditions

Lateral boundary conditions were based on flowpaths that were approximated from surface and bedrock topography maps and from piezometric surfaces. The resulting lateral boundary conditions are specified fluxes. Generally, due to the regional flow direction, water enters the system from the west (negative flux in FEFLOW) and exits to the east (positive flux). This is true except in the till and bedrock layers where a depression in bedrock topography likely takes water out the system in the northern half of the west lateral boundary. The lateral flux values in a given layer and location are the product of the hydraulic conductivity of the layer in question and the estimated topographic or hydraulic gradient depending on the available information. Calibration favoured the reduction of the fluxes, so the low end of the gradient range was selected (0.001 in a range of 0.001 to 0.006). Flux values in the resulting calibrated scenario are: +/-0.01 m/d in bedrock, +/-0.02 m/d in till, -0.00008 m/d at west and +0.0001 m/d at east for Champlain Sea deposits, -0.05 m/d at west where there is surficial sand and till, +0.001 m/d at east where surface geology is clay and 0.1m/d where it is sand.

River conductance and heads

River water levels play a role of some importance through their influence on Type III conditions. River water levels were lowered so that they would be lower than the DEM, in order to avoid submergence of riparian areas. Conductance (or transfer rate), which is the other component of Type III conditions, was set to 0.15 d^{-1} to ease water movement in and out of rivers; this value is slightly greater than those obtained in the field (section 5.3, Table 3), but still within a reasonable range.

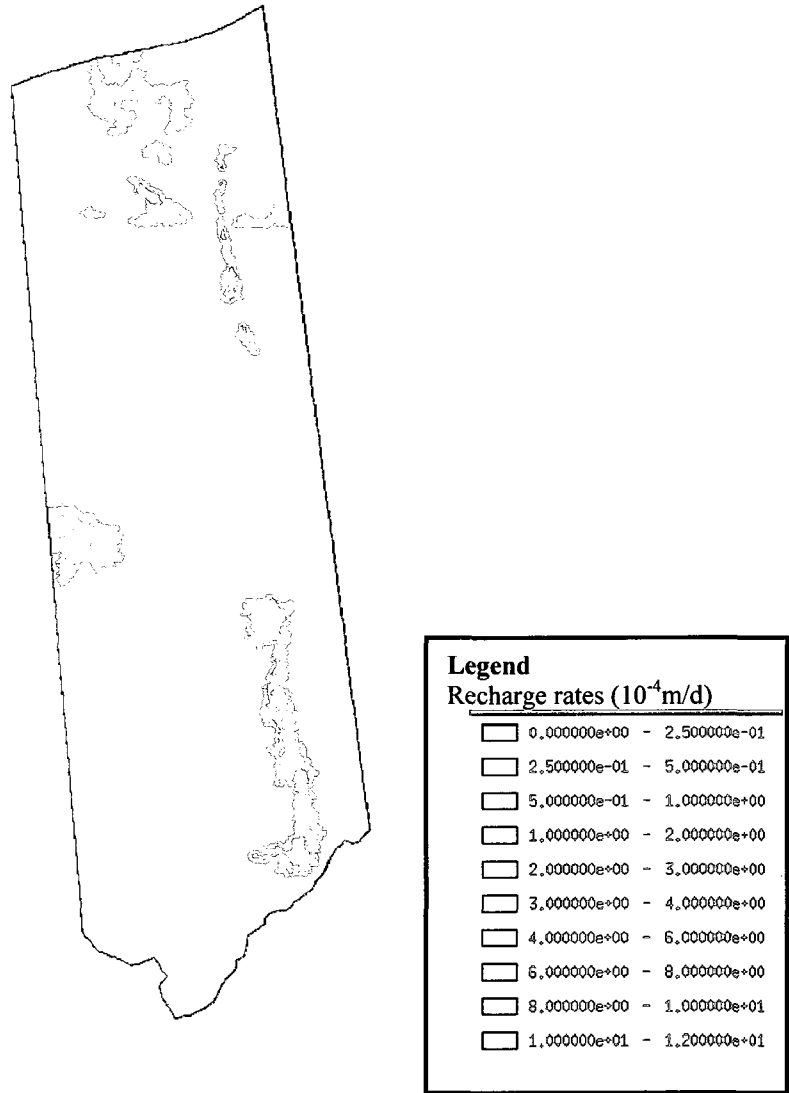


Figure 11: Final recharge distribution, showing lesser infiltration rates in blue contrasting with warmer colors in more permeable areas. The range of recharge goes from 0 to 438 mm/yr.

4.4 Calibration results and statistics

In order to calibrate the model, simulated head distributions were examined and the depths to the water table were calculated (Figure 12b). Early calibration scenarios, presented in Appendix E, led to widespread flooding and were dismissed without the need to compute calibration statistics. The calibration goals were to minimize areas of flooding (or achieve a residual within DEM error) and to minimize RMS residuals on observation wells.

Figure 12 shows the best calibrated results in which areas where water table elevations exceed the DEM are limited to a few areas within the clayey Champlain Sea deposits, and wherein the exceedances are within the vertical error range of the DEM (+/- 5 m). Simulation runs were made to try to dissipate this surplus water from stagnating in these points: deleting regional influx along southwestern boundary, increasing outflux (ten-fold) along southeastern boundary, increasing vertical conductivity (K_z) locally (by a factor of 100 in clay and of 10 in bedrock), both in the clay aquitard – slice 2 – and the bedrock aquifer – slices 6 and 7, all these possibilities were tested, with no noticeable change. The depth to the water table was also calculated using a different DEM (MNR, 2006, raster's cell size = 18 m x 18 m, error on vertical accuracy = 5 m), with no significant improvement (Figure 13). Therefore we have not been able to invoke any explanation to this problem, but given that it does not happen in too close proximity to municipal wells and falls within the error range, as debated above, we decided these results are therefore physically plausible and acceptable.

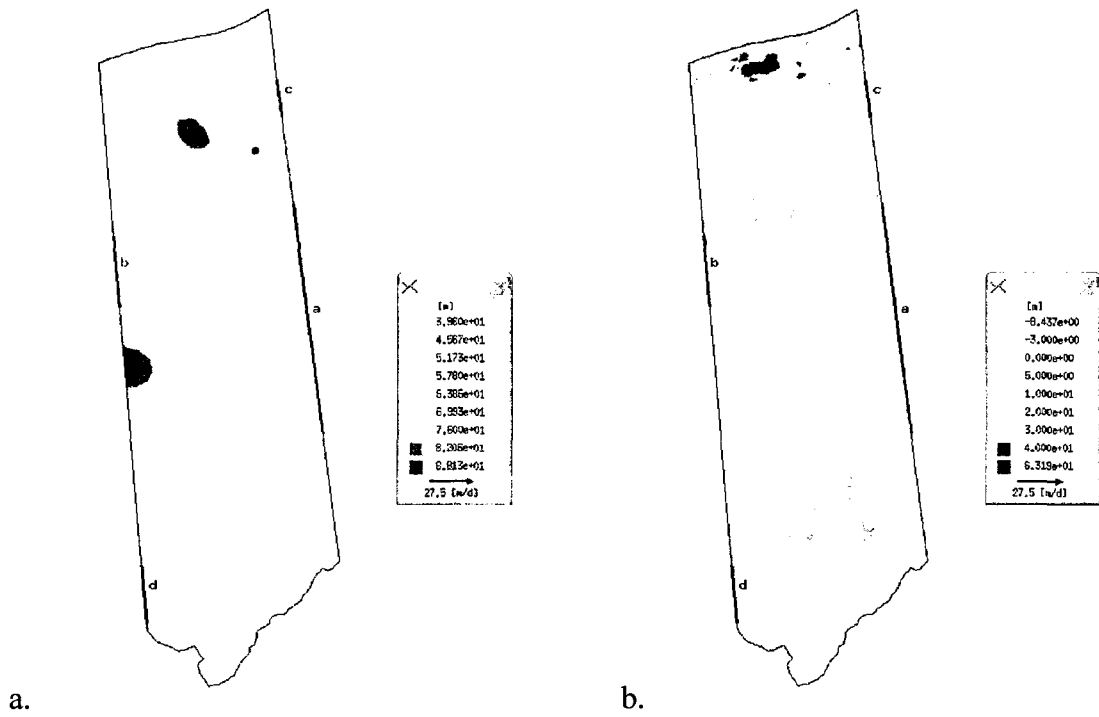
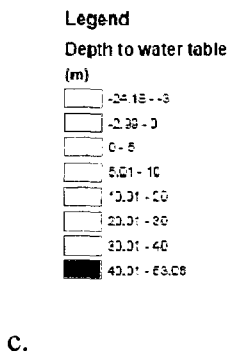


Figure 12: Calibrated model output showing (a) Water level distribution (topmost layer). (b) Depth to water table, representing abnormal inundated areas in white (up to 3m water surplus) and blue (more than 3m). (c) For comparison, depth to water table calculated from the DEM and the overburden potentiometric map produced by WESA.



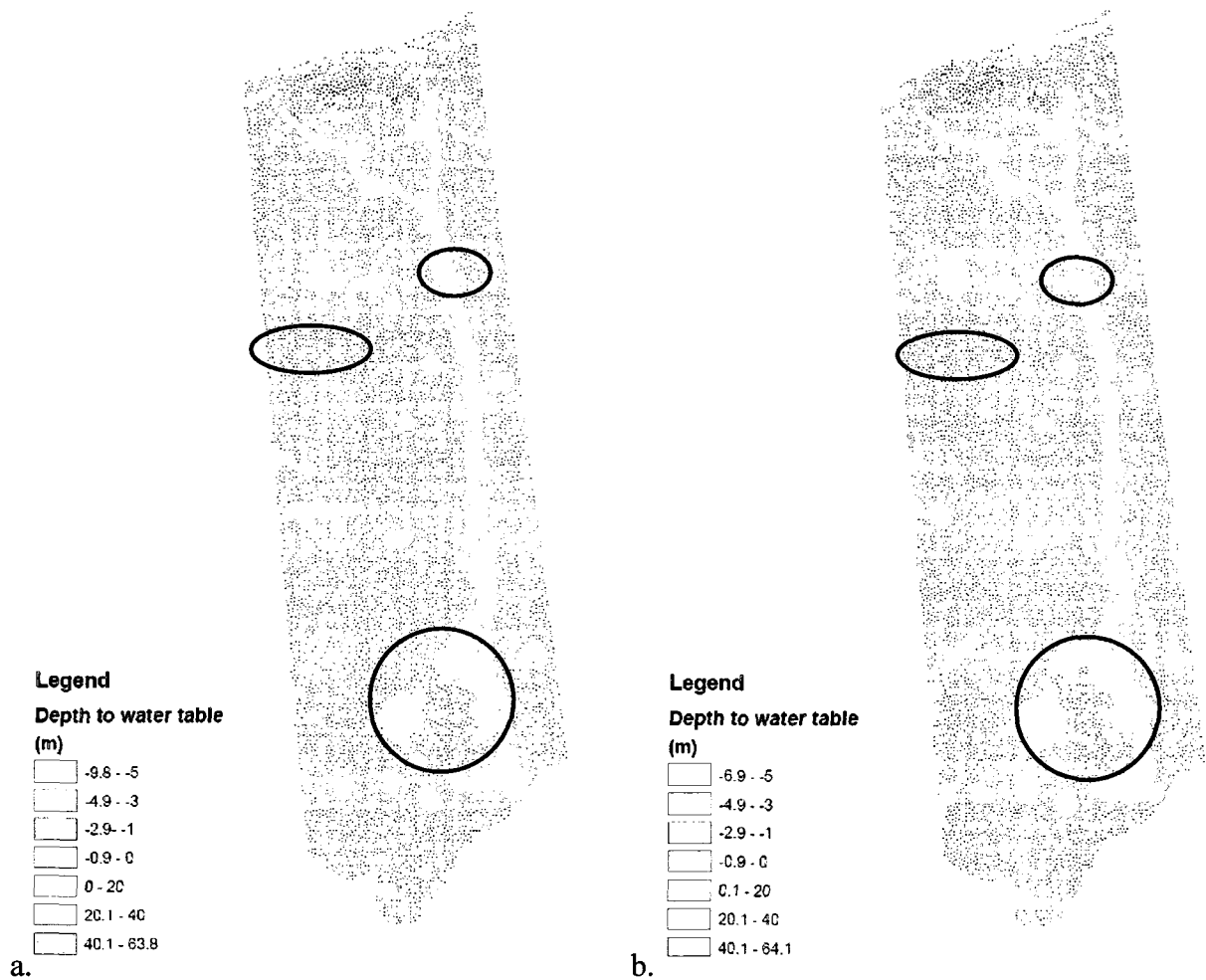
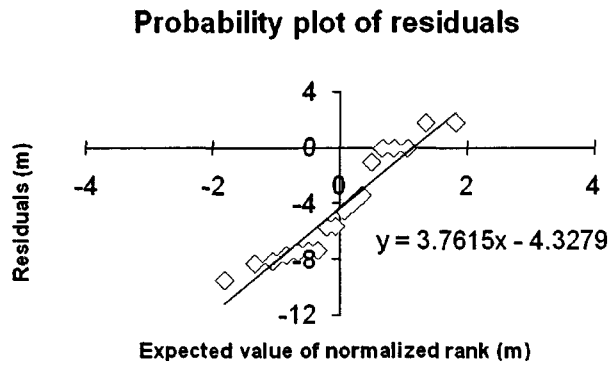


Figure 13: Evaluating the influence of DEM on calibration results. These maps represent nodal values of depth to water table (top elevation minus calibrated hydraulic head output for slice 1, topmost layer) using different DEMs: (a) original 2003 DEM (cell size = 10m x 10m) (b) recent 2008 DEM (cell size = 19mx19m). Notice that some negative values superior to 3m can be explained by the fact that they are located in surface water bodies; however, other negative depths cannot be explained, apart from the fact that they occur in topographic lows.

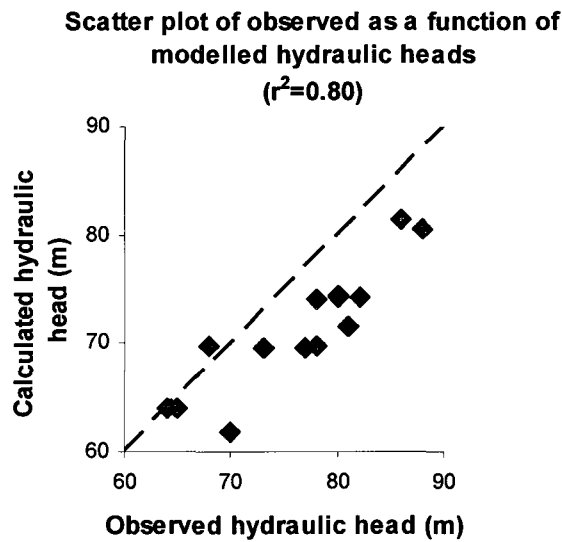
The statistics of the calibration for the best scenario, based on 18 calibration points are as follows:

Mean Error (or mean residual) = -4.33 m
Standard Deviation of residuals = 3.8 m
Root Mean Square = 5.67 m
nRMS _o = 23.61% (normalized by range of observations)
nRMS _s = 11.66% (normalized by range of calculated hydraulic heads in system)

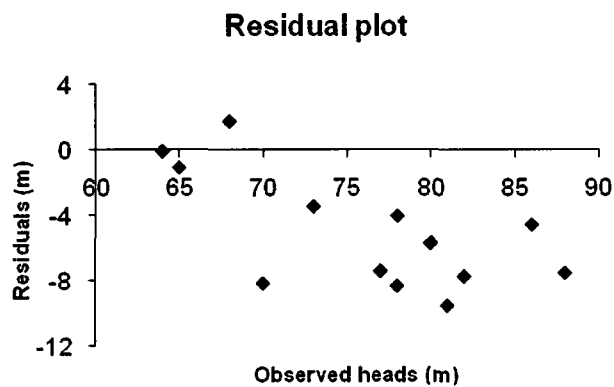
A probability plot suggests that the residuals are approximately normally distributed (Figure 14a); the Kolmogorov-Smirnov goodness of fit test shows the residuals are indeed normally distributed ($\alpha=0.05$). Using these data, a t-test showed that the mean residual was significantly less than zero (pvalue=0.0002) indicating that the modeled values are on average significantly less than the calibration targets. The coefficient of determination, $R^2=0.60$, indicates that 60 % of the variability in the observations is explained by the model. A scatter plot of the calculated versus observed hydraulic heads produces a Pearson correlation coefficient of 0.89 ($r^2=0.80$) (Figure 14b). Considering the number of unknown variables estimated, the variable quality of the data, the scale and complexity of the model, and the seasonal averaging of the water levels, the above analysis indicates that the simulated values are, in our professional judgement, within an acceptable range (see Appendix F).



a.



b.



c.

Figure 14: (a) Probability plot of residuals, showing the equation, in which the slope is the standard deviation and the intercept point is the mean of the residual distribution. (b) Scatter plot showing correspondence of observed and calculated hydraulic heads. (c) Plot of residuals, showing random scattering of residuals (no extreme values). The residuals are not centered on zero: negative values (underestimations of reality) were privileged in order to minimize flooding of model domain.

Following consultation with the Source Water Protection Technical Advisory Team, secondary calibration tests were performed to determine how well the model predicted water levels in the model domain around the esker (as opposed to within the esker). Two runs were done using water level readings (in m.a.s.l.) from as many bedrock wells as possible extracted from the SNC database (April 2008 version), as explained above. Results are presented in Table 7. When compared to a randomly selected set of water levels from a given year (selection criteria: bedrock and readings measured in 1984, n=48 wells), the ME and correlation coefficients are in the same range as with the 18 calibration points. When compared to an even larger number of MOE wells (selection criteria: screened in lower sediment or top 10 m bedrock, which after cleaning up of “no data” values came up to n=1007 wells, all years and seasons confounded), the same comment applies. In this case increasing the number of calibration points (n) improves the absolute value of ME; however, correlation coefficients lose in strength.

