Geoscience Canada

The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario

D. R. Sharpe, M. J. Hinton, H. A. J. Russell et A. J. Desbarats

Volume 29, numéro 1, march 2002

URI : https://id.erudit.org/iderudit/geocan29_1art01

Aller au sommaire du numéro

Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Découvrir la revue

Citer cet article

Sharpe, D. R., Hinton, M. J., Russell, H. A. J. & Desbarats, A. J. (2002). The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario. *Geoscience Canada*, *29*(1), 3–20.

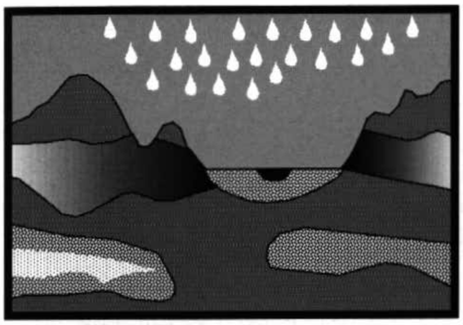
Résumé de l'article

Pour gérer de manière durable lesressources en eaux souterraines canadi-ennes, il est impératif d'acquérir uneconnaissance régionale des systèmesaquiferes. Avec les rares données hydro-géologiques qui existent, l'améliorationdes connaissances régionales doit recourirà l'approche multidisciplinaire pouraméliorer la compréhension géologiqued'un bassin. L'analyse de bassin — carto-graphie et caractérisation du potentiel duréservoir du bassin sédimentaire commecela se pratique en exploration pétrolière -est une approche qui peut s'appliquerdirectement aux études hydrogéologiquesrégionales ainsi qu'à l'aménagement duterritoire concerné. Le présent compterendu porte sur une analyse de bassin d'unterrain glaciaire par l'intégration dedonnées issues d'une variété de sources etd'échelles de recherche différentes en vuede l'élaboration d'un modèle hydrogéo-logique de la région de la moraine d'OakRidges (MOR), dans le sud de l'Ontario.

Lanalyse de bassin est un processusprogressif qui va de la compilation desdonnées et de la conceptualisation géolo-gique pour l'élaboration d'un modèle,jusqu'à l'analyse quantitative d'un systèmede circulation des fluides. Cette progres-sion comprend, notamment, l'élaborationde modèles géologiques de départ de lastratigraphie, de l'architecture sédimen-taire et de l'origine des dépôts de la régionde la MOR. L'analyse a permis de dis-cerner deux éléments régionaux trèsimportants dans la compréhension de dela circulation des eaux souterraines de larégion : 1) des hautes terres de till formantle principal aquitard; 2) des chenaux qui traversent le till, constituant des fenêtreshydrauliques et d'importants aquiferes dechenaux comblés. Cette configuration end'aquîfère en chenaux n'avait pas étéreconnue jusqu'à maintenant parce que sadétection n'était possible qu'en recourantà une approche géologique combinantdonnées topographiques, géologiques etgéophysiques de haute qualité. La consti-tution d'une banque de connaissancesgéologiques régionales n'aurait pu se faireen n'ayant recours qu'aux seuls registres dedonnées de piètre qualité des puitsexistants. On a eu recours à un modèlenumérique qui a permis d'illustrerl'importance de la composante verticalede la circulation à travers des chenauxgénériques.

L'approche par bassin hydrolo-gique inhérente à l'analyse de bassinfacilite grandement la communicationentre les géoscientifiques, les ingénieurs,les planificateurs et autres scientifiques. Lameilleure compréhension du cadreh yd rogéo logique améliore également lecaractère scientifique de la base deréférence pour l'aménagement du terri-toire. Les projets de restauration oud'aménagement repose généralement surles données du milieu et sur leur analyse,trop souvent limités aux données defaibles profondeurs et qui ne sont spéci-fiques qu'au projet en question. De tellesétudes tireront avantages de l'existenced'une base de connaissances régionale descaractéristiques hydrologiques ainsi quedu prolongement des systèmes de circula-tion au-delà du site, jusqu'aux échelles desbassins versants. En conséquence, nouspréconisons dans le présent compte renduque l'on investisse dans la collecte dedonnées de haute qualité et que l'onadopte l'approche régionale nécessaire àl'analyse de bassin, ce qui permettra unebien meilleure évaluation de la questiondes eaux souterraines des milieux hydro-géologiques complexes du Canada.

ARTICLES



The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario

D.R. Sharpe, M.J. Hinton, H.A.J. Russell and A.J. Desbarats
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8
dsharpe@nrcan.gc.ca

SUMMARY

To manage Canada's groundwater resources in a sustainable way there is a need for regional knowledge of aquifer systems. Improving regional knowledge, in light of scant hydrogeological data, requires a multidisciplinary approach that advances the geological understanding of a basin. Basin analysis — mapping and characterizing the reservoir potential of sedimentary basins as applied in petroleum exploration — provides an approach that is directly applicable to regional hydrogeology studies and related land use planning. This paper applies basin analysis to a glaciated terrain by integrating data from a variety of sources and scales of investigations to develop a hydrogeological model of the Oak Ridges Moraine Area (ORM), southern Ontario.

Basin analysis supports the progression from data compilation and geological conceptualization to model development, and ultimately, toward quantitative flow system analysis. This progression is achieved notably by developing primary geological models of the stratigraphy, sedimentary architecture and origin of deposits of the ORM area. The analysis outlines two regional elements highly significant to groundwater flow in the area: 1) regional till uplands that form the principal aquitard, and 2) channels that breach the till and form hydraulic windows and important channel-fill aquifers. The important channel aquifer setting had not been previously recognized because its identification required a geological framework based on high-quality topographic, geological and geophysical data. Development of the regional geological knowledge would not have been possible using relatively poor-quality water well records alone. A numerical model is then used to illustrate the significance of vertical flow through generic channels.

The watershed approach that is embodied in basin analysis strongly enhances communication between geoscientists and engineers, planners, and other scientists. Better understanding of regional hydrogeological settings also will improve the scientific basis for land use planning. Site remediation or development proposals generally rely on site-specific data and analysis, often restricted to shallow depths and predominantly for the purpose of site design. Such studies will benefit from regional knowledge of hydrogeological settings and of the extent of flow systems beyond the site to watershed or basin scales. Accordingly, the paper advocates investment in both high-quality data and the regional approach that underlies basin analysis, thus permitting a much more reliable assessment of groundwater issues in complex hydrogeological settings across Canada.

RÉSUMÉ

Pour gérer de manière durable les ressources en eaux souterraines canadiennes, il est impératif d'acquérir une connaissance régionale des systèmes aquifères. Avec les rares données hydrogéologiques qui existent, l'amélioration des connaissances régionales doit recourir à l'approche multidisciplinaire pour améliorer la compréhension géologique d'un bassin. L'analyse de bassin – cartographie et caractérisation du potentiel du réservoir du bassin sédimentaire comme cela se pratique en exploration pétrolière – est une approche qui peut s'appliquer directement aux études hydrogéologiques régionales ainsi qu'à l'aménagement du territoire concerné. Le présent compte rendu porte sur une analyse de bassin d'un terrain glaciaire par l'intégration de données issues d'une variété de sources et d'échelles de recherche différentes en vue de l'élaboration d'un modèle hydrogéologique de la région de la moraine d'Oak Ridges (MOR), dans le sud de l'Ontario.

L'analyse de bassin est un processus progressif qui va de la compilation des données et de la conceptualisation géologique pour l'élaboration d'un modèle, jusqu'à l'analyse quantitative d'un système de circulation des fluides. Cette progression comprend, notamment, l'élaboration de modèles géologiques de départ de la stratigraphie, de l'architecture sédimentaire et de l'origine des dépôts de la région de la MOR. L'analyse a permis de discerner deux éléments régionaux très importants dans la compréhension de de la circulation des eaux souterraines de la région : 1) des hautes terres de till formant le principal aquitard; 2) des chenaux qui

traversent le till, constituant des fenêtres hydrauliques et d'importants aquifères de chenaux comblés. Cette configuration en d'aquifère en chenaux n'avait pas été reconnue jusqu'à maintenant parce que sa détection n'était possible qu'en recourant à une approche géologique combinant données topographiques, géologiques et géophysiques de haute qualité. La constitution d'une banque de connaissances géologiques régionales n'aurait pu se faire en n'ayant recours qu'aux seuls registres de données de piètre qualité des puits existants. On a eu recours à un modèle numérique qui a permis d'illustrer l'importance de la composante verticale de la circulation à travers des chenaux génériques.

L'approche par bassin hydrologique inhérente à l'analyse de bassin facilite grandement la communication entre les géoscientifiques, les ingénieurs, les planificateurs et autres scientifiques. La meilleure compréhension du cadre hydrogéologique améliore également le caractère scientifique de la base de référence pour l'aménagement du territoire. Les projets de restauration ou d'aménagement repose généralement sur les données du milieu et sur leur analyse, trop souvent limités aux données de faibles profondeurs et qui ne sont spécifiques qu'au projet en question. De telles études tireront avantages de l'existence d'une base de connaissances régionale des caractéristiques hydrologiques ainsi que du prolongement des systèmes de circulation au-delà du site, jusqu'aux échelles des bassins versants. En conséquence, nous préconisons dans le présent compte rendu que l'on investisse dans la collecte de données de haute qualité et que l'on adopte l'approche régionale nécessaire à l'analyse de bassin, ce qui permettra une bien meilleure évaluation de la question des eaux souterraines des milieux hydrogéologiques complexes du Canada.

INTRODUCTION

Need for Regional Hydrogeological Studies

Groundwater is a strategic natural resource, vital to more than 6 million Canadians (1981) who rely on it for their daily needs (Hess, 1986). However, there are considerable regional disparities between the demand for groundwater and the scientific understanding required to ensure adequate supply and quality, which are cause for increasing societal concern. The Canadian Geoscience Council (1993, p.3) concluded that current Canadian efforts in groundwater inventory, protection, and research are inadequate "to achieve responsible and effective management of this important freshwater resource." Indeed, the last national synthesis of groundwater knowledge in Canada was published more than 30 years ago (Brown, 1967). Federal and provincial governments were very active in regional-scale hydrogeological investigations and research prior to the mid 1970s (Tóth, 1963; Meyboom, 1963; Trescott, 1968; Freeze, 1969; Haefeli, 1970; Sibul *et al.*, 1977). Since then, changes in government priorities and research programs, and the resultant loss of experienced personnel have led, in part, to a decrease in government capacity to conduct regional hydrogeological studies. Furthermore, shifting emphasis from water supply to environmental issues and contaminant research within government, university, and private sectors has resulted in a predominance of small-scale, site-specific investigations (<1-10 km^2). These factors, and the low valuation of water, led to a loss of focus on the need to assemble, integrate, and interpret enough geological data to establish appropriate conceptual models (Cherry, 1996) and regional geological frameworks for hydrogeological analysis. Consequently, current understanding of regional hydrogeology in Canada has not kept pace with the need for this knowledge and cannot address many emerging groundwater issues that confront governments.

In the United States, the ~20-year Regional Aquifer System Analysis (RASA) program (Sun and Johnston, 1994) provided a co-ordinated vision and government funding for necessary regional and national hydrogeological activities. The continuing need for regional-scale groundwater investigations in that country is recognized in a recent National Research Council report (NRC, 2000). In Ontario, the Ministry of Natural Resources has recognized the need for regional understanding of groundwater systems in the Greater Toronto Area (GTA), and specifically in the Oak Ridges Moraine (ORM) (Hunter and Raven Beck, 1996). Rapid urban expansion in this area has led to conflicts between land and water resource use; the Oak Ridges Moraine Conservation Act, 2001 was passed on 13 December to address these concerns. In order to develop the regional-scale hydrogeological understanding necessary for planning urban development while protecting groundwater resources, the Geological Survey of Canada (GSC) and the Ontario Geological Survey (OGS) initiated a study of the geological framework of the Oak Ridges Moraine in 1993. The 11,000 km^2 ORM study area includes most of the highly populated Greater Toronto Area (Fig. 1a).

HYDROGEOLOGICAL STUDIES IN GLACIATED TERRAIN

Southern Ontario Moraine Systems; Oak Ridges Moraine

In southern Ontario (Fig. 1a), thick glacial deposits overlie shallow-dipping Paleozoic strata, both of which host significant aquifers (*e.g.*, MacRitchie *et al.*, 1994; Singer *et al.*, 1997). The most productive glacial aquifer systems are found in large sand and gravel moraines >100 m thick. A number of these aquifer systems have been the subject of recent hydrogeological studies, including the Waterloo (Martin and Frind, 1998), Oro (Beckers and Frind, 2000; 2001), and Oak Ridges moraines (Howard *et al.*, 1995) (Fig. 1).

The Oak Ridges Moraine is a 160-km long landform, up to 20 km wide, that rises >300 m above the level of Lake Ontario (Fig. 2). It forms the height of land east of the Niagara Escarpment and the drainage divide between Lake Simcoe and Lake Ontario (Fig. 2a). The elevated sand and gravel deposits of the moraine make it the principal recharge area for regional aquifers (Sibul *et al.*, 1977; Fig. 2b). The ORM study area receives an average annual precipitation of ~710-820 mm with an estimated 530-560 mm/a returned to the atmosphere by evapotranspiration (1931-1960 normals, Phillips and McCulloch, 1972; Brown *et al.*, 1980). Average stream runoff for gauged watersheds ranges between 200 mm/a and 470 mm/a (Cumming Cockburn Limited, 1990). Locally, average groundwater recharge is estimated to vary between ~25 mm/a and 400 mm/a (Gerber and Howard, 2000). However, actual evapotranspiration, stream runoff and groundwater recharge vary significantly according to soils, geology, slope, vegetation, and land use.

