HYDROGEOLOGY OF A COMPLEX GLACIAL SYSTEM, ROUGE RIVER-HIGHLAND CREEK WATERSHED, SCARBOROUGH, ONTARIO

by

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A thesis submitted in conformity with the requirements
for the Degree of Master of Science
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ABSTRACT

Hydrogeology of a Complex Glacial System, Rouge River-Highland Creek Watershed, Scarborough, Ontario

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A conceptual three dimensional (3-D) numerical model representing the hydrostratigraphy and groundwater flow patterns for 500 km^2 of a rapidly urbanized watershed (Rouge River Highland Creek; RRHC) in the eastern Greater Toronto Area has been developed using an extensive GIS-based collection of subsurface geological and hydrogeological data.

Visual MODFLOW, a modular 3-D finite difference computer code was selected for the 3-D flow analysis. Water balance calculations indicate that 70% of the basin recharge (106,000 m^3/d) enters the upper aquifer along the crest and immediate flanks of the Oak Ridges Moraine. To the south, upper aquifer water moving through fractured till aquitards accounts for more than 75% of recharge to deeper aquifers. These data confirm previous observations that urban- and rural-sourced contaminants present in upper aquifer waters (chlorides and nitrates) are moving rapidly into deeper aquifers. Some 83% of total RRHC recharge water is ultimately discharged as baseflow to creeks draining to Lake Ontario; the remainder discharges along eroding lakeshore bluffs and from a deep (lower) aquifer that includes fractured bedrock.

Dedicated to my mother

Dr. Kobra Salimi

ACKNOWLEDGEMENTS

I wish to thank my supervisor Dr. Nick Eyles for his guidance and support. Special thanks go to my thesis committee members, Dr. Ken Howard for his advice and encouragement throughout the project and Dr. Tony Price for his helpful discussions.

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SUMMARY

The former City of Scarborough, presently a district of the City of Toronto (hereafter referred to as The City of Scarborough), lies within the Rouge River-Highland Creek (RRHC) watershed which comprises a 500 km^2 area located in the eastern Greater Toronto Area. The lower third of the watershed is heavily urbanized and includes the City of Scarborough and part of the adjacent Town of Pickering. In 1997, the University of Toronto initiated a detailed study of the geology and hydrogeology of the City of Scarborough and RRHC watershed at the request of the City of Scarborough. The primary objective of this work was to provide detailed baseline hydrogeologic information to guide the planning of further urban development within the city. Specific objectives were: i) to map the subsurface distribution of aquifers and aquitards; ii) quantify regional groundwater flow systems; iii) provide estimates of recharge and baseflow to streams; and iv) to identify the significance of aquifers in terms of linkages with surface water courses and Lake Ontario.

The study involved detailed reconstruction of the subsurface geological framework, a water balance study and numerical groundwater flow modeling. Geological strata within the basin were mapped as a series of surfaces and isopachs using a large subsurface database consisting of more than 8,000 borehole records and subsurface geophysical data. The basin geology consists of a thick sequence of Late Wisconsin tills (Halton and Northern Tills) and intervening interstadial deposits (Mackinaw Interstadial) overlying older glaciolacustrine sediments (Thorncliffe and Scarborough Formations). These strata rest on Ordovician shale bedrock and reach a thickness of over 150 m below the Oak Ridges Moraine (ORM). The ORM consists of a prominent west-east belt of hummocky topography which forms a surface water and shallow groundwater drainage divide across the northern margin of the RRHC watershed.

Hydrostratigraphic units (aquifers and aquitards) were identified through a GIS (Geographic Information System) query of water well data and contoured geologic surfaces. This analysis revealed the presence of three principal aquifer systems, an upper sand and gravel complex (*Upper Aquifer* ≈ 150-340 m a.s.l.), an intermediate aquifer (*Middle Aquifer* ≈ 120-240 m a.s.l.) and a lower aquifer defined between bedrock and 150 m a.s.l. (*Lower Aquifer*). Aquifers are developed in outwash and lacustrine deltaic sediments and are confined by finer-grained till sheets. The Upper and Middle Aquifer systems are regionally extensive, are primary targets for groundwater abstraction in the RRHC basin, and are separated by the regionally-extensive Northern Till unit (*Upper Aquitard*). The Upper Aquifer system consists of outwash sand and gravels of the ORM, interglacial sands and gravels of Mackinaw Interstadial and thin surficial Halton Till. The Middle Aquifer, developed in thick deltaic sands of the Thorncliffe Formation, is the major aquifer in the City of Scarborough. The Lower Aquifer consists of channel-bound bedrock valley aquifers which are of local importance in areas of thinner sediment cover in the southern part of the basin.

Regional groundwater flow patterns and principal recharge and discharge areas were delineated using water well information and a 3-D groundwater flow model (MODFLOW). The model incorporates a detailed 3-D hydrostratigraphic framework developed for the basin and is calibrated to point water well data, kriged heads (estimated values at points other than where measurements were taken using a variogram; see DeMers, 1997) and streamflow measurements. This analysis shows that groundwater flow in aquifers is generally southward, towards Lake Ontario with local deflections towards streams. Recharge of the Upper and Middle Aquifers occurs principally along the ORM in the northern headwater areas of the catchment, and also as a result of recharge/leakage through confining till units to the south.

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1.0 INTRODUCTION

1.1 Overview and Rationale for Study

The City of Scarborough occupies an area of 188 km^2 along the northern shore of Lake Ontario east of Toronto. The population is about 500,000 and is expected to double in the next 30 years. Approximately 50% of the city is residential and 30% is industrial. Industry is centered mainly in the southern portion of the city. Rural farmland is being rapidly developed to the north along the urban-fringe. Groundwater contaminant sources, subsurface geologic pathways and travel times both to Lake Ontario and to city watercourses are poorly understood and a major obstacle to protection and management of the city's water resources and watersheds. Dramatic growth and population increases coupled with anthropogenic stresses on natural resources provide the motivation for acquiring a sound understanding of the geology and hydrogeology in the area. A groundwater flow model is urgently needed for watershed studies and planning, ground and surface water protection, remediation of urban watercourses and the tracking of regional contaminant sources to Lake Ontario.

The hydrogeological analysis involves compilation of existing data into a conceptual and numerical flow model. A major obstacle to groundwater flow modeling is a lack of understanding of the subsurface stratigraphy and hydrostratigraphy of thick (<150 m depth) Pleistocene glacial sediments resting on bedrock. A detailed hydrogeological conceptual model of the RRHC watershed was established by analysis of lithologic evidence from stratigraphic borehole and outcrop logs, geologic interpretation of gamma and resistivity logs and analysis of spatial distribution and screen depth of water wells. Collaborative work to date between the University of Toronto and the City of Scarborough has resulted in development of a GIS-based computerized hydrostratigraphic database for the city. The focus of work reported in this thesis has been the creation of a numerical groundwater flow model from GIS database.

1.2 Database and Methods

The following sections describe in detail the data analyses performed in assigning aquifer/aquitard status to the lithostratigraphic units. The steps taken in aquifer/aquitard specification have been summarized in Figure 1.

GIS Subsurface Database

The subsurface GIS database assembled for this study includes more than 210 cored and geophysically logged (gamma and resistivity) stratigraphic boreholes and outcrop logs together with a large digital water well dataset (8,492 records) obtained from the Ontario Ministry of Environment and Energy (MOEE) (Figure 2). Water well records provide generalized lithologic data and useful hydrogeologic information including static water levels, specific capacity, pumping drawdown and recovery, and well construction details. The database structure was developed to accommodate a large existing provincial digital water well database (>210 Mb; see Eyles et al., 1997a) and to facilitate input of other geotechnical, stratigraphic and borehole geophysical information.

Pleistocene strata were subdivided into lithostratigraphic units based on lithofacies, texture, bounding surface characteristics (i.e., presence of erosional unconformity or conformity surfaces) and other defining properties in drillcore and outcrop. Correlation of lithostratigraphic units in the subsurface involved analysis of >210 stratigraphic boreholes and accompanying geophysical logs. A number of Pleistocene lithostratigraphic units (e.g., Northern Till) have well-defined responses on gamma and resistivity logs providing useful marker horizons for stratigraphic correlation. Shallow seismic profiles provide additional data regarding the continuity of strata and the presence of intraformational heterogeneities (Boyce et al., 1995; Boyce and Koseoglu, 1996; Siakoohi and West, 1997). More generalized lithologic information from water well records was found to be useful in extending correlations across areas where detailed stratigraphic borehole information was unavailable (Figure 2).

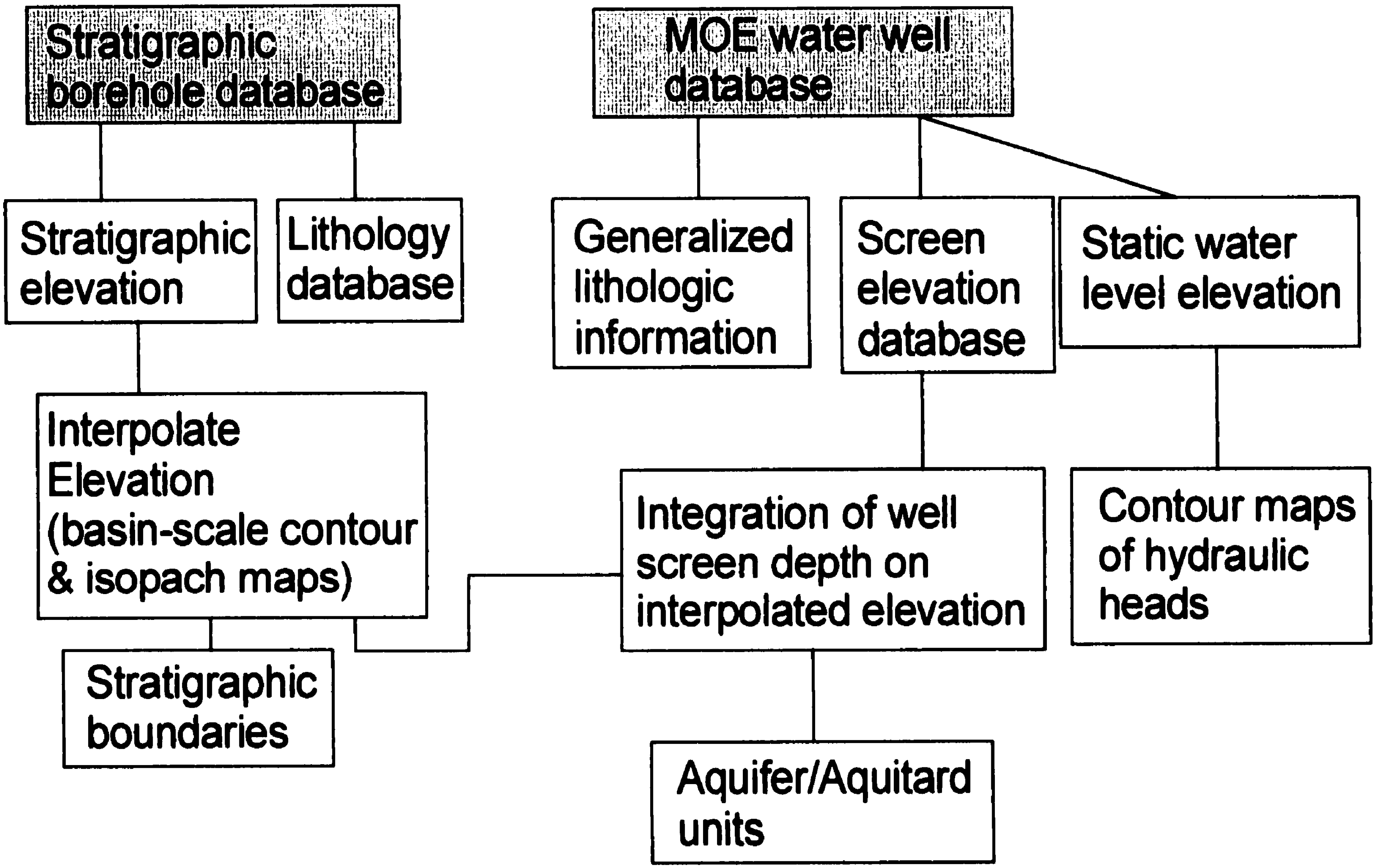


Figure 1. Methodology used in assigning aquifer/aquitard status to lithostratigraphic units.

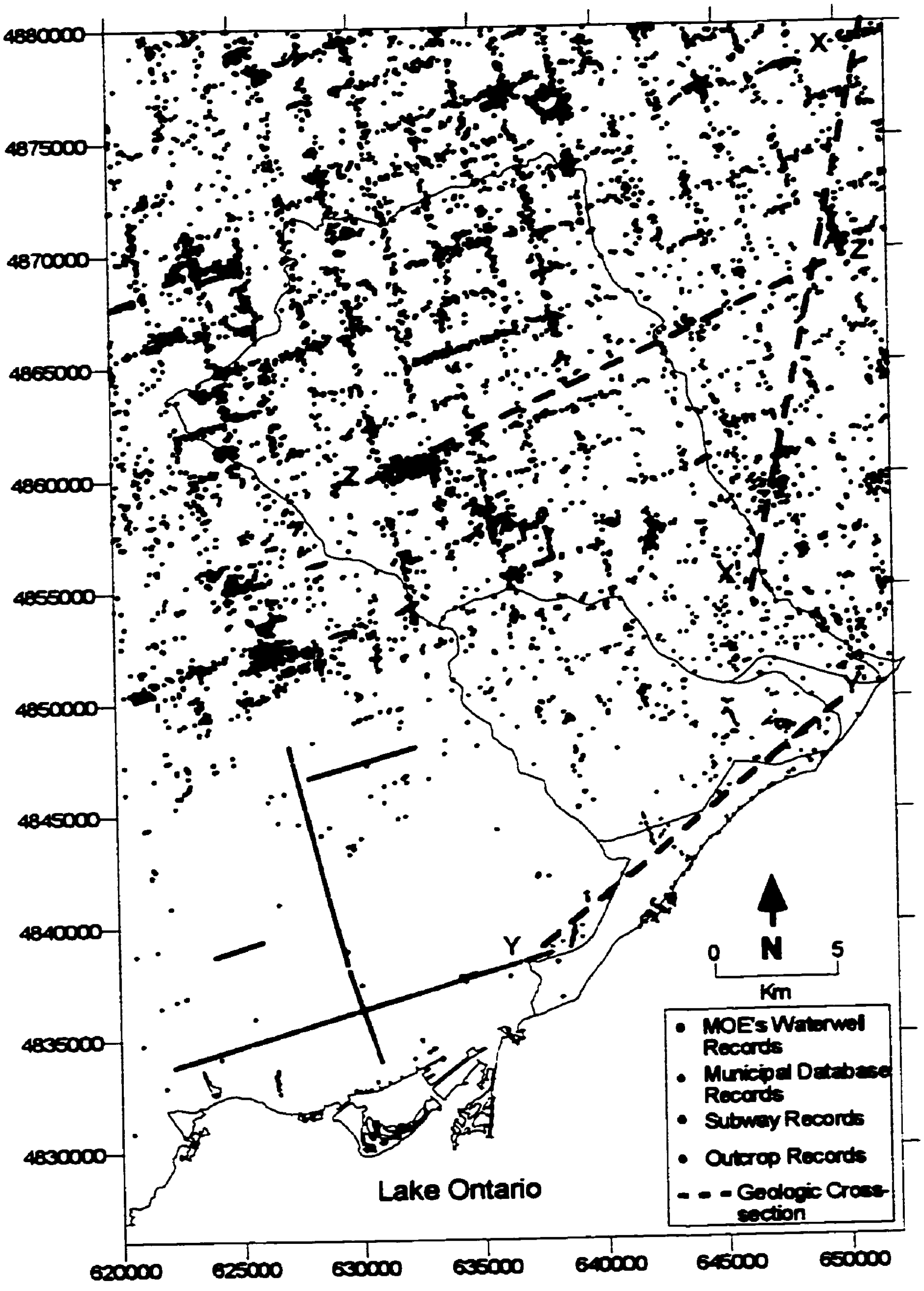


Figure 2 . Map showing distribution of stratigraphic boreholes, water wells and outcrops used in reconstruction of regional geology and hydrostratigraphy. Geologic sections shown in Figures 10, 11 and 12.

The depths to the tops and bases of lithostratigraphic units identified in borehole and geophysical logs were tabulated within the database and converted to elevations in metres above a reference datum (sea level). These data were then used to generate basin-scale contour and isopach maps of individual lithostratigraphic units (e.g., Jones et al., 1986). Data were interpolated using the kriging method with a 200 m grid-line spacing (Davis, 1986; Isaaks and Srivastava, 1989). This approach allows for superior handling of spatial trends in data which are not accounted for using other deterministic interpolation algorithms (e.g., inverse distance method; Wingle, 1992). Inaccuracies in the location of interpolated lithostratigraphic boundaries may occur where large distances exist between borehole control points resulting in over- or under-estimating of interpolated surfaces (Jones et al., 1986). Other effects include local thickening or thinning (erosion) of lithostratigraphic units which may not be resolved in interpolated data due to widely spaced boreholes or conversely, due to insufficient grid line density where boreholes are very closely spaced.

Gridded surfaces defining lithostratigraphic units were then imported into the GIS as a series of layers that can be queried (i.e., for elevation, thickness) and dissected along various transects producing two dimensional cross-sections. Details of this procedure and other methods for numerical contouring and cross-section generation are given elsewhere (Jones et al., 1986; Camp and Brown, 1993).

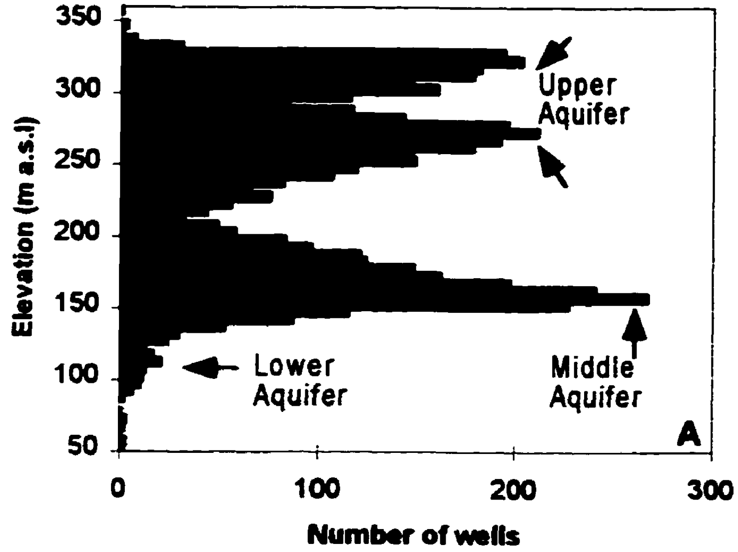
1.3 Hydrostratigraphic Analysis

Hydrostratigraphic units were defined as *mappable rock/sediment bodies characterized by their permeability, porosity and other identifiable hydrogeologic properties* (Seaber, 1988). Hydrogeologic properties are dependent to a large extent upon lithological characteristics (e.g., grain-size, porosity, pore geometry; Anderson and Woessner, 1992) such that boundaries between hydrostratigraphic units can often be related on a regional-scale to the sequence of lithostratigraphic units (Anderson, 1989).

For the purposes of this study, an *aquifer* is defined as a *hydrostratigraphic unit capable of providing groundwater supplies sufficient to meet the needs of a domestic well* (e.g., Sibul et al., 1977; Freeze and Cherry, 1979). Conversely, an *aquitard* is defined as *a relatively low permeability stratum which is incapable of providing domestic water supplies* (Freeze and Cherry, 1979).

Hydrostratigraphic units were identified in this study by analysis of more than 5,500 well screen elevations. Aquifers are identified as zones which are screened at similar elevation and are separated by layers of low permeability. Figure 3 clearly demonstrates a relationship between lithologic type and water-bearing zones. Histograms of well screen elevations were generated by a database query of selected areal zones (e.g., west-east “strips”) and are useful for identifying general occurrences of aquifers and aquitards. A systematic relationship between well screen distribution and lithostratigraphy is observed because of the close dependency of permeability on grain-size. *This analysis thus provides a rapid method for assigning lithostratigraphic units to aquifer or aquitard status.* The presence of an aquitard can be inferred where a lithostratigraphic unit contains no wells, or wells which have been abandoned due to insufficient yield.

The occurrence of well screens within characteristically “tight” formations (i.e., fine-grained till deposits; Figure 3) also yields valuable information regarding the presence of heterogeneities within aquitards. In situations where the distribution of aquifers is relatively predictable with respect to the lithostratigraphic sequence (e.g., Figure 3), well screen elevations can be used to locate approximate lithostratigraphic boundaries between widely spaced borehole control points.