Hypothesis	Continuous, heterogeneous esker			Discontinuous esker	Homogeneous esker (gravel)	Homogeneous esker (sand)
	18	48	1007			
n	18	48	1007	18	18	18
Wells	misc.	bedrock	bedrock	misc.	misc.	misc.
ME (m)	-4.3	-5.8	-4.2	-4.4	-4.3	-4.5
SD (m)	3.8	10.7	6.5	3.8	4.1	3.8
RMS (m)	5.7	13.2	7.7	5.7	5.9	5.9
nRMS_o (%)	23.6	21.3	10.5	23.9	24.5	24.4
nRMS_s (%)	11.7	27.1	15.8	11.8	12.1	12.0
R²	0.60	0.58	0.54	0.40	0.43	0.41
r²	0.79	0.56	0.40	0.80	0.76	0.80

Table 7: Calibration statistics for the favoured hypothesis of a continuous, heterogeneous esker deposit, and for other hypotheses challenging the continuity and heterogeneity assumptions. There was no significant difference between calculated MEs ($\alpha=0.05$).

As was to be expected, there is some variability in results depending on the calibration set chosen. For the contact zone aquifer (regional till and bedrock), in our judgement, the model predicts reasonable hydraulic heads. The distribution of the residuals for these wells is presented in Figure 15: it shows more discrepancy near Vars and the northern bedrock ridge,

as well as near Maple Ridge, but otherwise the distribution is approximately random over the domain. Since modeled water table is generally plane, it does not readily follow bedrock topography (as it does in reality). We hypothesize that in areas where discrepancy is observed, residuals increase because topography swells or changes abruptly.

Mean residual values are negative, which indicate that, on average, model predicted hydraulic heads are below observed hydraulic heads. However, we still observe flooding of the top layer in some localities; this may be due to the proximity to Type I, II or III boundaries or perhaps even to incorrect surface geology impeding groundwater flow. Future effort should concentrate on improving the accuracy of input variables in these regions.

Comparing discharge from rivers with field measurements, the model shows positive (upward) fluxes over the esker in the 0.0001-0.004 m/d range, compared to 0.0008-0.005 m/d measured in the field, which is well within experimental error. Whereas along rivers elsewhere (no field data available), the model shows negative (downward) fluxes less than 0.0005 m/d. These are judged to be physically plausible results.

Water balance error (total inflow minus total outflow, divided by either inflow or outflow), which should ideally be around 1 % (Anderson and Woessner, 1992), is of 0.01 % (Appendix G, Figure A-7), indicating that the premise of steady-state is indeed met.

Qualitatively, the model approximates groundwater flow as conceptualized. The general flow directions modelled support some of the conceptual model's assumptions. The map of vertical flow (Figure 16a) shows that bedrock mostly recharges along the esker. Bedrock discharge occurs near the Ottawa River, punctually South of Bearbrook, in Morewood, and in Maple Ridge. Bedrock water discharge into Bear Brook, the Castor River and the East Castor River is not apparent, except in a very narrow band along the rivers. Horizontal flow (Figure 16b) within the esker turns out to be very similar to the conceptual model: based on water table levels, water flows from high to low hydraulic head, i.e. recharge occurs in Maple Ridge, Morewood, and the bedrock high close to the Ottawa River, and discharge in the rivers. However, there is a component of flow going underneath the Castor, and another

away from the South Nation; this could be due to the pumping wells in close proximity to the rivers (although these are not GUDI wells). In some places a lateral flow component (following the regional gradient) is also apparent. In between Bearbrook and the Castor, it seems groundwater may be in stagnation.

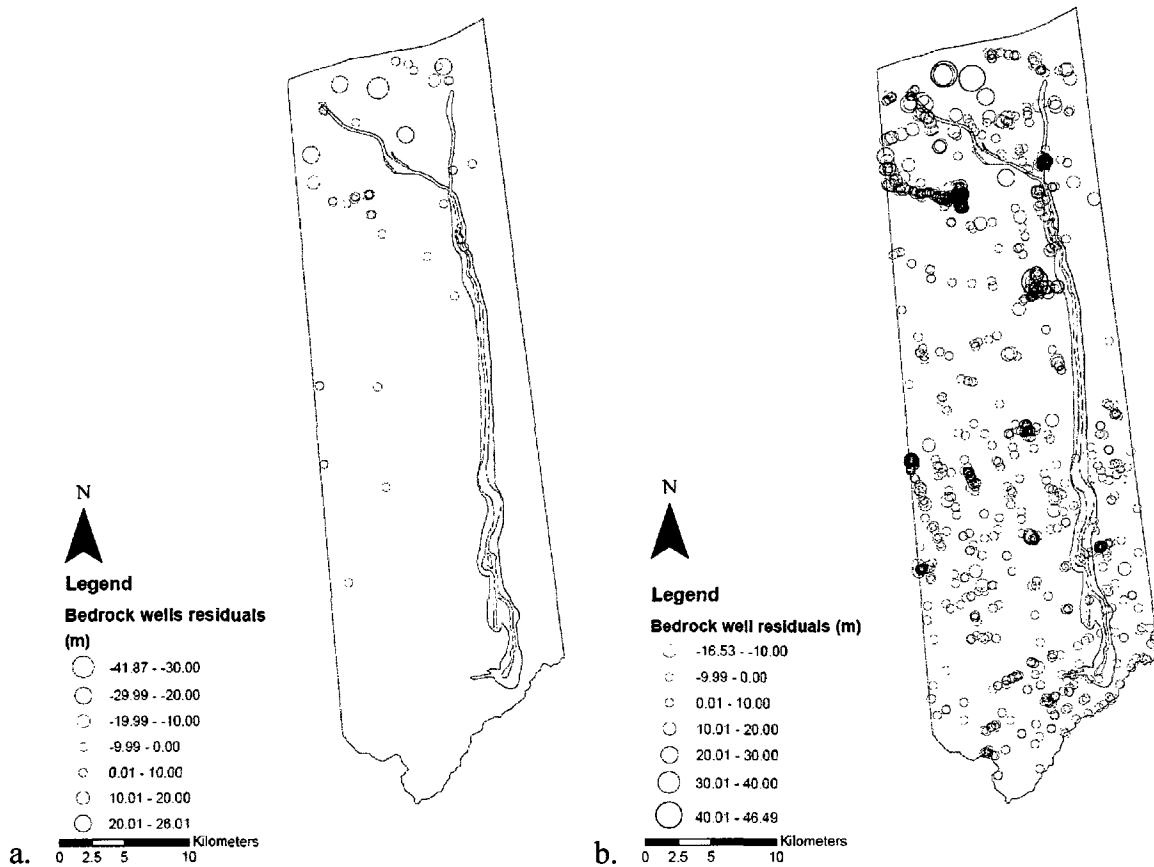


Figure 15: Spatial distribution of the residuals for the bedrock calibration wells (from SNC database). (a) n=48 bedrock wells and (b) n=1007 contact zone aquifer wells. Residuals are defined as residual =calculated hydraulic head – observed hydraulic head; so that positive values (in blue) means the model overestimates hydraulic head values, and inversely if the residuals are negative (in red) the model values are too low. The key observation to make is that, except for a few hotspots, the residuals are more or less randomly distributed across the domain.

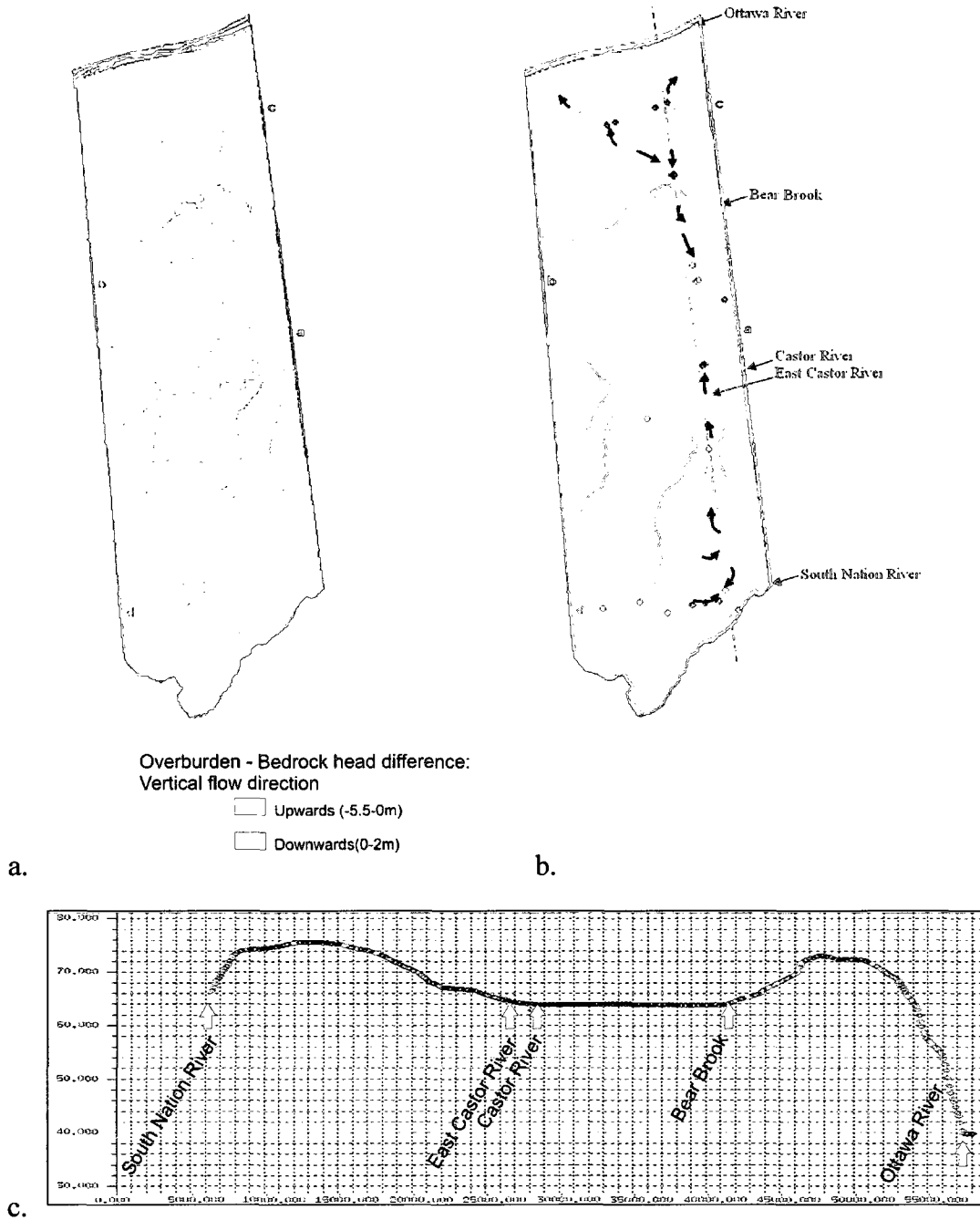


Figure 16: Flow direction in the model domain and esker: (a) Vertical flow direction between bedrock and overburden, inferred from the difference between hydraulic heads at the top and bottom slice (s1-s7). (b) Approximate horizontal flow field with arrows showing flow within the body of the esker from red (high hydraulic head) to greenish blue (lower heads), based on the calibrated model output (same trends in overburden as in bedrock). The arrows show major direction of flow but their length is unrelated to the magnitude of velocity (FEFLOW shows velocity vectors in proportion to grid density, so the output screen was not legible and had to be simplified). Green dots represent the 18 monitoring wells, and red dots the municipal water supply wells. (c) Water table levels along a North-South cross-section of the model (shown in purple in Figure 16b). Scale in metres (vertical exaggeration is x500).

Several other points can be discussed regarding uncertainty. For instance, there is uncertainty in the assumption regarding esker continuity. Previous field investigations have shown at least one incision in the esker whereas the model does not account for discontinuities. The impact of discontinuities was tested by inserting two gaps (approximate locations shown in Figure 6b), South of Vars and North of Maple Ridge (600 to 1000 m in length), along the esker, by establishing zones of less permeable hydraulic conductivity (equivalent to Champlain Sea deposits). The results (presented in Table 7) for the 18 observation wells in the esker area (represented in Figure 16b) showed negligible change in the calibration statistics. Consequently, it is concluded that the model is not very sensitive to esker discontinuity. This may be the result of the discontinuities being fortuitously located in areas of convergence or divergence of flow, or in areas of high permeability.

There also exists uncertainty in the assumption regarding gravelly core continuity. In this model, the esker is represented by two units: the gravelly core, considered continuous, and sandy overlying fans. Alternatively, the esker could be represented by one continuous unit with a homogeneous hydraulic conductivity. This assumption was tested in two ways. If we define all esker material with a conductivity of 10^{-2} m/s (which corresponds to present gravel K) therefore accentuating the contrast with the Champlain Sea deposit, the results for the 18 observation wells in the esker area show, once again, negligible change in the calibration statistics. The same can be said if, alternatively, we define all esker material with a conductivity of 5×10^{-3} m/s (which corresponds to present sand K). In both cases, it is concluded that the model is not very sensitive to esker homogeneity.

In conclusion, hydraulic conductivity and recharge were adjusted during model calibration to improve the relation between the calculated and measured water levels. Groundwater flow dynamics showed same trends as conceptualized (Figures 16b and 6). Hydraulic conductivities for the five main hydrostratigraphic units are much higher and present less contrast between one another than initially envisioned. The recharge rates are minimal, and much lower than anticipated. On the other hand, other aspects of the conceptual model were preserved, such as the two main assumptions made about esker structure: both esker continuity and the dual composition of the esker yielded slightly better results in terms of

ME than their counterparts (esker discontinuity and material homogeneity hypotheses). The ME of these two scenarios were not significantly different ($p\text{value} \gg 0.5$ for two-tailed t-tests with independent samples). Correlation results were contradictory and misleading, because Pearson's coefficient and the determination coefficient did not vary following the same trends. Consequently, the best simulation run was selected based on smallest ME value, which is -4.33 metres.

It is extremely important to point out that numerical solutions are not unique: acceptable calibrations can be obtained by a number of possible combinations of parameters. Concluding that the conceptual hydrogeological model corresponds to reality because of good calibration results is an improper inference. A more correct inference would be that the calibrated hydrogeological scenario at hand is one plausible rendition of reality. It is therefore very likely that additional scenarios will produce calibrated results of similar (or perhaps even better) quality.

4.5 Sources of error

A number of sources of error can be identified in order to explain this mean residual and to better judge the quality of the model predictions; this is addressed in this section.

Because it is not easy to measure parameters directly, estimates had to be obtained any way possible (based on empirical and theoretical data): they are therefore prone to having some possibly large uncertainty. Theoretical estimates may be ill-suited to represent heterogeneous and space-dependant variables; similarly, local measurements may not be representative of regional-scale trends. For estimates that were obtained by direct measurement methods, it is also relevant to question precision and accuracy. For instance, field-measurement error of calibration values reside in the correct recording of measurements and units, the error on the elevation of the reference point, the quality of the well construction and whether the screen was precisely built in the relevant hydrostratigraphic unit.

Another source of uncertainty arises from the many assumptions that had to be made to complete this model. Our two main assumptions are that the aquifer is fully confined (no

leakage) and at steady-state. The unnatural rectangular model boundaries, the large size of the model domain, the number of adjustable parameters, the extrapolation of parameter ranges based on limited field data, the complexity and heterogeneity of the geology, are only some of the most obvious sources of uncertainty which cannot be accounted for nor quantified. They are inherent aspects of the conceptual model, and as such, are interpretation errors that are very challenging (if at all possible) to avoid and to test.

In addition to thought-process, estimation and field methodology inaccuracies, some sources of error arise from the numerical computation method. These can be minimized by the user and FEFLOW to some extent, but are nonetheless present and worthy of mention:

- mesh error: global effects of bad mesh geometry (or finite element structure) and mesh optimization;
- interpolation errors: the difference between the interpolated and true functions, and the difference between the gradients of the interpolated and true functions;
- discretization error: the difference between the approximated computed solution and the true solution; and
- round-off error: inaccuracy that results from rounding off numbers in floating-point computations.

It is important to note that these numerical errors are probably orders of magnitude smaller than the errors caused by our limited conceptual understanding and parameter estimation. Also related to the numerical aspect of the model is the fact that finite element formulations give results that are accurate in a least squares sense over the entire domain but not necessarily locally. In order to improve local accuracy, we need to determine which areas need improvement, increase mesh refinement, and increase parameter detail locally.

The numerous potential sources of error in the VW esker conceptual and numerical model clearly suggest a cautious use of the model. Recommendations on what in retrospect we would have done otherwise, and on what future efforts should be focused on, are listed in Chapter 6. Nevertheless, a calibrated model should be put to use by testing scenarios and predicting the impact of unknown or fluctuating parameter changes: these sensitivity analyses are the topic of our next chapter.

CHAPTER 5: SENSITIVITY ANALYSES

5.1 Overview of scenarios

Ottawa is subject to demographic growth and urban sprawl and new developments are being constructed in areas that not so long ago were farmland or shrubland. These developments require municipal water, a need which can be resolved in several ways: either by pumping more water out of existing municipal wells, drilling new wells in promising locations, or bringing in treated water from the Ottawa River. In parallel, with observed climate change, the weather has become less predictable, subject to more frequent extreme weather conditions, i.e. drought or inundations. For groundwater-dependant farmers and residents, drought would be of most consequence on their immediate livelihood. Consequently, municipal growth and drought have the potential to add pressure on the aquifer by increasing water demand and decreasing groundwater recharge. In other words, if we are primarily concerned by water availability, the question we ask is this: what would happen to the VW esker system during extremely dry years and in the eventuality that the demand for municipal water raised significantly?