Regional Hydrogeological Studies

Given the scale and geological variability of glacial aquifer systems such as the ORM, there is a corresponding need for a regional approach to hydrogeological investigations that integrates geological analysis. This approach considers topography, lithology, stratigraphy, and structure as dominant controls on local and regional groundwater flow systems (Tóth, 1963; Meyboom, 1963; Freeze and Witherspoon, 1967; Fogg, 1986; Anderson *et al.*, 1999). These elements define the characteristic aquifer-aquitard properties that must be considered in groundwater flow system analysis. However, the geometry and continuity of hydrostratigraphic units and the distribution of their properties for flow models are often poorly known at the regional scale because relevant data are generally too sparse, relative to heterogeneity scales, for a full assessment of the geologic controls on groundwater flow. Archival data such as water well records are very important at the regional scale of investigation, and although their quality is low, their usefulness can be enhanced through the careful development of geologic and hydrogeologic models. The development of conceptual models also serves to assist interpretation and interpolation in areas of sparse control data and/or poor data quality (Logan *et al.*, 2001), to optimize new data collection (James and Freeze, 1993), and to provide regional context for site-specific studies (LeGrand and Rosen, 1998, 2000). Development of conceptual geologic and hydrogeologic models for the Oak Ridges Moraine has been a central element of GSC and OGS investigations, and this paper illustrates how these models can contribute to quantitative understanding of groundwater flow systems in glaciated terrain.

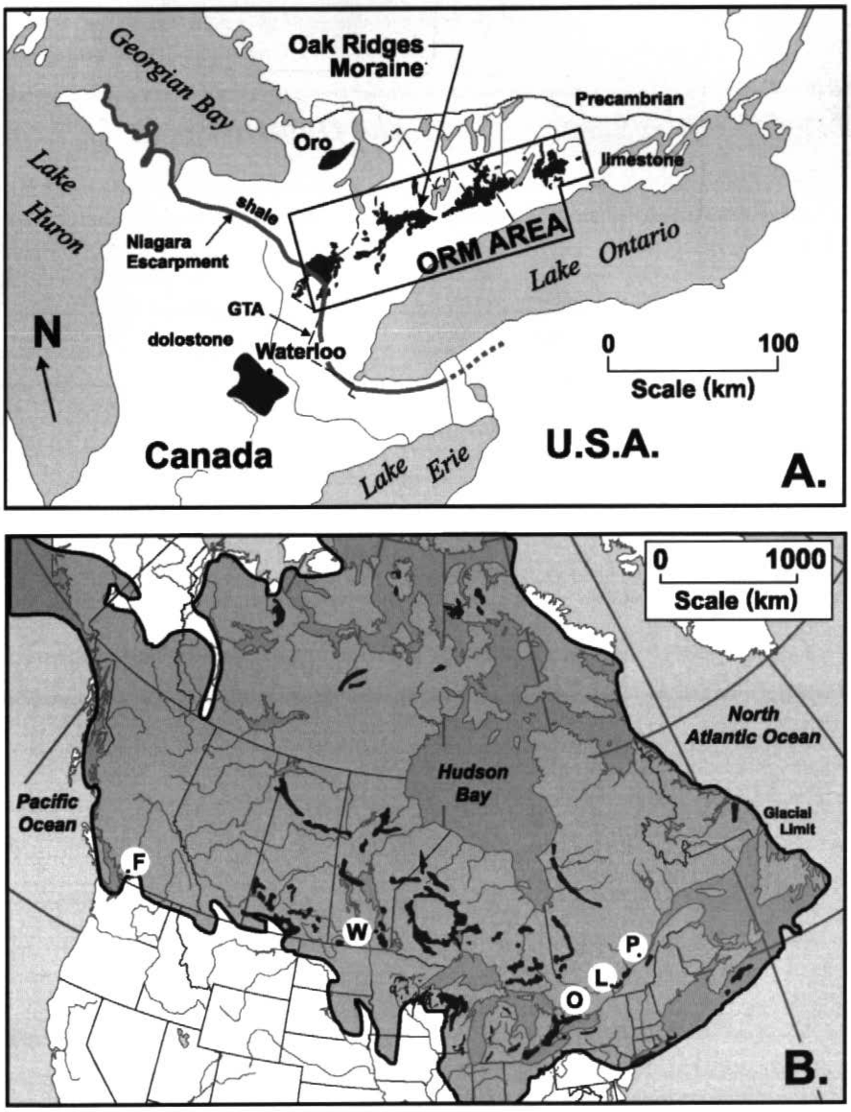


Figure 1 (**A**) Location map of Oak Ridges Moraine (ORM) and Greater Toronto Area (GTA) study areas, bedrock geology and the Oro and Waterloo stratified moraines. (**B**) Map of large stratified moraines with the Late Wisconsinan glacial limit. Location of GSC hydrogeology projects: O=ORM; L=Laurentian (Nastev *et al.*, 2000); P=Porteneuf (Fagan *et al.*, 1999); W=Winnipeg (Thorleifson *et al.*, 1998) and F=Fraser valley (Ricketts, 2000).

Regional groundwater flow is greatly influenced by large-scale patterns of hydrogeological heterogeneity (Freeze and Witherspoon, 1967; Fogg, 1986). While glaciogenic sediment is highly variable at all scales of observation (Shaw, 1985), its regional variability can be difficult to characterize. Facies models used to describe large-scale spatial trends in glacial and glaciofluvial aquifer systems (Anderson, 1989) tend to be generalized. For example, the dimensions, boundaries, and lateral facies variability in buried, glacial-channel aquifer systems (Kehew and Boettger, 1986; Lennox *et al.*, 1988; Ritzi *et al.*, 1994; 1999) are inferred with little primary sedimentological and structural data that are needed to characterize the heterogeneity of hydraulic properties. Thus, description of regional patterns of heterogeneity requires information specific to the extent and geometry of erosional events and depositional sequences, which control the architecture and continuity of aquifers and aquitards, and regional patterns of hydraulic conductivity. These primary elements of the geological framework need to be considered for hydrogeological conceptualization and model development. Borrowed from petroleum geology, basin analysis is a powerful, multidisciplinary approach for integrating these diverse elements in investigations of complex sedimentary environments (*e.g.*, Miall, 2000; Eyles *et al.*, 1985; Sharpe *et al.*, 1992). In addition to conventional geological methods, the basin analysis approach draws upon geophysical, hydrological, and geostatisti-

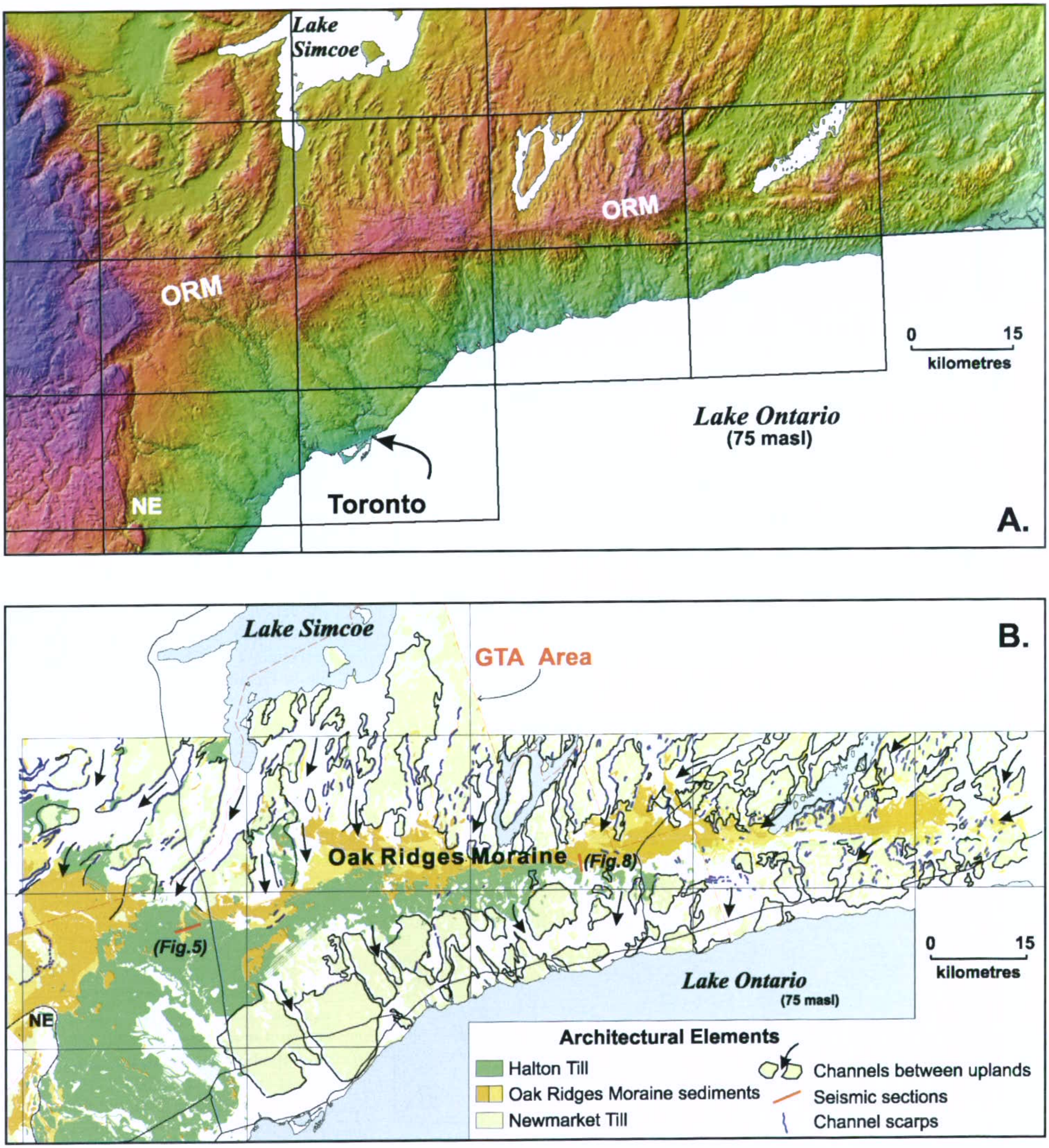


Figure 2 (**A**) Digital elevation (terrain) model (Kenny, 1997) showing the E-W crest of the ORM, the Niagara Escarpment (NE), streamlined terrain south of the moraine, and, to the north, a drumlinized landscape and N-S channel network. Channels change form and decrease in density south of the moraine, particularly in the central portion of the image. (**B**) Sediment and terrain features help define regional architectural elements of the study area. Locations of Figures 5 and 8 are shown. Outline of NTS map borders are shown on both maps.

cal methods in a systematic way. This approach provides an enhanced ability to characterize the geometry and properties of aquifers and aquitards for analysis of groundwater systems, particularly in glaciated terrain.

Oak Ridges Moraine Approach

In this paper, application of basin analysis is shown to be an important regional method that is illustrated in the development of a hydrogeological model of the Oak Ridges Moraine. The first goal is to show how basin analysis methods are used to develop primary geological models (stratigraphic, architectural, and depositional) for the ORM area. The second goal is to show how these models and additional basin analysis methods contribute to the development of conceptual and then digital hydrostratigraphic models. The final goal of the paper is to show how basin analysis culminates with the combination of hydrostratigraphic and numerical flow models in order to address groundwater issues in the study area.

The paper starts with a review of the data that have been assembled and integrated within the basin analysis approach. It then shows how this approach supports the progression from geological conceptualization and model development toward hydrogeological analysis and flow modelling. Throughout this progression, the paper focuses on two key regional architectural elements that have been identified as having considerable hydrogeological significance. The two elements are: 1) the regionally extensive Newmarket Till that forms the principal aquitard in the study area (Fig. 2b), and 2) the erosional channels that form hydraulic windows through this till and, locally, form productive channel-fill aquifers. The paper concludes with an assessment of the basin analysis approach applied to hydrogeological investigations of complex glacial environments and its significance for future regional-scale hydrogeological investigations in Canada.

BASIN ANALYSIS METHODS AND DATA ASSEMBLY IN THE ORM AREA

Basin analysis provides a methodological framework for regional hydrogeological analysis that integrates data from a variety of sources and scales of investigations (Miall, 2000). It is particularly appropriate for groundwater studies in geological environments where heterogeneities and flow systems occur on a hierarchy of scales (Tóth, 1963; Koltermann and Gorelick, 1996). The basin analysis approach used in this study outlines a progression of data compilation, conceptualization, model development, and quantitative analysis of flow systems (Fig. 3) similar to that proposed in the ASTM guideline for conceptualization and characterization of groundwater systems (ASTM, 1999). However, the basin analysis approach emphasizes geological analysis in the development of conceptual and predictive models in order to characterise the textural, stratigraphic. and structural controls on groundwater flow at the regional scale. By directly linking geological setting and basin history to aquifer properties (Miall, 2000), the basin analysis approach strives to develop more plausible hydrogeological models.

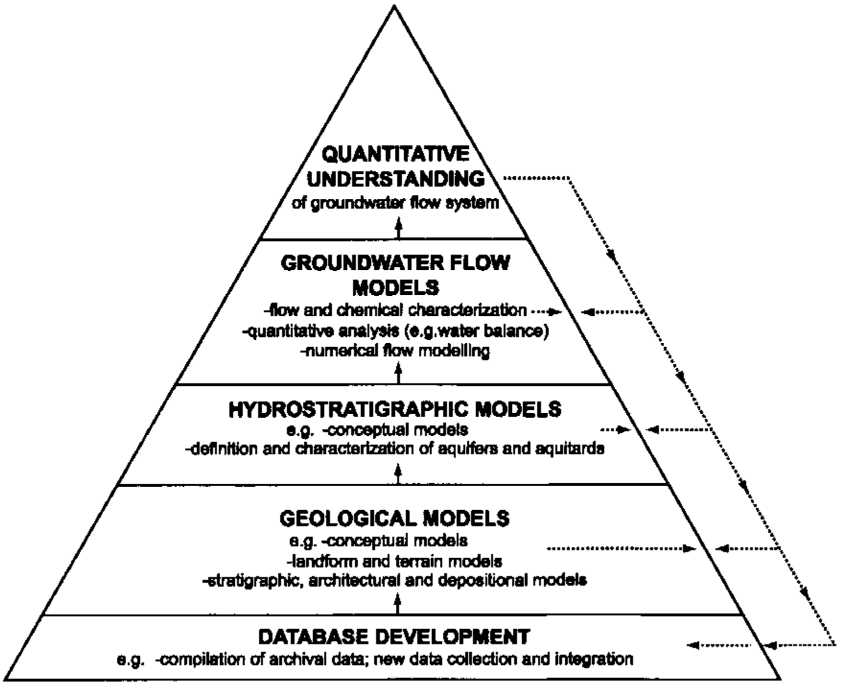


Figure 3 Simplified basin analysis approach used in the regional hydrogeology analysis of the ORM area. The approach leads progressively from data base development early in a study (base) to quantitative understanding of groundwater flow systems as the study matures (at the top).