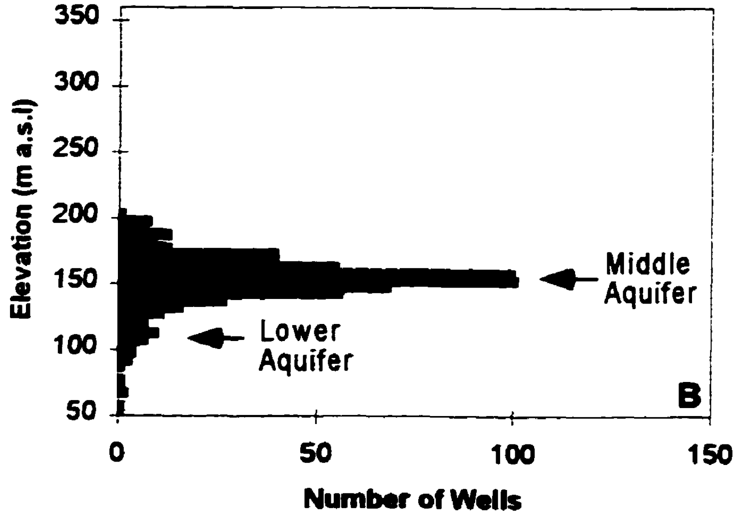


Figure 3. Pincipal hydrostratigraphic units identified by query of well screen elevations for: A. Study Area and B. City of Scarborough. Well screen data for the City of Scarborough showing Middle and Lower Aquifer units (screens above 175 m a.s.l are likely in Upper Aquifer).

2.0 PHYSICAL SETTING OF RRHC WATERSHED

2.1 Physiography

The study area is located within the South Slope and Lake Iroquois Plain physiographic regions of south-central Ontario (Figures 4, 5) (Chapman and Putnam, 1986). The Oak Ridges Moraine (ORM) is a prominent highland feature stretched across the northern part of the watershed extending for more than 160 km from Rice Lake (Trenton) in the east to the Niagara Escarpment in the west. It is an important groundwater recharge area for the aquifers beneath and along its flanks and sources over 30 major watercourses within the Greater Toronto Area. The ORM stands about 100 m above the surrounding landscape at approximately 340 m a.s.l in the study area (Figure 5). The South Slope consists predominantly of gently undulating drumlinized topography (Halton Till plain) extending northward from the Lake Iroquois shoreline to the southern limit of the ORM. The till plain occupies more than 60% of the RRHC watershed forming a tableland deeply incised (up to 40 m) by modern river valleys. The southern limit of the till plain is marked by relatively steep topographic gradients occurring between 140 and 165 m a.s.l. which define the former shoreline of Lake Iroquois (Figures 4, 5). Lake Iroquois was a high-level glacially-dammed lake which formed during regional deglaciation, about 12,500 years ago. The ancestral lake stood up to 40 m above the present level of Lake Ontario and deposited an extensive lacustrine plain south of the Iroquois shoreline (Lake Iroquois Plain; Figures 4, 5) (Chapman and Putnam, 1986). Rapid drainage of Lake Iroquois after 12,000 years ago, resulted in the deeply incised valleys of Humber River, West and East Don Rivers, and Rouge River as baselevel was lowered (Section 3.1). Postglacial rise in the level of the lake results in active erosion of the southern boundary of the study area (Lake Ontario Shoreline) and the cutting of a cliffed shoreline, known as the Scarborough Bluffs.

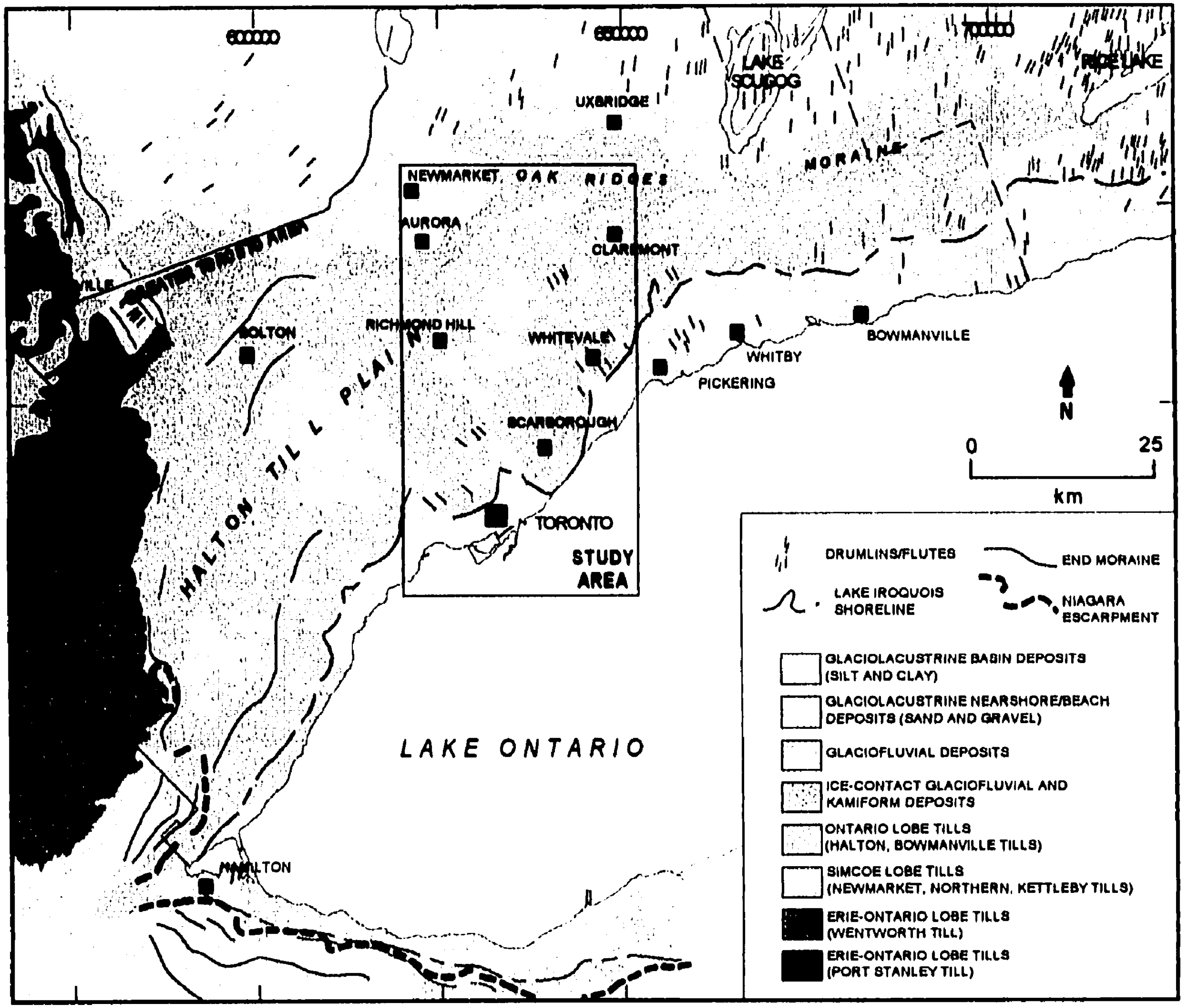


Figure 4. Surficial geology map of south-central Ontario showing location of watershed study area and major physiographic features (after Chapman and Putnam, 1984; Barnett et al., 1991).

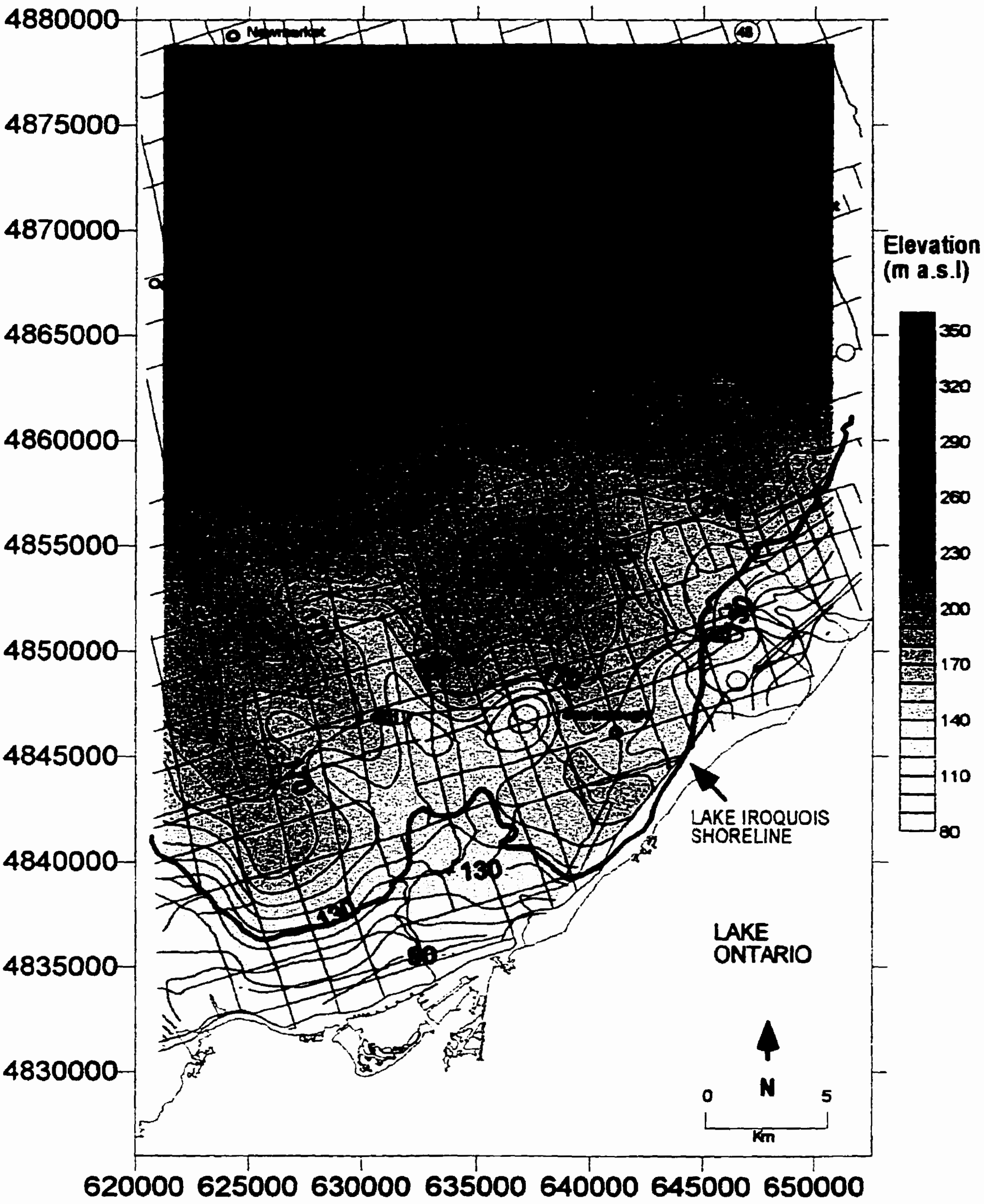


Figure 5. Generalized surface topography and major physiographic regions. Contour interval 10m.

2.2 *Climate*

The climate of the study area is modified by the presence of the Great Lakes which serve as temperature regulators (minimizing extremes in temperature) and as sources of atmospheric moisture. Mean annual temperature for the area is 6.9 °C with the thirty year (1951-1980) mean daily temperatures ranging from -7.9 °C in January to 20.4 °C in July (Environment Canada, 1980). The mean daily temperatures for the community of Oak Ridge in the northwestern part of the study area is 6.7 °C compared to 7.8 °C for the City of Scarborough (Environment Canada, 1980).

The mean annual precipitation for southern Ontario is 813 mm (1931-1960). A slightly lower mean annual precipitation value of 724 mm has been reported for Ontario by the Ontario Ministry of Natural Resources (1984). Less than half of the mean annual precipitation, 380 mm along the ORM and 356 mm along the shore of Lake Ontario, fall during the growing season from May to September (Brown et al., 1980).

Brown et al. (1980) estimate the mean annual potential evapotranspiration (PET) at 584 mm along the ORM (using the Thornthwaite Method) and 610 mm along the shore of Lake Ontario, while the actual evapotranspiration (AET) is reported as 533 mm. This compares to AET value of 533 to 559 mm for the area reported by Phillips and McCulloch (1972). The annual mean runoff ranges from less than 200 mm to more than 450 mm (Ministry of Environment and Energy, 1997).

2.3 *Land Use*

Land use maps showing existing/proposed uses for the City of Scarborough and Towns of Markham, Richmond Hill and Whitchurch-Stouffville were consolidated into a single land use map (Figure 6). Land use in the study area is 36% agricultural, 40% urban areas and roads and 24% green space including riparian zones. Riparian zones are influenced very little by reclamation in comparison with many other green or forested areas in the watershed. There are 32 documented closed landfills in the watershed, of which 27 occur in the City of Scarborough. Many of these landfills occur in old sand and gravel pits south of the Lake Iroquois Shoreline.

2.4 Surface Drainage

The RRHC watershed drains southward to Lake Ontario via four main branches (Rouge River, Little Rouge Creek, East and West Highland Creek) and their tributary streams (Figure 7). The headwater areas of the watershed lie on the southern slopes of the ORM and are spring fed. Due to good land drainage south of the ORM, the occurrence of swamps and bogs are limited to localized areas on the ORM and in the river valleys. The ORM forms a regional shallow groundwater and surface water drainage divide separating the Lake Ontario and Lake Simcoe basins (Howard et al., 1997).

3.0 GEOLOGIC SETTING

3.1 Bedrock Geology

Bedrock beneath the RRHC watershed is composed of Late Ordovician shales (Whitby Formation; Johnson et al., 1992). Figure 8 shows the bedrock surface topography beneath the study area reconstructed from water well depth-to-bedrock data. The bedrock surface slopes southward from an elevation of > 200 m a.s.l. beneath the ORM to < 50 m a.s.l. at the Lake Ontario shoreline, exhibiting a regional dip of approximately 10-15 m/km to the southwest. The bedrock surface is cut by a number of broad north-westward trending valleys which form part of a network of southward-draining bedrock channels underlying the ORM and South Slope area (Ostry, 1979; Eyles et al., 1993; Figure 8). The channel orientation is controlled by joints and faults in bedrock (Eyles and Scheidegger, 1995). Within the study area, shale bedrock is intermittently exposed along the floor of Rouge River and Little Rouge Creek.

3.2 Pleistocene Geology

The geology of the study area consists of Pleistocene glacial deposits resting on bedrock (Figure 9). The term *Pleistocene* refers to sediments which were deposited during marked changes in climate over the last 2 million years. The Pleistocene sediments in the study area are younger than 60,000 years and were deposited during the last (Wisconsin) glaciation and the recent postglacial period. The surficial deposits were mapped by Karrow (1967), Hewitt (1969) and most recently by Westgate (1979, unpublished). Three geologic cross-sections through the RRHC watershed are shown in Figures 10, 11 and 12. Pleistocene sediments are thickest (> 150 m) under the crest of the ORM and thin southwards to Lake Ontario; much of the uppermost stratigraphy has been eroded below the shoreline bluff of Lake Iroquois (Figures 10, 11). Four distinct phases of sedimentation can be identified which are discussed in turn in the following

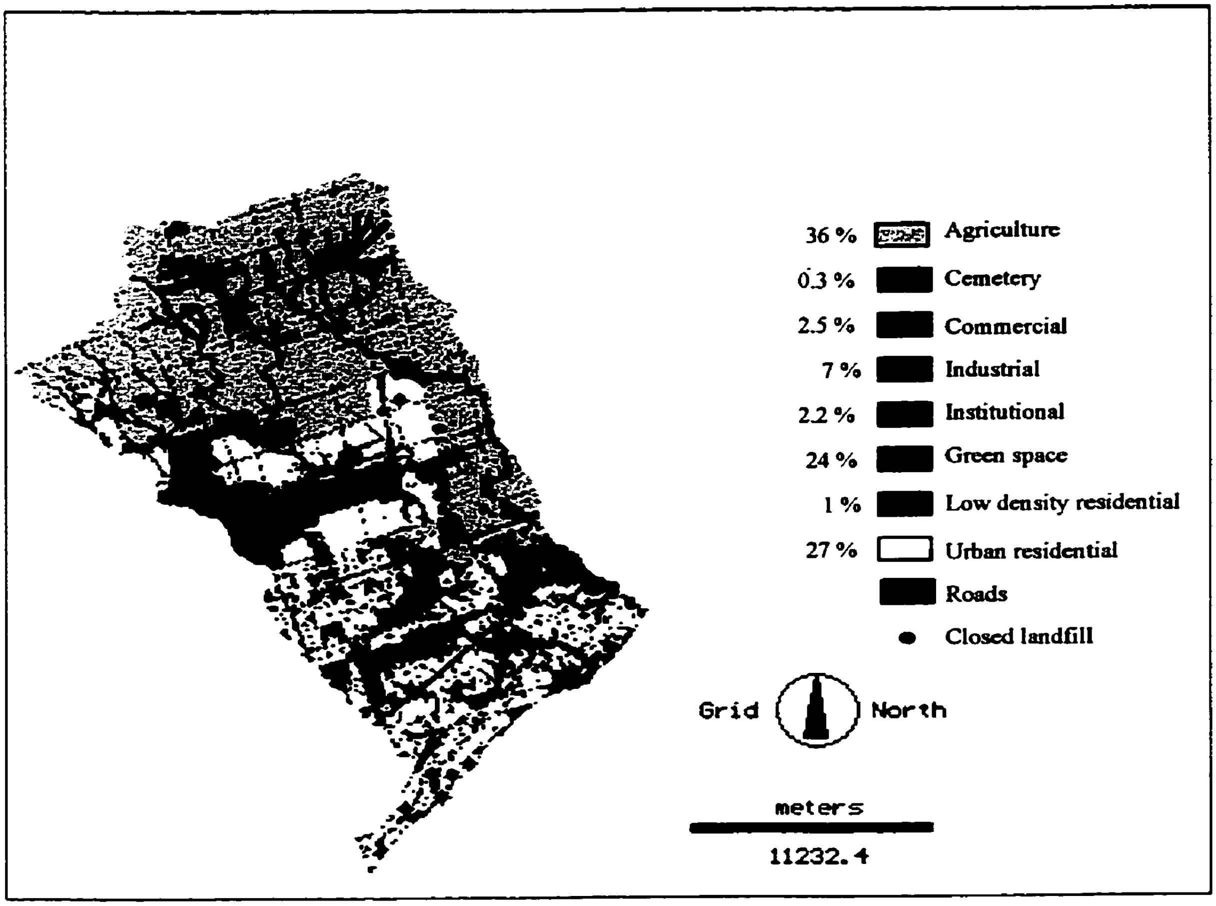


Figure 6. Land use map of RRHC watershed.