These two parameters – translated into recharge rates and pumping stress – will be tested in the following scenarios:

- a) Scenario 1: same pumping as present, no infiltration;
- b) Scenario 2: increased pumping, regular infiltration;
- c) Scenario 3: increased pumping, no infiltration.

These three scenarios are compared with the calibrated output model, unmodified (Base Case Scenario or Scenario 0), with current pumping stress and calibrated average infiltration. By “no infiltration” we literally mean 0 mm recharge over the whole model domain area; “increased pumping” refers to a ten-fold increase in municipal well pumping (note: the PTTW well and residential wells are ignored). While these are highly unlikely and extreme situations, they will serve well in assessing the sensitivity of the system to decreased recharge and/or increased demand.

5.2 Sensitivity analyses results

a) Scenario 1

The first scenario was obtained by running the calibrated model after having deleted all water input of water from the top slice. Removing the recharge component amounts to reducing water input to the system by 74,200 m³/d. However, because of specified hydraulic heads and fluxes, the only change occurs in the fluxes across outer and inner boundaries, namely of Type I (heads) and III (transfer) boundaries.

The impact of the drought scenario on the system is manifested by a water table drop of 3.3 m on average, or up to 5 m (on ~80 % of the area), with decreases as large as 10 m north of the Castor River in regions of relatively high elevation (Figure 17). These largest drops occur in topographic highs where bedrock outcrops, a direct consequence of the lack of recharge (refer to Figure 11 for recharge distribution). The area wedged between the Western boundary, and the Middle and North Castor river branches shows what probably is an artificial effect, because the western boundary is impermeable at that location (local topographic high). Surface geology is bedrock and till, with conductivity in the vicinity of 10⁻⁴m/s.

None of the municipal wells is severely impacted by this scenario; they could still pump at their current rates. Areas with water levels higher than ground surface in the base-case are still inundated in this scenario, but to a slightly lesser extent. This is unlikely for this drastic drought scenario, but is likely due to the specified hydraulic heads at rivers and lakes. These Type I boundary conditions will act as a source of water in this scenario. This, we believe, is a shortcoming of the FEFLOW software, which does not offer the possibility of a “drain” boundary condition that would allow the surface water bodies to drain.

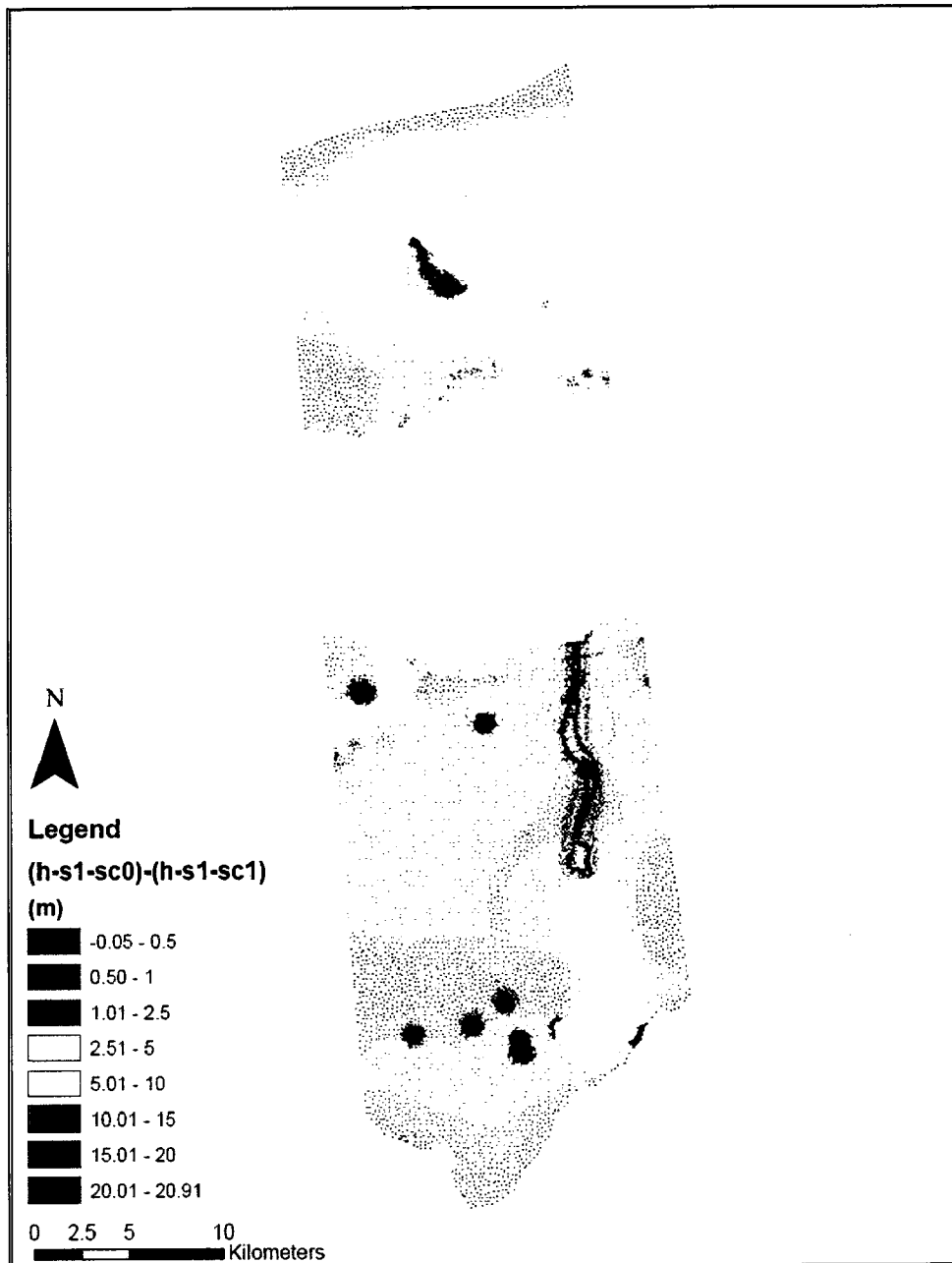


Figure 17: Hydraulic head drop induced by Scenario 1 (current pumping, no infiltration). There was no difference between the water table drop, the esker aquifer's potentiometric surface drop, and the bedrock aquifer's potentiometric surface drop.

b) Scenario 2

The second scenario was obtained by running the calibrated model after having increased by a factor of ten the pumping stresses imposed by municipal wells (Table 8). The pumping stress increases water takings by 54,644 m³/d so that the total volume of water removed by the wells is 60,890 m³/d.

X	Y	Well name	Pumping rate (m ³ /d)	Slice
472834	4992119	Winchester Well no.1	2350	6
470322	4992931	Winchester Well no.5	2350	6
467211	4992425	Winchester Well no.6	4150	6
471013	5008976	UNK-RUSL-???-PW1 (Russell Well)	8640	6
476602	5000426	GLD-WINC-1994-94-2 (Winchester Well no.7A)	4600	4
476609	5000483	MOE-WINC-1996-Well7B (Winchester Well no.7B)	4600	4
476618	5000489	MOE-WINC-1996-Well7C (Winchester Well no.7C)	0	4
474953	5022389	WES-VARS-1991-VARS-WELL-NO.1 (Vars Well no.1)	2280	4
474942	5022417	WES-VARS-1994-VARS-WELL-NO.2 (Vars Well no.2)	0	4
476416	5006558	GEL-RUSL-1982-PW1 (Embrun/Marionville 1)	19230	4
476397	5006557	GEL-RUSL-1982-PW2 (Embrun/Marionville 2)	1010	4
475425	5021088	GLD-LIMO-1994-WELL1 (Limoges Well no.1)	5640	4
475425	5021088	GLD-LIMO-1994-WELL2 (Limoges Well no.2)	0	4
477866	4994078	MBL-CHST-1989-PW5 (Chesterville Well no.5)	3020	4
477950	4994175	GLD-CHST-2003-BH03-1 (Chesterville Well no.6)	3020	4

Table 8: Inputted pumping rates of the 15 municipal wells, 3 of which are actually standby wells. X,Y coordinates are expressed as Easting and Northing using UTM NAD1983 (zone 18N). Slice number indicates that pumping is assigned to the bedrock aquifer (6) or esker gravel (4). These values are a ten-factor increase of the estimated takings presented in Table 5. Total takings amount to 60,890m³/d.

In this extreme pumping scenario, the water table levels drop by an approximate average of 1.4 m across the domain (Figure 18). The wells drilled into the bedrock aquifer have the most impact, whereas wells in the overburden aquifer seem to have little impact. Winchester wells 1, 5 and 6 have non-negligible impacts on the water table, as does the Russell Well. In both these locations, the bedrock is close to ground surface and is isolated only by a layer of till (with little or no clay). The model estimates the radial influence of the drawdown cones to be in the order of 2-3 kilometres; stagnation point calculations from capture zone analyses indicate a local groundwater divide 5.3 km downgradient from the Russell well, 2.8 km from Winchester no.6, and 1.4 km from Winchester wells 1 and 5. Since the Winchester wells are located further away from the esker (4-10 km from the esker), these wells are not

hydrologically connected to the overburden aquifer, and since the water flows eastwards, they do not access the esker's water reserves. The situation is less straightforward in the case of the Russell well, which is 4.5 km away from the esker, because of the presence of the Castor and East Castor Rivers; the Type III boundaries at these rivers feed sufficient water to the system, explaining why in the model the Russell well does not draw from the esker. As discussed in the following section, more representative boundary conditions at the surface water bodies would undoubtedly cause the Russell well to draw in part from the esker.

The impact of the increased pumping stresses on the system is apparent by a water table drop of up to 5 metres (on ~90 % of the area), with maximum drops of up to 20 metres around the Russell and Winchester bedrock wells.

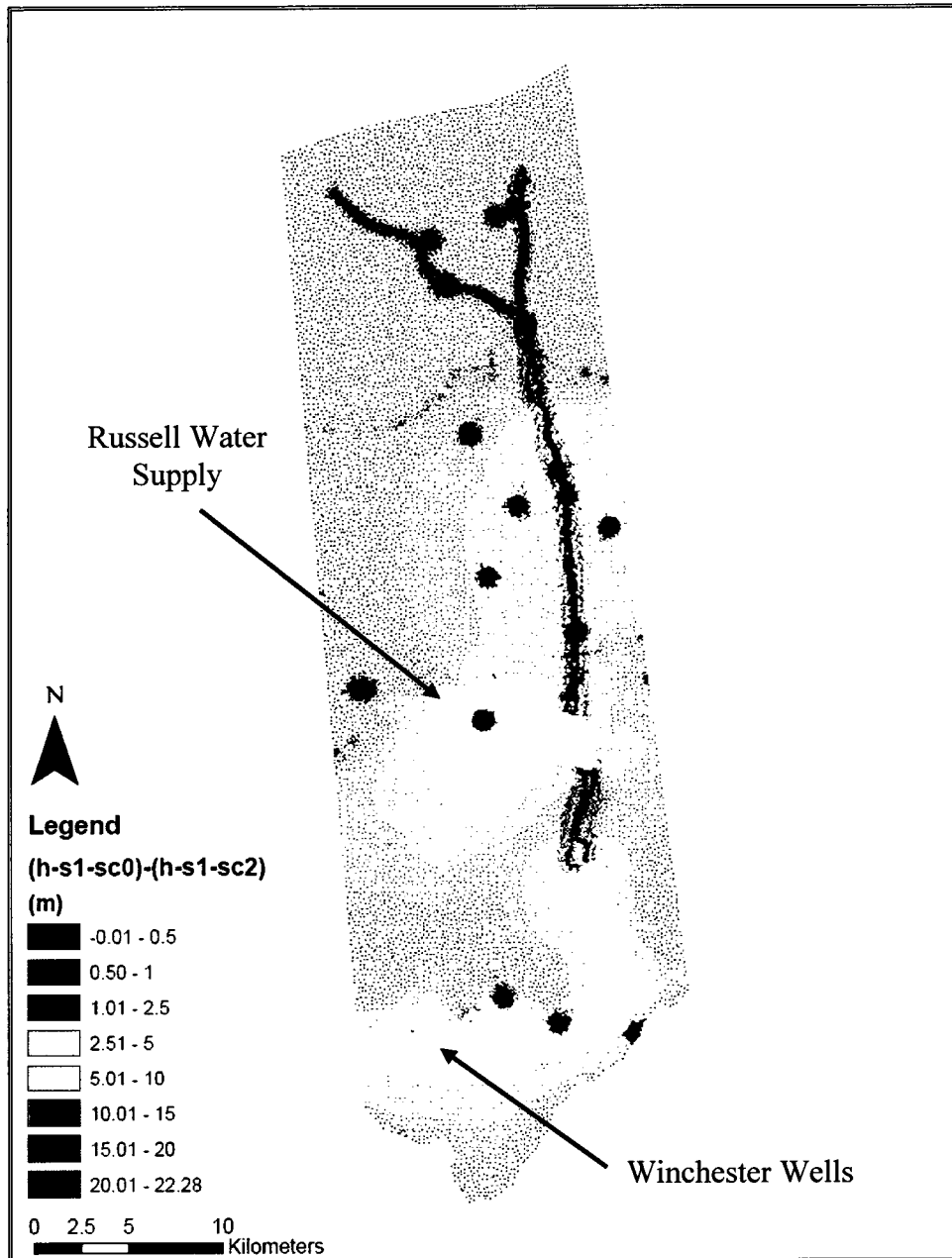


Figure 18: Hydraulic head drop induced by Scenario 2 (increased pumping, current infiltration). Relative hydraulic head drop calculations for esker aquifer and bedrock aquifer potentiometric surfaces yielded the same results.

c) Scenario 3

The third scenario is a combination of scenarios 1 and 2. It was obtained by running the calibrated model after having increased by a factor of ten the pumping stresses imposed by municipal wells and cancelled all water input by recharge from the top. This represents 74,200 m³/d less water than in Scenario 2, and 54,644 m³/d less water than in Scenario 1, for a total of 128,844 m³/d less compared to Scenario 0. Perhaps not surprisingly, results show that the combined effect of these parameters has greater impact than the parameters taken separately (Figures 19, 20, and 21).

The mapped results are a combination of previous scenarios' results. In this extreme pumping and extreme drought scenario, the water table levels drop by an approximate average of 4 m across the domain (Figure 19).

The impact of the increased pumping stress and absence of recharge on the system is apparent by a water table drop of up to 10 m (over ~90 % of the area), with maximum drops of up to 25 m around the Russell and Winchester bedrock wells. The average drop is 5.6 m across the domain. In this scenario, the esker would not discharge water into the South Nation; the river would in fact recharge the Maple Ridge fan deposit. This would be a concern as the esker would become vulnerable to surface water contamination which could jeopardize water quality in wells south of Marionville. However, in reality rivers would likely run dry; it would then be unlikely that the flow directions would be reversed. This will be discussed in the following section.

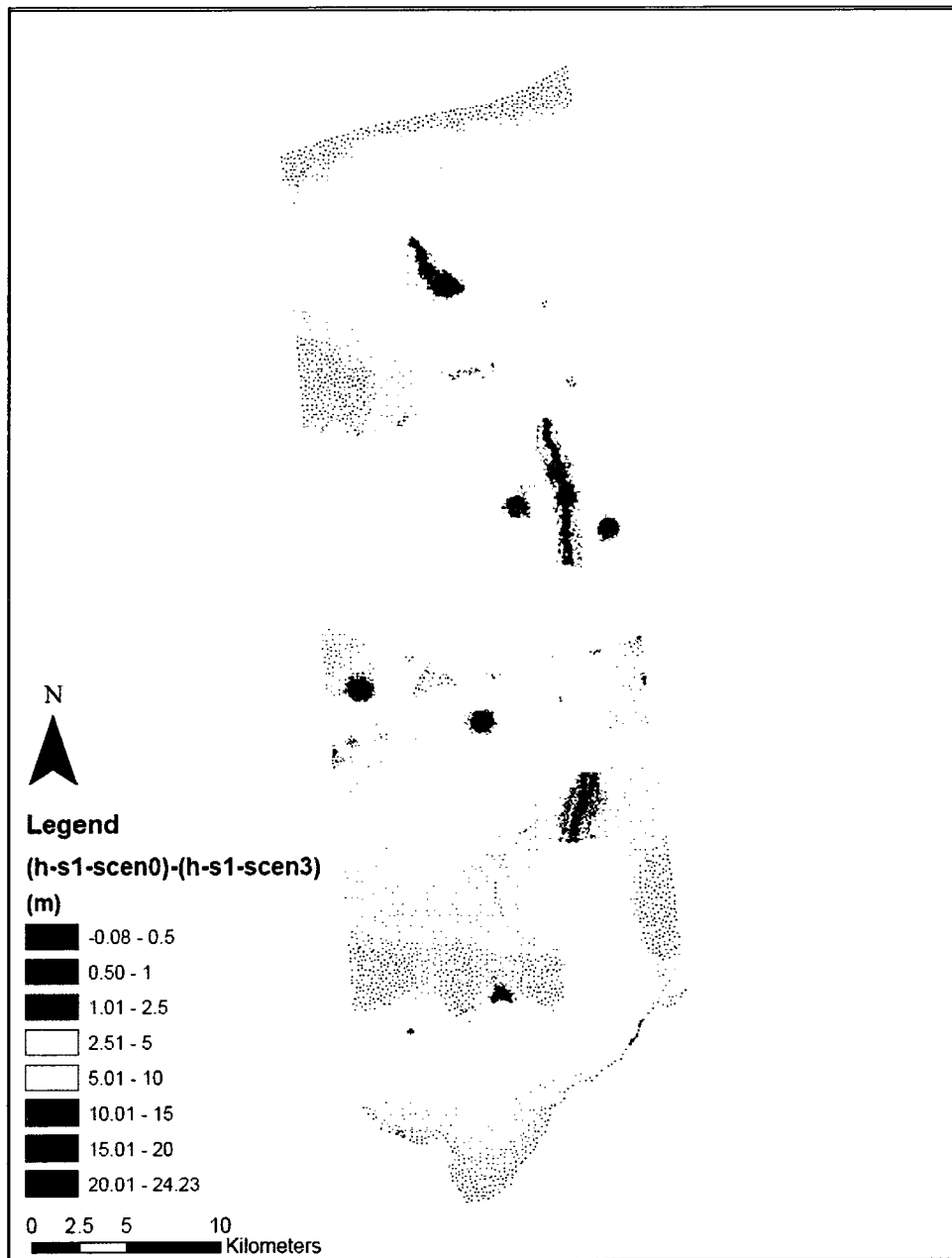


Figure 19: Head drop induced by Scenario 3 (increased pumping, no infiltration). Relative head drop calculations for esker aquifer and bedrock aquifer potentiometric surfaces yielded the same results.