Database Development

The first step in the ORM basin analysis was database development (Fig. 3). This involved combining archival and newly collected data in a relational database and geographic information system (GIS) (Russell *et al.*, 1996). Existing geological maps (*e.g.*, Gwyn and DiLabio, 1973) were integrated with 15 new detailed, 1:20,000 and 1:50,000 scale maps (*e.g.*, Barnett and Dodge, 1996; Gorrell and Brennand, 1997) in order to establish a geological framework and complete the regional correlation of key geological strata across the complex glacial landscape. This study captured regional geological data from more than 20,000 field sites, including hundreds of measured sections and existing stratigraphic drilling. Terrain mapping from a digital elevation model (Kenny, 1997) helped in identifying the regional extent of landforms in three dimensions (Fig. 2a). Terrain and geology data were then combined to define regional architectural elements (Fig. 2b). These new and archival data were integrated using principles developed in recent research, including meltwater-flood models of erosion and deposition (Shaw, 1996), to construct a conceptual geological model for the ORM area (Fig. 4; Sharpe *et al.*, 1996).

Key Data in Developing a Geological Model

The ORM conceptual model (Fig. 4)

guided development of a 3-D structural model by combining high-quality data from detailed maps, seismic profiles, and cored boreholes, with extensive archival water well records (Logan *et al.,* 2001). The process of identifying and mapping regional hydrogeological units in three dimensions began with the compilation and assessment of more than 75,000 provincial water well records, some wells as deep as 200 m. Although their resolution and quality vary, these records are the most widely distributed hydrogeological data. They not only provide sediment-depth information but also contain useful hydrogeological data such as water levels, screen intervals, and well yields. In addition to the water well records, new continuous-core drilling provided more than 50 deep (~100 m) sediment cores (*e.g.,* Barnett *et al.,* 1998; Russell *et al.,* 1998b; Fenco MacLaren, 1994a,b). Borehole geophysical logging of several new holes (Pullan *et al.,* 2000) and sedimentological study of the cores (Russell *et al.,* 1998b) has provided a bed-by-bed check on sediment facies, seismic facies and seismic-stratigraphic interpretations (Pugin *et al.,* 1999). Core descriptions and outcrop studies also contributed information about geological processes for developing key depositional models (see Fig. 7; Barnett *et al.,* 1998; Russell, 2001) as discussed in the next section.

These new, cored boreholes, termed "golden spikes," provided stratigraphic benchmarks for regional units, confirmation of unconformities (Fig. 5), and a vital link for the interpretation of the rough geological descriptions contained in archival water well records (Russell *et al.,* 1998a). For example, water well records grossly overestimate the clay composition of the Oak Ridges Moraine (by ~1500%; Russell, 2001). Stratigraphic assignment of till is difficult, and was further confounded by the low resolution of unit-thickness and incomplete material reporting (Russell *et al.,* 1998a). In short, geological models cannot be developed readily from water well records. However, the controlled geological framework provided by the new boreholes and seismic profiles was used as a guide to re-classify water well data. The lateral continuity of stratigraphic units was more accurately mapped with the acquisition of more than 50 line-kms of seismic reflection profiles (Pugin *et al.,* 1999) and borehole geophysics (Hunter *et al.,* 1998). These data helped to define reflector boundaries, the regional 3-D architecture of till aquitards (Pugin *et al.,* 1999, 2001) and the cross-sections of buried channel aquifers (Fig. 5). Interpolating from digital map coverage, cored boreholes, and seismic lines, it was then possible to first correlate and then generate regional 3-D stratigraphic surfaces in a GIS (Logan *et al.,* 2001). The resulting regional 3-D model permitted the integration and interpretation of all data according to hydrostratigraphic unit. Preliminary stratigraphic surfaces from the model, for example, assisted in the interpretation of watershed base flow data (Hinton *et al.,* 1998) and in improved hydrostratigraphic assignment of water level measurements (Desbarats *et al.,* 2002a). Aquitard thicknesses were used to generate digital maps of aquitard leakance and spatial continuity that can provide support for flow modelling (Fig. 6; Desbarats *et al.,* 2001).

Additional Studies

Streamflow surveys of selected watersheds within the ORM provided important data on the controls and spatial distribution of groundwater baseflow and discharge (Hinton, 1995; Hinton *et al.,* 1998), which are of value for characterizing flow, constraining groundwater models, and for water table mapping. New geological mapping and thermal imagery identified important discharge features such as groundwater piping and potential springs (Dyke *et al.,* 1997). Baseflow and water well chemistry surveys (Bowen and Hinton, 1998; Dyke, 1999) were conducted to help characterize the flow system or to provide information on the evolution of groundwater flow from recharge to discharge areas. Maps of water table elevation (Desbarats *et al.,* 2002b) were constructed from water well records and from the digital elevation model (Kenny *et al.,* 1999). Porosity estimates were derived from borehole geophysical data (Corona and Mavko, 1999). Integration of these hydraulic and chemical data into the ORM hydrogeologic framework is an ongoing goal of the ORM basin analysis.

The following sections describe in more detail how basin analysis methods are used to develop geological and

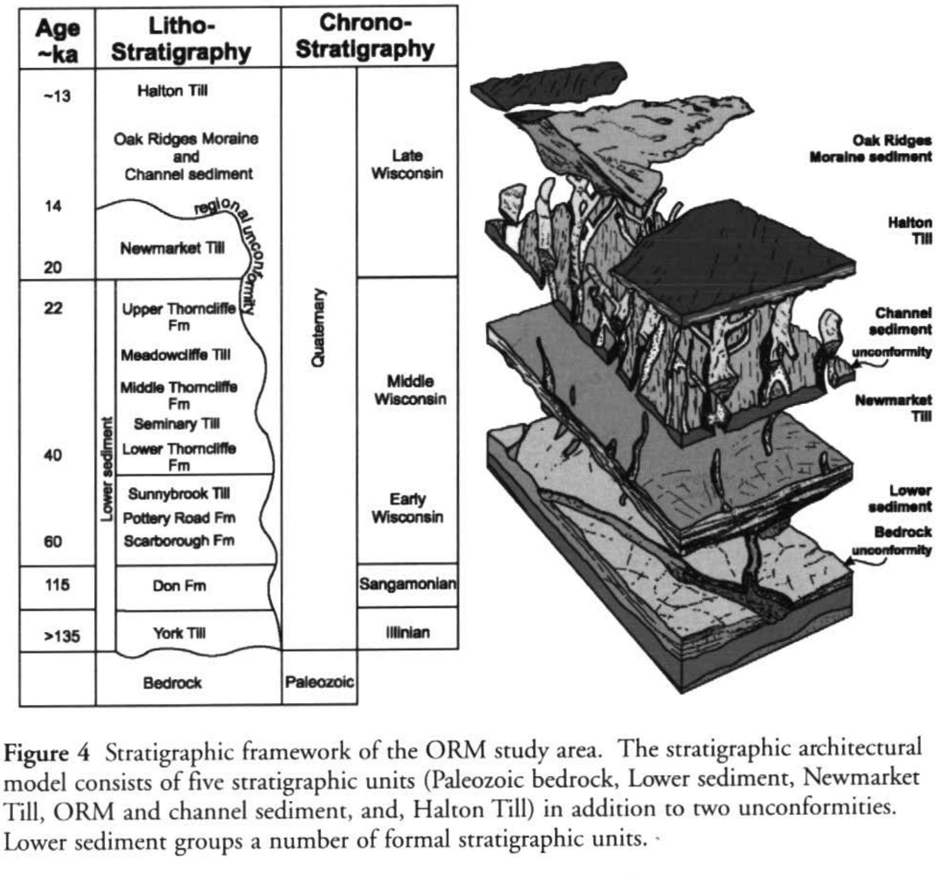


Figure 4 Stratigraphic framework of the ORM study area. The stratigraphic architectural model consists of five stratigraphic units (Paleozoic bedrock, Lower sediment, Newmarket Till, ORM and channel sediment, and, Halton Till) in addition to two unconformities. Lower sediment groups a number of formal stratigraphic units.

hydrogeological models from the assembled data described here.

DEVELOPMENT OF THE GEOLOGICAL MODEL

The geological model is the foundation of an integrated basin analysis approach to the Oak Ridges Moraine area. The earliest geological models for the area were based on the Quaternary stratigraphic succession developed from work on exposures at Scarborough Bluffs (Coleman, 1932; Karrow, 1967), physiographic setting (Chapman and Putnam, 1984), and, from geological mapping south of the ORM *(e.g.,* Watt, 1957; Karrow, 1967). The Quaternary succession records a series of depositional and erosional events during the last 125 ka (Wisconsinan glaciation), and is the basis for defining a formal lithostratigraphy (Fig. 4; Karrow, 1967; 1974). Following the last interglacial, a series of high-level lakes is recorded by the Scarborough and Thorncliffe formations (Karrow, 1967; Eyles and Eyles, 1983). These prominent formations are intercalated with local diamicton layers in most cases interpreted as till (Karrow, 1974) and overlain by regionally extensive till sheets such as the Newmarket Till and its equivalents (Sharpe *et al.,* 1994). The extensive tabular nature of these well-exposed lake and river bluff strata (Karrow, 1967) means that they can be correlated over distances of more than 40 km on geophysical logs (Fligg and Rodriques, 1983; Eyles *et al.,* 1985). This fact provided the basis for the current simple "layer-cake" geological model adopted in groundwater flow studies and models in the ORM area (*e.g.,* Smart, 1994; Meriano, 1999). However, a more detailed geological model can be developed using basin analysis methods.

Event-sequence Stratigraphy

Event-sequence stratigraphy (Walker, 1992) is used to investigate the role and inter-relationship of depositional and erosional events within intricate sedimentary sequences. Application of event-sequence concepts to the ORM area introduces important modifications to the current layer-cake geological model. Initially, Karrow (1967, 1974) used a depositional model of drumlin formation to infer lateral continuity of drumlinized till plains. Later, Boyce and Eyles (1991) used a deforming-bed, depositional-erosional model of drumlin formation to infer primary till thickness variations and regional continuity, and to suggest that drumlin-field sediment is younger than the ORM. Neither of these models identified erosional valleys in the drumlinized till sheets (Fig. 2a) nor the relationship of these breaches to overlying depositional events (Barnett, 1990; Barnett *et al.,* 1998). However, recent work indicates that regional subglacial meltwater flows extensively scoured this till surface (Fig. 7a) and formed a network

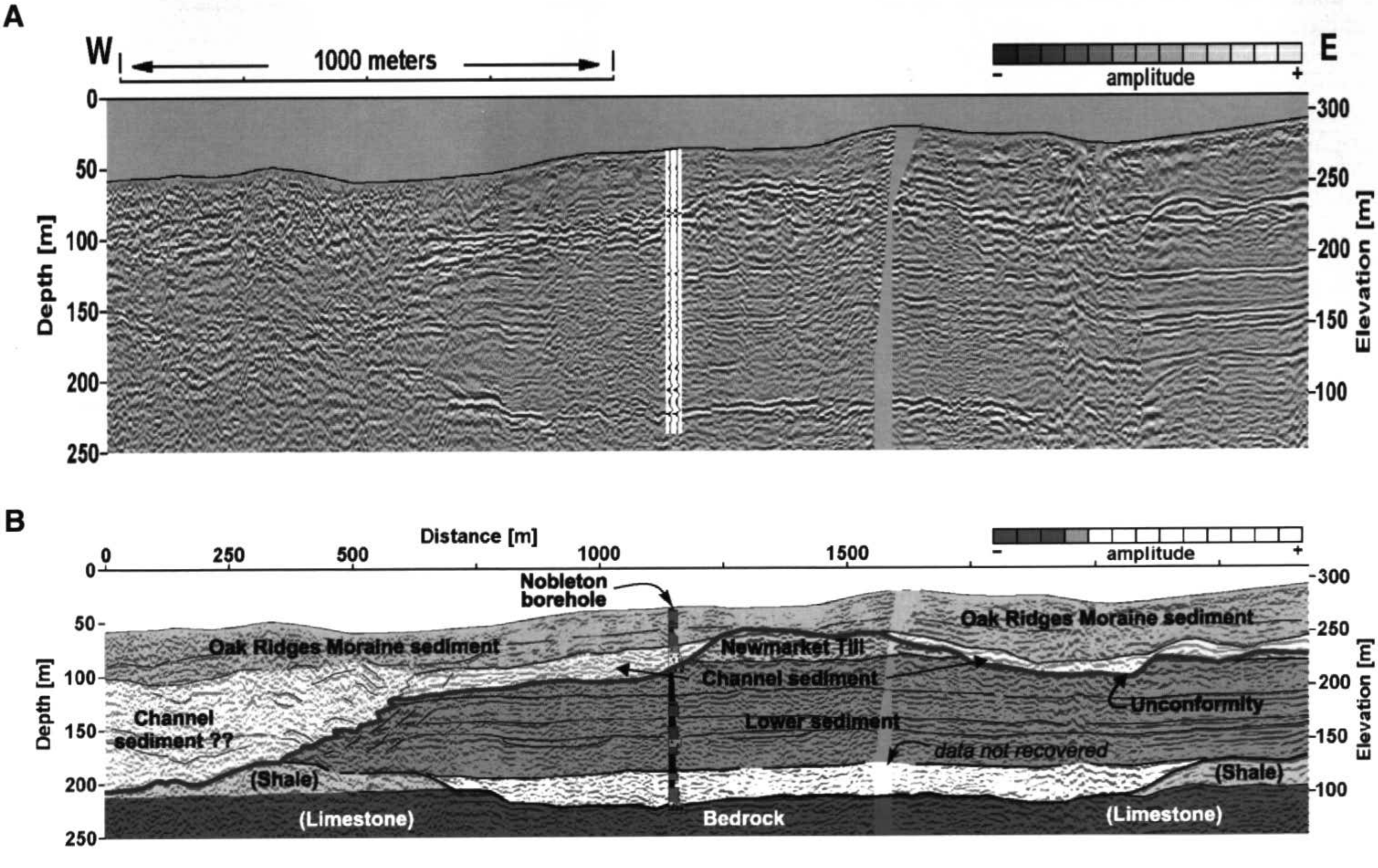


Figure 5 Seismic profile (**A**) and interpretation (**B**) of the Nobleton area (see western portion of the ORM, Fig. 2b) showing an unconformity defined by channels cross-cutting Newmarket Till and Lower sediment, in places to bedrock (from Pugin *et al.,* 1999). A GSC continuously cored borehole is shown on both sections, (A) seismic velocity profile, (B) sediment log.

of deep N-S trending tunnel channels and interfluve-drumlin uplands (Shaw and Sharpe, 1987; Shaw and Gilbert, 1990; Brennand and Shaw, 1994; Barnett *et al.,* 1998). Subsequent waning-flow sedimentation within the eroded channel network (Fig. 7b; Russell *et al.,* 2000) resulted in regionally extensive coarse sediment sequences that grade upward into ORM sediment. Hence, the ORM was formed by rapid sedimentation from episodic outburst floods (jökulhlaups) and later seasonal meltwater discharges that infilled basin lows and constructed the moraine ridge (Barnett *et al.,* 1998; Russell, 2001). ORM sedimentation occurred in a number of subglacial and ice-supported depositional environments: channel, esker, subaqueous fan, basin, and delta (Barnett *et al.,* 1998; Gilbert, 1997; Russell, 2001).