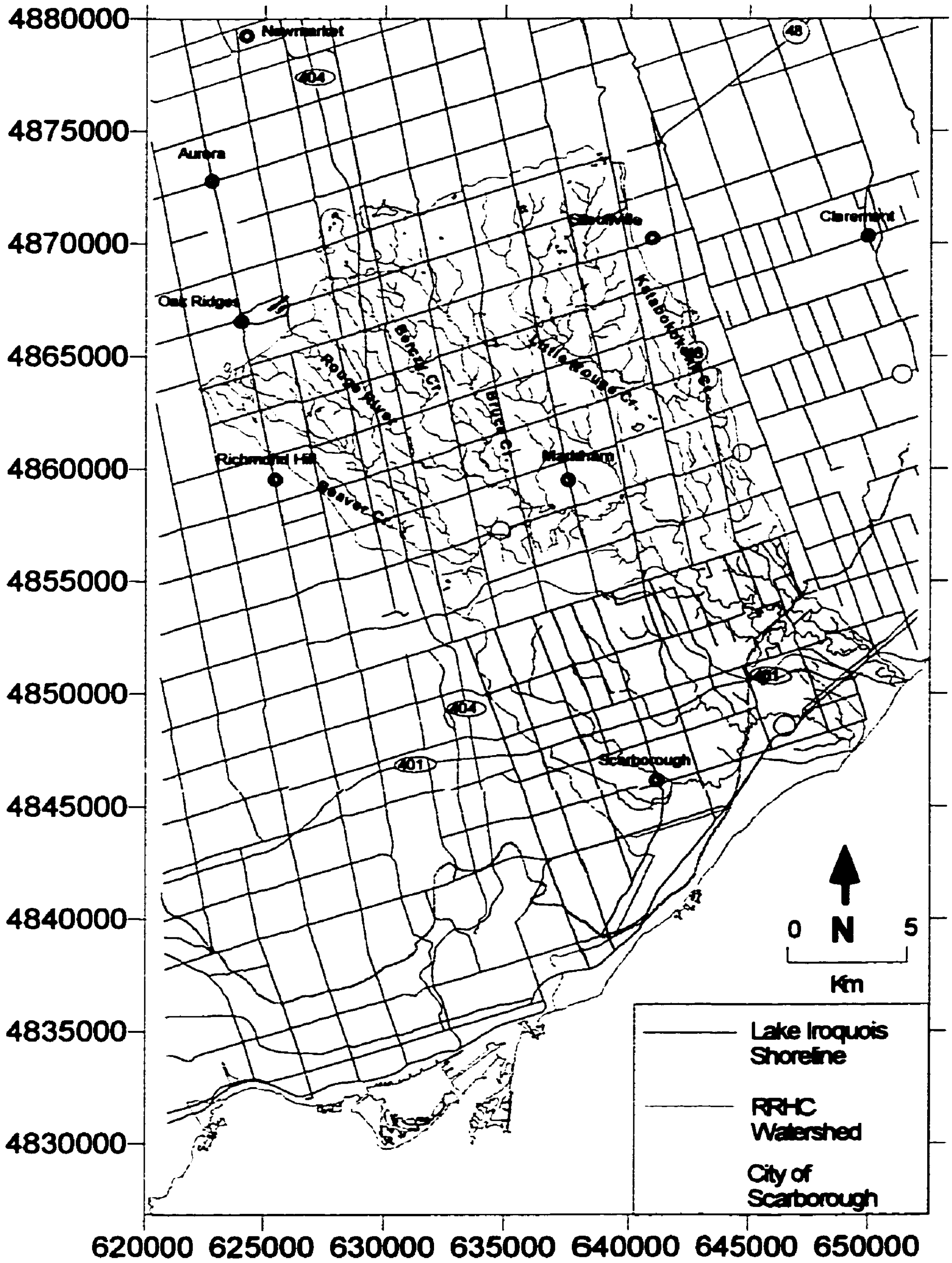


Figure 7. Map of study area showing location of City of Scarborough within the Rouge River-Highland Creek (RRHC) watershed area.

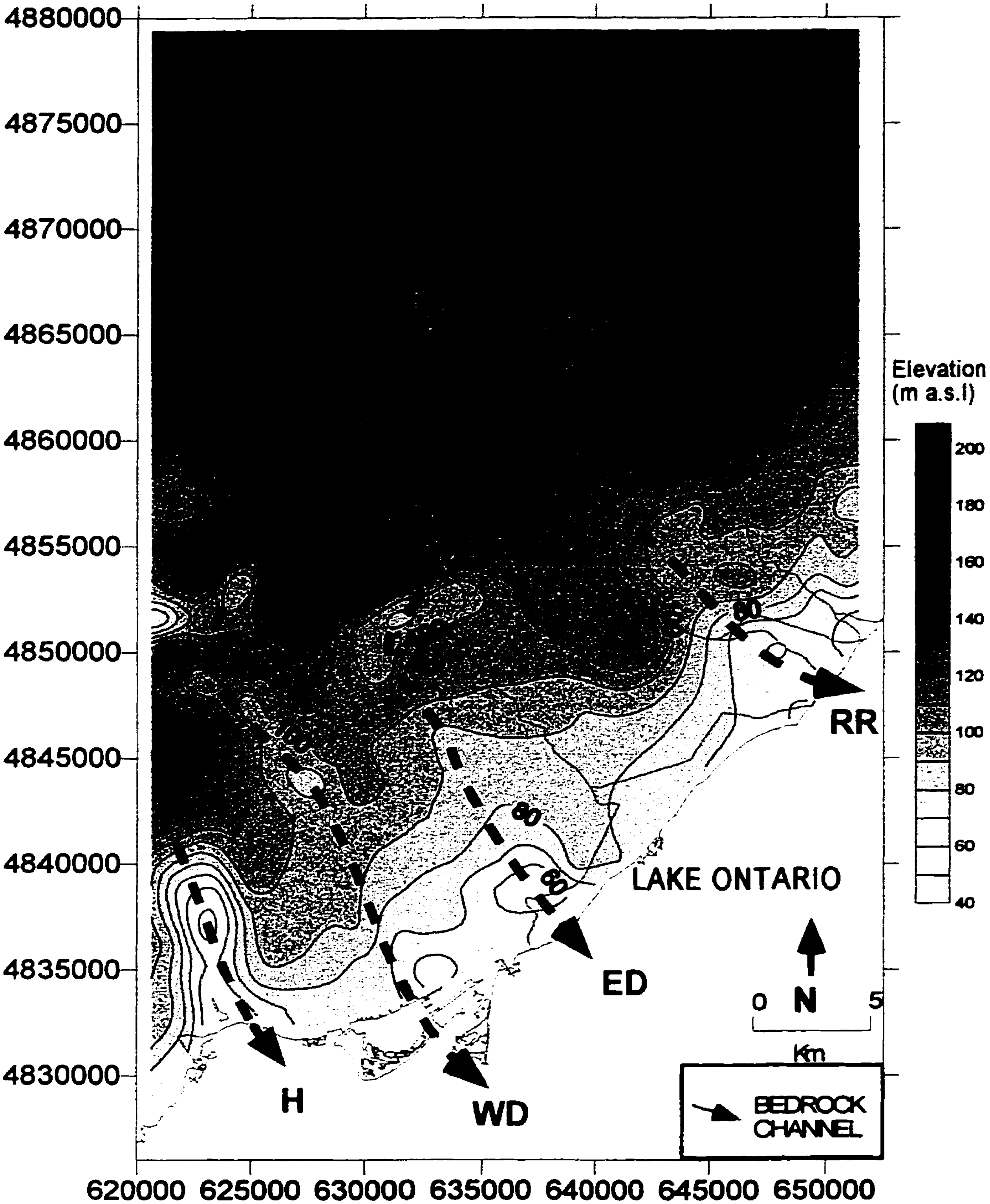


Figure 8. Bedrock surface topography with major bedrock channels indicated. (contour interval 10m).
H, WD, ED, and RR denote Humber, West Don, East Don, and Rouge River bedrock valleys respectively.

sections (also see Figure 9). York Till, a lodgement till, deposited during the Illinoian Glaciation and the bioturbated sands and muds of the Don Formation deposited during the Sangamon Interglacial (Coleman, 1932 and Terasmae, 1960) have limited regional extent that are not well represented within the study area.

3.2.1 Early and Mid-Wisconsin Glacial

The first depositional phase, beginning about 60,000 years ago and terminating at 25,000 years ago (Berger and Eyles, 1994), coincides with the flooding of the study area below a deep ancestral Lake Ontario dammed by ice blocking the St. Lawrence River valley. The thick sands and silts of the Scarborough and Thorncliffe formations, separated by pebbly muds of the Sunnybrook Formation, record this first phase. Both the Scarborough and Sunnybrook units cannot be traced further north than Stouffville where they terminate against a rising bedrock surface (Figure 11). The Scarborough Formation has a deltaic origin and consists of clay and silt rythmites at the base, and of cross-bedded sands at the top (Karrow, 1967). The Sunnybrook Diamict is well exposed along the lower branch of Highland Creek. This deposit consists of two

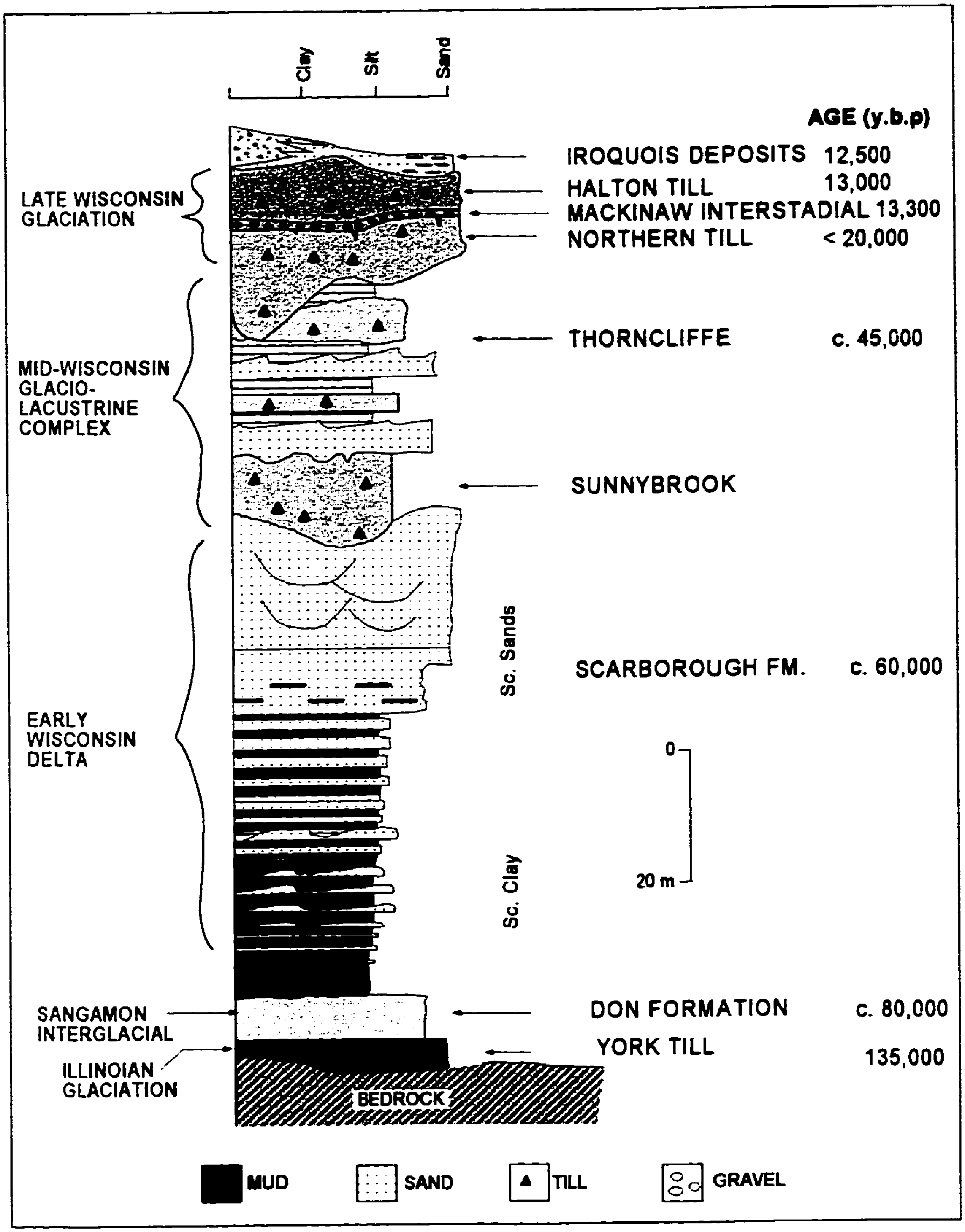


Figure 9 Stratigraphic column of glacial deposits in the study area.

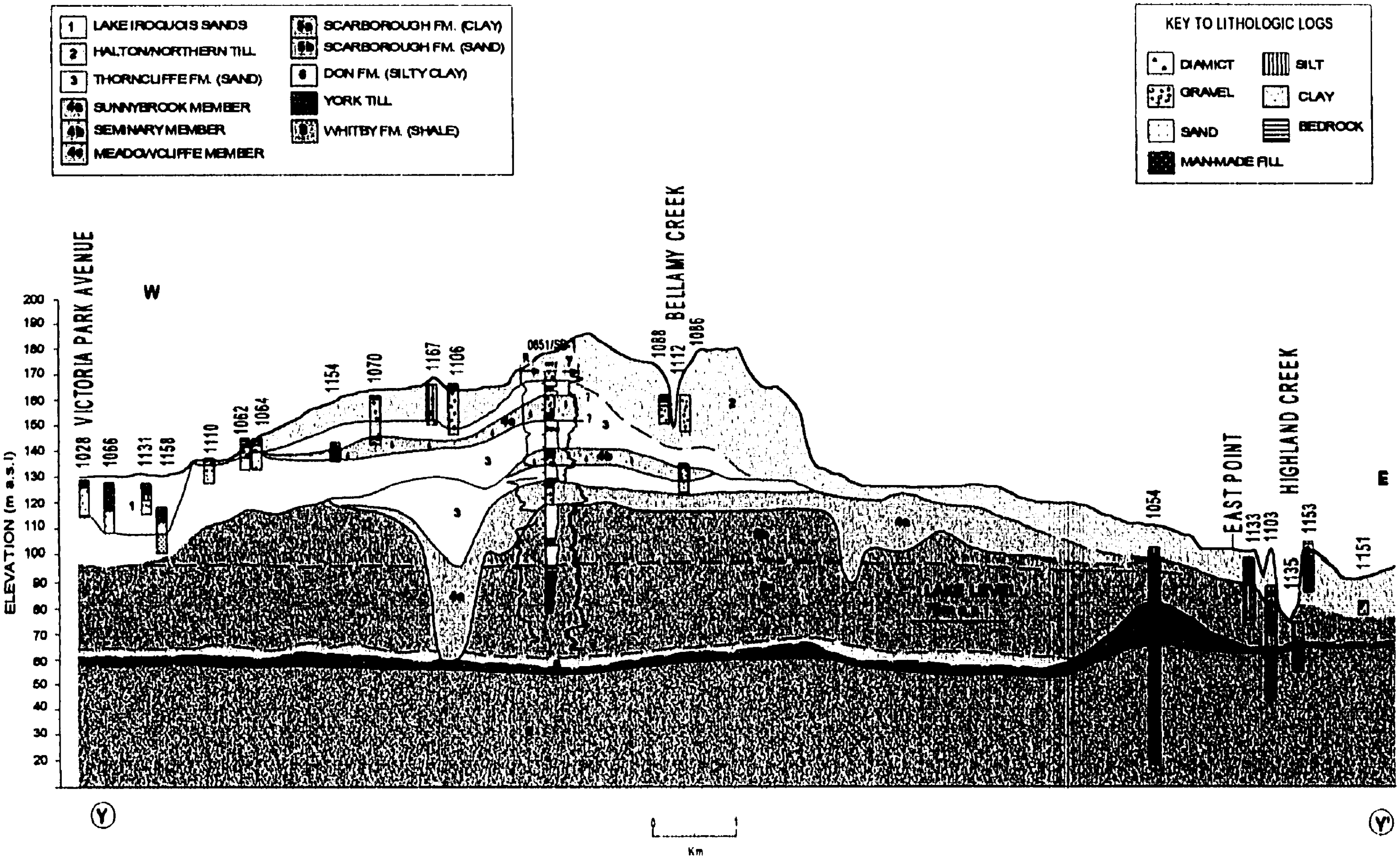


Figure 10. West-east geologic cross-section through the City of Scarborough (Y-Y' Fig. 2).

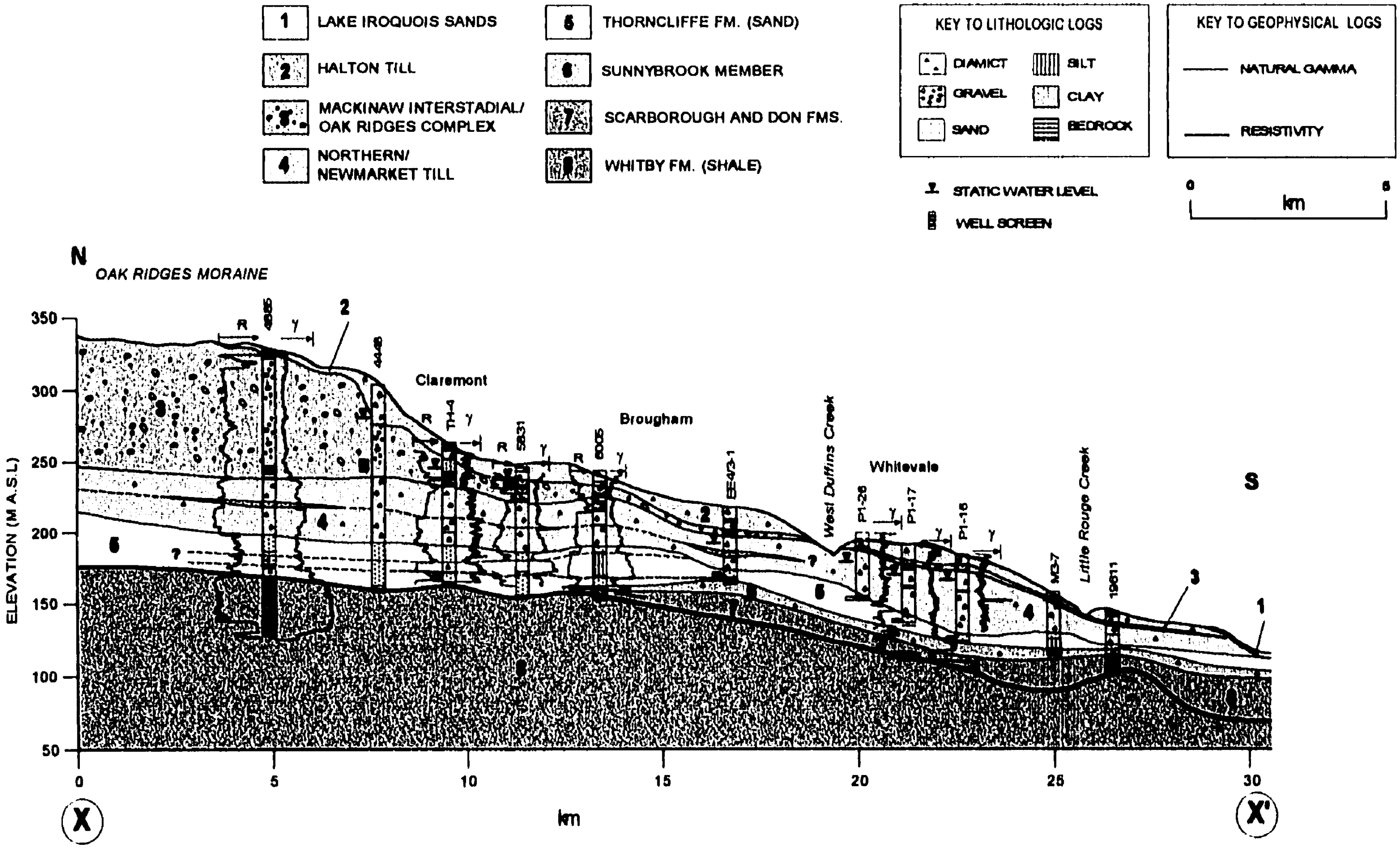


Figure 11. North-south stratigraphic cross-section (X-X' Fig. 2) showing subsurface geology of Rouge River-Highland Creek watershed (after Boyce, 1997).