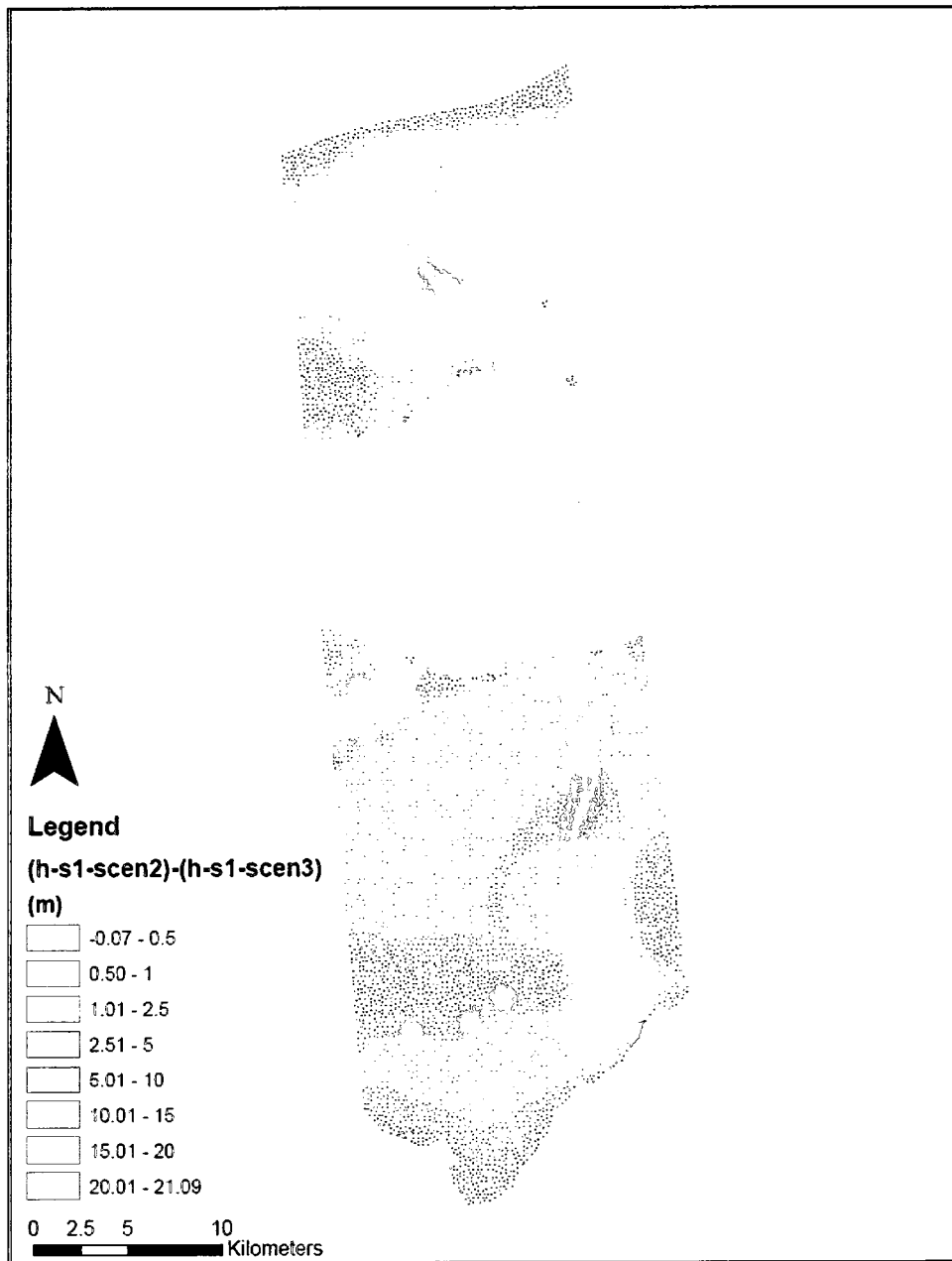


Figure 20: Hydraulic head drop induced by Scenario 3 (increased pumping, no infiltration) compared to Scenario 2 (increased pumping, current infiltration). Relative head drop calculations for esker aquifer and bedrock aquifer potentiometric surfaces yielded the same results.

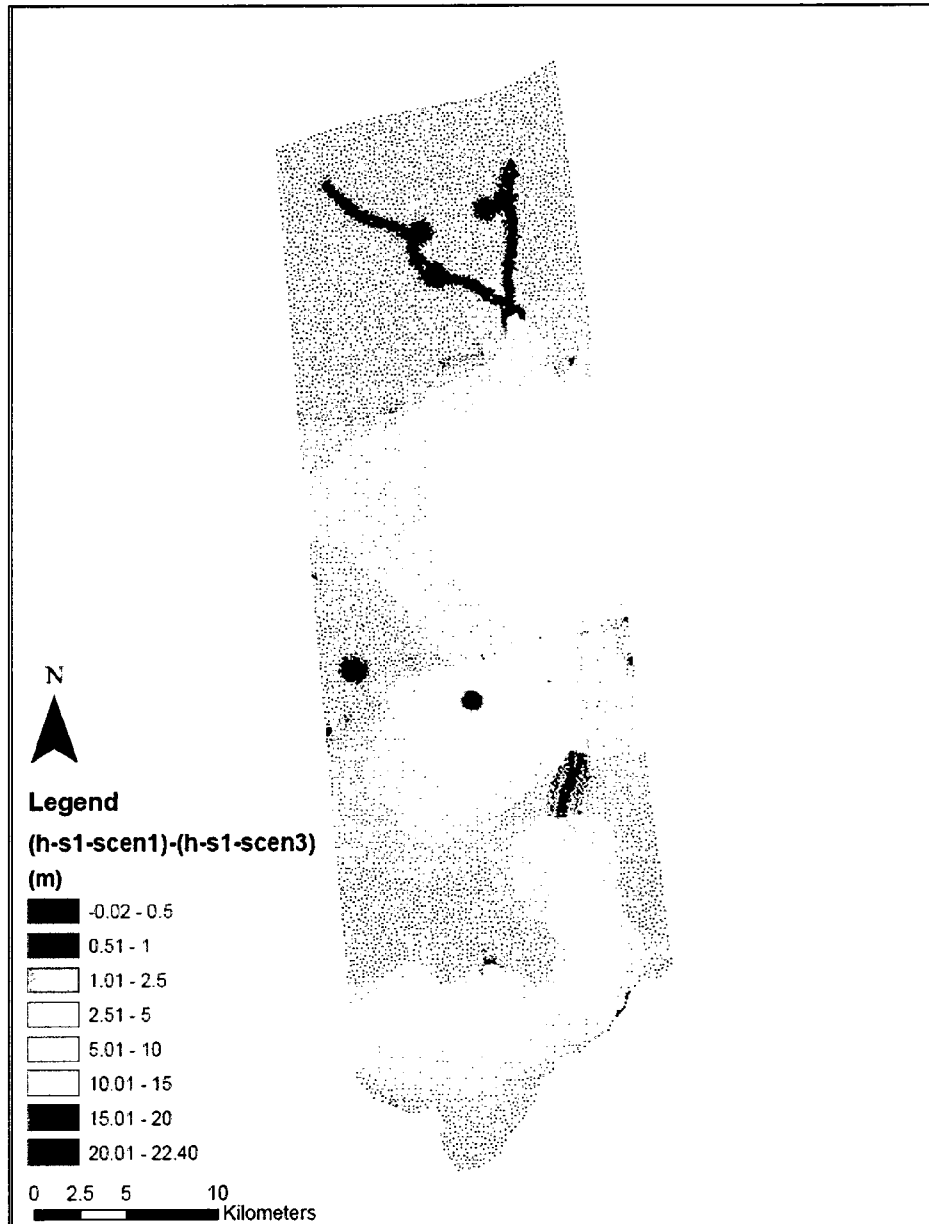


Figure 21: Hydraulic head drop induced by Scenario 3 (increased pumping, no infiltration) compared to Scenario 1 (regular pumping, no infiltration). Relative head drop calculations for esker aquifer and bedrock aquifer potentiometric surfaces yielded the same results.

These results suggest that the lack of recharge impacts the system most compared to a ten-fold increase in pumping stress. Both factors affect the water table more when the system is already stressed by the other factor. Results are summarized in the following table (Table 9). From this table we can conclude that drought and its effect on the water table levels would be of primary concern. According to this model, pumping has relatively smaller and localized effect.

Comparison	Average	Standard Deviation	Cause of effect	
			absence of recharge	increased pumping stress
Scenario 0 - Scenario 1	3.3395	2.7348	•	
Scenario 0 - Scenario 2	1.3944	2.0046		•
Scenario 0 - Scenario 3	5.5971	3.7393	•	•
Scenario 2 - Scenario 3	4.1674	3.389	•	
Scenario 1 - Scenario 3	2.2215	2.5665		•

Table 9: Averages of deviations (m) from initial or previous scenarios. Note that these statistics are not exactly representative as the deviations are weighted by the density of nodes, but are useful when comparing impacts.

5.3 Discussion of predictions

The level of stress involved in the scenarios is exaggerated. The simulation runs test the effect of a ten-fold increase in municipal pumping (which is unlikely for population-growth alone) and of complete drought (which is possible during the dryer late summer months) situations. According to the simulations of this model, the system is sensitive to pumping and recharge, but not as much as we might have expected. The following section is a discussion of the plausibility of these scenarios, and the likelihood of the model's responses.

Climate change and admittedly other causes (such as water diversion) may accentuate the variability of water levels and participate in the long-term decline of water levels in Ontario's lakes (including the Great Lakes system) and rivers. However, the threat of a drought of the magnitude modeled is not very likely in Eastern Ontario; there is no reason for immediate alarm for farming and municipal water supply. At this time, water demand can be satisfied by water from wells drilled into the esker and bedrock aquifers, as well as from water brought in from the Ottawa River. Indeed, since January 2008, based on its incapacity to meet the 20-year demand in terms of supply, storage, treatment and distribution

(Russell.ca, 2009 Master Plan), Russell decided to share Ottawa's water supply instead of relying on groundwater. Ottawa takes its water from the Ottawa River; and diversion of water from the Ottawa River is permitted as long as the water stays within the watershed. A 28-km pipeline is to be built in order to bring water from the Ottawa River (filtered and treated with ammonia, chlorine and fluoride) to the communities of Russell, Embrun, Limoges and Marionville; a project that will cost \$13 million (CBC News, 2008). As this shows, increased water demand may induce a change in water supply sources, alleviating the stress on some aquifers, and putting strain on other aquifers and on rivers.

In parallel, it is important to point out that the increased pumping simulations take into account only municipal pumping, and ignore potential industrial, residential and commercial significant PTTW-regulated water uses, which may very well increase on their part as well. However, the majority of these wells are deeper wells, in confined bedrock, and their water levels are independent of water level fluctuations.

Even so, simulations show that the Winchester bedrock wells and Russell well would be most impacted by hypothetical drought and pumping, while overburden (esker aquifer) wells would not suffer significantly. This may be due to the depth and location of these wells: the Winchester and Russell wells would likely "dry out" because they are shallower bedrock wells, located in areas where the aquifer is not capped by Champlain clay. Indeed, in both cases the overburden is composed of till, 10 m thick near the Winchester wells, and about 20 m in the case of the Russell well. Municipal well depths range between 11.5 and 28 m, with water pumps usually installed in the lower third of the well.

These results support intuitive predictions. In case of drought and/or high water demand, we expect the water table would drop both in rivers and in wells; so would the potentiometric surface of the VW esker aquifer and bedrock aquifer. Modeled water levels did fall regionally and in wells, but not in rivers and lakes where Types I or III boundaries had been specified. We also predicted the wells would be much more sensitive than previously to pumping. The deep "contact zone" aquifer is at most 5-10 metres of weathered bedrock, overlain by till; excessive pumping should create a steeper drawdown cone than pumping in

the esker, which is a larger and slightly more conducive aquifer. This idea was supported by the impact noted on the Winchester and Russell wells. However, we would expect draw-down cones to be more pronounced and affect larger areas, possibly drying out nearby shallower wells. Wells located in proximity to rivers or gravel pits might start drawing water from these adjacent surface water features and thus become vulnerable to contamination. This was noticed only between the South Nation River and Maple Ridge in Scenario 3, but attributed to a modeling artefact.

The model did soften the system's response because of its boundary conditions. Given that boundary conditions are not modified from one scenario to the next (i.e. rivers and lakes are fixed specified hydraulic heads, and lateral fluxes do not decrease), most defined boundaries in the model domain have a buffering effect on well response since they supply water to the model. Unfortunately, FEFLOW does not allow passive, gravity driven drain boundary conditions at rivers (like MODFLOW does). These would be more adapted (as an alternative to Type I and III boundaries) and much more realistic because rivers could then run dry instead of feeding the aquifers and preventing drought from being more manifest in the simulation runs. The effects of pumping, however, are visible through both drawdown around the wells and regional water levels, which points to a regional effect of potential consequence.

To date, several studies have been carried out to discern whether municipal wells are classified as Groundwater Under the Direct Influence (GUDI) of surface water wells, and necessitate more monitoring and protection. Studies done on Winchester, Vars and Chesterville wells report that these are not GUDI wells. In fact, the wells closest to rivers are drilled into the contact zone or bedrock aquifer so are not likely to become a threat in this respect. But, had the model pointed to eventual GUDI wells, it would have been imperative to verify the conductance of river-bottom sediments by repeating the sampling and K-testing measurements as done by Hall (2008). It would also be appropriate to use FEFLOW's particle tracking options to better study the potential impact of surface water contamination on the VW esker aquifer. Finally, it would be crucial to pinpoint the range of pumping stress and recharge as well as other factors that may influence the safety and yield of the well.

In conclusion, the model is sensitive to both recharge and pumping rates. In a way it supports Russell's findings that the Russell well could not withstand higher demand. One of Russell's alternatives would have been to take water from Morewood (where Winchester 7 wells are) or Maple Ridge (in which Chesterville wells are located) aquifers, which are part of the esker system. This model may be useful to make further simulations focusing on these particular areas. This model provides evidence that a change in recharge and pumping could significantly impact the system; evidence that was understated due to boundary conditions.

CHAPTER 6: CONCLUSIONS

6.1 Recommendations

This modelling project was initialized three years ago and evolved gradually as data became available for it. All data gaps could not be addressed at once. In this section are recommendations and considerations for future work on this esker project, such as where efforts could be focused in order to improve the quality and availability of data for future modeling exercises.

The modeller should be a trained expert in FEFLOW or use more user-friendly software. This project would have been easier had there been an expert FEFLOW-modeller assisting with the learning and application of FEFLOW tools in all steps of the process. The complexity of the object of modeling is sufficient that the modeling tool should be a facilitator, not an obstacle. Schlumberger offers 4-day groundwater modeling courses which, although expensive, would really benefit the user and give full merit to the software's capabilities. The biggest setbacks were approaching the software as a novice, finding ways to commute files between ArcMap and FEFLOW, and especially interpreting the visualisation tools' outputs.

Improving the quality of estimates by accumulating more field data would be a feasible and great improvement. New, high quality data would improve the model framework and the strength of the calibration. Higher quality well log data and water level measurements would bring a significant improvement to the well database used for the geological framework and the potentiometric surfaces. Testing conductivity of hydrostratigraphic units and river sediments would increase confidence in chosen ranges of hydraulic conductivity and river bottom conductance. Improving the accuracy of the DEM would also greatly reduce uncertainty in depth-to-water-table calculations. In addition, we should strive towards obtaining meaningful recharge rates at different locations all over the area.

We mentioned before that our conceptual model may be overlooking important geological features such as bedrock valleys, or permeable lenses in the Champlain Sea deposits. Although it is not possible to account for all interesting features, efforts should be placed on investigating the subsurface in more detail, in particular bedrock topography. If bedrock valleys (deep incisions in the bedrock caused by erosion by ancient rivers) exist, their presence might significantly modify the regional flow dynamics. They could be important draining features for the system, their steep hydraulic gradients driving groundwater flow into the conduits rather than over the otherwise quasi-flat bedrock. Likewise it may be unjustified to assume that small scale geological heterogeneity is not hydrogeologically significant. Quantification of the global and local effects of increasing geological complexity should be attempted in order to improve our conceptual model. Recommendations on field work methods are made in the next and final section.

Calibration could be enhanced if we had good quality calibration targets coupled with weather data. This would be a way of reducing uncertainty and dealing with seasonal variability, rather than trying to calibrate the model at a seasonal average using targets from all seasons. It would require systematic monitoring over a complete year (at least) of water levels in monitoring wells and of precipitation (preferably, infiltration). On the same note, another recommendation concerns the time coverage of the model. This model represents the system at steady-state; the next step would be to make step-wise steady-state models or a transient, time-dependent model to approach monthly variability of climate and pumping stress. This would provide an examination of the effects of trends in climate and water usage in the long-term and help focus future management strategies.