Thus, consideration of these event-sequence concepts, particularly the role of subglacial floods and identification of erosional events or unconformities (Barnett *et al.,* 1998) within the existing lithostratigraphic framework, suggests a revised stratigraphic model for the ORM area (Fig. 4; Sharpe *et al.,* 1996). This model recognizes five regional stratigraphic units and two unconformites (Fig. 4). At the base of the succession, pre-glacial differential erosion of Paleozoic carbonates and shales resulted in more than 400 m of relief on the bedrock unconformity (Brennand *et al.,* 1998). The lowermost unit, termed Lower sediment, is formed of poorly exposed, pre-Late Wisconsinan interbedded lake sediment and till, which are combined into a single regional layer (Fig. 4). The overlying Newmarket Till forms an extensive tabular unit truncated above by a well-developed erosional surface (Fig. 5) or unconformity characterized by drumlinized uplands and incised subglacial meltwater channels (tunnel channels; Fig. 7a). The channel (Fig. 7b) and Oak Ridges Moraine sediments that overlie this unconformity show essentially uninterrupted sedimentation from the base of channels to the top of the ORM sequence and into overlying, inter-bedded Halton Till strata (Fig. 4).

Stratigraphic Architecture

Stratigraphic architecture defines the geometry and continuity of regional geologic units, which in turn, helps determine related hydrostratigraphic units. Although they add important architectural detail on the extent, thickness and continuity of individual strata (Figs. 4, 5), regional unconformities are seldom recognized in stratigraphic models of continental glaciation (Shaw, 1996). Here, a Late Wisconsinan regional unconformity cuts deeply into sequences underlying the ORM, occasionally down to bedrock, and defines two distinct, high-relief (up to ~150 m) terrains or architectural elements: 1) drumlinized Newmarket Till uplands, and 2) incised tunnel channels (Figs. 2b, 4; Barnett *et al.,* 1998). Seismic reflection surveys in particular (Fig. 5; Pugin *et al.,* 1999), allow the undulating nature of the unconformity to be traced regionally. This unconformity and the meltwater events that shaped it (Fig. 7), impart regional control on the geometry of eroded stratigraphic units such as the Newmarket Till, and the character of the resulting channel depositional sequences (*e.g.,* Russell, 2001).

Newmarket Till uplands with drumlins and shallow scours occur as interfluves to large tunnel channels (Fig. 2b, 4). Geological and geophysical mapping shows that Newmarket Till uplands extend beneath the ORM (Fig. 5; Barnett *et al.,* 1998). Uplands are most clearly developed north of the moraine where channels are deep (Fig. 2). Upland

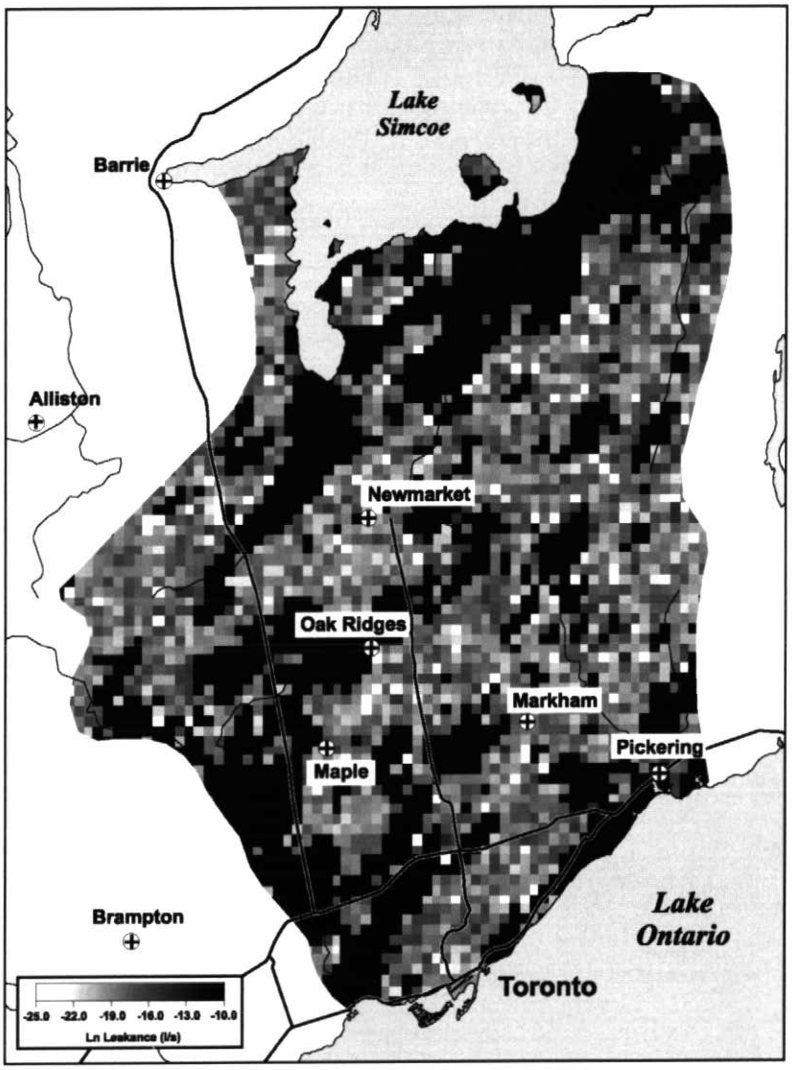


Figure 6 Map of simulated aquitard leakance for 1-km² grid blocks. Leakance values are important in constraining estimates of flow to lower aquifers (from Desbarats *et al.,* 2001). High leakance estimates correspond to areas of channels and/or thin aquitard. Leakance scale ranges from $1.4*10^{-11}$ l/s to $4.5*10^{-5}$ l/s.

areas are typically 5-10 km across and 10-20 km long with drumlins up to 30 m high. Shallow channels within the uplands are 10-1000 m wide, 1-5 kms in length, and exhibit up to 10 m of relief (Fig. 5). South of the moraine, drumlinized uplands in the east become more subdued westward, and form a plain dominated by broad, shallow channels underlain by Newmarket Till (Figs. 2b, 4).

A network of tunnel channels has been deeply eroded into approximately 25% of Newmarket Till mapped north of the ORM (Fig. 2b; Barnett *et al.,* 1998) and this pattern appears to extend beneath the ORM (Desbarats *et al.,* 2001). The channels are up to 5 km wide and 40 km long. Channels have surface relief up to 50 m (as observed north of the ORM) and total depths >100 m (Fig. 5; Pugin *et al.,* 1999). Channel margins are steep with slopes of up to 60° (Pugin *et al.,* 1999) becoming gentler as channels broaden (Fig. 2). The deepest, most incised channels occur south of Lake Simcoe and near Nobleton (Fig. 5) where the ~200-m deep Laurentian channel bedrock valley provided space for the deposition of thick Lower sediment deposits. These deposits were locally eroded to bedrock, forming deep channels, which were then rapidly filled with thick sand sequences (Russell, 2001).

Depositional Environments

Depositional models are being developed to help understand and predict the distribution, arrangement, and variability of sediment facies within key strata of the ORM study area (Barnett *et al.,* 1998; Russell *et al.,* 2000; Russell, 2001). Depositional models for two regionally significant architectural elements, Newmarket Till and channel-fill sediment, are discussed here.

Newmarket Till

Surface and subsurface mapping show that the Newmarket Till forms a semi-continuous sheet over more than 75% of the study area (Fig. 2b). It is up to 50 m thick and forms a thin sediment drape where underlying sand and silt are thick. It has a planar, abrupt or gradational contact with underlying Lower sediment (Pugin *et al.,* 1999). The till has a dense, massive silty sand matrix with 10-15% pebbles and cobbles, key characteristics used to map its regional distribution (Sharpe *et al.,* 1997). Generally thin (<1 m thick) and discontinuous (<20 m long), sand and silt strata and clast pavements locally separate Newmarket Till into beds 3-5 m thick (Sharpe *et al.,* 1999; Boyce and Eyles, 2000). Lateral to these horizons, the till is massive or forms amalgamated diamicton beds. Overall, the lithology and internal architecture of the Newmarket Till suggest a subglacial origin of incremental till accumulation, periodically interrupted by meltwater scours and localized deposition of sand and silt (Sharpe and Barnett, 1997; Boyce and Eyles, 2000). It is interpreted that the Newmarket Till formed a continuous deposit across the area prior to its dissection by regional channel erosion (Fig. 7a).

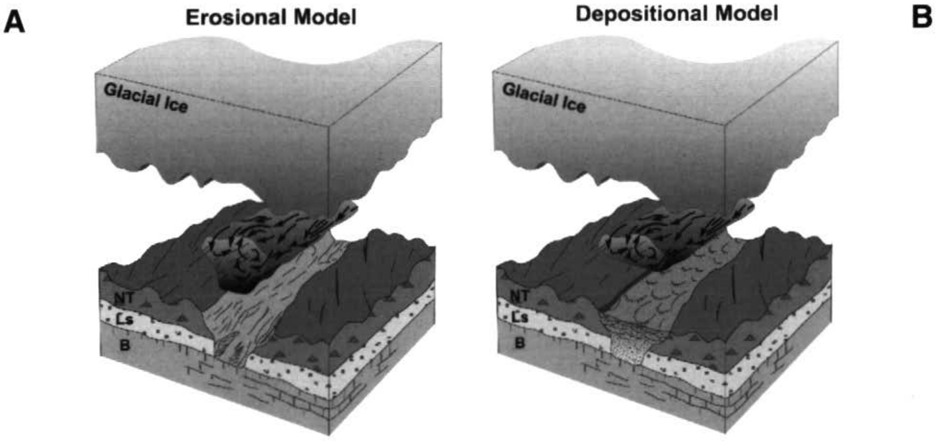


Figure 7 Event sequence models for tunnel channels in the ORM area. (**A**) erosional; (**B**) depositional. NT=Newmarket Till; Ls=Lower sediment; B=bedrock. Dark arrows represent turbulent meltwater flow.

Channel-fill Sediment

Depending on the amount of channel erosion, thick deposits of channel-fill sediment abruptly overlie bedrock, Lower sediment or Newmarket Till. Strata form 1-3 fining-upward successions of gravel, sand, silt, and minor clay. Gravel deposits are 10-50 m thick, 100-500 m wide, and up to 1-3 km long and occur near the base of channels (Fig. 8). Cross-bed sets, 10-15 m thick, interpreted from inclined seismic reflectors, overlie undulating, longitudinal, channel profiles (Pugin *et al.,* 1999). The dominant channel sediment is diffusely graded, massive, and dewatered fine sand up to 50 m thick. This facies is correlated with a chaotic seismic facies that may fill ~75% of deep, wide channels (Fig. 5; Russell, 2001; Pugin *et al.,* 1999). Flow-parallel, gravel-sand transitions may occur over distances of up to 3 km or more. Furthermore, sand successions tens of metres thick, with only minor facies transitions, may extend longitudinally up to 10 km. Locally, 0.10-m to 5-m thick fine sand-silt-clay rhythmites form successions up to 15 m thick and these may be continuous for >5 km^2. Rhythmite intervals are observed in western channels but are generally not found overlying the coarser sediment of shallower (<80 m), eastern channels (Fig. 8; Pugin *et al.,* 1999).

Depositional System

These observations describe a depositional system characterized by rapid sedimentation from subglacial outburst floods (Barnett *et al.,* 1998). These floods deposited thick, wedge-shaped beds of coarse sediment in an extensive network of large, deep, steep-walled channels. Cross-channel unit geometry is tabular, whereas along-channel sedimentary elements are conformable with undulating longitudinal channel profiles. Sediment facies may represent a number of depositional environments that link high-magnitude, episodic processes within confined-conduit flow through to deep basin discharge. These events produced facies assemblages similar to those in proglacial, glaciofluvial, and glaciolacustrine systems, but subglacial channels commonly had greater flow depths, flow velocities, and depositional rates. Associated subglacial bedforms (Shaw and Gorrell, 1991) are similar to X but larger than those from existing braided-fluvial depositional models (*e.g.,* Walker, 1992). The thick, massive sand sequences found in subglacial channels are not found in proglacial sequences. These fine sand deposits record rapid and voluminous deposition from rapid, sediment-laden flows during flow expansion, such as that inferred from subaqueous fans (Russell, 2001). Rhythmites were deposited across the basin by low-energy events from seasonal meltwater discharge (Gilbert, 1997; Russell, 2001).

Importance of Geological Models to Hydrogeology

In summary, basin analysis methods, the use of event-sequence stratigraphy, and depositional models, have contributed to the development of a more detailed geological model of the Oak Ridges Moraine area compared to the simple "layer-cake" model. By integrating information from a variety of sources, the basin analysis approach has led to the recognition of important geological features that must be considered in the subsequent development of a regional hydrostratigraphic model. These are Newmarket Till uplands, an incised network of sediment-filled channels, and complete breaches or "windows" in the till. In addition, better understanding of depositional facies and vertical and lateral sediment variations provides an improved framework for assessing hydraulic properties (Miall, 1988). Stratigraphic architecture and depositional analysis are recognized as keys to a better understanding of aquifer connectivity, geometry, and heterogeneity (Fogg, 1986; Miall, 1988; Anderson, 1989; Fogg and Noyes, 1998). For example, channel attributes affect the vertical hydraulic connectivity and horizontal transmissivity in other buried-valley (van der Kamp, 1986; Shaver and Pusc, 1992) or valley-fill aquifers (Randall, 2001). In the past, the descriptive character of much geological data and related sedimentary models (Anderson, 1989) has hampered their integration into numerical groundwater flow modelling. Hydrogeological models of the ORM need to proceed from the qualitative geological model presented above to more quantitative analysis, such as used in geostatistical (*e.g.,* Weissmann *et al.,* 1999; Desbarats *et al.,* 2001) and deterministic approaches.