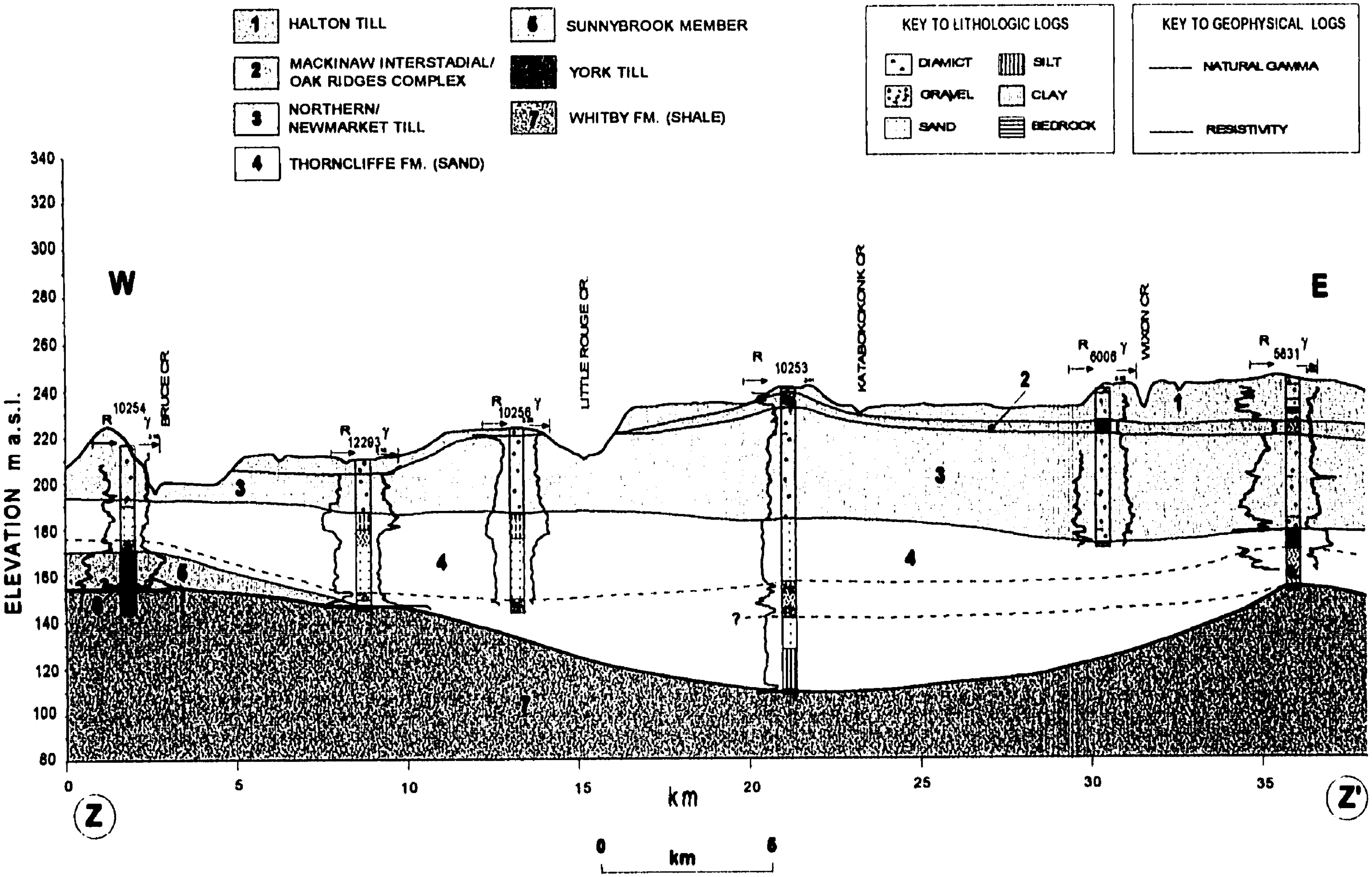


Figure 12. East-west stratigraphic cross-section (Z-Z' Fig. 2) showing subsurface geology of the Rouge River basin.

depositional segments; a lower silt to silty-clay diamict and an upper varved clay unit separated by a distinct contact. North of Stouffville, the Thorncliffe Formation rests directly on bedrock and passes into interbedded sand, gravel and diamict below the ORM (Figures 11 and 12). Fine-grained strata (e.g., Sunnybrook) occur within the Thorncliffe Formation separating this unit into a Lower, Middle and Upper members. These fine grained strata (Seminary and Meadowcliffe), however, are pinched out further inland where the Thorncliffe Formation becomes a continuous unit to the southern part of the study area.

3.2.2 Late Wisconsin Nissouri Stadial

The next phase of deposition commenced just after 25,000 years ago and is recorded by the thick (up to 50 m) Northern Till. This was deposited below the southward-flowing Laurentide Ice Sheet as it expanded to cover all of southern Canada and the adjacent parts of the U.S. during the Nissouri Stadial (between 22-18,000 years ago; Karrow and Ochietti, 1989). The till can be traced in the subsurface across the entire study area and is exposed north of the ORM where it has been mapped as the Newmarket Till (Gwyn, 1972; Sharpe et al., 1994). The Northern Till is clearly exposed to the south, along the steep sidewalls of West Duffins Creek (east of the study area), where it has been described in detail by Boyce et al. (1995). The till is grey in colour, highly over-consolidated and very-poorly-sorted (composed of pebbles and boulders set in a sandy-silt matrix). This unit forms a regional aquitard separating the Upper and Middle Aquifer complexes. Boyce et al. (1995) identified the presence of sand and gravel beds within the till which, in addition to fractures, impart a bulk permeability that is greater than that indicated by laboratory investigations alone (M.M. Dillon Limited, 1990; Gerber and Howard, 1996; Boyce and Koseoglu, 1997). Most of the upper stratigraphy south of the Lake Iroquois shoreline has been eroded by wave action and fluvial dissection except within discrete paleo river channels where the Late Wisconsin tripartite sequence (Halton Till, Mackinaw Interstadial and Northern Till) has been selectively preserved.

3.2.3 Mackinaw Interstadial and Port Huron Stadial

A third phase of sedimentation resulted from northward retreat of the ice sheet margin during a brief 500-year ice-free interval (Mackinaw Interstadial; 13,800 to 13,500 years ago; Karrow and Ochietti, 1989). Extensive outwash sands and gravels were deposited across the South Slope area by meltwater rivers draining southward from the ice front. These deposits are thickest (up to 5 m) in the vicinity of the modern river valleys and likely record an ancestral drainage system very similar to that of the present day. After 13,300, ice readvanced into the area from the southeast and moved north depositing the Halton Till during the Port Huron Stadial (Karrow and Ochietti, 1989). Halton Till is primarily a sandy silt to silt till with a limited thickness of less than 15 m in the study area. The surface of the Halton Till forms a low relief till plain with undulating streamlined hills (drumlins). The ORM was deposited during this phase and results from the deposition of large volumes of outwash sediment in a lake ponded between ice flowing to the north and ice remaining to the north in the vicinity of Uxbridge. Large masses of ice were trapped in the lake, buried by sediment and, upon melting, produced many hundreds of kettle lakes (Carman, 1941).

As the ice margin retreated southward, downslope from the ORM, ice marginal lakes were ponded between the ice front and moraine. Glacial Lake Markham was ponded between the moraine and a west-east trending ice front that passes across the study area immediately north of Markham (Figure 13). This lake overflowed eastward through the Duffins Creek drainage basin. Deposits of Glacial Lake Markham form a broad belt in the northern part of the study area. These are thin, less than 5 m, deposits of laminated and massive silty-clays (Markham Clays) of restricted permeability that are extensively fractured (Westgate, 1979; Figure 13).

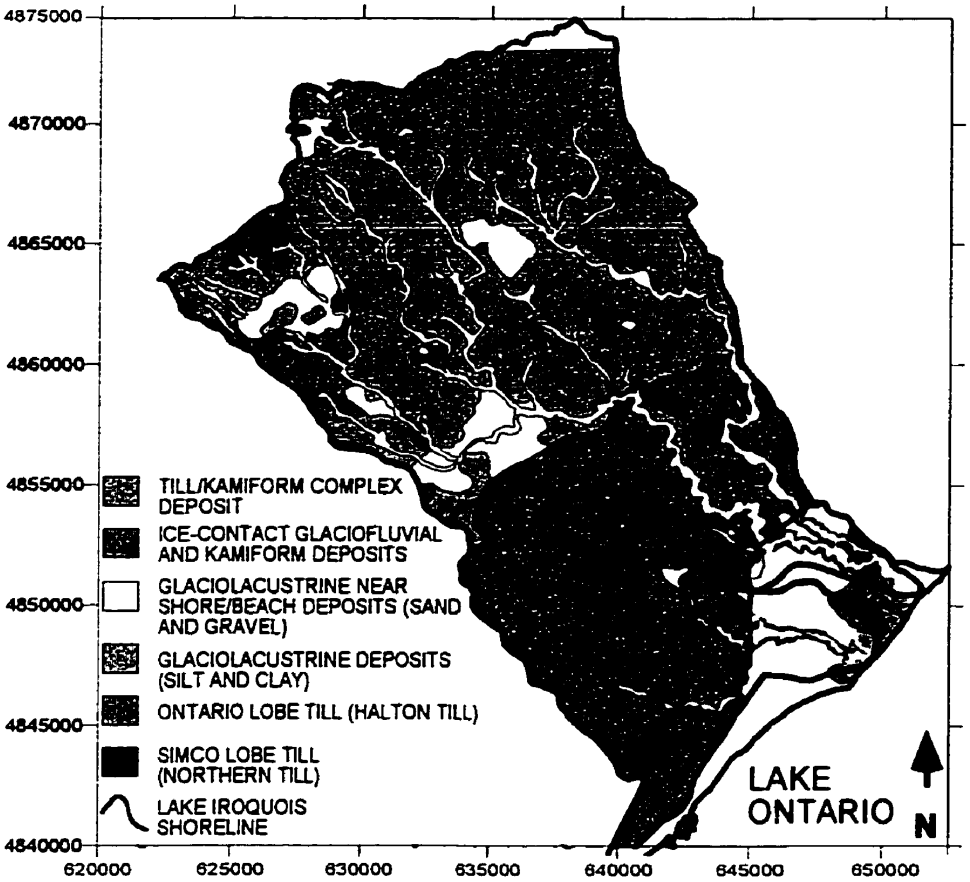


Figure 13. Surfacial geology of Rouge River River-Highland Creek watershed (after Westgate, 1979).

3.2.4 Postglacial Period

The final depositional phase commenced with south-eastward ice retreat from the study area at about 12,500 years ago, and the formation, once again, of a deep glacial lake (Lake Iroquois) dammed by ice remaining along the St. Lawrence River valley. A steep bluff, up to 35 m high, near the southern boundary of the RRHC watershed, divides the elevated Halton Till plain to the north from the flat Iroquois Lake plain to the south (Figure 5). The Northern Till has been eroded south of the bluff (Section 4.2.2.1; Figure 19A) and Iroquois lacustrine silts, sands and muds rest directly on sands of the Thorncliffe Formation. Many landfills occupy former gravel pits in Iroquois beach deposits (Figure 10).

With drainage of Lake Iroquois shortly after 12,300 years ago, the modern postglacial period began. At this time the St. Lawrence River valley was at a much lower elevation than at present as a result of loading of the Earth's crust by the ice sheet (glacio-isostatic depression). Sea-level was also lower and consequently, water levels fell in the Lake Ontario basin and much of the lake basin was exposed. Regional rivers were rejuvenated and cut down rapidly into the Pleistocene sediments creating steep-sided valleys. Commencing about 9000 years ago, through to the present day, slow uplift of the St. Lawrence River valley (glacio-isostatic rebound) has resulted in deepening of Lake Ontario, flooding of lower river valleys to form large lagoons (e.g., Frenchmans Bay) and the erosion of coastal bluffs (e.g., Scarborough Bluffs).

Finally, the last 150 years has seen European immigration, the clearance of an extensive forest cover from the ORM and South Slope area beginning in about 1840, resulting in rapid soil erosion and aggradation of sediment along regional river valleys (Howard et al., 1997).

4.0 HYDROSTRATIGRAPHY AND GROUNDWATER FLOW MODEL

The methodology involved in the conceptualization of the groundwater flow system utilized in the construction of the groundwater flow model is described in the following sections. A summary of the steps taken in developing the conceptual model is shown in Figure 14.

4.1 Previous Hydrogeological Studies

Previous regional groundwater studies by Sibul et al. (1977) and Ostry (1979) delineated and mapped the distribution of 14 separate aquifer systems in the study area. They also recognized the importance of the ORM in providing baseflow to headwaters of streams and as a source of recharge for deeper regional aquifers. Subsequent work by Howard and Beck (1986) showed a similarity in the hydrochemistry of groundwaters collected from shallow and deep aquifers which they argued was evidence of hydraulic interconnection and the existence of a regional groundwater flow system.

More recent work has focused on quantifying recharge inputs to aquifer systems and regional groundwater flow systems using water balance and numerical modeling methods (Smart, 1994; Gerber, 1994; Howard et al., 1997). Isotopic analysis of porewaters in Pleistocene sediments (Gerber and Howard, 1996) has also identified the presence of significant groundwater recharge through the regionally extensive Northern Till (Boyce et al., 1995), previously considered as an impervious aquitard restricting recharge to underlying aquifers (Sibul et al., 1977). A major objective of the present study was to better resolve the spatial distribution and geometry of aquifer and aquitard units within the study area and to identify their hydrogeologic function.

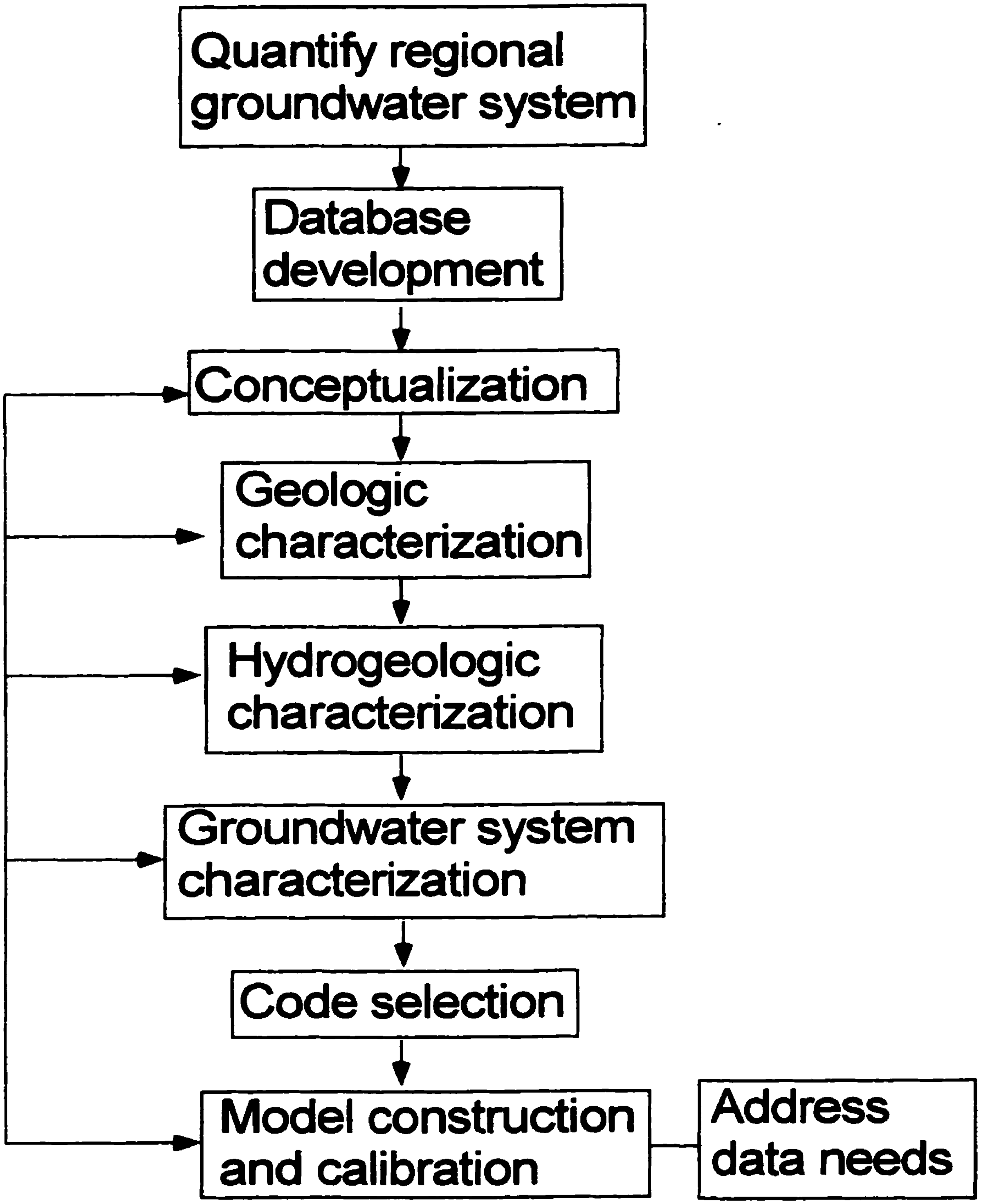


Figure 14. Methodology for groundwater flow model development.

4.2 Hydrostratigraphy and Hydrogeologic Function of Geologic Units

As noted above (Section 1.3), it is common practice to identify regional aquifer systems and aquitards by analysis of the depth to which water wells have been drilled and screened. In this study, the principal aquifer units were identified by a query of the digital water well database combined with knowledge of the elevations of the geologic units discussed below. Figure 3 shows histograms summarizing the well screen elevations of more than 5,500 water wells located in the study area. This analysis indicates the presence of three primary overburden aquifer systems within the study area, the Upper, Middle and Lower Aquifers (Figure 15).

Aquifers are developed in relatively coarse-grained outwash and lacustrine deposits and are confined by finer-grained till deposits (aquitards). Specific capacity distribution for these deposits in southern Ontario has been determined by the Ministry of Environment and Energy (1997) to be a useful index to describe the water-yielding characteristics of a well in a particular formation. In general, high specific capacities are indicative of high transmissivities and, consequently, high water yielding capabilities. Table 1 summarizes specific capacity distribution for glaciofluvial and glaciolacustrine deposits deposited in various parts of southern Ontario (MOEE, 1997). The following section describes the principal hydrostratigraphic units and their hydraulic parameters for the study area as summarized in Table 2.

4.2.1 Aquifer Units

4.2.1.1 Upper Aquifer

The Upper Aquifer system is developed in thick outwash sands and gravels of the ORM. The Upper Aquifer reaches a maximum thickness of > 90 m below the crest of the ridge and thins rapidly to < 15 m southward of the ORM flanks (Figure 16A). The histogram analysis of well screens reveals the aquifer to be present at elevations between 150-340 m a.s.l (Figure 3). The outwash deposits forming the core of the ridge are stratigraphically equivalent to, and in direct hydraulic communication with thin interstadial sands and gravels of the Mackinaw Interstadial which separates the Halton and Northern Tills to the south of the ORM. Upper Aquifer deposits have limited thickness (< 10 m) and extent in the southern portion of the study area (Figure 16A).

The Upper Aquifer is unconfined along the crest of the ORM and forms the principal groundwater recharge area for the South Slope region. South of the ORM, the Halton Till overlies the aquifer. Available data (Howard and Beck, 1986) indicates that the Halton Till is a fairly permeable unit. Outcrops of the till in the study area display a very sandy silt diamict with many clasts. The average hydraulic conductivity of this unit is reported to range from 10^{-9} to 10^{-5} m/s (Table 2). Howard and Beck (1986) provide evidence which suggests the occurrence of chemically young waters (i.e., tritiated and calcium bicarbonate in character) below the Halton Till, hence, indicating the relative permeable nature of this confining unit. Further chemical evidence reported by Kaye (1986) suggests that point source contamination south of Musselman Lake may also be a function of the secondary permeability of the confining unit. Higher permeable zones or 'windows' through the Halton Till are a major factor in the recharge of the Upper Aquifer on the southern flanks on the ORM. The Upper Aquifer is locally confined beneath the Glacial Lake Markham deposits where springs and flowing wells may occur. The Halton Till has an average thickness of about 15 m across the South Slope region, a more limited thickness of less than 5 m across most of the City of Scarborough and is absent south of the Lake Iroquois shoreline. The majority of wells in the ORM area are screened in the Upper Aquifer at elevations between 250 and 340 m a.s.l. (Figure 3).

The Upper Aquifer is characterized by relatively high hydraulic conductivity values (up to 8 x 10^{-5} m/s; Table 2). Domestic well yields of up to 4 L/s are commonly obtained in the Upper Aquifer within the ORM (Sibul et al., 1977). The aquifer also supports a number of high capacity wells (up to 53 L/s) for the communities of Oak Ridges and Stouffville. Although it is at relatively shallow depth (< 30 m), the Upper Aquifer is not widely utilized for groundwater abstraction on the South Slope region because of its restricted thickness and susceptibility to contamination by surface-related pollutants (road salts, pesticides, etc.; see Eyles and Howard 1988) (Sibul et al., 1977).