As mentioned in section 4.5, this model is the first one built to represent the VW esker system. It is one among many plausible reconstructions of what may be, and contains many uncertainties. As such, we recommend that the results of this model be used with extreme caution and objectivity. By no means should the results presented in this thesis be used to justify base-flow management. On the contrary, we believe that the lack of responsiveness of the aquifer model to intense stresses is a consequence of the model properties and limitations, which may not be an accurate reflection of reality. The importance of monitoring

water levels, both groundwater and surface water, and updating databases, is paramount for the advancement of knowledge of this unique aquifer. For instance, a regional scale model (with natural boundary conditions around its edges) as well as local scale models (of municipal well fields) may bring welcome insights into the system's inner workings. Smaller scale models as recommended by the MOE would have to have hydrological boundaries (since hydrogeological boundaries occur at very large scale) and therefore a certain number of additional debatable assumptions would have to be made in that regard. However, the purpose of increasing accuracy locally would be fulfilled. In the long run, the different models could be incorporated together and re-evaluated in light of newly acquired data to provide sufficient detail for another improved model.

6.2 Conclusions

Maintaining surface water and groundwater quality is of prime importance due to the number of contamination threats from both urban and agricultural sources (such as pathogens from fecal matter, fuel, road salts, endocrine disrupting compounds (EDCs) and pharmaceutical and personal care products (PPCPs), and other toxic substances). The risk of contamination is higher where the aquifer is not confined by a protective lining of Champlain Sea clay: aquifer vulnerability is highest at permeable groundwater recharge areas such as aggregate exploitation sites and rivers where contaminants can access directly the aquifer and propagate quickly across it. For this reason, it is important to know surface geology and groundwater flow patterns. Although water treatment solutions exist for municipal supplies to ensure "safe" drinking water (coagulation, filtration, reverse osmosis, powder-activated carbon, chlorination, biofiltration, just to name a few), groundwater that is pumped by individuals (residents and farmers) often undergoes minimal treatment in their homes. For this public safety reason, plus on long-term moral grounds of preserving the environment and water for future generations, raw drinking water sources should be kept as pristine as possible.

This study fuels a better understanding of esker aquifers in eastern Ontario, in the context of the ECP and source water protection. The numerical finite-element model built to represent the Vars-Winchester esker system proposes a possible scenario that approximates observed

data with a mean error under 5 m. As any modeller would say when asked to comment on the quality of a model, “a model is only as good as its calibration”. We could add that a model is only as good as the data fed into it, and the means used to construct it.

Any conceptualization of a system is a crude simplification entailing a great number of assumptions. Indeed, even though the best data in existence were selected for the model, the complexity of the calibration stage underlined the large number of uncertainties and knowledge gaps in the conceptual model, which made it difficult to be confident about any of the parameter settings. The most influential unknown variables turned out to be calibration parameters: these were recharge, followed by boundary conditions and hydraulic conductivity. Precipitation records exist, but infiltration and aquifer recharge are seldom measured in situ; it is more common to assess them based on common-sense driven index calculations (taking into account soil type, topography, and vegetation cover). In this case, the model could have greatly benefitted from direct measurement of recharge. Geological parameters also request judgement calls, which can easily be backed up with testing. Arguably, one of the greatest risks in modeling is the geological simplification. Inevitably, we are confronted with complex geology and deep buried features that certainly have an impact on water flow, but which we cannot realistically reproduce. For instance, the esker’s dual structure is a simplistic rendition of what in reality appears as multiple irregular overlapping sand lobes of various granulometry, as evidenced in quarries. These geological assumptions of material homogeneity and error in elevation and thicknesses of the hydrostratigraphic units are sources of uncertainty that come on top of already complex (albeit smaller) numerical problems related to mesh design and elemental structure.

FEFLOW proved to be a good tool in many aspects. It was able to handle the system’s versatile components, be quick in its computation, and provide good visualization options. However, although it is a commercial software growing in popularity, its complexity is still a deterrent. Finite elements are considered a step up from finite differences, and are well worth the investment of time and money in the long term, given that proper user training is provided.

We therefore believe the VW esker model is a good ambitious first try at large-scale modelling of the Vars-Winchester esker system, setting a solid foundation for continued studies on the esker. It is a good tool to test assumptions and parameter combinations; however, its ability to predict changes in the system is very restricted. This is due to the boundary conditions assigned, which maintains surficial waters at specified levels. Consequently, predictions of extreme scenario simulations must be interpreted with critical judgement. However, the model can be improved and updated when relevant and better quality data become available.

Meanwhile, as mentioned in section 6.1, priorities for future related studies lie in improving data quality and abundance, mainly in respect to recharge, hydraulic conductivity and geology. A few methods are suggested in the next paragraphs.

Recharge is difficult to measure directly but can be achieved with physical, chemical and isotopic methods (Sophocleous, 2004). A lysimeter is essentially a hydrologically-isolated box filled with soil in which a water balance can be calculated. Among its disadvantages, is the fact that the device is expensive and permanent; many would be required over the study area, making this method cost-ineffective. A better alternative would be tracers, which can be used to track percolating water and quantify recharge indirectly. This method could corroborate empirical recharge calculations and minimize uncertainty in our estimates.

Falling-head permeametry, such as described and performed on river sediments by Hall (2008), would be a possible method to assess hydraulic conductivity empirically. Representative samples of the different hydrostratigraphic units could be sampled and tested; the average of replications would eventually point out to an order of magnitude to best represent each type of sediment.

Seismic surveying is the only way of investigating bedrock topography without drilling holes all over the area. Since surface topography is relatively flat and groundwater flow is topography-driven, bedrock topography may have a bigger role in impeding or diverting

regional groundwater flow than first envisioned. Buried bedrock features should be a topic of utmost importance for immediate action in the ECP.

Finally, using alternate modeling software and/or modeling at a smaller-scale might be useful to approximate groundwater flow movement with better precision locally and testing plausibility of predictions. Through comparative studies, we would expect (and hope) all the methods of parameter estimation and groundwater flow simulation would converge towards similar conclusions and estimates, increasing our confidence in them. Estimations of this quality would then be priceless in subsequent vulnerability analyses, and ultimately for the development of source water protection plans.

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APPENDICES

APPENDIX A: UOTTAWA FIELD METHODOLOGY BASICS

The following is a short explanatory text reviewing the methodology used by University of Ottawa students over the past few years in the Vars-Winchester study area. It was a contribution to the Methods section of the CANQUA fieldtrip guidebook, published in March 2007.

Simple, inexpensive methods for hydraulic head measurements and groundwater flux estimations (Charland, 2007)

This section describes three simple techniques used to measure groundwater flow interactions with surface water. The quantification of seepage or discharge of groundwater in surface water bodies is an important element to water balance calculations.

Miniature piezometers and seepage meters are devices that can be manually installed in saturated surficial sediments (rivers, lakes, ditches) overlying the aquifer of interest. Shallow piezometers are used to obtain hydraulic head and hydraulic conductivity of sediments, while seepage meters show direction (vertical gradients) and rate of groundwater flow. Both consist in inexpensive materials which make them a useful alternative and addition to deep drilling. The last method described here uses an electrical conductivity probe to reveal groundwater discharge areas, which is useful in deeper water or to determine the location of possible discharge zones.

All calculations are based on Darcy's Law, $Q=A K dh/dl$, where Q is the groundwater flowrate [L^3/T], A the area through which flow occurs [L^2], dh/dl the hydraulic gradient [] and K the hydraulic conductivity of the sediments [L/T].

1) Shallow piezometers

Material needed: drive bolts, drive pipe, drive head, fence-post hammer, PVS pipe, hand-made screens (for example: 15cm pipes, 7 notches or slots, mesh – size function of deposit - glued or welded around in place) (Figure A-1)

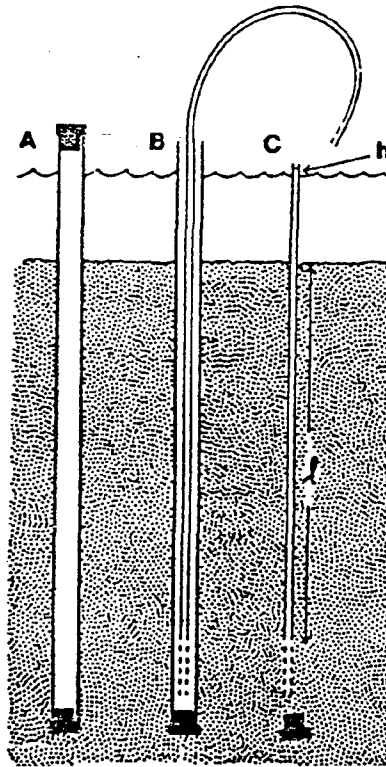


Figure A-1: Steps to the installation of a shallow piezometer. "A, casing driven into the sediment; B, plastic tube with screened tip inserted in the casing; C, plastic tube is a piezometer and indicates differential head (h) with respect to the surface water." (Lee and Cherry, 1978) Secure loose pipe downwards (but not in the water) on a wooden stake.

From this device, we obtain:

- water levels of the water table, measured from the top of the piezometer (m);
- vertical hydraulic gradient (unitless) $i = \Delta h / \Delta l$ (with Δh the difference between the water level inside and outside the pipe, and Δl the depth to which the pipe is set below the sediment-water interface);
- hydraulic conductivity (m/s or m/d), using slug or bail tests (Freeze and Cherry, 1979).

2) Seepage meters

a) Open-top seepage meters

Material needed: large pipe, coupling to use as drive head if necessary, fence-post hammer, small plastic tubing for siphon, bag, and elastic bands (Figure A-2)

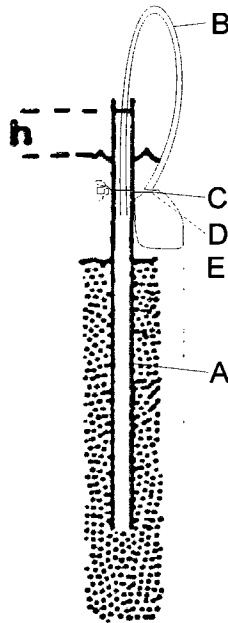


Figure A-2: Open-top seepage meter. A, big piping; B, tube; C, small tube; D, elastic band; E, plastic bag. The flexible tubing is secured to the pipe to keep bag under water level.

An initial volume of water is placed in the bag and monitored over a period of time, making the calculation of flux in or out possible. Corrections must be done to take into account variations in surface water level.

Three parameters can be calculated with the data obtained from this device:

- the vertical hydraulic gradient (unitless) $i = \Delta h / \Delta l$ (with Δh the difference between the water level inside and outside the pipe, and Δl the depth to which the pipe is set below the sediment-water interface);
- the discharge rate (m^3/d) $r = V / \Delta t$ with V the change in volume (corrected to take into account surface water level variation) and Δt the time lapse between measures
- the flux ($\text{m}^3/\text{m}^2/\text{day}$ or m/day) $Q = r / A$ with A the area of the seepage meter pipe.

b) Closed-top seepage meters

Material needed: bucket, rubber stopper, plastic tubing, plastic bag, elastic bands (Figure A-3)

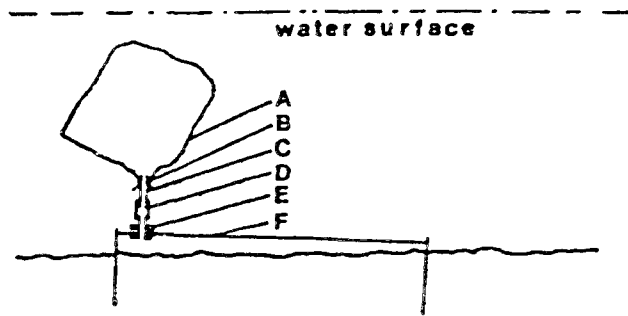


Figure A-3: Closed-top seepage meter, using a tilted bucket, well pushed into sediments so that sides are sealed. A, plastic bag, open end sealed; B, elastic band; C, small tube; D, larger tube; E, rubber stopper; F, drum or bucket. (Lee, 1977; Lee and Cherry, 1978)

The data obtained from this device are the following:

- the discharge rate (m^3/d) $r=V/\Delta t$ with V the change in volume and Δt the time lapse between measures
- the vertical flux ($\text{m}^3/\text{m}^2/\text{day}$ or m/day) $Q= r/A$ with A the area of the bucket or drum.

3) Bottom sediment electrical conductivity mapping

Material needed: boat, EC&T probe (Figure A-4)

This technique requires a probe capable of measuring electrical conductivity and temperature. By dragging the probe at the water-sediments interface of a lake or river, changes in sediment pore water EC is measured and anomalies can be detected indicating possible areas of groundwater discharge (Harvey et al., 1997), which can be double-checked using seepage meters.

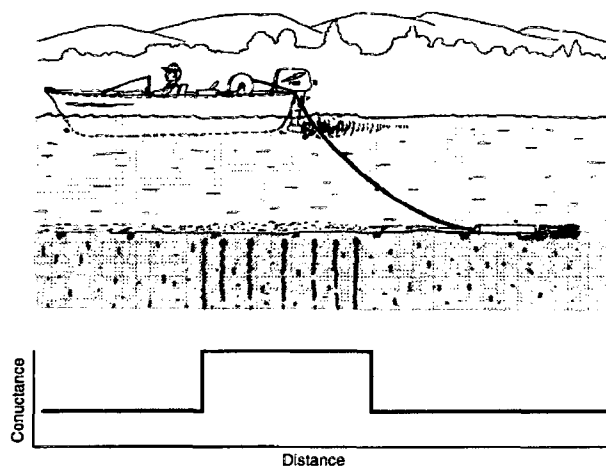


Figure A-4: Conductivity survey for groundwater discharge at the base of rivers or lakes (figure from Harvey et al., 1997).

Installation protocols (Sargent, 2007)

Piezometer Installation Protocol

1. Make sure this is where you want to install your piezometer. Is it safe and practical or is there a better spot close by?
2. Insert drive bolt into the bottom of the drive pipe. Masking tape may be used to hold the bolt onto the pipe if the water is deep.
3. Cover the tip of the drive pipe that is not in the water with the drive head.
4. Place the fence-post hammer over the drive head and drive pipe.
5. Hammer drive pipe through the sediments into the ground with the fence-post hammer. The drive pipe should be into the ground as far as it can be hammered (1 m at least). If the pipe hits a rock pull the pipe out and start again in another location.
6. Attach the screen onto the piezometer pipe with masking tape.
7. Feed the piezometer, screen first, into the drive pipe until it hits the bottom of the hole.
8. To guarantee the sediments fill in around the piezometer, pull the drive pipe out a little bit then stomp feet around the pipe to collapse the sediments into the empty space. Repeat this formula until the drive pipe is completely free.
9. Tug lightly on the piezometer to see if it is correctly installed.
10. Insert wooden stake or vacuum pipe into the ground 10-20cm away from the piezometer.
11. Attach the piezometer to this wooden or plastic support with flagging tape. The top of the piezometer should not be facing upwards or in the water. Bend it in a loop and secure it to the support.
12. Measure water level.

Open Top Seepage Meter (OTSM)

1. Using large plastic piping place one end in the water. Attach a coupling on the end that is facing upwards.
2. Pound the pipe into the ground, using the fence-post hammer, as far down as it will go into the ground. If the pipe hits a rock then remove the pipe and choose another location.
3. Take the small plastic piping and create a siphon. To create a siphon fill the large pipe that is in the water with water to the top. Take the small piping and fill it completely with water. Using thumbs to cover the ends of the small pipe, keeping the water inside the pipe, and insert one end of the small pipe into the large pipe. Make sure the end of the small pipe that is not in the large pipe is still covered with thumb.
4. Once one end of the small pipe is into the large pipe, put the other end of the small pipe that is still pressured by your thumb into the water body. Remove your thumb.

5. Once the pressure has equilibrated (you will feel water coming out of the pipe), attach a plastic bag at the end of the small pipe that is in the water body, securing the bag with an elastic.
6. Tie the small pipe to the large pipe with flagging tape so that the bag is under water.
7. When you take the OTSM out, look if the bottom end was damaged and calculate area again if required.

Closed Top Seepage Meter (CTSM) Installation Protocol

1. Calculate area of bucket or drum.
2. Place bucket/drum upside down into the water with the hole towards the sky.
3. Push bucket/drum into the sediments making sure there is a good seal by running fingers around contact edge.
4. Ensure the hole at the top of the container is at the highest point (may have to be tilted upwards).
5. Let bucket/drum sit in sediments for a while.
6. Assemble rubber stopper, plastic tube, plastic bag and elastic band together.
7. Plug bucket/drum with rubber stopper/plastic bag combination and start timer.
8. Make sure bucket/drum and plastic bag is all under water.
9. When you take the CTSM out, look at the edges of the bucket, and adjust area if necessary.
10. Measure the amount of water in the bag. Calculate the flux in or out.

APPENDIX B: REGIONAL GEOLOGICAL MODEL

The consultant firm Water and Earth Science Associates (WESA) constructed a database system which made possible the creation of a stratigraphic framework based on the OGS 2003 Surficial Geology of Southern Ontario map. This appendix will provide cross-sections and unit descriptions which were published in the Draft conceptual model report (WESA, 2006) for the SNC.

Geological cross-sections were built using ViewLog (an EarthFX software), a borehole data management program which allows interpretation of data from:

- MOE well records (low quality),
- borehole logs from consultant reports (high quality), and
- published geological reports and maps.