DEVELOPMENT OF A HYDROGEOLOGICAL MODEL

The enhanced geological model of the ORM is further developed into a quantitative hydrogeological model. This step of the basin analysis approach calls for additional data from hydraulic testing and grain size analyses and data integration using geostatistical methods. The development of a hydrogeological model for

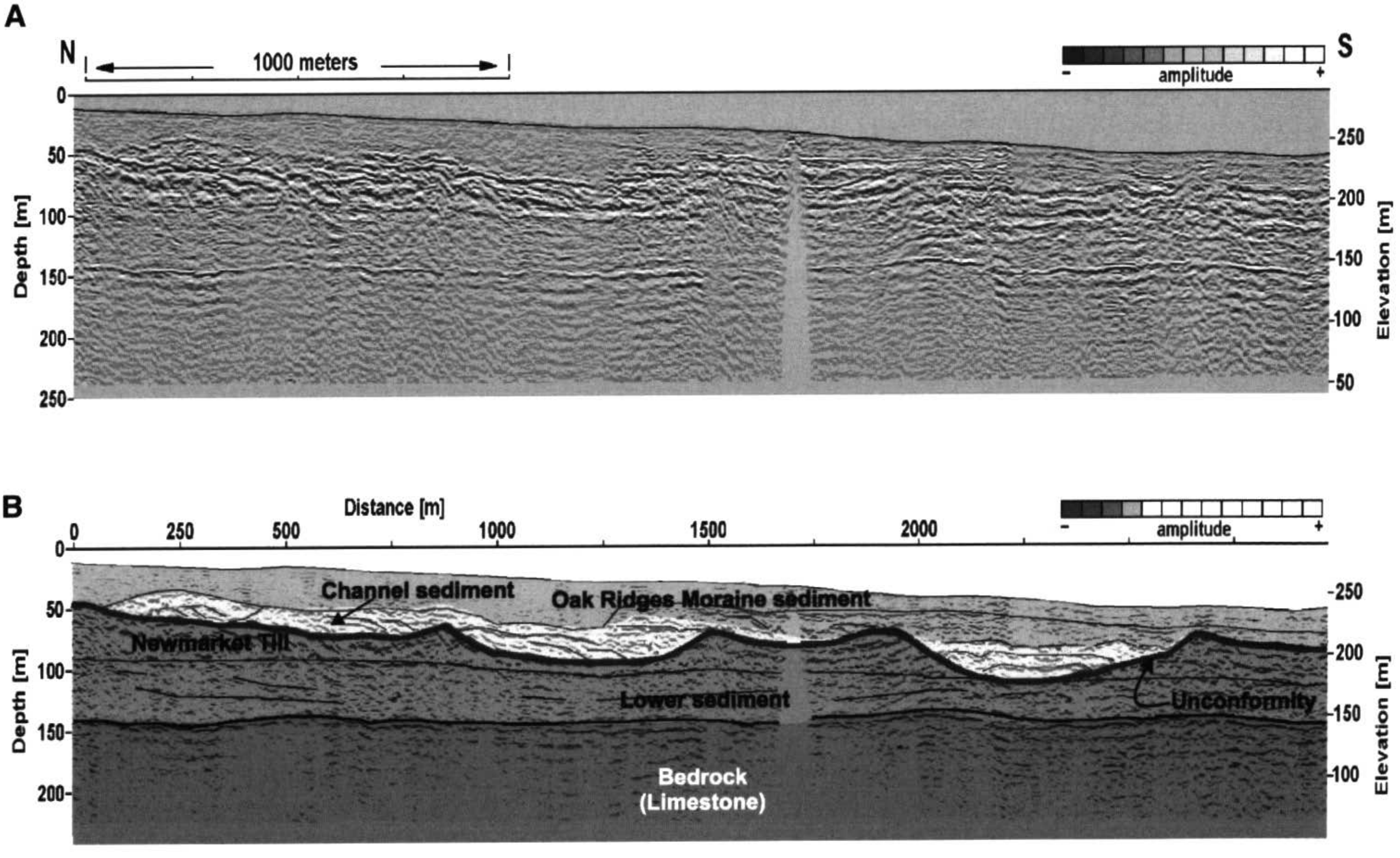


Figure 8 Seismic profile (**A**) and interpretation (**B**) along Grasshopper Road (see eastern portion of the ORM, Fig. 2b) showing reflector structures representing channel (unconformity) and channel sediment on Newmarket Till, and Lower sediment seismic-stratigraphic units; other units are Oak Ridges Moraine sediment and limestone; foresets occur beneath label, Oak Ridges Moraine. Vertical exaggeration is ~3. Profile is oriented parallel to the inferred channel axis (from Pugin *et al.,* 1999).

the ORM is illustrated for two distinct settings within the geological model: 1) the Newmarket Till upland aquitard and, 2) permeable channels that breach the Newmarket Till aquitard (Fig. 9).

Newmarket Till Aquitard

The Newmarket Till uplands form a regional aquitard that confines aquifers within the Lower sediment (Fig. 9a). The nature and magnitude of groundwater flow within the Newmarket Till aquitard and its hydraulic properties have been the focus of several recent investigations summarized in Table 1 (Gerber and Howard, 1996; Gerber, 1999; Gerber and Howard, 2000; Gerber *et al.*, 2001; Desbarats *et al.*, 2001). Flow through the Newmarket Till aquitard is attributed primarily to interconnections among various heterogeneities, including horizontal sandy interbeds and fractures that enhance the bulk vertical hydraulic conductivity of the unit to ~10^{-9} m/s (Gerber *et al.*, 2001). Flow within the diamicton matrix itself is considered to be minor since its vertical hydraulic conductivity, as measured in core, is ~10^{-11}-10^{-10} m/s (see Gerber *et al.*, 2001). Variable vertical hydraulic gradients within the aquitard confirm the heterogeneous distribution of hydraulic conductivities within the unit (Gerber *et al.*, 2001). Vertical groundwater flow across the aquitard is estimated to be <35 mm/a, yet it is believed to account for roughly 18% of baseflow in the Duffins Creek watershed (Gerber, 1999). Outcrop observations, core measurements (Corona and Mavko, 1999) and high seismic velocities (Pullan *et al.*, 2000) suggest that the Newmarket Till aquitard is over-consolidated. Consequently, specific storage is very low to negligible as demonstrated by hydraulic head responses to pumping of Lower sediment aquifers (Gerber, 1999).

To assess the hydrogeological significance of thickness and conductivity variations in the aquitard quantitatively at the regional scale, geostatistical mapping of its leakance was performed (Desbarats *et al.*, 2001). Leakance is a hydraulic property that characterizes the ability of a confining unit to transmit flow vertically, and is defined as the ratio of the unit's vertical hydraulic conductivity to its thickness. The geostatistical model was based on aquitard thickness determined from re-classified water well records, archival logs and preliminary assignment from stratigraphic studies. For this assessment, the aquitard included Newmarket Till and adjacent low-conductivity layers. Where the aquitard is present, its thickness ranges up to a maximum of ~118 m, with a median value of 12.2 m (Desbarats *et al.*, 2001). Lower thickness is usually associated with incised portions of the till whereas greater thickness generally corresponds to interfluvial uplands, with underlying silty sediment. The spatial correlation of thickness reproduced the orientation and patterns of incised channels in the Newmarket Till that were observed independently in the digital elevation model (Fig. 2a). Conductivity measurements, on the other hand, were too sparse and too clustered to be of much use for characterizing regional variations within the aquitard. However, limited hydraulic test data from landfill investigations (*e.g.*, M.M. Dillon Limited, 1994) provided some measure of conductivity variability that could be incorporated into the geostatistical model. The geostatistical modelling culminated in histograms and maps of leakance (Fig. 6) averaged over 1 km square grid blocks (Desbarats *et al.*, 2001). The histograms show that, where the aquitard is present, block leakance ranges between $3.5*10^{-12}$ 1/s and $4.1*10^{-8}$ 1/s, with an average of roughly $1.3*10^{-9}$ 1/s. However, the modelling study also revealed that the aquitard was absent in approximately one fifth of wells. The hydrogeological model for these breaches or "windows" in the aquitard is discussed next.

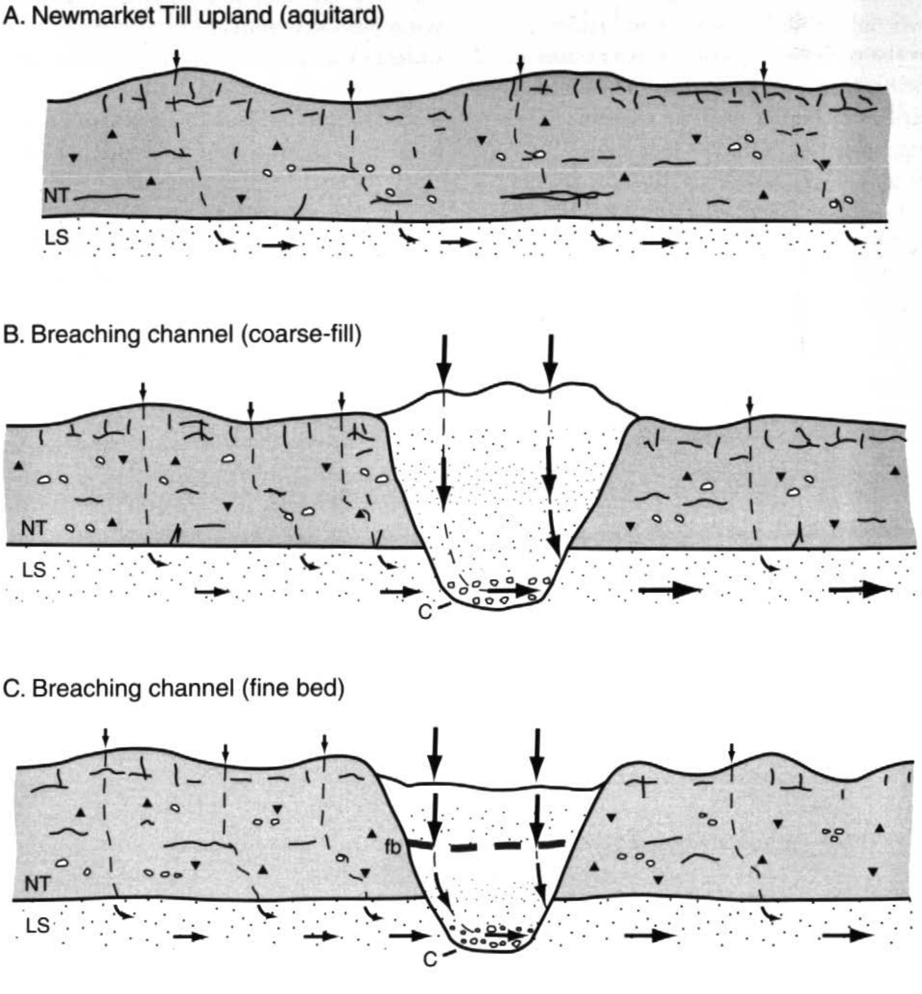


Figure 9 Hydrogeological terrains: (**A**) thick aquitard setting: Newmarket Till upland; (**B**) aquitard breach with coarse channel sediment, and (**C**) aquitard breach with fine-grained sediment beds (fb). Arrows indicate generalized groundwater flux. NT=Newmarket Till; C=channel; LS=lower sediment aquifer.

Breaches in the Newmarket Till Aquitard

Sediment-filled channels that breach Newmarket Till aquitard form a distinct hydrogeological setting (Fig. 9b,c). Such channels have not been described previously because of inadequate data and geological models of the region, and as a result, few hydrologic studies adequately document or quantify groundwater flow in this setting. Hydrogeological properties are expected to vary among and within channels over scales that are defined by the dimensions and architecture of facies depositional models and by the geometry of incised channels. In general, individual permeable units of subaqueous fan and channel sand are up to 50 m thick and several kilometres long, and likely to include very permeable sediment. Consequently, sand and gravel channel deposits may also form significant aquifers in their own right with hydraulic conductivities on the order of $2\text{-}9{*}10^{-4}$ m/s (Easton, 1998). In more distal subaqueous fan settings or higher in some channel sequences (*e.g.*, Fenco MacLaren, 1994b), silt and clayey-silt rhythmites form low-permeability layers separating sandy beds within channel sediments (Fig. 9c). The depositional model suggests that silty layers are generally discontinuous, with variable thickness, elevation, and texture (Russell, 2001). Hydraulic conductivities of the rhythmite layers are also variable and range between $6{*}10^{-11}$ and $6{*}10^{-7}$ m/s with a geometric mean of $1{*}10^{-8}$ m/s in piezometer tests at one site (Fenco MacLaren, 1994b). The loss of hydraulic head across silty clay layers indicates that they may locally form leaky aquitards. In the geostatistical mapping of aquitard leakance discussed previously, aquitard breaches or windows were represented by a uniform layer ~12.2 m thick with a conductivity of $5.6{*}10^{-4}$ m/s, which may be appropriate for coarser channel-fill sediments. With these assumptions, the average leakance of aquitard breaches is $4.6{*}10^{-5}$ 1/s, or roughly four orders of magnitude greater than that of the aquitard itself. Even when silty layers are present within channel-fill sediments, the bulk vertical hydraulic conductivity of the windows likely remains one or more orders of magnitude greater than that of the Newmarket Till aquitard (Table 1). Therefore, it is reasonable to expect that breaching channels are more permeable than Newmarket Till uplands.

On the basis of the above analysis, channels that breach Newmarket Till are thought to form preferential pathways for groundwater flow between unconfined aquifers of the overlying Oak Ridges Moraine and confined aquifers within the underlying Lower sediment (Fig. 9). The geometry of strata within channels may also be an important consideration for aquifer interconnection since interfingering sandy lenses may provide a permeable pathway around silty layers, as suggested in the vicinity of Aurora (Gartner Lee Limited, 1999). However, the actual vertical flow or leakage through these windows in the Newmarket Till aquitard will depend on several factors, including: 1) the area and bulk vertical hydraulic conductivity of channel sediment relative to that of the Newmarket Till, 2) transmissivity and hydraulic gradient within Lower sediment or channel aquifers, 3) channel orientation, and 4) pumping from Lower sediment or channel aquifers.