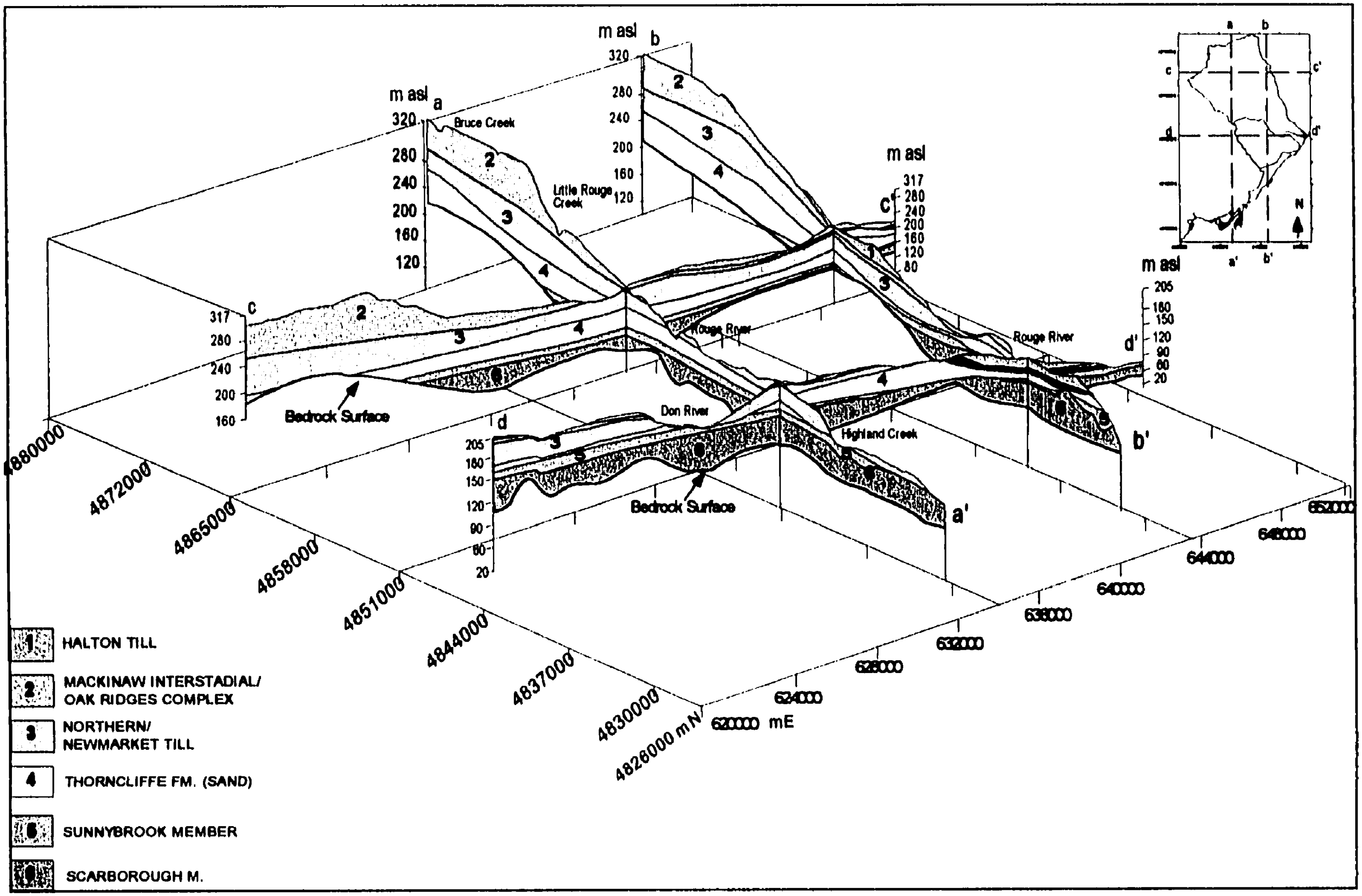


Figure 15. Fence diagram showing hydrostratigraphy of RRHC watershed.

Table 1. Specific capacity distribution for glaciofluvial and glaciolacustrine sediments deposited in various parts of southern Ontario (MOEE, 1997)

	Specific Capacity (m^2/d)				
	Min	10 Percentile	Geometric Mean	90 Percentile	Max
Ice-contact deposits (i.e., eskers, kames, interlobate morains) n=5628	1.0E-01	1.9	8.6	5.4E+01	7.8E+03
Outwash deposits (predominantly sands and gravels) n=3341	1.7E-01	2.7	1.5E+01	1.1E+02	6.9E+03
Sands and gravels of glaciolacustrine origin n=8025	9.0E-02	1.7	1.0E+01	7.2E+01	3.2E+03
Silts and clays of glaciolacustrine origin n=4376	9.0E-02	1.6	1.1E+01	7.2E+01	3.4E+03

Table 2. Summary of the stratigraphy, hydrostratigraphy and hydrogeologic characteristics for Aquifer/Aquitard units identified in the RRHC watershed. Modified from Howard and Gerber, 1997, and Eyles et al., 1996.

Stratigraphic Unit	**Age (Yrs)**	Lithology	**Thickness (m)**	**Hydraulic Conductivity K(m/s)**		**Porosity (n%)**		**Hydrostratigraphic Unit**	**Model Layer**
				Min	**Max**	**Min**	**Max**		
Lake Iroquois Deposits	<12,500	Beach sands and gravels Lacustrine silt and clay	<5	1E-07	2E-05	35		Local Aquifer/Aquitard	1
Lake Markham deposits	< 13,000	Clay, silts and sands	<5						
Halton Till	<13,000	Silty/Sandy till, sand and gravel lenses	<25	2E-09	2E-05	30			
Oak Ridges Aquifer Complex	13,3 - <13,000	Sand and gravel outwash	<100	1E-05	8E-05			Upper Aquifer	2
Mackinaw Interstadial	13.5-13,000	Fluvial gravel with lacustrine silt and clay.	<15	3E-08	5E-04				
Northern Till	< 20,000	Silt till with sand lenses	<60	7E-10	3E-09	2	20	Upper Aquitard	3
Thorncliffe Formation	c. 45,000	Glaciolacustrine silty clay and sand.	<40	1E-08	3E-04	30		Middle Aquifer	4
Sunnybrook Member		Clayey silt massive and laminated with pebbles.	<20	1E-09	4E-07	20		Middle Aquitard	5
Scarborough Formation Don Formation	c. 60,000 c. 80,000	Deltaic sands and lacustrine deposits of silts and clays. Interglacial lacustrine clay and sand.	<40	2E-08	2E-04	30		Lower Aquifer	6
York Till/Basal Gravel Complex	135,000	Sandy till, sand and gravel.	<5					Local Aquitard/Aquifer	
Whitby Formation (Bedrock)	Late Ordovician	Black fractured/weathered shale						Lower Aquitard (Regional Aquitard/Aquifer)	7

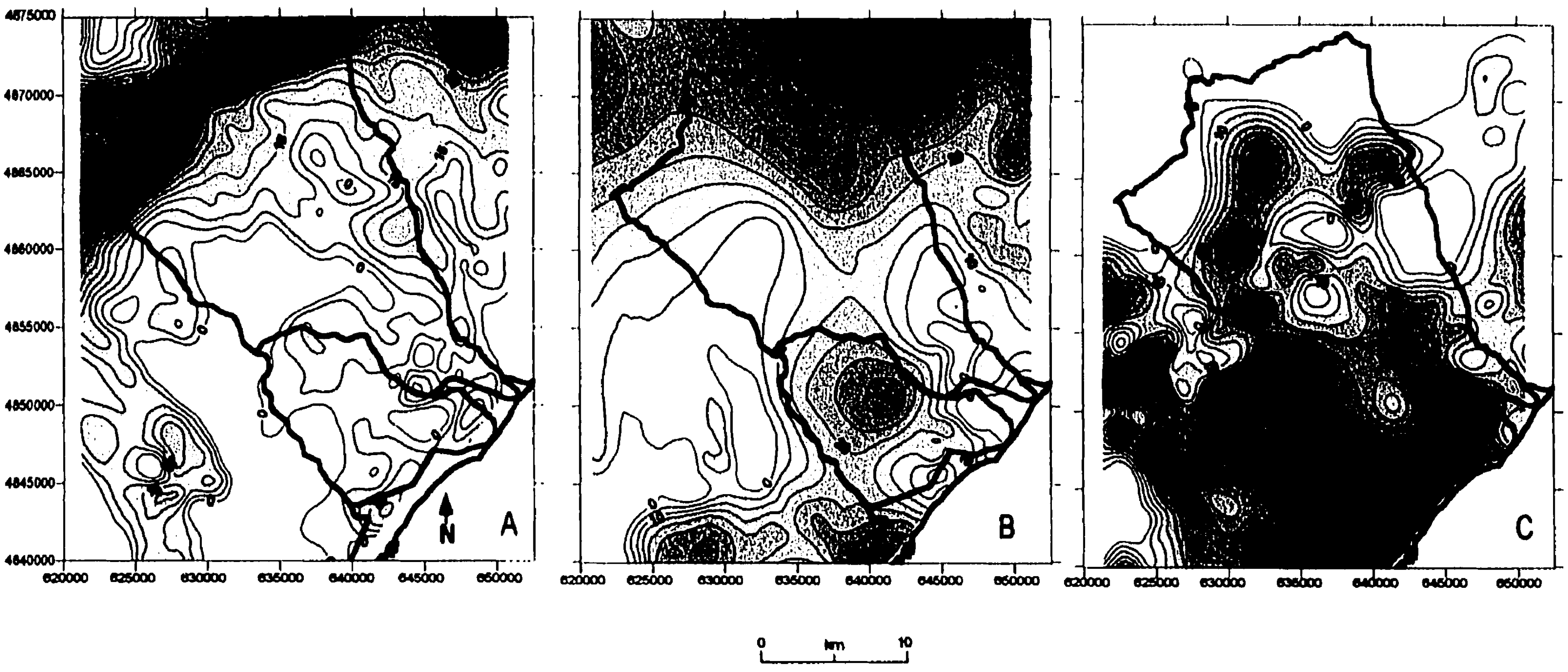


Figure 16. Isopachs of the Top (A), Middle (B) and Bottom Aquifers. Contour interval 5 m.

4.2.1.2 Middle Aquifer

The Middle Aquifer within the study area consists of a thick sequence (up to 55 m; Figure 16B) of glaciolacustrine silt, sand (Thorncliffe Formation) and fluvial gravels (Figures 15 and 16B). In the vicinity of RRHC watershed, the Middle Aquifer is defined by wells screened at elevations between 120 and 180 m a.s.l. (Figure 3). The aquifer is confined regionally by the overlying Northern Till (Upper Aquitard). Unconfined conditions occur locally along the Lake Iroquois shoreline where the overlying stratigraphy has been removed by erosion. The isopach map of the Middle Aquifer (Figure 16B) shows that the aquifer generally decreases in thickness to the south, with the exception of bedrock lows where most of the Pleistocene stratigraphy has been selectively preserved..

This Aquifer is the primary source of groundwater for wells on the South Slope as identified by Sibul et al. (1977), particularly in the City of Scarborough (Figure 3). The aquifer has a wide range of hydraulic conductivity values (1×10^{-8} to 3×10^{-4} m/s; Table 2) reflecting the sedimentologic variability of the Thorncliffe Formation. Well yields are, as a result, variable but are generally adequate for the requirements of domestic wells (Sibul et al., 1977). Groundwater discharge, in the form of springs, at the terminus of this aquifer is an important factor in the pervasive erosion of the Scarborough Bluffs.

4.2.1.3 Lower Aquifer

The Lower Aquifer consists of a number of separate but hydraulically interconnected water-bearing geologic units. These include deltaic sands, silts and thin fluvial gravels of the Scarborough Formation, gravels, sands, silts and clays of the Don Formation and the fractured and weathered upper surface of shale bedrock (Whitby Formation). The Lower Aquifer has a restricted extent in the subsurface and is constrained to bedrock valleys occurring below 160 m a.s.l. (Figure 17C). The aquifer is confined across this area by the Sunnybrook Diamict (Middle Aquitard; section 4.2.2.2).

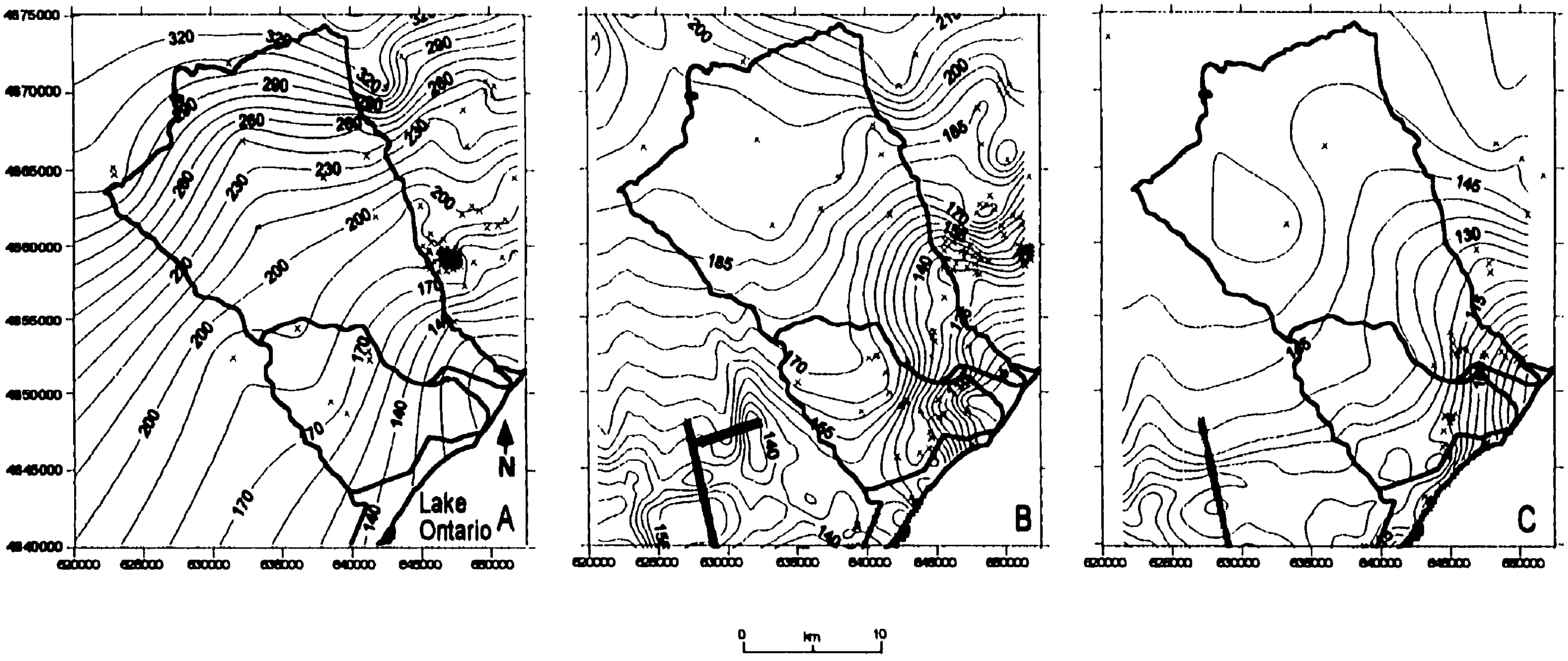


Figure 17. Contoured upper surface of the Upper Aquifer (A, contour interval 10m), Middle Aquifer (B, contour interval 5m) and Bottom Aquifer (C, contour interval 5m).

The Lower Aquifer reaches a maximum thickness within the study area of over 40 m in a bedrock valley underlying the Rouge River (Figure 16C). Thick Lower Aquifer deposits also occur in a bedrock valley underlying East Don (60 m) and Humber Rivers in the south-west corner of the study area (Figure 16C).

The bulk hydraulic properties of the Lower Aquifer are not well understood due to a lack of deep borehole information. Reported values of hydraulic conductivity for the deltaic deposits (Scarborough Formation) which constitute a significant stratigraphic thickness of this aquifer unit are in the range of 2×10^{-8} to 2×10^{-4} m/s. A relatively small number of wells (< 50) obtain groundwater supplies from the Lower Aquifer system (Figure 3).

4.2.2 Aquitard Units

4.2.2.1 Upper Aquitard

The Upper Aquitard consists of the dense silty Northern Till unit which has a wide regional extent in the subsurface of southern Ontario (Boyce et al., 1995). The aquitard separates the Upper and Middle Aquifer systems and reaches a maximum thickness of 50 m below the ORM (Figure 18). The upper surface of the aquitard generally conforms with the surface topographic contours (Figure 19A).

The Upper Aquitard is up to 10 m in thickness in the City of Scarborough except where it has been removed along the southern portion of the study area by erosion along the Iroquois shoreline (Figures 18 and 19A). In these areas, the Upper and Middle Aquifer systems are in direct hydraulic communication.

The Upper Aquitard is characterized by hydraulic conductivities which range over several orders of magnitude (Table 2). This reflects the presence of laterally extensive sand and gravel beds, boulder concentrations and fractures within the till providing pathways for groundwater flow (Boyce et al., 1995; Gerber and Howard, 1996). The estimated bulk hydraulic conductivity for the Upper Aquitard ranges from 5×10^{-10} to 5×10^{-9} m/s (Gerber, 1998).

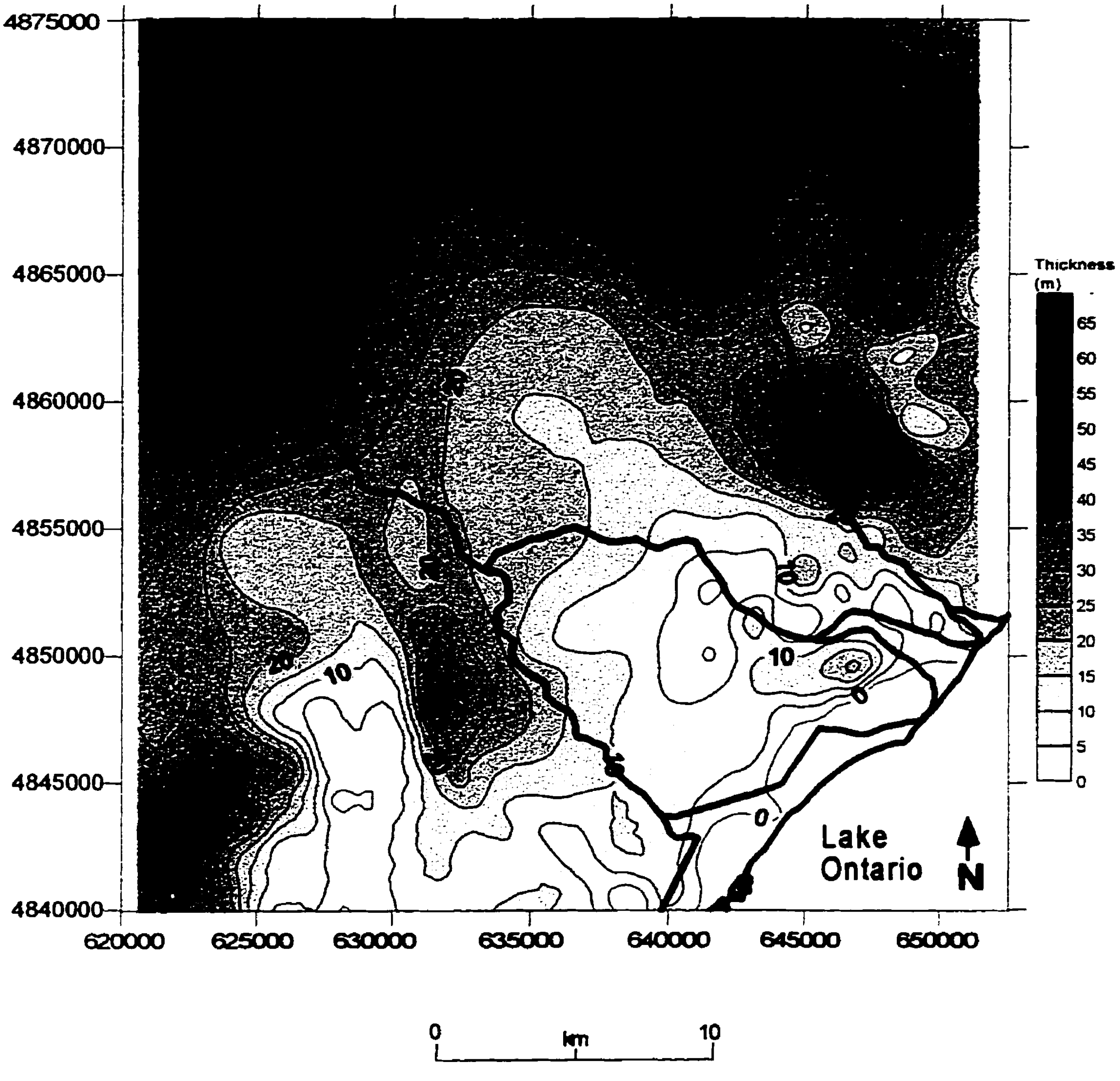


Figure 18. Isopach map of the Upper Aquitard (Northern Till). Contour interval 5 m.