Cross-sections of varying lengths were drawn through significant features (municipal wells and eskers). Two of the North-South sections along the VW esker were selected to illustrate the ViewLog model.

As its precursor, this geological conceptual model is slightly different from the geological framework of the model of this thesis project. Excerpts of the original unit descriptions based on OGS legend coding are given below, taken word for word from Appendix F, Draft conceptual model report (WESA, 2006).

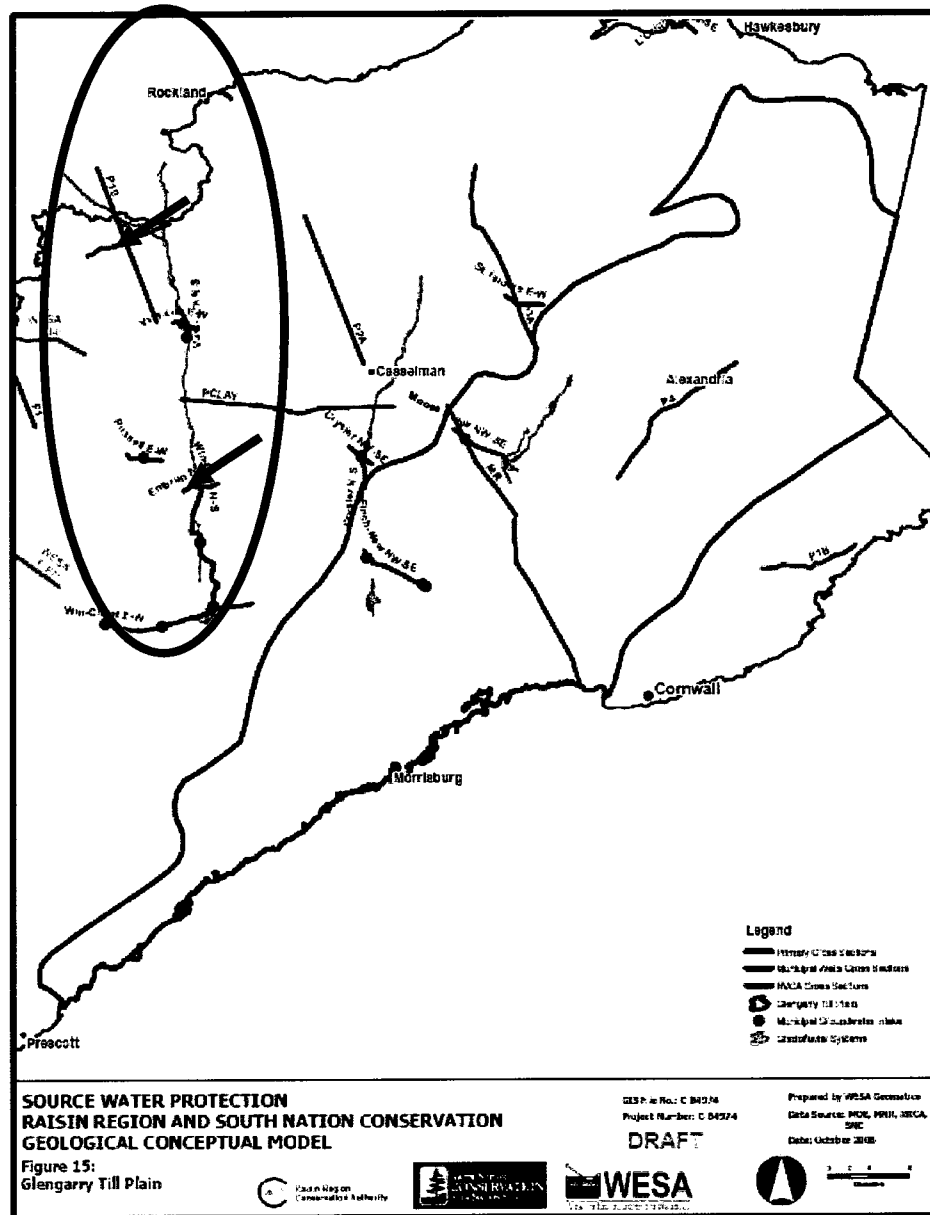


Figure A-5a: Location of cross-sections drawn along the VW esker (modified from WESA draft report, 2006). Arrows point at sections P10 and Winchester-Chesterville N-S.

Surficial Geology Stratigraphic Framework and Unit Descriptions

The stratigraphic framework contains all deposits that were chosen to be modeled within the SWP region. Each unit is both lithologically and chronologically based in that each unit is characterized by a particular lithology and was deposited during a specific time interval.

Our stratigraphic framework was derived from the OGS 2003 Surficial Geology of Southern Ontario map. No deposit type is assumed not to be exposed at the surface somewhere in the region, and therefore this map is an exhaustive list of all surficial sediments.

The stratigraphic framework for this exercise contains all deposit types found within the SWP region with the exception of a few which were not included because of their limited extent. Pleistocene fine-textured glaciolacustrine deposits (map unit 8 from the OGS 2003 Surficial Geology of Southern Ontario map) were excluded from the stratigraphic framework because they were only located in two small patches in the extreme southwest of the SWP region.

Subdivisions of deposit types (i.e. Pleistocene fine-textured glaciomarine deposits (map unit 10) are subdivided into two subunits) made in the 2003 Surficial Geology map were not carried through to the stratigraphic framework as this level of detail was not consistently available from wells and boreholes across the SWP region.

The stratigraphic framework used in developing 3-D conceptual geological models is illustrated below in Table X.

WESA Framework Units	OGS Surficial Geology Map Units
Organic deposits	(20) Organic deposits
Modern alluvial deposits (MA)	(19) Modern alluvial deposits
Colluvial deposits	(18) Colluvial deposits
Eolian deposits	(17) Eolian deposits
Post-glacial alluvium and shallow marine deltaic deposits (PGAD)	(12) Older alluvial deposits (11a) Coarse-textured glaciomarine deposits: Deltaic deposits
Coarse-textured glaciomarine deposits (CTG)	(11b) Coarse-textured glaciomarine deposits: Littoral Deposits (11c) Coarse-textured glaciomarine deposits: Foreshore and basinal deposits
Fine-textured glaciomarine deposits (FTG)	(10) Fine-textured glaciomarine deposits
Glaciofluvial deposits (GF)	(7) Glaciofluvial deposits
Till deposits	(5) Till deposits

Throughout this report a number of sources are referenced which contain similar geological information. In order to avoid confusion the following phraseology is employed:

- “logged as”, or “originally described as” refers to the original well descriptors given by the well driller.
- “coded as” refers to the GSC code applied to the original well description.
- “interpreted as” refers to the application, by WESA, of a framework unit to a sediment interval in a well or borehole.
- The location of wells, boreholes, cross-sections, etc. are commonly referenced in the text in relation to the deposit type they are located in on the OGS 2003 Surficial Geology map.
- A sediment interval refers to a distinct portion of a well or borehole logged by a driller or consultant.
- “Wells” refers to MOE wells; boreholes refer to a hole drilled and logged by a consultant.
- Acronyms may be used for WESA stratigraphic units but are never used when referring to an OGS Surficial Geology map unit.

4.1.2 DESCRIPTION OF STRATIGRAPHIC FRAMEWORK UNITS

The following sections describe each of the framework units, and describes the rules used to apply each of these units to the geologic stratigraphic units in the constructed cross sections.

Organic Deposits

The OGS 2003 Surficial Geology of Southern Ontario map legend describes Organic deposits as: peat, muck, marl. However, an examination of wells located in Organic deposits revealed that their uppermost sediment was logged as any one of a variety of sediment types (Figure of lithology of wells by deposit type); rarely were expected sediment types like muck or peat encountered. The discrepancy between expected and logged lithologies is puzzling. However, in producing cross-sections and 3-D surfaces, the OGS 2003 Surficial Geology of Southern Ontario map was used in defining where Organic deposits were located unless wells provided overwhelming evidence to the contrary.

Organic deposits are widely distributed across the entire SWP region and range in aerial extent ranging from a couple of hundred square metres up to tens of kilometres squared such as the Mer Bleu Bog (Figure 4). An isopach thickness map of organic deposits in the study area can be found in Figure 8. Organic deposits are not overlain by other framework units and their distribution is therefore restricted to where they are shown on the surficial geology map (Figure 4).

Modern Alluvial deposits (MA)

Modern alluvial deposits are described from the OGS 2003 Surficial Geology map as: “clay, silt, sand, gravel, may contain organic remnants”. An examination of the uppermost sediment interval from wells located within Modern alluvial deposits showed that they are commonly coded as clay and diamicton (Figure of lithologies).

Modern alluvial deposits cover only a small area of the SWP zone and are constrained within modern river and stream channels and floodplains (Figure 4). For the purpose of this project, and keeping in mind that these framework units may be used to derive layers in a numerical groundwater model, they are assumed not to be overlain by other sediments, although it is possible that they could be overlain by Colluvial deposits. However, due to their lithological similarity it would be difficult to distinguish overlying Colluvial deposits from underlying Modern alluvial deposits from well records alone. Therefore, Modern alluvial deposits were restricted to where they are identified on the surficial geology map in producing cross-sections and 3-D surfaces.

Colluvial Deposits

Colluvial deposits are described from the OGS 2003 Surficial Geology map as boulders, scree, talus, undifferentiated landslide material. Two boreholes (WES-TW-STPB-1987-D9 and WES-TW-STPB-1987-D10) located near St. Pascal de Baylon are located within Colluvial deposits and contained approximately 24 metres of silt and clay with a few gravel layers down to a gravel till. These two wells illustrate the difficulty of trying to separate overlying Colluvial deposits from underlying older stratigraphic framework unit deposits. An examination of wells located within Colluvial deposits showed that their upper most sediment interval was most commonly coded as clay and was typically between 20 to 60 metres thick.

Colluvial deposits are restricted to the north end of the SWP region and are mostly located around Clarence-Rockland, Plantagenet, and Lefaivre (Figure 4).

Colluvial deposits were assumed for this project not to be overlain by any younger stratigraphic unit, although geologically speaking it is possible. However it would be difficult to distinguish them from other framework units that were lithologically similar, such as Modern alluvial or Fine-textured glaciomarine deposits. Therefore, Colluvial deposits were restricted to where they are found on the OGS 2003 Surficial Geology map in producing cross-sections and 3-D surfaces.

Eolian Deposits

Eolian deposits are described from the OGS 2003 Surficial Geology Map as fine to very fine sand and silt. One borehole, WES-BH-VARS-1987-VW77, located 2.8 km east of Vars, is located in this deposit type, and upper 2 metres of sediment consists of fine-grained sand with 5% silt. This is consistent with the legend description of this unit. An examination of wells located in Eolian deposits (there are not many) showed that their upper most sediment interval was dominantly coded as sand and less commonly as

gravel (originally logged as sand and gravel) or fill (Figure of lithologies – need to include Eolian in the figure). The borehole and well descriptions of their upper most sediment interval indicate good agreement, for the most part, with the OGS 2003 Surficial Geology map.

Eolian deposits are almost entirely located in the northwest and southwest of the SWP region, and are almost always surrounded by either Deltaic deposits or Foreshore and basinal deposits (Figure 4). Eolian deposits are small in extent (~0.1 km square) and mostly occur in clusters. They are not interpreted to be overlain by younger deposits and thus are restricted to where they are identified on the surficial geology map.

Post-glacial Alluvium and Shallow Marine Deltaic Deposits (PGAD)

This framework unit consists of two units from the OGS 2003 Surficial Geology map: Deltaic deposits (sub-unit 11a) from Coarse-textured glaciomarine deposits, and Older alluvial deposits (unit 12). These units were combined into one framework unit because they are contemporaneous, lithologically similar, and geographically close.

Older alluvial deposits are described from the map legend as: clay, silt, sand, gravel, may contain organic remains. An examination of the uppermost sediment interval from wells located within this deposit type showed that their upper most sediment unit consisted most commonly as sand (figure of lithologies).

Deltaic deposits are described from the map legend for Coarse-textured glaciomarine deposits as consisting of: sand, gravel, minor silt and clay. An examination of the 56 boreholes located in three clusters around Vars, Alfred, and Fournier showed that their upper sediment interval typically consisted of fine-grained sand and less commonly of very fine- and medium-grained sand. A fraction of 5-15% silt was common, and pebbles were sub-common. Examples of boreholes intersecting Deltaic deposits are WES-MW-VARS-1987-WV89 and WES-MW-VARS-1987-VW90. The uppermost sediment interval from wells located in Deltaic deposits showed that their sediments were coded most commonly as sand.

Based on the above observations, the lithology for the combined unit Post-glacial alluvium and shallow marine-deltaic deposits is described as consisting of sand, silt or clay.

This combined framework unit is entirely restricted to the northern end of the SWP region and to the southeastern area (Figure 4). This unit is entirely restricted to these two areas and may be overlain by any younger deposits. However, recognizing the boundary between this framework unit and overlying younger deposits that are lithologically similar (e.g. Eolian deposits) is likely impossible with well logs. Therefore, this framework unit was interpreted to be found only where it was mapped, and to be overlain by younger deposits, such as Eolian deposits, only where they are found within its boundaries.

Coarse-textured Glaciomarine Deposits (CTG)

This framework unit consists of two sub-units for Coarse-textured glaciomarine deposits from the OGS Surficial Geology map: Littoral deposits (11b) and Foreshore and basinal deposits (11c). The map describes the lithology of these units as sand, gravel, minor silt and clay.

Boreholes located within these deposit sub-types showed that the uppermost sediment interval consisted of sand and gravel of varying proportions (sometimes exclusively of one sediment type). Wells located within these deposit sub-types showed that their uppermost sediment interval consisted dominantly of sand and gravel, with gravel more common in Littoral deposits (Figure of lithologies).

This framework unit is dominantly exposed at the surface in the western and south-central areas of the SWP region. This framework unit may underlie younger units however this was not commonly observed, indicating that this unit is mostly restricted to areas where it is mapped at the surface.

Fine-textured Glaciomarine Deposits (FTG)

This framework unit's OGS equivalent is described as consisting of silt and clay, minor sand and gravel. Boreholes located in Fine-textured glaciomarine deposits contain upper sediments that were described as clay, silt, silty clay, clayey silt, interbedded silt and clay, or interbedded sand and silt. Traces of gravel or pebbles were not common. Type boreholes for this framework unit are WES-BH-CHST-1988-DH8 and INT-MS-STIS-1991-TW6. An examination the uppermost sediment interval from wells located in this deposit type showed that their upper sediments were most commonly coded as clay. Exceptions to this were mostly found in areas where Till deposits were abundant and the overburden was thin. In such areas, the uppermost interval typically was coded as diamicton. The above observations indicate the fairly good agreement between the OGS 2003 Surficial Geology map and borehole and well logs. Discrepancies are most likely to be found where Fine-textured glaciomarine deposits are located close to Till deposits in areas of thin overburden.

This framework unit covers a very large area of the SWP region, particularly the central, northern and eastern areas.

It may be overlain by any younger deposit. It was commonly observed to be overlain by PGAD deposits and CTG deposits.

Glaciofluvial Deposits (GF)

Glaciofluvial deposits are described from the OGS 2003 Surficial Geology map as consisting of sandy and gravelly deposits. An examination of the uppermost sediment interval from wells located within this deposit type showed that they dominantly consist of gravel and sand (figure of lithologies). Glaciofluvial deposits are shown on the OGS 2003 Surficial Geology map as mostly located along the western boundary of the SWP region, particularly south of Ottawa. Another source consulted regarding Glaciofluvial deposits was a report by George Gorrell (1991) on "Buried Sand and Gravel Features and Blending Sand in Eastern Ontario." This report identified a number of glaciofluvial systems in the region (Figure of Gorrell's eskers), and was thus used to help identify sub-surface glaciofluvial deposits. An examination of boreholes located within the trace of these north-south oriented systems showed that the sediment immediately overlying Till deposits, and interpreted as Glaciofluvial deposits, consisted of metres to tens of metres of gravel and sand.

Till Deposits

Five Till sub-unit deposits are listed in the OGS 2003 Surficial Geology map; however, only one is found in the SWP region, this being sub-unit 5b: Stone-pocr, sand silt to silty sand-textured till on Paleozoic terrain. Boreholes containing basal sediment logged as till showed more lithological variation. Till in boreholes was commonly described as silt or silty sand with common gravel and/or one or more of the following: cobbles, pebbles, boulders, bedrock fragments. Less commonly, this unit was described as clay-rich. Interestingly, some boreholes contained basal sediment logged as gravel till. In wells, basal sediments interpreted as till showed the same variability. Many wells showed basal sediments coded as diamicton, which were originally described as till, or hardpan, or clay with a mixture of sand, gravel, stones, cobbles, boulders and bedrock fragments and descriptors like hard or packed. Many wells include descriptions of basal sediment coded as gravel. Basal gravel was originally described solely as gravel, or gravel with a mixture of the following: clay, sand, stones, boulders, bedrock fragments, and terms like hard or packed. Basal gravel sediment was commonly interpreted as Till deposits because it was interbedded with or underlay diamicton, or because of presence of clay or bedrock fragments, or because of the proximity to other wells containing diamicton in stratigraphically identical positions. The identification of gravel till in boreholes also lends credence to its interpretation from wells.

Till deposits exposed at the surface cover a large portion of the SWP region, particularly a large south-central area that extends northeast (Figure 4). Till was commonly identified under younger sediments across the entire region.

APPENDIX C: CAPTURE ZONE ANALYSIS

Analyzing the extent of capture zones prior to designing the numerical model was crucial. Since the model was created to aid municipal water supply management and source water protection plans, the model domain had to be large enough to cover the potential capture zones around municipal water supply wells.