In order to provide a quantitative assessment concerning the relative significance of vertical flow through aquitard and windows, it is necessary to take the basin analysis approach one further step, to a numerical flow model.

APPLICATION OF THE HYDROGEOLOGICAL MODEL

This section presents an example of a key objective of basin analysis in which a numerical model is developed to improve

Table 1 Generalized properties and characteristics of Newmarket Till upland and breaching channel hydrogeologic settings[1].

Property or Characteristic	Newmarket Till Upland	Channel Fill
• Regional distribution	· occurs across 75-80% of area, variable thickness: up to 50 m, commonly ~10 m thick	· occurs across 20-25% of area, variable width and depth: 0.5-5 km wide, up to 150 m deep
• Internal heterogeneity	· related to fractures and sand lenses within till matrix	· related to texture, bedding, and geometry of units
• Nature of flow/permeability	· flow predominantly in fractures, interbeds, and sedimentary structures	· matrix flow, greater in coarser sediment
• Sand beds, percentage of total thickness	· usually <3%	· usually 40-75%
• Clay beds, percentage of total thickness	· usually <1%	· usually <2%
• Hydraulic conductivity-horizontal	· 10^{-10} to 10^{-11} m/s, till matrix up to 10^{-5} m/s, sandy interbeds	· 10^{-3} to 10^{-8} m/s, gravel to silty sand 10^{-6} to 10^{-10} m/s, silt/clay
• Hydraulic conductivity-vertical	· 10^{-10} to 10^{-11} m/s, till matrix 10^{-9} m/s, bulk	· 10^{-5} to 10^{-8} m/s, bulk (estimated)
• Recharge, vertical flux	· <35 mm/year, regional average	· variable, depends on channel hydraulic conductivity and Lower sediment transmissivity (see text)
• Response to pumping in Lower sediment or channel aquifers	· leaky, specific storage of Newmarket Till, $<10^{-5}$ m^{-1}	· leaky, specific storage of channel sediment, 10^{-4} to 10^{-5} m^{-1}

---

[1] Based on Gerber (1999), Gerber and Howard (2000), Gerber *et al.*, (2001), International Water Supply (1996), Fenco MacLaren (1994b), and unpublished GSC data.

understanding of the nature of groundwater flow. Here, the numerical model is used to consider the potential hydraulic significance of aquitard breaches.

Role of Confined Aquifers to Groundwater Flow across Aquitards and Aquitard Breaches

Under natural hydraulic gradients, a potentially important control on vertical groundwater flow through channel windows and the Newmarket Till aquitard is the horizontal transmissivity of Lower sediment aquifers (Figs. 4, 9). Vertical groundwater flow to the Lower sediment aquifers occurs over a large area (Fig. 9a). Flow is then transmitted horizontally and, in some areas, discharges to the ground surface where Lower sediment outcrops (*e.g.,* Sibul, *et al.,* 1977). If the transmissivity of these aquifers is moderate or low, horizontal flow through the confined aquifers can limit the vertical flux through the aquitard and the aquitard windows. Therefore, in these areas the vertical hydraulic conductivity of the aquitard would not be the limiting control on the regional flow to the Lower sediment aquifers. Similarly, the presence of windows through the Newmarket Till (Fig. 9b,c) would have little effect on groundwater flow paths if the regional flow was controlled predominantly by the transmissivity of the Lower sediment aquifers. Therefore to evaluate such settings, it is important to understand stratigraphic architecture and sediment facies variability, for example in confined aquifers (Lower sediment), as a basis for improved numerical analysis.

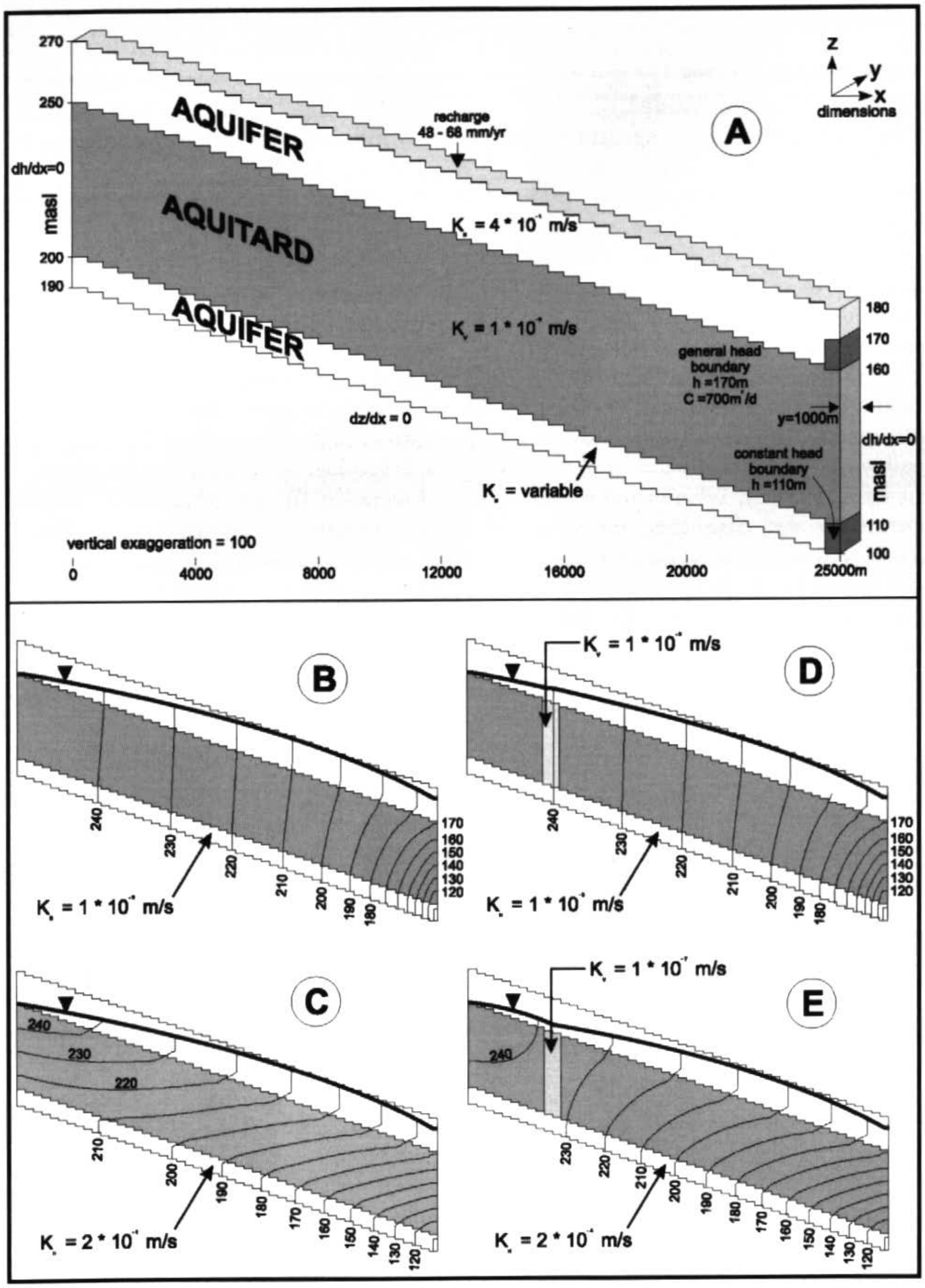


Figure 10 Visual MODFLOW groundwater flow simulations illustrating the role of confined aquifer transmissivity (T) on vertical flow through a regional aquitard and channels in a generalized 2-D cross-section of 1 km in width. **(A)** Hydraulic properties and boundary conditions. The 1-km width is only shown in figure (A). **(B)** Horizontal hydraulic conductivity (Kh) of $1*10^{-5}$ m/s (T=8.6 m^2 /d) in the confined aquifer. **(C)** Kh of $2*10^{-4}$ m/s (T=173 m^2 /d) in the confined aquifer. **(D)** Same as simulation (B) with a 1-km channel (vertical hydraulic conductivity (Kv) of $1*10^{-5}$ m/s) that breaches the regional aquitard. **(E)** Same as simulation (C) with a 1-km channel (Kv of $1*10^{-7}$ m/s) that breaches the regional aquitard. Anisotropy ratio Kh = 10 Kv in all units. Dark line is the phreatic surface of the unconfined aquifer.

The confined aquifer controls on vertical flow are demonstrated with steady-state groundwater flow simulations (using Visual MODFLOW) in a hypothetical 2-D flow system where an outcropping confined aquifer is overlain by a regional aquitard and a surficial aquifer (Fig. 10a). When confined aquifer transmissivity is small to moderate (Fig, 10b, transmissivity (T) = 8.6 m^2/d), the outflow from the confined aquifer is equivalent to an average vertical flux of 5 mm/a through the regional aquitard. When the confined aquifer transmissivity is increased by a factor of 20 (Fig. 10c, T = 173 m^2/d), the average vertical flux increases to 25 mm/a. Breaching channels, even with permeable fill, have very little impact on fluxes and equipotential levels where the transmissivity of the confined aquifer is limiting (Fig. 10d). However, breaching channels, even of moderate permeability, become important when the confined aquifer transmissivity does not limit vertical flow (Fig. 10e). Although the total flux through the confined aquifer is almost the same in simulations (C) and (E) of Figure 10, the change in equipotential patterns (*e.g.*, vertical gradients near the channel) results in a different flow distribution where a substantial proportion of the flow (in this case 37%) is transmitted to the confined aquifer *via* the channel. Transmissivity within Lower sediment aquifers varies by more than four orders of magnitude (0.1-1400 m^2/d, Gerber, 1999; IWS, 1988) such that all four scenarios (Fig. 10b- e) are possible in the study area.

Role of Channel Orientation and Pumping to Regional Groundwater Flow

Channel orientation may also influence groundwater flow; particularly where channel sediment is very permeable (*e.g.*, parallel to N-S paleoflow direction at Grasshopper Road, Pugin *et al.*, 1999) or where adjacent Lower sediment aquifers have low transmissivity (*e.g.*, perpendicular to depositional paleoflow). If oriented parallel to the regional hydraulic gradient, channel aquifers may transmit significant groundwater fluxes horizontally toward discharge zones. These channels may focus regional groundwater flow as discussed by Freeze and Witherspoon (1967) and produce areas of very high groundwater discharge. Most channels to the north of the moraine and in eastern portions of the study area are oriented approximately parallel to regional groundwater flow and are potentially significant flow paths.

Pumping of Lower sediment or channel aquifers can change vertical hydraulic gradients and flow directions. Consequently, pumping would be particularly important in the vicinity of windows through the Newmarket Till aquitard. Where considerable vertical flow occurs through a window under natural hydraulic gradients (Fig. 10e), increased gradients have the potential to draw more water from shallow aquifers. Where windows have low vertical flow due to small natural vertical hydraulic gradients (Fig. 10d), pumping may increase gradients and induce vertical groundwater flow. In either context, leakage would be higher and drawdown cones would be smaller for wells pumping near windows than for wells beneath a broad, upland Newmarket Till-aquitard setting. Modelling of deep aquifer pumping near similar aquitard windows in the Waterloo moraine of southern Ontario (Fig. 1) has demonstrated that they can have significant effects on groundwater flow paths and the size of well capture zones (Martin and Frind, 1998).

Implications of the Hydrogeological Model

The hydrogeological settings represented by the ORM hydrogeological model reveal important implications for both regional and site scale investigations. At the regional scale, the presence of hydraulic windows can influence the relative fluxes of groundwater in the local, intermediate and regional flow systems, and consequently can influence the distribution of groundwater discharge and stream baseflow. Windows can also influence the regional patterns of hydraulic head (Fig. 10). Where windows are permeable (*e.g.*, channel aquifers; Fig. 10e), vertical hydraulic gradients between the surficial and lower aquifers in recharge areas are expected to be smaller than in areas where the Newmarket Till aquitard is continuous (Fig. 10c). For site investigations, recognition of the regional setting is important, since the presence of a breaching channel could influence the local fluxes and directions of groundwater flow and ultimately the nature and scale of potential impacts. Consequently, the presence or absence of Newmarket Till aquitard and the related degree of interconnection (channel aquifer) between upper Oak Ridges Moraine and Lower sediment aquifers can greatly influence the scope, drilling depth, and therefore the cost of site investigations.

In addition to the direct influences of breaching channels on the groundwater flow system in a given area, identification of the breaching tunnel channel hydrogeological setting expands the range of geological and hydrogeological interpretations and conceptualization. Consequently, geological and hydrogeological interpretation are more difficult because stratigraphic and hydrostratigraphic assignment of units based on a "layer-cake" stratigraphic architecture model may not be justified. To date, groundwater flow models in the study area have assumed a continuous Newmarket Till aquitard beneath the Oak Ridges Moraine (Smart, 1994; Meriano, 1999; Gerber and Howard, 2000). In addition, short- and long-term pumping impacts, or the nature of solute migration, may differ for the two hydrogeological settings and require different hydrogeological interpretation. Conceptualization of the breaching channel setting may be particularly important beneath recharge areas of the Oak Ridges Moraine, where channels may influence regional flow systems and where data are sparse.

CONCLUSIONS

The hydrogeological framework of the Oak Ridges Moraine area is more complex than previously recognized. New understanding of stratigraphic architecture and event-sequence concepts derived from basin analysis allowed two related hydrogeological settings of the ORM hydrogeological model to be described: Newmarket Till upland aquitards, and breaching tunnel channel aquifers. The recognition of these settings emerged from the reinterpretation of the regional geology using improved subsurface data, meltwater-process models, and mapping of regional unconformities. As demonstrated in the geostatistical estimation of leakance and the numerical modelling (Fig. 10e), tunnel channels have the potential to allow significant vertical flow from shallow aquifers to deeper, confined aquifers. The recognition of breaching channels is an important contribution to the development of geologic models and hydrogeologic conceptualization in glaciated terrain like the Oak Ridges Moraine area. Hence, the identification of these and other hydrogeological settings (*e.g.*, LeGrand, 1970; MacMillan *et al.*, 2000), could allow them to be applied at other locations within and beyond the study area, much as depositional facies models (Walker, 1992) can be applied to similar sedimentary terrains and basins. However, the detailed regional extent of tunnel channel sediments, their hydrogeological characteristics, function, and significance are not yet well defined. Thus this setting, and that of Lower sediment confined aquifers, will require more detailed hydrogeological characterization from specific hydraulic monitoring and testing.