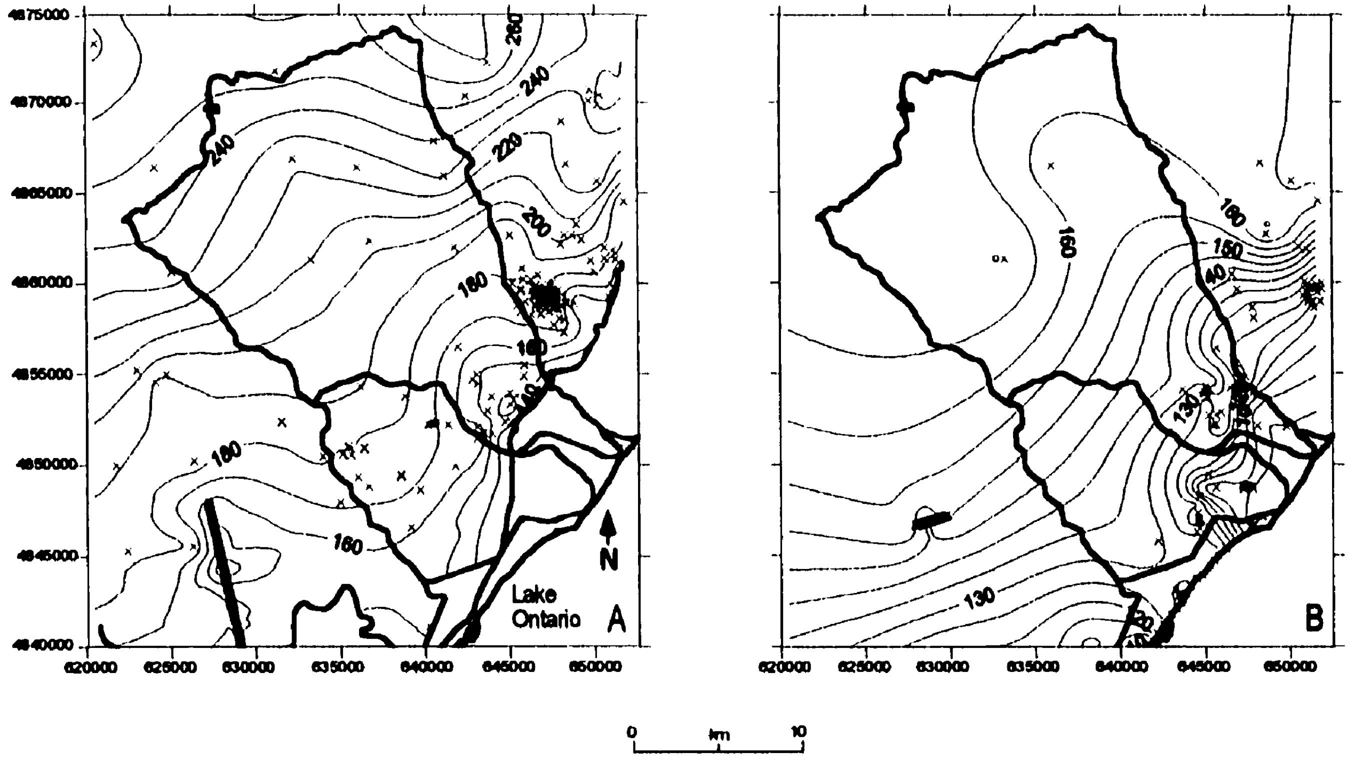


Figure 19. Contoured upper surface of the Upper Aquitard (A, contour interval 10m) and Middle Aquitard (B, contour interval 5m). Crosshairs show data location.

4.2.2.2 Middle Aquitard

The Middle Aquitard consists of fine-grained Sunnybrook Diamict and associated lacustrine silty clays. The aquitard has a maximum thickness of approximately10 m in the study area and confines the Lower Aquifer system over the southern half of the study region. The aquitard pinches out towards the north against the rising bedrock surface and is not found north of Stouffville (Figures 11 and 19B). Data, however, are not adequate to describe the exact spatial extent of the Sunnybrook Diamict.

The Middle Aquitard is of moderately low permeability ranging from 1×10^{-9} to 4×10^{-7} m/s (Table 2). Locally, the aquitard contains sand and gravel horizons up to several metres in thickness which provide potential pathways for more rapid groundwater movement. The movement of groundwater through the Lower Aquitard is also linked to pervasive fractures and jointing in the Sunnybrook Diamict (Eyles and Howard, 1988).

4.2.2.3 Lower (Bedrock) Aquitard

The Whitby Formation shales underlying the study area constitute a basal aquitard forming the lower impermeable boundary for the circulating fresh water. Locally, poorly transmissive zones are associated with the fractured and weathered upper surface of the bedrock. Bedrock groundwaters are commonly saline or sulphurous and are not suitable for drinking water purposes (Sibul et al., 1977).

4.3 Groundwater Flow System

4.3.1 Groundwater Flow Directions

In the RRHC drainage basin, groundwater flow is generally from north to south in the Upper Aquifer and northwest to southeast in the deeper aquifers, except in parts of the flow system where directions and hydraulic gradients are controlled by the streams or surface topography (Figure 20). ORM acts as the major recharge zone as well as the groundwater divide in the area, separating the Lake Ontario and Lake Simcoe basins (Howard et al., 1997). Groundwater and surface water flow both north and south from the ORM near the headwaters of the RRHC watershed (Figure 20). Flow directions in the Middle and Lower Aquifers are influenced by the discharge areas on the Scarborough Bluffs and in the major river valleys, Rouge River, Little Rouge Creek and Highland Creek to the north.

4.3.2 Potentiometric Surfaces and Flow Vectors

Static water level data from the water well dataset were used to develop regional maps of hydraulic head for the three aquifer systems. Initially, the water well records were sorted according to the hydrostratigraphic unit in which they were completed. The data were then used to map groundwater flow directions for the study area. Flow vectors having lengths proportional to hydraulic gradients were derived in SURFER (Golden Software Inc., 1996) by manipulation of interpolated horizontal gradient data. The algorithm used calculates the first derivative of the interpolated hydraulic head at a grid node (i.e., along the direction of maximum local gradient) to obtain the direction and magnitude of flow vectors.

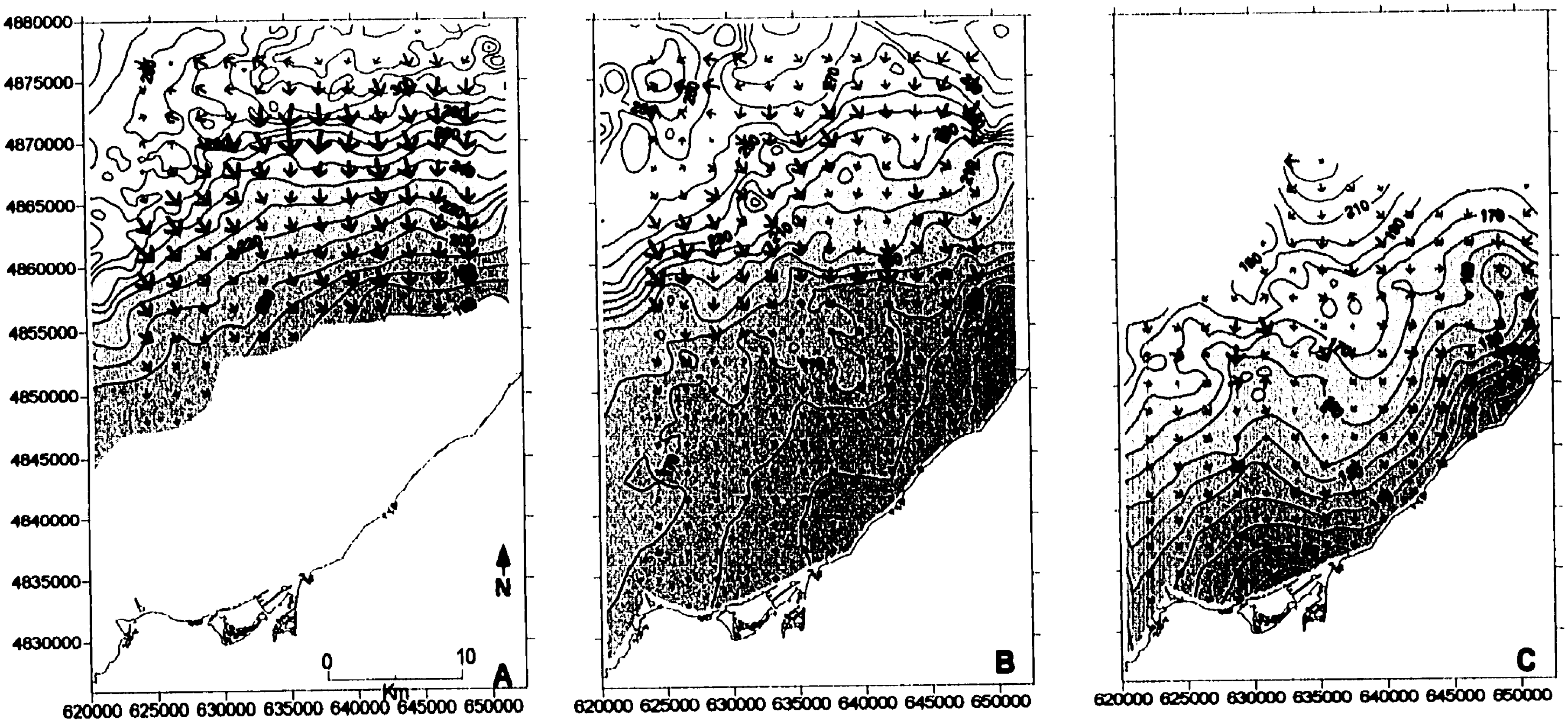


Figure 20. Contoured hydraulic heads and groundwater flow directions for A. Upper Aquifer, B. Middle Aquifer C. Lower Aquifer.

4.3.2.1 Upper Aquifer

Contoured hydraulic head and groundwater flow directions for the Upper Aquifer are shown on Figure 20A prepared from MOEE well records. The regional direction of groundwater flow is generally from north to south at a horizontal hydraulic gradient of 0.01. Local deflections occur towards creeks where horizontal groundwater flow gradients increase towards Rouge River and Little Rouge River as shown in Figure 20A. Surface drainage basin divides approximate groundwater flow divides for the Upper Aquifer. The contour map of the hydraulic head closely parallels that of the surface topography and demonstrates the presence of a groundwater flow divide within the Upper Aquifer along the height of the land forming the crest of the ORM.

Groundwater flow within the Upper Aquifer is predominantly horizontal, but local upward vertical gradients exist (confined conditions) where the overlying Halton Till and Glacial Lake Markham deposits are of sufficiently low hydraulic conductivity (Gerber, 1998). The average horizontal flow velocity is estimated at 30 m/a, assuming an average horizontal hydraulic conductivity (K_h) of 3×10^{-5} m/s, a horizontal gradient (i_h) of 0.01 and a porosity of 0.30.

4.3.2.2 Middle Aquifer

Groundwater flow within the Middle Aquifer is predominantly horizontal towards the south at a regional i_h of approximately 0.008 (Figure 20B). Higher horizontal gradients (0.01) occur where the Thorncliffe Formation deposits pinch out beneath the Northern Till near discharge zones to rivers. The average horizontal flow velocity is estimated at < 10 m/a assuming an average K_h of 1×10^{-5} m/s, an i_h of 0.008 and a porosity of 0.30.

Groundwater enters the RRHC drainage basin along the northern boundary. Doming of the static water level across the northern part of the study area, beneath the ORM, suggests the continuance of a groundwater drainage divide within the Middle Aquifer (Boyce, 1997). Groundwater within the Middle Aquifer system also flows towards the southeast into the Rouge River and Highland Creek drainage basin (Figure 20B). Local deflections occur in areas where the Thorncliffe Formation deposits pinch out beneath the Northern Till. Evaluation of the groundwater flow directions within the Middle Aquifer south of the Town of Markham is difficult due to a limited number of water wells completed within the Thorncliffe Formation.

4.3.2.3 Lower Aquifer

Groundwater flow directions within the Lower Aquifer are towards the southeast at a regional gradient of approximately 0.005 (Figure 20C). Flow directions deflect towards the Rouge River and Little Rouge Creek valleys and horizontal gradients increase where these flow deflections occur. While the Lower Aquifer system is separate from the Middle Aquifer, the Lower Aquifer likely converges with the Middle Aquifer to the north, where the Middle Aquitard (Sunnybrook Diamict) is absent (Figures 11 and 12). The average horizontal flow velocity in the Lower Aquifer is on the order of 1 m/a assuming a K_h of $2X10^{-6}$ m/s, an i_h of 0.005 and a porosity of 0.30.

Groundwater flow between drainage basins is also expected to occur within the Lower Aquifer but is difficult to specifically address at present due to a lack of reliable deep stratigraphic and hydrogeologic data for the RRHC drainage basin.

4.3.3 Groundwater Recharge/Discharge

A map showing areal distribution of groundwater recharge and discharge (vertical gradient) from the Upper Aquifer was prepared by calculating the difference between ground surface elevation and the water table elevation (Figure 21). The analysis involved production of a water table map by interpolation of river elevations and water levels in shallow wells of less than 10 m deep across the study area (Figure 22). Groundwater recharge through downward vertical gradient) is represented by positive head difference, while a negative head difference represents areas of groundwater discharge (i.e., upward vertical gradient).

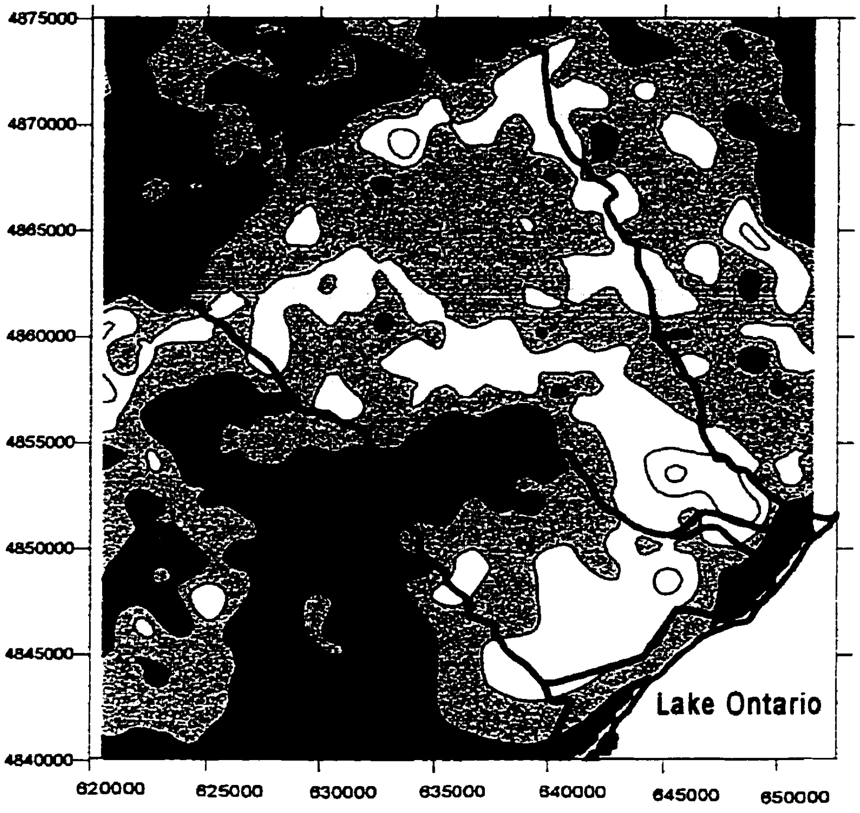


Figure 21. Discharge and recharge zones within RRHC watershed. Blue and yellow colours illustrate recharge and discharge zones respectively.

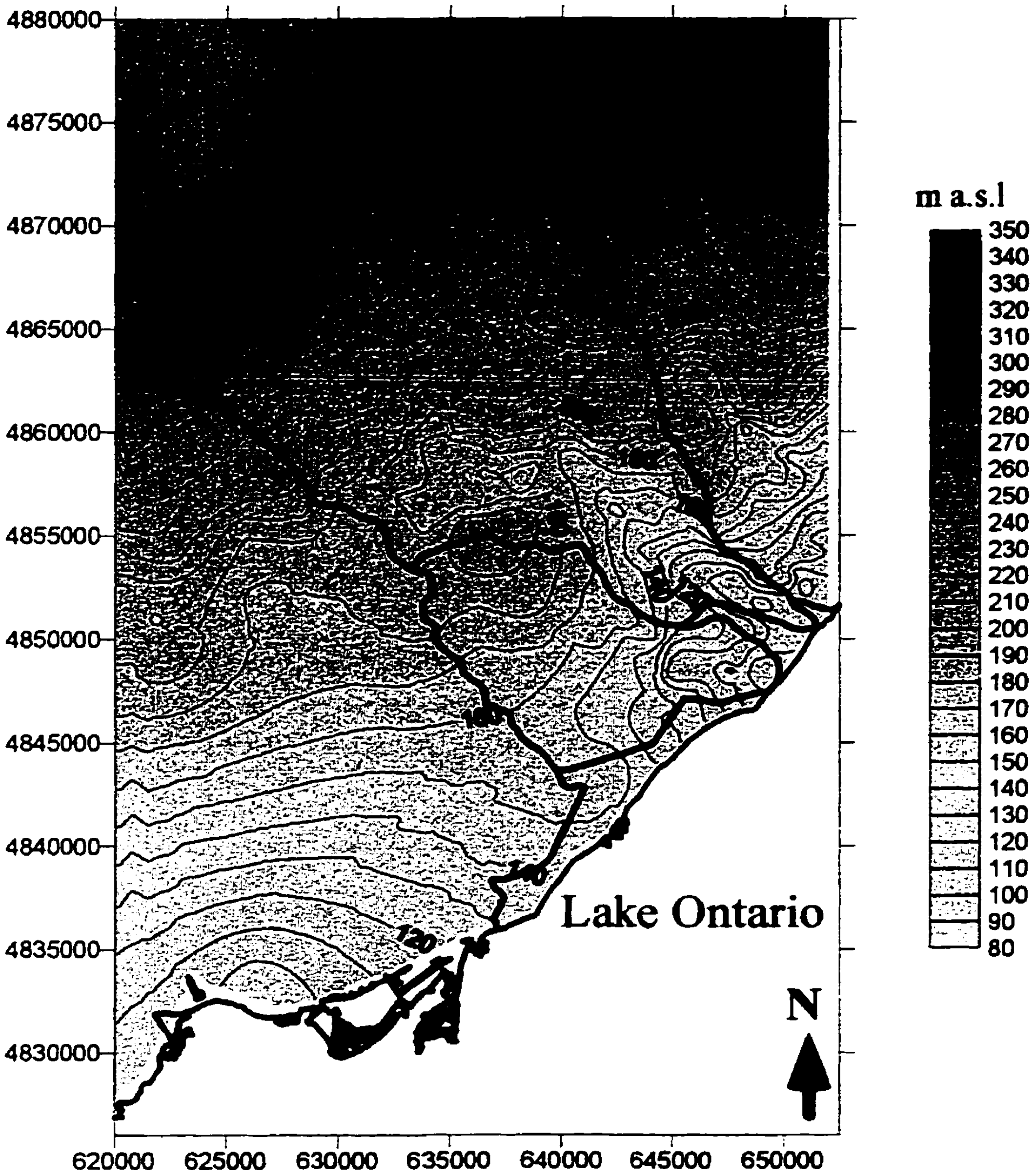


Figure 22. Contoured map of the water table for the RRHC watershed. Contour interval 10 m.

Groundwater recharge and discharge zones are closely related to topography and surficial geology. The upland areas of the ORM form a recharge area with recharge rates ranging from 300 to 400 mm/a (Gerber, 1994). These rates have been verified by Smart (1994) and Gerber (1998). Groundwater recharge to the Upper Aquifer also occurs over the Halton Till plain with rates of approximately 130 mm/a (Gerber, 1994; Gerber, 1998).

Groundwater discharge from the Upper Aquifer occurs at the break in topographic slope along the south flank of the ORM. This discharge forms the headwaters for the various creeks shown on Figure 7. Groundwater discharge from the Upper Aquifer occurs to local creeks away from the ORM flank and forms seeps along the margins of deeply incised valleys in the Rouge River drainage basin. Groundwater discharge in the form of springs also occurs where glacial Lake Markham deposits confine underlying Mackinaw Interstadial deposits which are recharged by, and are in hydraulic connection with, the Upper Aquifer system along the ORM crest.

The Middle Aquifer is recharged by inter-aquifer flow in the subsurface and also by downward vertical leakage through the overlying Northern Till (Upper Aquitard) from the Upper Aquifer. Vertical hydraulic gradients downwards through the Northern Till range from 0.4 east of the study area in the northern part of the Duffins Creek basin and increase to approximately 0.8 downwards over the RRHC watershed (Gerber and Howard, 1996; IWA Ltd., 1994a,b). Over the southern part of the RRHC watershed, the Middle Aquifer is also recharged by vertical leakage upwards from the Lower Aquifer through the Middle Aquitard (Sunnybrook Diamict).

The Lower Aquifer is recharged by inter-aquifer groundwater flow entering the basin in the subsurface and discharges within the stream valleys and to Lake Ontario (Gerber, 1998). Minor recharge from the Middle Aquifer may result from leakage through the Middle Aquitard (Gerber, 1998).

Direct discharge of groundwater into Lake Ontario was identified by Haefeli (1972). Direct groundwater discharge into Lake Ontario for RRHC watershed was calculated to be approximately 700 m^3/d using estimates of mean transmissivity for the Rouge River drainage basin, flow system width (i.e., length of the shoreline in study area) and a hydraulic gradient value of 0.0111 (Haefeli, 1972).