The capture zone defines the geographical area from which a well draws its water from, at a given pumping rate. It can extend upgradient theoretically up to a regional groundwater divide, and extend downgradient as far as the stagnation point (or local groundwater divide) created by the cone of depression of the well. The edge of the capture zone for confined aquifers at steady state can be estimated with the following equation (Todd, 1980; Grubb, 1993; in Fetter 1994):

$$x = -y / (\tan(2\pi Kbi/Q))$$

where x and y are coordinate values, Q is the pumping rate of the well [m³/d], K is the hydraulic conductivity of the aquifer [m/d], b is the initial saturated thickness of the aquifer [m], i is the regional initial hydraulic gradient [], and $\tan []$ is in radians.

The distance to the downgradient stagnation point created by the well is given by:

$$x_0 = -Q / (2\pi Kbi)$$

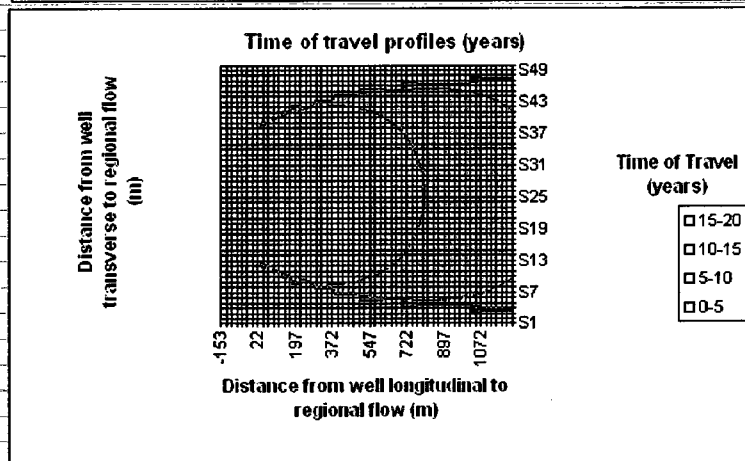
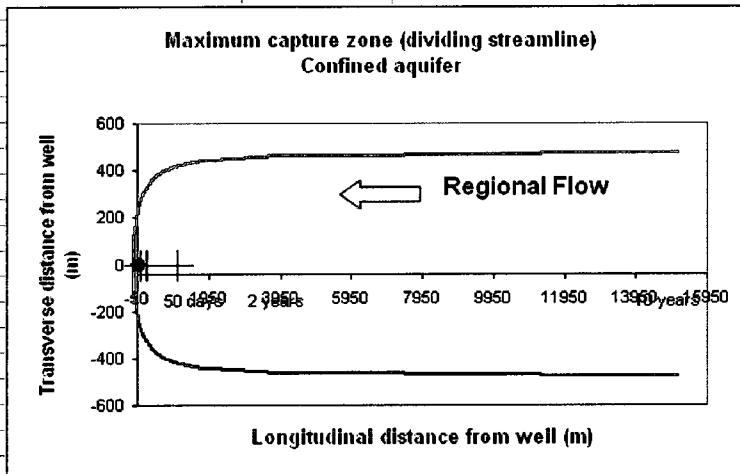
The maximum half-width of the capture zone as x approaches infinity is given by:

$$y_{\max} = \pm Q / (2Kbi)$$

Based on these equations, the following spreadsheet was used to calculate the location of the stagnation point, the maximum radius and the upgradient extent of the capture zone for different periods of time:

Uniform Flow Method - Confined Aquifer

- Accounts for a regional gradient, i ; regional flow is longitudinal to the x axis; well is at $(0, 0)$.
- For confined aquifers only, at steady state.
- This sheet calculates the steady-state maximum extent of the capture zone and a travel of travel map. It is given by the position of the steady-state groundwater divide produced by the pumping well. It also corresponds to the outermost streamline or dividing streamline.



Input constant parameters:				
Q_w	=	151475	= maximum approved pumping rate of the well [L^3 / T] e.g. (m^3 / y)	
n	=	0.3	= porosity [L^3 / L^3]	
b	=	5	= saturated thickness of screened interval [L] e.g. (m)	
K	=	3153.6	= hydraulic conductivity [L / T] e.g. (m / y)	
i	=	0.01	= Regional hydraulic gradient [L / L]	
Output:				
x_{stag}	=	-152.8919	= null point or stagnation point (m)	
y_{div}	=	480.32407	= half-width of capture zone as x approaches infinity (m)	
		(50 days)	(2 years)	(10 years)
Input: independent variable	tot (years) -->	0.136986	2	10
Output: upgradient extent:	$x(tot)$ (m) -->	14.4	210.24	1051.2
				(25 years)
				2628

Figure A-6: Example of capture zone calculations for Winchester Well no.6, which pumps 415 m^3/d from the confined bedrock aquifer ($K=0.0001m/s$). The upgradient extent for 25-years is estimated at 2.6 km. Calculation spreadsheet courtesy of M. Robin (modified).

APPENDIX D: LIST OF WELLS

Well	ID	X	Y	NAME	PTTW	RATE (m ³ /d)	Ground elevation	Bottom elevation	Static water level	Model slice	ASSUMPTION
Commercial/Industrial	1	464680	5010670		01-P-4085					slice 6	Having no information on the design and depth of these commercial and industrial wells, we have to assume that these wells take their water from the bedrock aquifer. It is possible that these water-yielding wells are open along a certain depth of the well and therefore take water from more than one layer. With limited knowledge of their log data, this is a reasonable and safe assumption; however, it may be a source of error. According to Francois Richard (MESA, personal communication 2008), 18 out of the 20 PTTWA should be removed as outdated. 1 permit is left with 2 records. FR recommended that 50% of permitted use be used as approximation for actual taking. This permit is for ponds used to mix concrete and wash trucks; water is taken from shallow groundwater, and quickly makes its way back
	2	464600	5010725		01-P-4085					slice 6	
	3	464450	5010750		01-P-4085					slice 6	
	4	464415	5010720		01-P-4085					slice 6	
	5	464420	5010700		01-P-4085					slice 6	
	6	470275	5024430		03-P-4069	145.46				slice 6	
	7	470225	5024360		03-P-4069	12.27				slice 6	
	8	470275	5024430		03-P-4069A					slice 6	
	9	470225	5024360		03-P-4069A					slice 6	
	10	477907	4999811		412-62NR19					slice 6	
	11	477880	4994150		412-62NR19					slice 6	
	12	472638	4991630		81-P-4045					slice 6	
	13	473014	4991448		81-P-4045					slice 6	
	14	468606	5032636		88-P-4056					slice 6	
	15	468606	5032405		88-P-4056					slice 6	
	16	489124	5032366		88-P-4056					slice 6	
	17	476791	4999208		88-P-4043					slice 6	
	18	472367	4994160		92-P-4027					slice 6	
	19	472825	5020450		95-P-4014					slice 6	
	20	471201	5016676		98-P-4092					slice 6	
Municipal	1	476820	5000483	MOE-WINC-1936-Well/B		460	77.00	62.50		slice 4	Municipal wells generally have long screens (approx 4-5m) and go down to sand/gravel/silt/clay/diamion unit. Since the screen lengths cover potentially multiple aquifers, the most representative aquifer of the water which would be pumped in these wells would be the most productive (water-yielding) aquifers. Some of the slices could be assigned to sand (like the Chesterville wells, perhaps even Limoges) instead of gravel.
	2	476807	5000428	G.D.-WINC-1994-94-2 (Winchester 7A)		460	76.19	64.69		slice 4	
	3	472634	4992119	Winchester Well No. 1		236	76.80	18.80		slice 6	
	4	470822	4992931	Winchester Well No. 5		236	74.63	46.83		slice 6	
	5	467211	4992426	Winchester Well No. 6		416	79.00	63.20		slice 6	
	6	476818	5000469	MOE-WINC-1986-Well/C		0	77.00	63.00		slice 4	
	7	474942	5022417	WES-VARS-1984-VARS-WELL-NO.2		0	75.67	51.27	71.36	slice 4	
	8	474963	5022399	WES-VARS-1981-VARS-WELL-NO.1		228	75.65	52.65	70.64	slice 4	
	9	476416	5006959	GEL-RUSL-1962-PW1		1923	77.40	61.24	67.07	slice 4	
	10	476397	5006957	GEL-RUSL-1962-PW2		101	77.40	61.24	71.26	slice 4	
	11	475425	5021096	G.D.-LIMO-1994-WELL NO.2		0	74.67	53.37	71.44	slice 4	
	12	475425	5021099	G.D.-LIMO-1994-WELL1		564	74.77	50.27	71.44	slice 4	
	13	477850	4994175	G.D.-CHST-2003-BH03-1		302	96.85	86.75		slice 4	
	14	477866	4994078	MBL-CHST-1989-PW5		302	76.99	64.99		slice 4	
	15	471013	5008978	UNK-RUSL-????-PW1		664				slice 6	
Observation	1	479332	5013692	SNC-RUSL-2007-RT300-W1		69.37	30.74	64.17	64.17	slice 2	Observation wells were built using 10 feet (3m) 20-slot screens (or 5 feet), cutting across multiple aquifers. The most representative aquifer is thus the most water yielding (and open on most length). These are the wells used for calibration.
	2	479333	5013692	SNC-RUSL-2007-RT300-W2		68.28	59.47	64.65	64.65	slice 4	
	3	479377	5013751	SNC-RUSL-2007-RT300-E1		67.67	56.39	64.15	64.15	slice 4	
	4	479376	5013759	SNC-RUSL-2007-RT300-E2-MULTI		67.5	43.46	64.14	64.14	slice 3	
	5	477665	5019370	SNC-RUSL-2007-ST1mm		73.74	45	69.72	69.72	slice 6	
	6	473159	5030244	SNC-RUSL-2007-WP1		79.61	72.56	77.69	77.69	slice 3	
	7	473171	5030160	SNC-RUSL-2007-WP2		94.59	70.46	77.46	77.46	slice 5	
	8	473267	5030224	SNC-RUSL-2007-WP3		66.96	71.62	76.63	76.63	slice 5	
	9	476144	4992993	SNC-MPLR-2007-MRE		71.4	80.26	80.26	80.26	slice 5	
	10	474875	4992606	SNC-MPLR-2007-MRW		81.37	72.42	77.7	77.7	slice 3	
	11	477338	4993134	SNC-MPLR-2007-MRH-W1		90.29	78.09	82.16	82.16	slice 4	
	12	477348	4993132	SNC-MPLR-2007-MRH-W2		89.96	89.96	79.94	79.94	slice 3	
	13	471681	5036074	SNC-CMBL-2007-2930-FH2		87.64	61.5	80.87	80.87	slice 6	
	14	472700	5036574	SNC-CMBL-2007-3233-FH1		87.07	53.78	72.99	72.99	slice 6	
	15	468198	5034656	SNC-CMBL-2007-FH3		88.03	65.6	65.6	65.6	slice 6	
	16	478994	4992399	SNC-CHST-2007-BahH		72.86	55.77	67.97	67.97	slice 5	
17	478994	4992341	SNC-CHST-2007-BahW2		72.77	65.52	68.22	68.22	slice 4		
18	468198	5034656	SNC-CMBL-2007-1975-FH4		87.35	87.35	flowing (?)	flowing (?)	slice 6		

Table A-1: Complete available well data, showing geographical coordinates (UTM), pumping rates or water levels of industrial, municipal and observation wells. The stratigraphic layer each well takes water from was interpreted from well logs or background information (6=bedrock, 5=till; 4=esker gravel, 3=esker sand, and 2=clay).

APPENDIX E: LIST OF TRIAL CALIBRATION SCENARIOS

Condition	Value tested	Results
Scenario 1		
Recharge	None	Reasonable regional gradient and range, head distribution does not follow topography, specified heads force at edges.
Hydraulic conductivity	CS deposits 1e-7m/s, sand 1e-3m/s, gravel 1e-2m/s, till 1e-6m/s and bedrock 1e-4m/s.	
Anisotropy	Kx=Kz=10Kz for all layers	
Boundary conditions	Specified heads (type 1) for western northern and eastern b.c., Type 3 for SNR and rivers	
Conductance	First set at 0.0008 at Castor, 0.00864 at East Castor and 0.0864 d-1 at South Nation and other rivers with no field measurements. Then fixed at 0.15 d-1 (in and out) globally.	
Scenario 2		
Recharge	MOE distribution	Incorrect head distribution: water mounding at inopportune places (between Bearbrook and Castor, and along SNR).
Other parameters	Same as in Scenario 1	
Scenario 3		
Recharge	Calculated infiltration as vertical fluxes based on thicknesses and K values	Highly unlikely distribution and values. Discarded.
Other parameters	Same as in Scenario 1	
Scenario 4		
Recharge	Robin&Daneshfar uncalibrated recharge distribution. Values ranging from -5.6 to 5.56 m/month (many outliers).	Values unlikely, but homogeneous distribution which could be used.
Other parameters	Same as in Scenario 1	
Scenario 5		
Recharge	New trial with MOE distribution. Tried dividing by a factor of 2 and 4. Locally reducing the infiltration (over permeable but thin surficial deposits) did not get rid of water mounds.	Incorrect head distribution: water mounding at inopportune places (especially south). 5 to over 50% domain area flooded.
Hydraulic conductivity	CS deposits 1e-7m/s, sand 1e-3m/s, gravel 1e-2m/s, till 1e-6m/s and bedrock 1e-4m/s. Tried changing K contrasts by increasing bedrock and sand K with little improvement.	
Boundary conditions	Modified lateral Type 1 b.c. to Type 2, still too much water in the system. However, model is sensitive to magnitude and location of lateral in/outflux. Tested whether high vertical outflux from the bedrock layer could help: still major flooding and problems.	
Other parameters	Same as in Scenario 1	

<p>Scenario 6 Recharge</p>	<p>Robin&Daneshtar distribution, cleaned of extreme values. Initial distribution ranging between 0 and 33*10-4m/d (or 0 and 1205 mm/year), reduced by a factor of 5 up to 30, settled at 12 (0-2.75 e-4 m/d (0-100mm/yr)) as minimal reasonable range. More water flooded Bearbrook valley and numerous zones in the South and along the SNR.</p>	<p>Water level follows too loosely topography. Infiltration too low. Inundation zones in East Castor and Bearbrook valleys. Mounding in South.</p>
<p>Hydraulic conductivity</p>	<p>CS deposits 1e-6m/s, sand 5e-3m/s, gravel 1e-2m/s, till 5e-5m/s and bedrock 5e-4m/s. Improvement when increasing Champlain Sea deposits to 5e-6, 1e-5, 2.5e-4m/s, but more had minor impact and would be unlikely (getting too close to range of sand K).</p>	
<p>Anisotropy Boundary conditions</p>	<p>Same as in Scenario 1 Model still sensitive to lateral flux changes in a subtle way. If too high, undesirable edge effects. If deleted: surprisingly little overall effect (?). Corrected levels of rivers, lowered in order to reduce flooding. Marshes inputted as Type 1 b.c. and deleted when too close to wells. Lowered by 1-2 m.</p>	
<p>Conductance</p>	<p>Increasing transfer rate helps, but is unlikely. Fixed at 0.15 d-1 (in and out) globally.</p>	
<p>Scenario 7</p>		
<p>Recharge</p>	<p>Modified new Robin&Daneshtar distribution (1), where background distribution is Robin&Daneshtar distribution /120 (0-10mm/yr), with 4e-4m/d at esker outcrops, half as much in esker buffers (200m) and bedrock outcrops, and 1e-4m/d at bedrock buffers (300m). Several attempts. Doubling the infiltration locally influences the nRMS by 1 or 2%.</p>	<p>NB: Corrected DEM at a few isolated nodes in riverbed of the Ottawa river (unjustifiable dips). Additional dips in other rivers could be corrected. Head distribution follows too loosely topography, especially in the west. Depth to water table reasonable.</p>
<p>Hydraulic conductivity</p>	<p>CS deposits decreased from 2.5e-4m/s back to 1e-7m/s (little difference with 1e-6m/s). CS deposits 1e-7m/s, sand 5e-3m/s, gravel 1e-2m/s, till 5e-5m/s and bedrock 5e-4m/s. Increasing Till K changes little, but better results than decreasing. Lowering bedrock K improves flooding but increases depth to water table too much.</p>	
<p>Anisotropy Boundary conditions</p>	<p>CS deposit K changed from anisotropic to isotropic so $K_x=K_y=K_z=1e-7m/s$ Increasing lateral fluxes in bedrock and till layers when heads to high and reducing eastern outflux has minor effect. South Nation River as Type 3 causes southern pools; left as Type 1. Heads in East Castor lowered in order to reduce flood zone in that area.</p>	
<p>Conductance</p>	<p>When increased 2 (or more) orders of magnitude, visible improvement. Left at 0.15 d-1 (in and out).</p>	

Scenario B		
Recharge	Modified new Robin&Daneshfar distribution (2), where background distribution is Robin&Daneshfar distribution /120 where "depth to sand layer" (clay thickness) is thicker than 5m, but same *1.5/120 where thinner than 5m; with max 12e-4m/d (438mm/yr) at esker outcrops, half as much in bedrock outcrops, and grading values at buffer zones (200m or more if close association to till).	Generally plausible potentiometric surfaces. Better depth to water table distribution. Greatest depth to water table found north of Bearbrook (bedrock ridge south of Ottawa River). Inundation of river segments (<10m) and some clayey zones adjacent to rivers (<5m). Interestingly, changes which improve RMS worsen the inundations. When compared to observed heads, modeled heads are almost systematically lower.
Anisotropy	CS deposit K changed to $K_x=K_y=K_z=1e-6m/s$ (isotropic)	
Hydraulic conductivity	CS deposits 1e-6m/s, sand 5e-3m/s, gravel 1e-2m/s, till 2e-4m/s and bedrock 1e-4m/s. Bedrock and till K are in same order of magnitude: $K_{till}>K_{bedrock}$ yields better results than $K_{bedrock}>K_{till}$. (RMS=6m) Reducing bedrock conductivity by half increases inundation zones, improves RMS (RMS=4.9m).	
Boundary conditions	Assuming a 0.001 topo gradient, lateral fluxes become: ± 0.01 m/d in bedrock, ± 0.02 m/d in till, -0.00008 m/d at west and $+0.0001$ m/d at east for CS deposits, -0.05 m/d at west where there is surficial sand and till, $+0.001$ m/d at east where surface geology is clay and 0.1 m/d where it is sand. (decreased flux at depth and surface)	
Conductance	0.15 d-1 (in and out)	

Table A-2: List of calibration and sensitivity analyses performed. It is important to note that along the way the calibration well data was slightly modified, so tests may not exactly compare to final calibration results (differences in the decimal numbers).