Regional understanding of groundwater flow systems is increasingly necessary in the Greater Toronto Area and other areas of Canada, to address the growing significance and scope of groundwater-related issues. Regional geologic models are becoming an essential element of regional hydrogeological analysis, and these models are readily developed within a basin analysis framework. As demonstrated in the Oak Ridges Moraine area, the development of regional geologic models often requires new high-quality data (*e.g.*, reflection seismic surveys and cored boreholes) to characterize stratigraphic architecture and depositional environments: key controls on the groundwater flow system that generally cannot be obtained from water well records or hydraulic data alone. Geologic models may require considerable effort and resources, and generally cannot be developed solely by compiling existing data. Therefore, further development of geologic models, particularly incorporation of knowledge on regional heterogeneity of depositional environments such as glacial terrain, should be considered by governments as an investment in regional knowledge and expertise that will improve the quality of hydrogeologic conceptualization in future studies. Use of basin analysis methods to characterize hydrogeologic settings will advance regional and national hydrogeologic understanding of glaciated regions of North America.

ACKNOWLEDGMENTS

Reviews by Larry Dyke, John Gartner, Charles Logan, Sue Pullan, Alfonso Rivera, Harvey Thorleifson, and Robert Van Everdingen are appreciated. Funding for the Oak Ridges Moraine study was from the Geological Survey of Canada Hydrogeology and National Mapping (NATMAP) programs. Significant funding and/or assistance was received from the Ontario Geological Survey, Ontario Ministry of Environment, Ontario Ministry of Natural Resources, Ontario Ministry of Municipal Affairs and Housing, Regional Municipalities of Durham, Peel and York, City of Toronto, Toronto Regional Conservation Authority, and Ontario Power Generation. Discussions with and data from Peter Barnett, Tracy Brennand, George Gorrell, Andre Pugin, Frank Kenny, and Sue Pullan from the ORM study team helped in developing geological concepts in the area.

REFERENCES

Anderson, M.P., 1989, Hydrogeological facies models to delineate large-scale spatial trends in glacial and glaciofluvial sediments: Geological Society of America Bulletin, v. 101, p. 501-511.

Anderson, M.P., Aiken, J.S., Webb, E.K. and Mickelson, D.M., 1999, Sedimentology and hydrogeology of two braided stream deposits: Sedimentary Geology, v. 129, n. 3-4, p. 187-199.

ASTM, 1999, Standard guide for conceptualization and characterization of ground-water systems, D 5979-96, *in* American Society for Testing Materials (ASTM) standards on design, planning and reporting of ground water and vadose zone investigations, 2nd edition: ASTM, West Conshohochen, Pennsylvania, p. 278-284.

Barnett, P.J., 1990, Tunnel valleys: evidence of catastrophic release of subglacial meltwater, central-southern Ontario, Canada, *in* Abstracts with Programs, Annual meeting of the Northeastern Section of the Geological Society of America, Syracuse, New York, p. 3.

Barnett, P.J. and Dodge, J.E.P., 1996, Quaternary geology of the Uxbridge area: Ontario Geological Survey, Map 2633, Toronto, ON, scale 1:20,000.

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F.M. and Pugin, A., 1998, On the origin of the Oak Ridges Moraine: Canadian Journal of Earth Sciences, v. 31, n. 10, p. 1152-1167.

Beckers, J. and Frind, E.O., 2000, Simulating groundwater flow and runoff for the Oro Moraine aquifer system. Part I. Model formulation and conceptual analysis: Journal of Hydrology, v. 229, p. 265-280.

Beckers, J. and Frind, E.O., 2001, Simulating groundwater flow and runoff for the Oro Moraine aquifer system. Part II. Automated calibration and mass balance calculations: Journal of Hydrology, v. 243, p. 73-90.

Bowen, G.S. and Hinton, M.J., 1998, The temporal and spatial impacts of road salt on streams draining the Greater Toronto Area, *in* Proceedings of the Groundwater in a Watershed Context Symposium, Canada Centre for Inland Waters, Burlington, Ontario, December 2-4, 1998: Canadian Water Resources Association, p. 303-310.

Boyce, J.I. and Eyles, N., 1991, Drumlins carved by deforming till streams below the Laurentide Ice Sheet: Geology, v. 19, p. 787-790.

Boyce, J.I. and Eyles, N., 2000, Architectural analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada: Geological Society of America Bulletin, v. 112, p. 98-118.

Brennand, T.A. and Shaw, J., 1994, Tunnel channels and associated landforms: their implication for ice sheet hydrology: Canadian Journal of Earth Sciences, v. 31, p. 502-522.

Brennand, T.A., Logan, C., Kenny, F.M., Moore, A., Russell, H.A.J., Sharpe, D.R. and Barnett, P.J., 1998, Bedrock topography of the Greater Toronto and Oak Ridges Moraine NATMAP areas, southern Ontario: Geological Survey of Canada, Open File 3419, Ottawa, ON, scale 1:200 000.

Brown, D.M., McKay, G.A. and Chapman, L.J., 1980, The climate of southern Ontario: Atmospheric Environment Service, Climatological Studies n. 5, Environment Canada, Toronto, ON, 67 p.

Brown, I.C., ed., 1967, Groundwater in Canada: Geological Survey of Canada, Economic Geology Report No. 24, Department of Energy, Mines and Resources, Ottawa, ON, 228 p.

Canadian Geoscience Council, 1993, Groundwater issues and research in Canada, a report prepared for the Canadian Geoscience Council by the Task Force on Groundwater Resources Research, Morgan, A. V., ed.: Canadian Geoscience Council, Waterloo, ON, 16 p.

Chapman, L.J. and Putnam, D.F., 1984, The physiography of southern Ontario, 3rd edition, Ontario Geological Survey special volume, 2: Ontario Ministry of Natural Resources, Toronto, ON, 270 p.

Cherry, J.A., 1996, Politics and economics: geological research bridging the gulf–the near-term future–Part 2; Perspective 5: From site investigations to site remediation: implications for hydrogeology: GSA Today, v. 6, n. 4, p. 13-15.

Coleman, A. P., 1932, The Pleistocene of the Toronto region: Ontario Department of Mines, Map no. 42g, Toronto, ON, scale 1:63 360.

Corona, W.W. and Mavko, G., 1999, Predicting clay content and porosity from gamma-ray and conductivity logs, *in* Proceedings, SAGEEP'99, Symposium on the application of geophysics to engineering and environmental problems, Oakland, CA, March 14-18, 1999, p. 425-433.

Cumming Cockburn Limited, 1990, Low flow characteristics in Ontario, Appendix B: Central region, Prepared for: Water Resources Branch, Ontario Ministry of the Environment.

Desbarats, A.J., Hinton, M.J., Logan, C.E. and Sharpe, D. R., 2001, Geostatistical mapping of leakance in a regional aquitard, Oak Ridges Moraine area, Ontario, Canada: Hydrogeology Journal, v. 9, p. 79-96.

Desbarats, A.J., Logan, C.E., Hinton, M.J. and Sharpe, D.R., 2002a, On the kriging of water table elevations using collateral information from a digital elevation model: Journal of Hydrology, v. 255, p. 25-38.

Desbarats, A.J., Logan, C.E., Hinton, M.J. and Sharpe, D.R., 2002b, Mapping the phreatic surface in the Goodwood area, Oak Ridges Moraine: Geological Survey of Canada, Open File 4238, Ottawa, ON, scale 1:50 000.

Dyke, L., 1999, Regional groundwater and stream chemistry survey, Oak Ridges Moraine, Ontario, *in* Current Research 1999-E: Geological Survey of Canada, Ottawa, ON, p. 111-121.

Dyke, L., Sharpe, D. R., Ross, I., and Hinton, M., 1997, Potential springs in the Oak Ridges Moraine, southern Ontario: Mapping from aerial thermography: Geological Survey of Canada and Ontario Ministry of Natural Resources, Geological Survey of Canada, Open File 3374, Ottawa, ON, scale 1:200 000.

Easton, J., 1998, Water resources of the Willow Creek tunnel valley aquifer, *in* Proceedings of the Groundwater in a Watershed Context Symposium, Canada Centre for Inland Waters, Burlington, Ontario, December 2-4, 1998: Canadian Water Resources Association, p. 239-246.

Eyles, C.H. and Eyles, N., 1983, Sedimentation in a large lake: a reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada: Geology, v. 11, n. 3, p. 146-152.

Eyles, N., Clark, B.M., Kaye, B.G., Howard, K.W.F. and Eyles, C.H., 1985, The application of basin analysis techniques to glaciated terrains: an example from the Lake Ontario basin, Canada: Geoscience Canada, v. 12, p. 22-32.

Fagnan, N., Bourque, É., Michaud, Y., Lefebvre, R., Boisvert, É., Parent, M. and Martel, R., 1999, Hydrogéologie des complexes deltaïques sur la marge nord de la Mer de Champlain: Hydrogéologie, v. 4, p. 9-22.

Fenco MacLaren Inc., 1994a, IWA landfill site search, Metro/York Region, Step 6 hydrogeological report, Site M6: Prepared for the Interim Waste Authority, Willowdale, ON, February 1994.

Fenco MacLaren Inc., 1994b, Detailed assessment of the proposed site V4A, Appendices C, CA-CJ, Geology/Hydrogeology, Metropolitan Toronto/York Region landfill site search: Prepared for the Interim Waste Authority, Willowdale, ON, November 1994.

Fligg, K. and Rodrigues, B., 1983, Geophysical well log correlations between Barrie and the Oak Ridges Moraine: Water Resources Branch, Ontario Ministry of the Environment, Map 2273, Toronto, ON.

Fogg, G.E., 1986, Groundwater flow and sand body interconnectedness in a thick, multi-aquifer system: Water Resources Research, v. 22, n. 5, p. 679-694.

Fogg, G.E. and Noyes, C.D., 1998, Geologically based model of heterogeneous hydraulic conductivity in an alluvial setting: Hydrogeology Journal, v. 6, p. 131-143.

Freeze, R.A., 1969, Theoretical analysis of regional groundwater flow: Inland Waters Branch, Scientific Series n. 3, Department of Energy Mines and Resources, Ottawa, ON, 147 p.

Freeze, R.A. and Witherspoon, P.A., 1967, Theoretical analysis of regional groundwater flow. 2. Effect of water-table configuration and subsurface permeability variation: Water Resources Research, v. 3, n. 2, p. 623-634.

Gartner Lee Limited, 1999, Water supply study, Magna golf course, Aurora, Ontario: Prepared for: Magna International Developments Inc., Markham, ON, May 1999.

Gerber, R.E., 1999, Hydrogeological behaviour of the Northern Till aquitard near Toronto, Ontario [Unpublished Ph.D. thesis], Department of Geology, University of Toronto, Toronto, ON, 253 p.

Gerber, R.E. and Howard, K.W.F., 1996, Evidence for recent groundwater flow through Late Wisconsinan till near Toronto, Ontario: Canadian Geotechnical Journal, v. 33, p. 538-555.

Gerber, R. E., and Howard, K., 2000, Recharge through a regional till aquitard: three-dimensional flow model water balance approach: Ground Water, v. 38, n. 3, p. 410-422.

Gerber, R.E., Boyce, J.I. and Howard, K.W.F., 2001, Evaluation of heterogeneity and field-scale groundwater flow regime in a leaky till aquitard: Hydrogeology Journal, v. 9, n. 1, p. 60-78.

Gilbert, R., 1997, Glaciolacustrine sedimentation in part of the Oak Ridges Moraine: Géographie physique et Quaternaire, v. 7, no. 1, p. 55-66.

Gorrell, G. and Brennand, T.A., 1997, Surficial geology of the Rice Lake area, NTS 31D/1, southern Ontario: Geological Survey of Canada, Open File 3332, Ottawa, ON, scale 1:50 000.

Gwyn, Q.H.J. and DiLabio, R.N.W., 1973, Quaternary geology of the Newmarket area, southern Ontario: Ontario Division of Mines, Preliminary Map P 836, Toronto, ON, scale 1:50,000.

Haefeli, C.J., 1970, Regional groundwater flow between Lake Simcoe and Lake Ontario: Inland Waters Branch, Technical Bulletin 23, Department of Energy, Mines and Resources, Ottawa, ON, 42 p.

Hess, P.J., 1986, Groundwater use in Canada, 1981: National Hydrology Research Institute, Inland Waters Directorate, NHRI Paper No. 28, IWD Technical Bulletin n. 140, Environment Canada, Ottawa, Ontario, 43 p.

Hinton, M.J., 1995, Measuring stream discharge to infer the spatial distribution of groundwater discharge, *in* Proceedings of the Watershed Management Symposium, Canada Centre for Inland Waters, Burlington, ON, December 6-8, 1995, p. 27-32.

Hinton, M.J., Russell, H.A.J., Bowen, G.S., and Ahad, M.E., 1998, Groundwater discharge in the Humber River watershed, *in* Proceedings of the Groundwater in a Watershed Context Symposium, Canada Centre for Inland Waters, Burlington, Ontario: Canadian Water Resources Association, p. 213-220.

Howard, K.W. F., Eyles, N., Smart, P.J., Boyce, J.I., Gerber, R.E., Salvatori, S.L. and Doughty, M., 1995, The Oak Ridges Moraine of southern Ontario: a groundwater resource at risk: Geoscience Canada, v. 22, n. 3, p. 101-120.

Hunter and Associates, and Raven Beck Environmental Ltd., 1996, Hydrogeological evaluation of the Oak Ridges Moraine area, technical report: Prepared for the Oak Ridges Moraine Technical Working Committee, Mississauga, Ontario, 31 January, 1996.

Hunter, J.A., Pullan, S.E., Burns, R.A., Good, R.L., Harris, J.B., Pugin, A., Skvortsov, A. and Goriainov, N.N., 1998, Downhole seismic logging for high resolution reflection surveying in unconsolidated overburden: Geophysics, v. 63, n. 4, p. 1371-1384.

International Water Supply Ltd. (IWS), 1988, Regional Municipality of York, Holland Landing, 1988 Groundwater investigation: Prepared for: York Region, Newmarket, ON.