5.0 NUMERICAL MODEL OF GROUNDWATER FLOW

5.1 Model Structure

Groundwater flow in the study area was simulated using Visual MODFLOW (v. 2.60; Waterloo Hydrogeologic Software Inc., 1996) a commercially enhanced version of MODFLOW available from the U.S. Geological Survey (McDonald and Harbaugh, 1988). MODFLOW was selected as the code because it is a well documented, extensively tested and verified model (Anderson and Woessner, 1992) which can be readily incorporated into future studies for optimal groundwater management. The block-centered, modular three-dimensional finite difference code simulates steady-state and transient groundwater flow in confined, leaky confined, unconfined and mixed aquifer systems (Anderson and Woessner, 1992). MODFLOW can determine groundwater head distribution in space and time and calculate fluxes across cell boundaries. The modeling program has distinct subroutines (modules) to simulate the effects of rivers, drains, and boundaries. The WHS (WHSSOLV) solver was chosen as the method of matrix solution for all model runs with a convergence criteria of 0.001 m.

5.2 Discretization

The finite difference grid is homogenous with blocks or cells measuring 250 m on each side (Figure 23). The number of active block centered cells (nodes) in the model is 8,100. There are more than 1,000 active flow cells in each layer of the model. The model is set up with seven layers representing the three aquifers and three aquitards including the basal aquitard (bedrock) of the hydrogeologic system. An additional layer representing the upper surface of the bedrock (top 5 m), was set up to simulate groundwater flow within this higher transmissive zone.

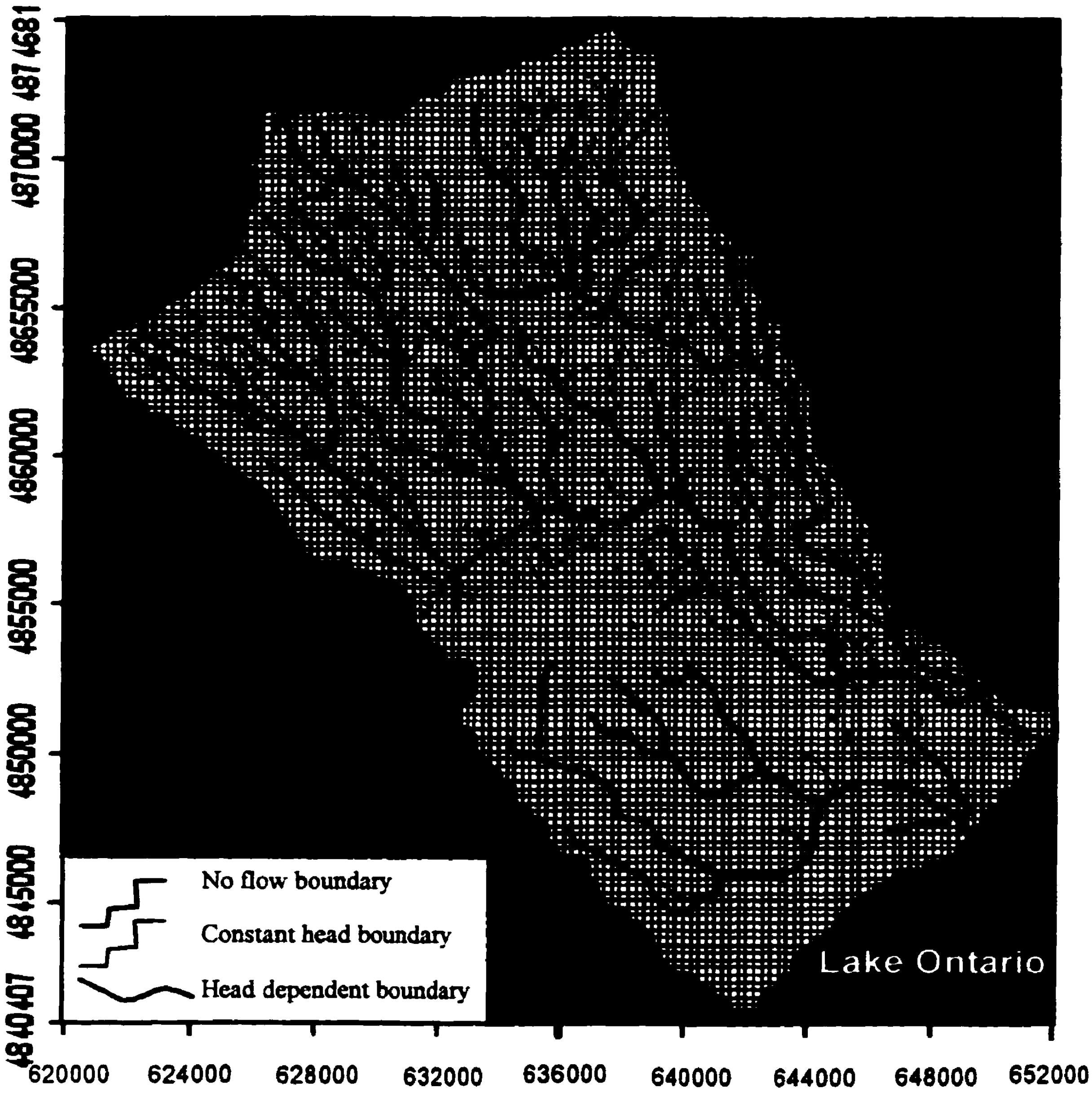


Figure 23. Finite difference grid and boundary conditions.

5.3 Model Inputs

The model inputs include hydrogeologic parameters, recharge, river characteristics and boundary conditions. Table 2 summarizes the hydrogeologic characteristics of the aquifer/aquitard units identified in the RRHC watershed. The parameters with greatest uncertainty in the regional model were the components of hydraulic conductivity (K_x, K_y) and Recharge (R).

5.3.1 Hydrogeologic Parameters

Hydraulic conductivity estimates from previous studies (Howard and Gerber, 1997; Boyce, 1997; Gerber and Howard, 1996 and Eyles et al., 1996) were applied to the model domain in broad zones and were subsequently modified within observed ranges during the trial and error calibration. Hydraulic conductivity (K) is assumed to be constant within each lithologically defined zone with the exception of small variations which were made in order to more effectively simulate flow direction. Anisotropy for all model layers was represented by assigning to the vertical component of hydraulic conductivity (K_z) a value one order of magnitude less than horizontal components of hydraulic conductivity (K_x, K_y). For example, $K_z = 1/10$ (K_x, K_y), where $K_x = K_y$ (Gerber, 1998) (Table 3). Porosity , specific yield and storage coefficients are constant across the lithologic zones.

5.3.2 Areal Recharge

Recharge in the study area is from direct precipitation infiltration. MODFLOW's recharge package simulates areally distributed recharge to the groundwater flow system. Seven different zones of recharge were applied to the uppermost active cells in the grid based on geologic characteristics and urban cover (Figures 6 and 13). Recharge estimates were initially based on previous water balance studies by Gerber (1994) and Gerber and Howard (1997) and were subsequently revised within acceptable limits during the calibration. A recharge rate of 335 mm/a to 400 mm/a was applied to the ORM deposits, while lower recharge rates ranging from 35 mm/a to 200 mm/a were applied to represent infiltration through various geologic units and urban cover south of the ORM (Table 4). A recharge of zero was assigned to nodes along the streams where vertical flow component is predominantly upward. Recharge data for urbanized regions is not well known, therefore, urban recharge was treated as a variable in the groundwater model and was estimated during calibration.

5.4 Boundary Conditions

Model boundaries for the RRHC watershed are shown in Figure 23. The boundaries are assigned to define the active portion of the model domain and to simulate natural influences on the groundwater flow system.

5.4.1 Specified Head Boundary

On the basis that the area adjoins Lake Ontario, the relevant boundary cells were assigned constant heads of 75 masl, (i.e., the mean annual water level of Lake Ontario).

5.4.2 No Flow Boundary

Boundary cells designated as 'no flow' (i.e., where no flow enters or escapes the active part of the model domain) were excluded from the head calculations. Based on the direction of regional groundwater flow (Figure 20) and results of previous model studies completed for the neighboring watersheds (Gerber, 1998 and Smart, 1994) net lateral inflow/outflow to middle and lower aquifer systems in the study area is considered to be negligible. Primarily, no flow

Table 3. **Calibrated Hydraulic conductivity of lithologic zones in the groundwater model.**

Lithology	Field Measurement K (m/s)	Final Calibrated (m/s)	
		K_h	K_v
Sands and gravels, lacustrine silt and clay	1E-07 to 2E-05	5E-07 to 2E-05	5E-08 to 2E-06
Clay, silts and sands	N/A	5E-07 to 2E-05	5E-08 to 2E-06
Silty/sandy till, sand and gravel lenses	2E-09 to 2E-05	9E-06	9E-07
Sand and gravel outwash, fluvial gravel with lacustrine silt and clay	1E-05 to 8E-05	1E-05 to 4E-05	1E-06 to 4E-06
Silt till with sand lenses	7E-10 to 3E-09	4E-09	4E-10
Silty clay and sand	1E-08 to 3E-04	2E-07 to 2E-05	2E-08 to 2E-06
Clayey silt, massive	1E-09 to 4E-07	1E-09	1E-10
Deltaic sands, lacustrine silt and clay	2E-08 to 2E-04	4E-05	4E-06
Shale	N/A	1E-11	1E-12

Table 4. Calibrated recharge values for various zones in the groundwater model (mm/year).

ORMC	335 - 400
Halton Till	150 - 200
Lake Markham Sands	200
Lake Markham Clays	35
Lake Iroquois Sands	200
Urban Cover	50
River Nodes	0

boundaries for the three aquifer systems were placed along flow lines representing their eastern and western margins. Subsequently, the no flow boundary assigned to layer 4 (Middle Aquifer) was modified along the western and eastern borders where lateral flow to and from adjacent aquifers is believed to occur (Section 5.4.4). The northern boundary behaves as a groundwater divide for all three aquifers and is appropriately treated as 'no flow'.

5.4.3 River Boundary

River boundaries simulate the effects of flow between surface waters and groundwater systems. River nodes are assigned to stream reaches and stream aquifer seepage is simulated for each model cell containing a river node. In the study area, outflow from the aquifer systems is due to groundwater seepage to surface water features. The interaction between streamflow and groundwater seepage is governed by the conductance of the stream bed and the head gradient between the river and the aquifer system.

The conductance term is a function of the length and the width of the stream reach, and of the thickness and hydraulic conductivity of the stream bed. River width and elevation were approximated from 1:50000 topographical map (Energy, Mines and Resources, 1985). Stream bed thickness was arbitrarily set at 1 m (Gerber, 1998) and stream bed conductivity was assigned the K value of the lithologic zone the river node occurred in. Stream bed conductance was further subject to calibration. An interpreted program written in Perl was developed to facilitate subsequent modifications to the river conductance values during the calibration process.

5.4.4 General Head Boundary (GHB)

Head dependent flux boundaries are used to simulate lateral flow from the western and eastern margins of the Middle Aquifer into and out of the study area. The data required are specified head values interpolated from the potentiometric map of the aquifer system (Figure 20B) and conductance values. The flow across this boundary is a measure of the difference between simulated head and assigned head, and the ease with which water is allowed to flow across the boundary, as determined by the conductance value. Estimates of the conductance terms were refined during calibration of the groundwater model.

5.4.5 Drain Boundary

A drain boundary was used to simulate flow where the aquifer systems discharge into steep river valleys above the elevation of the river stage and along the topographic break at the Scarborough Bluffs. The data required are the same as for GHB, however, the flow across a drain boundary can only occur from the model domain to the drain. Thus, no water crosses the boundary if the specified head is greater than the model calculated head. Drain elevations were set at the base of the aquifer system and drain conductances were adjusted during calibration.

5.5 MODEL CALIBRATION

Model calibration, as practiced here, is a process by which finite difference equations (matrix equation) are iteratively solved following progressive changes of input parameters (single type at a time), in order to obtain an acceptable match between observed and computed heads and fluxes. This maintains consistency with prior information concerning measured/field parameters and departs as little as possible from the original conceptual model. Calibration was based on the following criteria (Samper-Calvete and Garcia-Vera, 1998):

1) Fitting of computed hydraulic heads with potentiometric surfaces of the three aquifer systems.
2) Consistency of computed baseflow values with existing estimates of lowest flow at three streamflow gauging stations present in the area.
3) Estimated values of hydraulic conductivity should be consistent with prior estimates of hydraulic conductivity from field tests (Table 2).
4) The spatial patterns of parameters should be consistent with available geologic information.

Steady-state flow conditions were assumed for the regional model on the basis of the following:

1) Monitoring well data was limited to 16 wells with records since 1981 (Figure 24). The short records mean that long term transient effects may not be observed.
2) Municipal abstraction is the largest stress to the regional groundwater flow system causing transient groundwater flow. These abstractions have increased steadily to supply a growing rural population. However, extensive abstractions have occurred since about 1960 and it is therefore assumed that regional water levels in the area have maintained a state of dynamic balance, with water levels fluctuating seasonally about a relatively constant average.

The numerical model was run to steady-state and was calibrated to point water level data, kriged heads and streamflow measurements.

5.5.1 Calibration Procedures

5.5.1.1 Groundwater Flow Levels

In trial-and-error calibration (Anderson and Woessner, 1992), computed and measured hydraulic head values are compared and model parameters are adjusted to improve the agreement between the two sets of values. The degree of agreement between the simulated and observed water levels is a measure of the head residuals. Analysis of the difference between measured and computed heads gives an indication as to the magnitude and location of parameter adjustment in order to minimize the difference.

A total of 5 shallow and 11 deep wells were selected where measured heads were considered sufficiently accurate for the steady-state calibration (MOEE and Toronto Region Conservation Authority). Due to the small number of monitoring wells in the area, and with the objective to gain a better insight to the trend of head differences, the model generated hydraulic head distributions were compared to contour plots of hydraulic head distributions determined from the MOEE water well head data. Data analyses by Christenson et al., 1998 indicate that small variations in head, due to factors such as heterogeneity or partial penetration wells, may

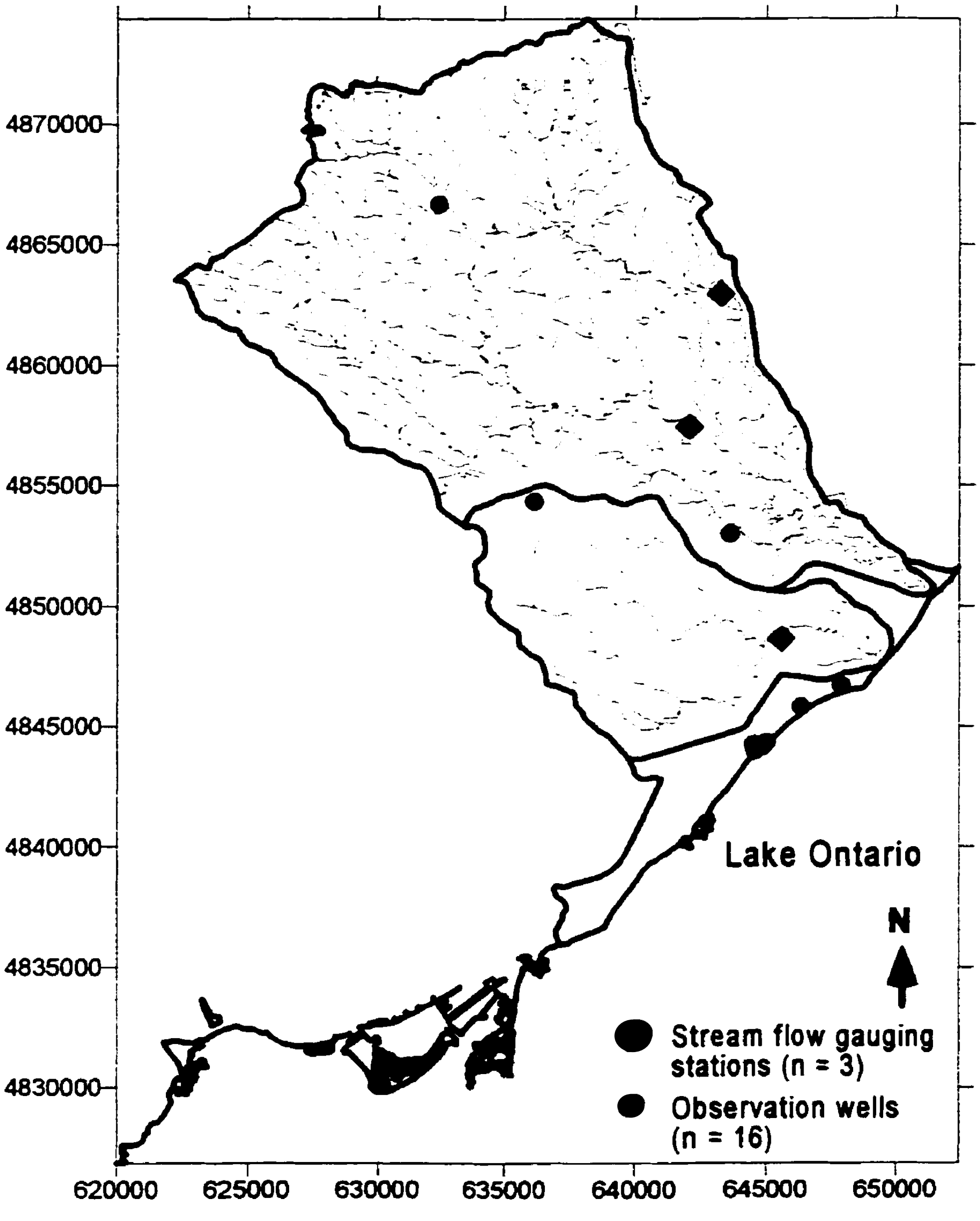


Figure 24. Map showing location of observation wells and streamflow gauging stations in RRHC watershed.

dominate over the measurement error found in the water well records. Thus, using the MOEE water well head data for model calibration on a regional scale should not significantly affect the calibration results.

Comparison of the model calculated hydraulic heads to the gridded potentiometric maps was done separately for each aquifer system in SURFER. Subsequently, the error values were contoured yielding better insight to the trend of the residuals. Negative head residuals indicate simulated water levels are lower than the observed. In this case, either the hydraulic conductivity was decreased or recharge was increased. Positive head residuals were treated conversely. Most of the calibration fits illustrated in Figures 25-27 were reasonable given the uncertainties in data quality. The difference between the calibrated heads and contoured maps of field data was generally within ±10 m for all the aquifer systems (Figure 28). However, local residual heads of up to ±20 m were calculated for the deeper aquifers.

Areas of limited and/or no data, particularly in the deeper aquifers, results in mis-interpolaton of water level elevations across these locations when making use of kriging. Generally, areas where residuals exceed ±10 m coincide with zones of poor data density (Figures 28B & 28C). Areas that are poorly simulated by the model may also reflect areas with increased gradients such as those observed along the northern and southern boundaries. A good calibration occurs when the mean of the residual is close to zero and the standard deviation is less than 10% of the overall range in head for the model layer (Howard et al., 1996). Results of the statistical analysis listed in Table 5 suggest that both the mean error and the standard deviation for model layers are within acceptable limits.