APPENDIX F: CALIBRATION STATISTICS

	Observed Head (m)	Calculated Head (m)	Residual	Squared residuals
	86.0	81.4	-4.60	21.1
	88.0	80.4	-7.56	57.1
	81.0	71.5	-9.54	91.1
	73.0	69.5	-3.48	12.1
	78.0	69.7	-8.35	69.7
	77.0	69.5	-7.46	55.6
	77.0	69.6	-7.42	55.0
	70.0	61.8	-8.19	67.0
	64.0	63.9	0.12	0.0
	64.0	63.9	-0.12	0.0
	64.0	63.9	-0.11	0.0
	65.0	63.9	-1.11	1.2
	68.0	69.7	1.70	2.9
	68.0	69.7	1.71	2.9
	82.0	74.2	-7.75	60.1
	80.0	74.2	-5.75	33.1
	80.0	74.3	-5.69	32.4
	78.0	73.9	-4.07	16.5
Average	74.6	70.3	-4.3	32.1
Standard deviation			3.8	
Maximum	88.0			
Minimum	64.0			
ME			-4.33	
RMS				m
nRMS (set)				5.67 m
nRMS (system)				23.61 %
NB Observed loss of set is 24.0 (=88.0-64.0)				
nRMS (system)				11.66 %
NB Modelled total loss of system is 48.6 (=88.2-39.6)				

Calibration plot

Table A-3a: Example of calibration calculations, for the latest simulation, using the 18 observation wells for mean error (ME) and Root Mean Square (RMS). Note that the total loss within the system may in reality be larger than modelled; based on the DEM, elevation loss in the model domain is 120-31=89m.

Residuals	"Regression"	Squared residuals	Squared "regression"
-4.60	6.79	21.15	46.11
-7.56	5.83	57.09	34.03
-9.54	-3.16	91.10	9.96
-3.48	-5.09	12.11	25.93
-8.35	-4.96	69.66	24.58
-7.46	-5.07	55.58	25.67
-7.42	-5.03	54.99	25.27
-8.19	-12.80	67.00	163.75
-0.12	-10.73	0.01	115.11
-0.12	-10.73	0.01	115.11
-0.11	-10.73	0.01	115.03
-1.11	-10.73	1.24	115.03
1.70	-4.92	2.88	24.16
1.71	-4.90	2.93	24.01
-7.75	-0.36	60.12	0.13
-5.75	-0.36	33.10	0.13
-5.69	-0.30	32.36	0.09
-4.07	-0.68	16.55	0.46
SS_{res}			
r²			
SS_{res}/(SS_{res}+SS_{reg}) =			
Calculated head - Observed head			
Calculated head - Mean of observed heads (74.7m)			
Residuals =			
"Regression" =			
r ² =			
closer to 1 is best (means model accounts for most variability observed)			

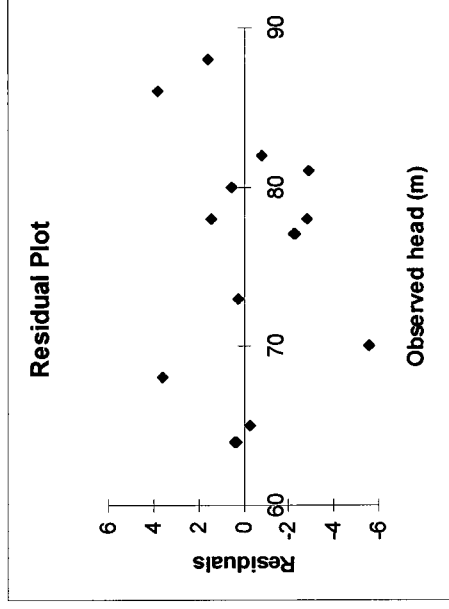


Table A-3b: Example of calculations of the determination coefficient r^2 , for the favoured calibration scenario, using the 18 observation wells. The Kolmogorov-Smirnov normality test on the residuals gave $D=0.176$ compared to a critical D ($n=18$, $\alpha=0.05$) of 0.309 : we do not reject the null hypothesis, the residuals are normally distributed. Note the residual plot shows the regression residuals.

APPENDIX G: SCENARIOS FOR SENSITIVITY ANALYSES

Sensitivity analyses aimed at quantifying the effect of two essential variables in the model: recharge rates and pumping stress. The four scenarios were named as follow:

- Scenario 0 (Base Case Scenario): present pumping, regular infiltration (calibrated model output);
- Scenario 1: same pumping as present, no infiltration;
- Scenario 2: increased pumping, regular infiltration;
- Scenario 3: increased pumping, no infiltration.

The following figures are FEFLOW generated fluid flux mass balances, breaking down water inputs and outputs by flux type and boundary type. Flux types are divided among: fluxes through inner and outer boundaries, injections and withdrawals at wells, and areal fluxes such as recharge. Boundary types correspond to types described in body of thesis: 1st kind refers to specified head (Type I boundary), 2nd kind to specified fluxes (Type II boundary), 3rd kind to fluxes across river bottom sediments of specified conductance (Type III boundary), and 4th kind to specified pumping rates for wells. The model domain maps show the mesh with circles indicated the direction of vertical flux across the top layer: red is for downward flux (e.g. recharge), blue is for upward flux (e.g. groundwater discharge).

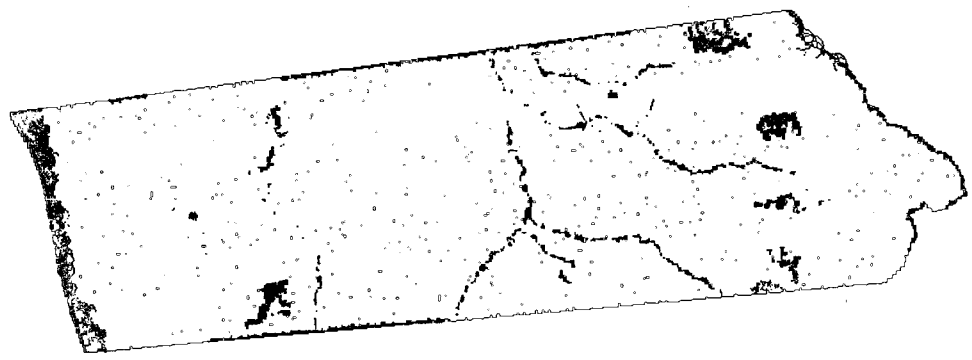
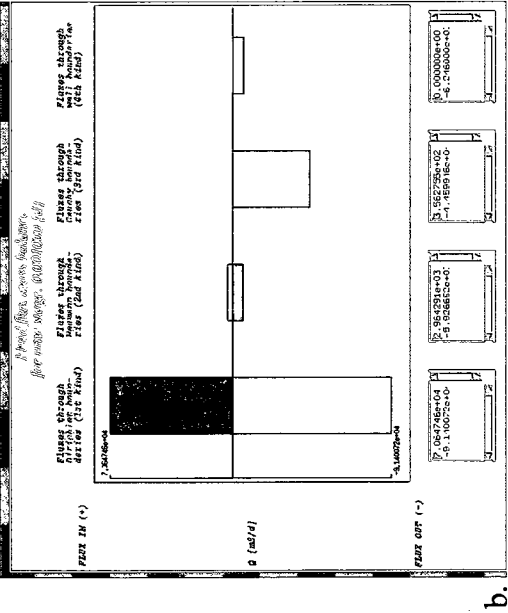
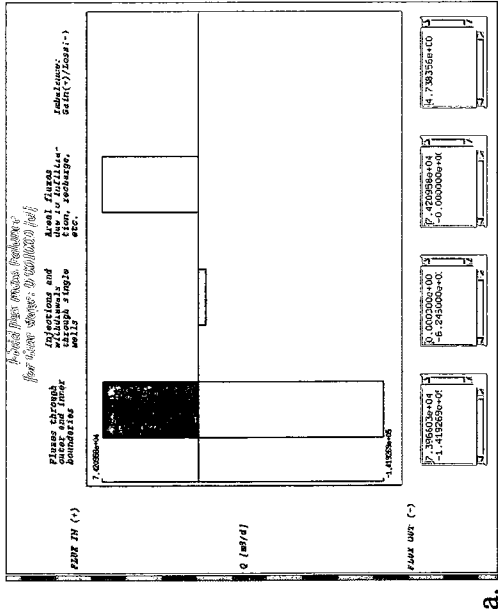


Figure A-7: Scenario 0 (best calibrated output). Graphs of water mass balance by (a) flux type and (b) boundary type. (c) The map of the model domain shows in blue= areas of outflux, and in red= zones of influx. Recharge occurs on the large scale, with discharge in rivers and surficial water bodies.

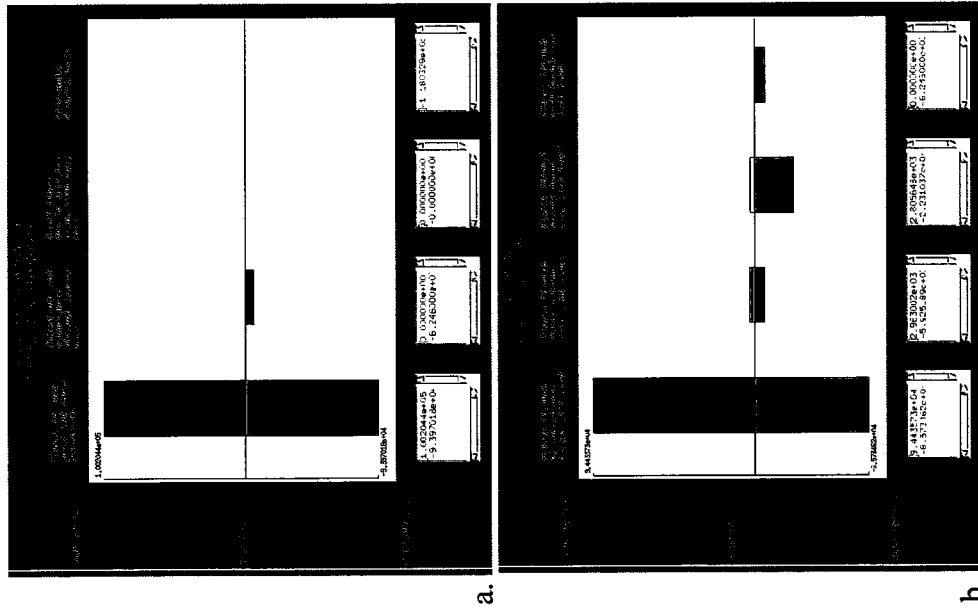
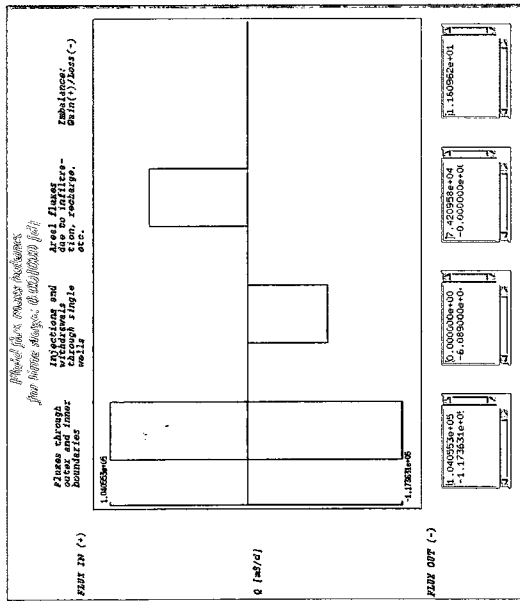
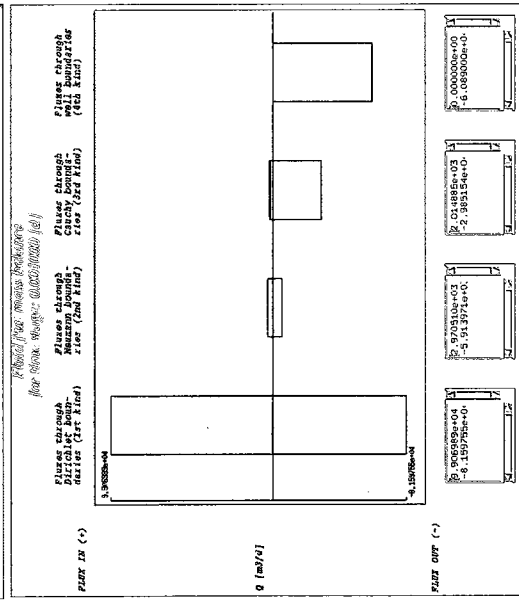


Figure A-8: Scenario 1 (no infiltration). Green graphs are fluid flux mass balances generated by FEFLOW, broken down by (a) flux type and (b) boundary type. (c) The map of the model domain shows in blue= areas of outflux, and in red= zones of influx, and in black= near zero flux. Notice in this case that some rivers and water bodies would recharge the aquifers.



a.

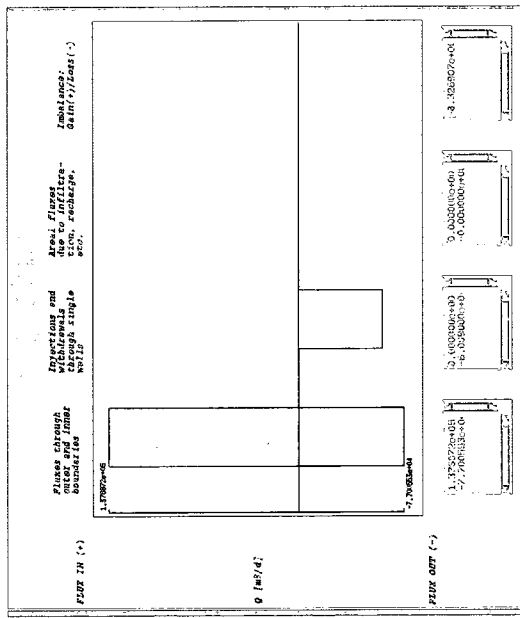


b.

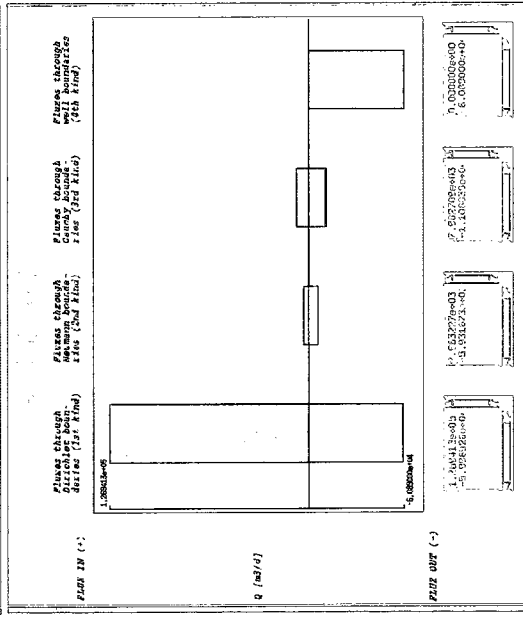


c.

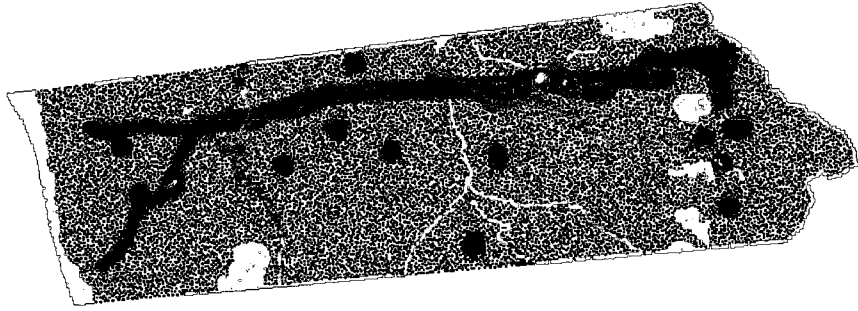
Figure A-9: Scenario 2 (10x more pumping). There is little difference with Scenario 0 in regard to flux distribution.



a.



b.



c.

Figure A-10: Scenario 3 (no infiltration and 10x more pumping). In this extreme scenario, rivers are less likely to receive recharge from ground. South of the Maple Ridge fan deposits, we see that the esker would cease to feed the South Nation River. The esker would the recharge from the river and be threatened by contamination (Blue= flux out; Red= flux in; Black=near zero).

APPENDIX H: CONTENT OF DATA DVD

Attached to this thesis is a data DVD containing MS Office, ArcMap and FEFLOW files.

The contents of the DVD are the following:

- *.pdf version of thesis
- Excel versions of calculation spreadsheets
- Explanatory file on use of all below datasets:
 - o topography of all layers
 - o surface geology
 - o initial head estimates
 - o infiltration distributions
 - o files used to assign K to each layer
 - o rivers, quarries, marshes shapefiles
 - o heads assigned to rivers
 - o data relevant to all different wells used
- FEFLOW model problem files (*.fem) and results in post-processor format (*.dac) for the calibrated output (Base Case Scenario) and 3 sensitivity analyses scenarios.