International Water Supply Ltd. (IWS), 1996, Regional Municipality of York, Ballantrae, Aquifer test No. 2 well: Prepared for: York Region, Newmarket, ON.

James, B.R. and Freeze, R.A., 1993, The worth of data in predicting aquitard continuity in hydrogeological design: Water Resources Research, v. 29, no. 7, p. 2049-2065.

Karrow, P.F., 1967, Pleistocene geology of the Scarborough area: Ontario Department of Mines, Geological Report n. 46, Toronto, ON.

Karrow, P.F., 1974, Till stratigraphy in parts of southwestern Ontario: Geological Society of America Bulletin, v. 85, p. 761-768.

Kehew, A.E. and Boettger, W.E., 1986, Depositional environments of buried valley aquifers in North Dakota: Ground Water, v. 24, n. 6, p. 728-734.

Kenny, F., 1997, A chromostereo enhanced Digital Elevation Model of the Oak Ridges Moraine Area, southern Ontario: Geological Survey of Canada, Open File 3374, Ottawa, ON, scale 1:200 000.

Kenny, F.M., Paquette, J., Russell, H.A.J., Moore, A.M. and Hinton, M.J., 1999, A Digital Elevation Model of the Greater Toronto Area, Southern Ontario and Lake Ontario Bathymetry: Geological Survey of Canada, Ontario Ministry of Natural Resources, and Canadian Hydrographic Service, Geological Survey of Canada, Open File D3678, Ottawa, ON, 1 March 1999.

Koltermann, C.E. and Gorelick, S.M., 1996, Heterogeneity in sedimentary deposits: a review of structure-imitating, process-imitating, and descriptive approaches: Water Resources Research, v. 32, n. 9, p. 2617-2658.

LeGrand, H.E., 1970, Comparative hydrogeology: an example of its use: Geological Society of America Bulletin, v. 81, p. 1243-1248.

LeGrand, H.E. and Rosen, L., 1998, Putting hydrogeological site studies on track: Ground Water, v. 36, p. 193.

LeGrand, H. E., and Rosen, L., 2000, Systematic makings of early stage hydrogeologic conceptual models: Ground Water, v. 38, p. 887-893.

Lennox, D. H., Maathuis, H., and Pederson, D., 1988, Western Glaciated Plains, Region 13, Chapter 16, *in* Back, W., Rosenheim, J. S., and Seaber, P. R., eds., The geology of North America, v. O-2, Hydrogeology: The Geological Society of America, Boulder, Colorado, p. 115-128.

Logan, C., Russell, H. A. J., and Sharpe, D. R., 2001, Regional three-dimensional stratigraphic modelling of the Oak Ridges Moraine area, southern Ontario: Geological Survey of Canada, Current Research 2001-D1, Ottawa, ON, 19 p.

M.M. Dillon Limited, 1994, Detailed assessment of the proposed site EE11 for Durham Region landfill site search, Technical Appendices (parts 1 and 3 of 4), Appendix C, Geology/Hydrogeology: Interim Waste Authority Limited, Toronto, ON, October 1994.

MacMillan, A.A., Heathcote, J.A., Klinck, B.A., Shepley, M.G., Jackson, C.P. and Degnan, P.J., 2000, Hydrogeological characterization of the onshore Quaternary sediments at Sellafield using the concept of domains: Quarterly Journal of Engineering Geology and Hydrology, v. 33, p. 301-323.

MacRitchie, S.M., Pupp, C., Grove, G., Howard, K.W.F. and Lapcevic, P., 1994, Groundwater in Ontario: Hydrogeology, quality concerns and management: National Hydrology Research Institute No. CS-94011, Environment Canada, Ottawa, ON, 117 p.

Martin, P.J. and Frind, E.O., 1998, Modeling a complex multi-aquifer system: the Waterloo Moraine: Ground Water, v. 36, n. 4, p. 679-690.

Meriano, M., 1999, Hydrogeology of a complex glacial system, Rouge River-Highland Creek watershed, Scarborough, Ontario [Unpublished M.Sc. thesis], Department of Geology, University of Toronto, Toronto, ON, 86 p.

Meyboom, P., 1963, Patterns of groundwater flow in the prairie profile, *in* Groundwater: proceedings of the Hydrology Symposium n. 3, University of Alberta, 1962: Subcommittee on Hydrology, Water Resources Branch, Department of Northern Affairs and National Resources and Geological Survey of Canada, Department of Mines and Technical Surveys, p. 5-33.

Miall, A.D., 1988, Reservoir heterogeneities in fluvial sandstones: Lessons from outcrop studies: The American Association of Petroleum Geologists Bulletin, v. 72, n. 6, p. 682-697.

Miall, A.D., 2000, Principles of sedimentary basin analysis, 3rd edition: Springer, Berlin, New York, 616 p.

Nastev, M., Lapcevic, F.G., Etienne, M., Voralec, M.M. and Savard, M.M., 2000, Hydraulic characterization of fractured aquifers of St. Lawrence lowlands in southwestern Quebec, *in* Proceedings, Canadian Geotechnical Society-IAH meeting, Montreal, PQ, October 2000, p. 33-39.

National Research Council (NRC), 2000, Investigating groundwater systems at regional and national scales, Committee on USGS Water Resources Research, National Research Council: National Academy Press, Washington, D.C., 143 p.

Phillips, D.W. and McCulloch, J.A.W., 1972, The climate of the Great Lakes basin: Atmospheric Environment Service, Climatological Studies N. 20, Environment Canada, Toronto, ON, 40 p.

Pugin, A., Pullan, S.E. and Sharpe, D.R., 1999, Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario: Canadian Journal of Earth Sciences, v. 36, p. 409-432.

Pugin, A., Pullan, S.E. and Sharpe, D.R., 2001, Seismic reflection profiles and their contribution to the development of a geological model of the Oak Ridges Moraine area, southern Ontario: Geological Survey of Canada, Open File 3561, Ottawa, ON.

Pullan, S.E., Hunter, J.A., Pugin, A., Burns, R.A. and Hinton, M.J., 2000, Downhole seismic logging techniques in a regional hydrogeology study, Oak Ridges Moraine, southern Ontario, *in* Proceedings, SAGEEP 2000, Symposium on the application of geophysics to engineering and environmental problems,, Arlington, Virginia: Environmental and Engineering Geophysical Society, p. 643-652.

Randall, A.D., 2001, Hydrogeologic framework of stratified-drift aquifers in the glaciated northeastern United States, Regional Aquifer-System Analysis–northeastern United States: U.S. Geological Survey, Professional Paper 1415-B, Reston, Virginia, 179 p.

Ricketts, B.D., 2000, Mapping, geophysics, and groundwater modelling in aquifer delineation, Fraser lowland and delta, British Columbia: Geological Survey of Canada Bulletin 552, Ottawa, ON, 131 p.

Ritzi, R.W., Zarhradnik, A.D.J. and Fogg, G., 1994, Heterogeneity in a glacio-fluvial aquifer: Ground Water, v. 32, p. 666-674.

Ritzi, R.W., Dominic, D.F., Slesers, A.J., Greer, C.B., Reboulet, E.C., Telford, J.A., Masters, C.A., Bogle, J.L. and B.M., 1999, Comparing statistical models of physical heterogeneity in buried-valley aquifers: Water Resources Research, v. 36, n. 11, p. 3179-3192.

Russell, H. A. J., 2001, The record of high-energy episodic sedimentation in the western Oak Ridges Moraine, southern Ontario [unpublished Ph.D. thesis], Department of Earth Sciences, University of Ottawa, Ottawa, ON, 297 p.

Russell, H. A. J., Logan, C., Brennand, T. A., Hinton, M., and Sharpe, D. R., 1996, A regional geoscience database: an example from Oak Ridges Moraine NATMAP / Hydrogeology project, *in* Current research 1996-E: Geological Survey of Canada, Ottawa, ON, p. 191-200.

Russell, H. A. J., Brennand, T. A., Logan, C., and Sharpe, D. R., 1998a, Standardization and assessment of geological descriptions from water well records: Greater Toronto and Oak Ridges Moraine areas, southern Ontario, *in* Current Research 1998-E: Geological Survey of Canada, Ottawa, ON, p. 89-102.

Russell, H.A.J., Sharpe, D.R. and Arnott, W., 1998b, Sedimentology of the Oak Ridges Moraine, Humber River watershed, southern Ontario: a preliminary report, *in* Current Research 1998-C: Geological Survey of Canada, Ottawa, ON, p. 155-166.

Russell, H.A.J., Sharpe, D.R., Pullen, S.E. and Barnett, P. J., 2000, Form and sedimentary fill of tunnel channels beneath the Oak Ridges Moraine, southern Ontario: the Holland Marsh-King City channel system: Geological Survey of Canada Open File, 3841, Ottawa, ON.

Sharpe, D.R. and Barnett, P.J., eds., 1997, Where is the water? Regional geological/hydrological framework, Oak Ridges Moraine area, southern Ontario, Ottawa '97, Joint Annual Meeting of the Geological Association of Canada and Mineralogical Association of Canada, Field Trip A1, Guidebook: Ottawa, ON 49 p.

Sharpe, D.R., Pullan, S.E. and Warman, T.A., 1992, A basin analysis of the Wabigoon basin of Lake Agassiz, a Quaternary clay basin in northwestern Ontario: Géographie physique et Quaternaire, v. 45, n. 3, p. 295-309.

Sharpe, D.R., Barnett, P.J., Dyke, L.D., Howard, K.W.F., Hunter, G.T., Gerber, R.E., Paterson, J. and Pullan, S.E., 1994, Quaternary geology and hydrogeology of the Oak Ridges Moraine area: Waterloo '94, Joint annual meeting of the Geological Association of Canada and the Mineralogical Association of Canada, Field Trip A7, Guidebook, 15 May 1994, 32 p.

Sharpe, D.R., Dyke, L.D., Hinton, M.J., Pullan, S.E., Russell, H.A.J., Brennand, T.A., Barnett, P.J. and Pugin, A., 1996, Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geological models, *in* Current Research 1996-E: Geological Survey of Canada, Ottawa, ON, p. 181-190.

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

Sharpe, D.R., Barnett, P.J., Russell, H.A.J., Brennand, T.A. and Gorrell, G., 1999, Regional geological mapping of the Oak Ridges Moraine, Greater Toronto Area, southern Ontario, *in* Current Research 1999-E: Geological Survey of Canada, Ottawa, ON, p. 123-136.

Shaver, R.B. and Pusc, S.W., 1992, Hydraulic barriers in Pleistocene buried-valley aquifers: Ground Water, v. 30, n. 1, p. 21-28.

Shaw, J., 1985, Subglacial and ice marginal environments, *in* Ashley, G. M., Shaw, J., and Smith, N. D., eds., Glacial sedimentary environments: SEPM Short Course No. 16, Tulsa, Oklahoma, p. 7-84.

Shaw, J., 1996, A meltwater model for Laurentide subglacial landscapes, *in* McCann, S.B., and Ford, D.C., eds., Geomorphology Sans Frontières, Publication n. 6, International Association of Geomorphologists: John Wiley and Sons Ltd, Toronto, Ontario, p. 181-236.

Shaw, J. and Sharpe, D.R., 1987, Drumlin formation by subglacial meltwater erosion: Canadian Journal of Earth Sciences, v. 24, p. 2316-2322.

Shaw, J. and Gilbert, R., 1990, Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State: Geology, v. 18, p. 1169-1172.

Shaw, J. and Gorrell, G.A., 1991, Subglacially formed dunes with bimodal and graded gravel in the Trenton drumlin field, Ontario, Canada: Géographie physique et Quaternaire, v. 45, p. 21-34.

Sibul, U., Wang, K.T. and Vallery, D., 1977, Ground-water resources of the Duffins Creek-Rouge River drainage basins, Water Resources Report 8: Ministry of the Environment, Water Resources Branch, Toronto, ON, 109 p.

Singer, S.N., Cheng, C.K. and Scafe, M.G., 1997, The hydrogeology of southern Ontario, Hydrogeology of Ontario Series, Report 1: Ministry of Environment and Energy, Toronto, ON.

Smart, P.J., 1994, A water balance numerical groundwater flow model analysis of the Oak Ridges aquifer complex, south central Ontario [Unpublished M.Sc. thesis], Department of Geology, University of Toronto, Toronto, ON, 155 p.

Sun, R.J. and Johnston, R.H., 1994, Regional aquifer-system analysis program of the U.S. G.S., 1978-1992: U.S. Geological Survey Circular 1099, Washington, D.C., 126 p.

Thorleifson, L.H., Betcher, R., Birks, J., Boyle, D., Cherry, A., Clark, I., Desbarats, A.J., Edwards, T., Farrell, D., Grasby, S., Hinton, M., Kaszycki, C., Kennedy, P., Leybourne, M., McDougall, W., McRitchie, D., Osadetz, K., Remenda, V., Render, F., Ryan, S. and Woodbury, A., 1998, Hydrogeology and hydrogeochemistry of the Red River valley/Interlake region of Manitoba, *in* Manitoba Energy and Mines, Minerals Division Report of Activities, 1998: p. 172-185.

Tóth, J., 1963, A theoretical analysis of groundwater flow in drainage basins: Journal of Geophysical Research, v. 68, n. 16, p. 4795-4812.

Trescott, P.C., 1968, Groundwater resources and hydrogeology of the Annapolis-Cornwallis Valley, Nova Scotia: Nova Scotia Department of Mines Memoir 6, Halifax, NS, 159 p.

van der Kamp, G., 1986, The groundwater resources of Saskatchewan's deep buried-valley aquifers, *in* Proceedings of the Canadian Hydrology Symposium n. 16 - 1986: drought, the impending crisis?, Regina, SK, 3-6 June 1986: National Research Council Canada, p. 529-543.

Walker, R.G., 1992, Facies, facies models and modern stratigraphic concepts, *in* Walker, R. G., and James, N. J., eds., Facies models: Response to sea level changes: Geological Association of Canada, St. John's, NF, p. 1-14.

Watt, A.K., 1957, Pleistocene geology and groundwater resources of the township of North York, York County, Annual Report 1955: Ontario Department of Mines, Toronto, ON, v. 64 pt. 7.

Weissman, G.S., Carle, S.F. and Fogg, G.F., 1999, Three-dimensional hydrofacies modeling based on soil surveys and transition probability geostatistics: Water Resources Research, v. 35, n. 6, p. 1761-1770.

Accepted as revised 18 January 2002