The average difference between the simulated and point measured heads is expressed by the mean error (ME), the mean absolute error (MAE) and the root mean squared (RMS) error. The errors are considered to be only a small part of the overall model response if the ratio of the RMS error to the total head loss in the system is small (Anderson and Woessner, 1992). In this modeling study the RMS is about 8 m or within 3% of the total head loss in the system, which is 275 m (Figure 22). The head residuals in the graph of linear regression (Figure 29) are equal to the horizontal distance from the symbols to the straight line and have an absolute mean value of 6.5 m. The residual scatter in the plot can be explained by uncertainties in borehole elevation and water level measurements, as well as the level of

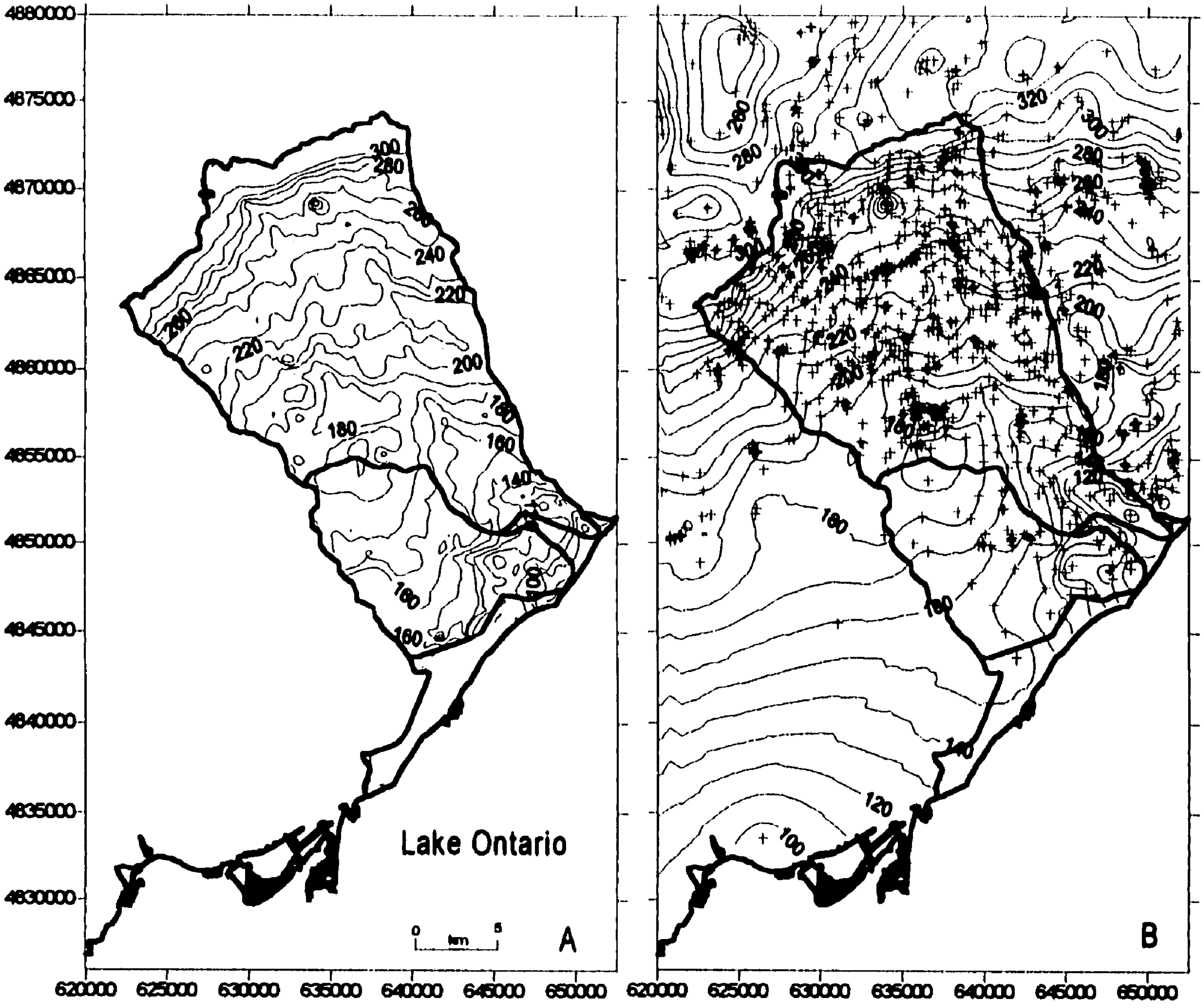


Figure 25. A) Model simulated heads for the Upper/water table Aquifer, B) Calculated heads for the Upper/water table Aquifer. Location of data points shown by crosshairs. Contour interval 10 m.

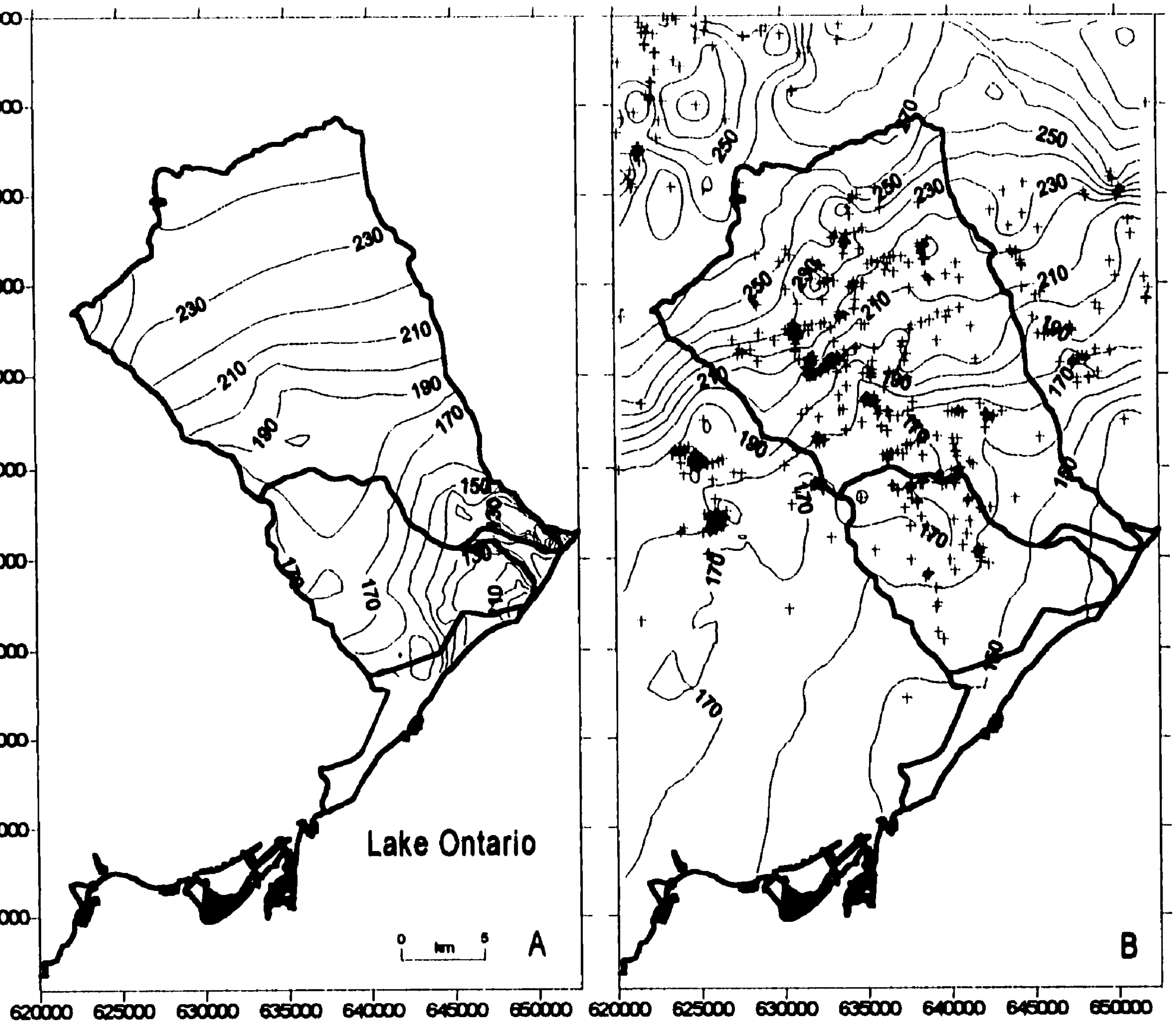


Figure 26. A) Model simulated heads for the Middle Aquifer, B) Calculated heads for the Middle Aquifer. Location of data points shown by crosshairs. Contour interval 10 m.

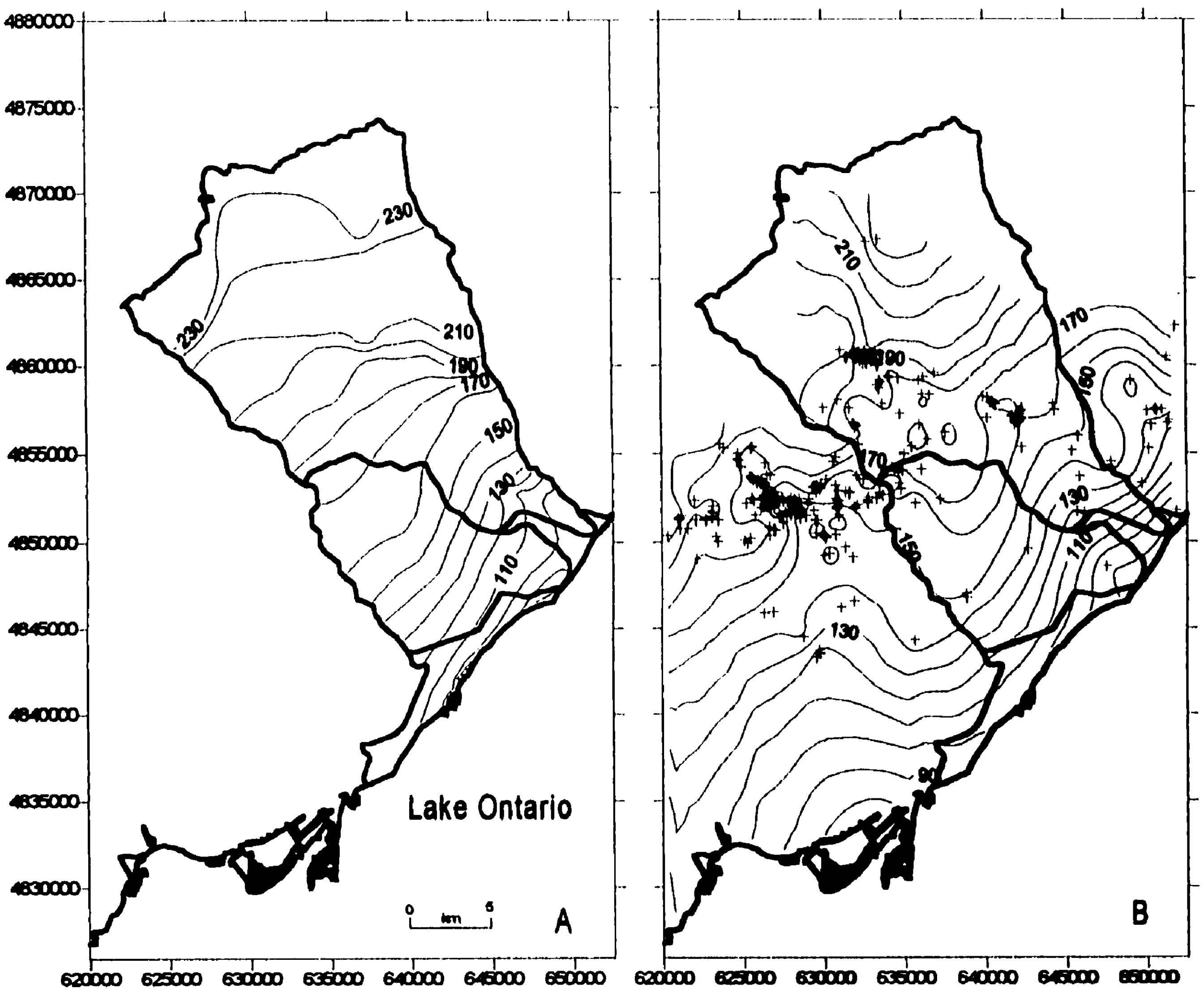


Figure 27. A) Model simulated heads for the Lower Aquifer, B) Calculated heads for the Lower Aquifer. Location of data points shown by crosshairs. Contour interval 10 m.

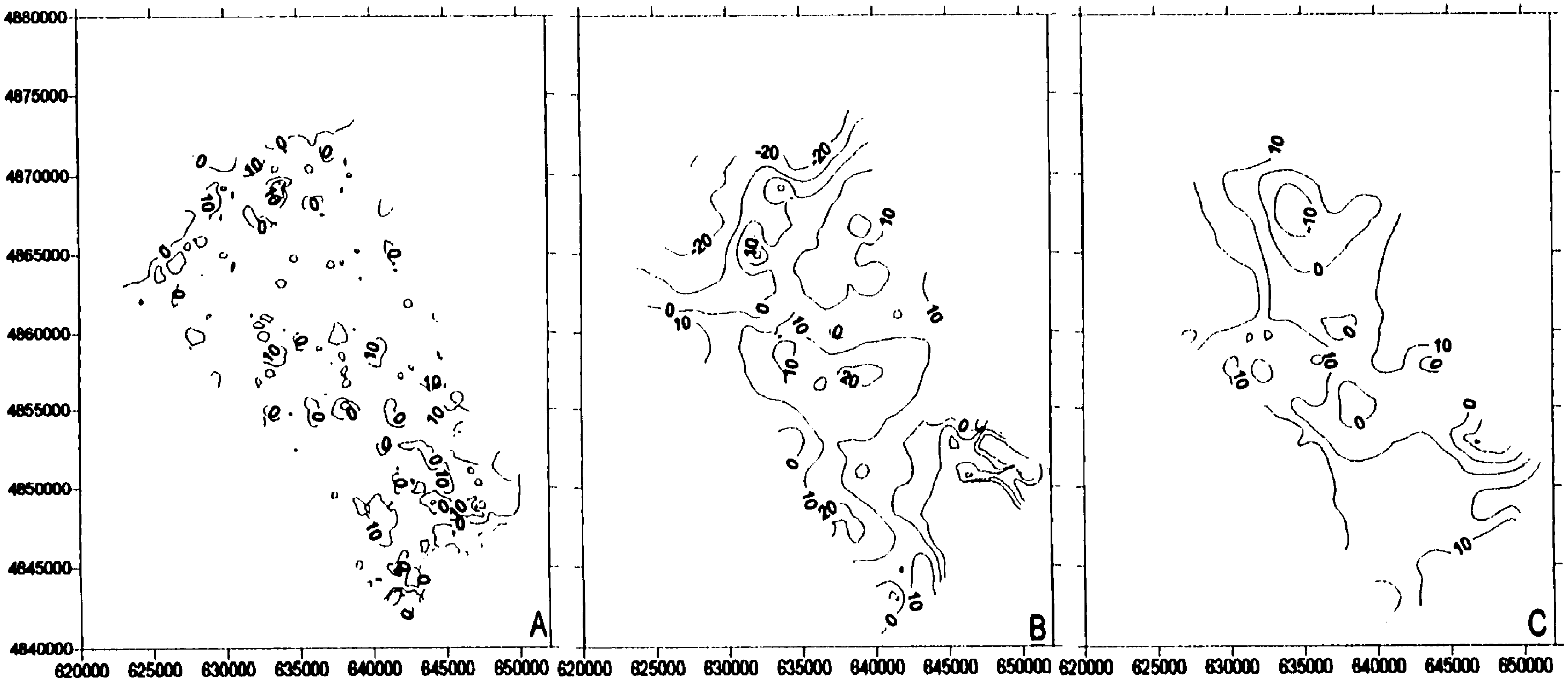


Figure 28. Head residulas for the A) Upper Aquifer, B) Middle Aquifer and C) Lower Aquifer. Contour interval 10 m.

Table 5. Statistic results for residual heads of the aquifer layers.

Aquifer Layer	Mean	Standard Deviation	Percentage of std. dev to data range
Water Table Aquifer (layer 1)	3.9	6.6	2.8 %
Middle Aquifer (layer 4)	0.9	13.6	8.2 %
Lower Aquifer (layer 6)	12.2	11.7	7.6 %

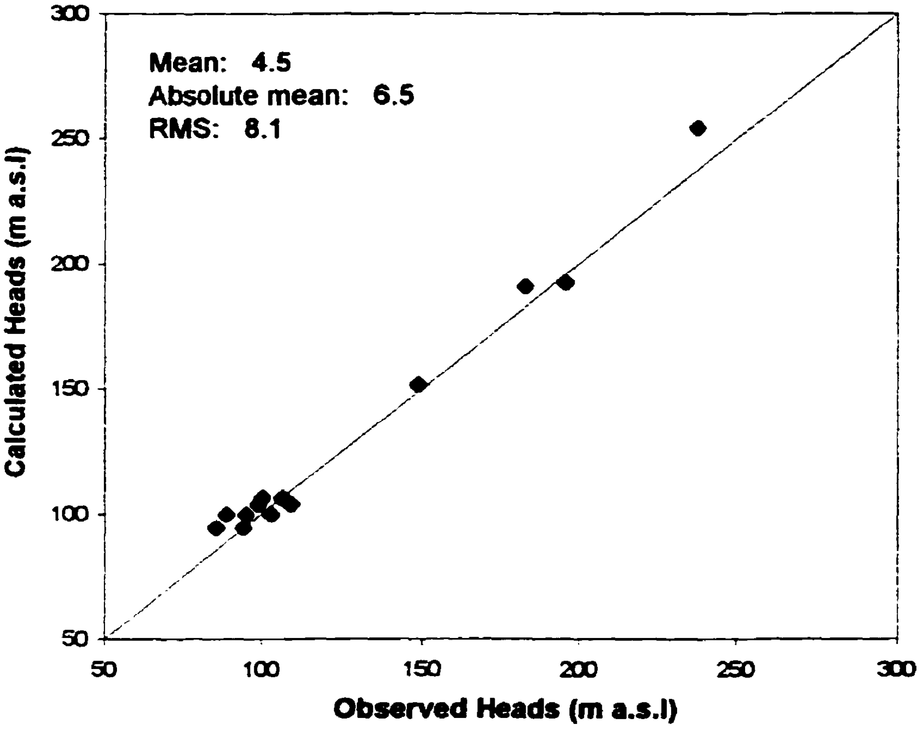


Figure 29. Relationship between simulated and observed heads.

discretization ceasing to accurately capture the small-scale heterogeneities in the system (Gerber, 1998; Martin and Frind, 1998).

5.5.1.2 Groundwater Flow Distribution

Groundwater budget components are calculated by ZONEBUDGET using simulation results from MODFLOW. Groundwater seepage from aquifer systems into streams was estimated using 1980 to 1990 streamflow data collected at three Environment Canada weirs in the RRHC watershed (Tables A1-A3, Appendix A). Due to uncertainties in baseflow estimates for Highland Creek reported by Environment Canada (Table A3, Appendix A), streamflow measurements at this weir were compared to an independent study by Howard and Haynes (1993). The monthly mean discharges based on 1980-1990 data (Water Survey of Canada, 1992) is shown on Table A3, Appendix A. The monthly mean flows for this period range from a minimum of 0.8 m^3/s (January) to 2 m^3/s (March) and average 1.33 m^3/s over the 10 year period representing an annual recharge of approximately 490 mm to the 86.2 km^2 catchment. On the other hand, baseflow contributions of 0.3 m^3/s to 1.2 m^3/s for Highland Creek have been reported by Howard and Haynes (1993) based on two years of daily streamflow data collected at the same Environment Canada weir between 1989 and 1991. Since the minimum daily mean flow of 0.3 m^3/s reported by Howard and Haynes (1993) is a more accurate approximation of baseflow contributions, model calculated baseflow for Highland Creek was compared to this estimate for calibration.

River reaches represented by the three streamflow gauging stations in the area (Figure 24) were zoned and comparisons between simulated and estimated baseflow values were made at each gauging station. Stream baseflow estimates help validate the model by providing an accurate means of assessing whether the model generated baseflows fall within an acceptable range of the existing estimates. The simulated baseflow for Rouge River and Little Rouge Creek are 57470 m^3/d and 21200 m^3/d respectively. These values are within 2.9% and 6.5% of the measured baseflows for Rouge River and Little Rouge Creek respectively (Table 6). Model calculated baseflow for Highland Creek, however, does not correlate as well with the existing estimates. The simulated baseflow for Highland Creek is ~45% of the estimated baseflow (estimated 25930 m^3/d; simulated 14115 m^3/d). It is suspected that urbanization in Highland Creek drainage basin has modified the hydrogeologic system to the extent that modern baseflow levels can not be sustained without additional sources of water.

Minimum daily discharges for Highland Creek from 1959 to 1985 are shown in Figure 30. The increase in stream baseflow over this 26 year period may be caused by new sources of recharge introduced by urbanization. These new sources of recharge may include (Lerner et al., 1990):

- leaking water mains;
- over-irrigation of domestic and municipal gardens;
- deliberate recharge of storm runoff; and
- unintentional recharge of effluent and storm runoff discharged to rivers.

Water input to a highly urbanized catchment such as Highland Creek in the summer may be much greater than previously thought. Increased soil moisture during the warmer, drier months is coincident with the period of irrigation. When this is combined with a greater waterproofing of the urban surface and reduced rates of evapotranspiration most of the water in this small catchment becomes recharge and runoff. Further, additional infiltration from leaking water mains may result in higher streamflows during the warmer, drier months, such as those observed in Highland Creek. Baseflow discharge surveys in the Humber River watershed, west of the study area, indicate increases in stream baseflows within urban areas of the watershed due to drainage from culverts into the rivers (Hinton et al., 1998). Analysis of isotopic composition (^2H and ^{18}O) of the baseflow by Hinton et al., (1998) suggests that urban streams may have between 27 and 88% of Lake Ontario water. The error may also be attributed to the scale of the regional model lacking adequate grid refinement in the catchment.

Table 6. **Water balance at gauged river boundaries.**

Stream Segment	Observed Baseflow (m^3/d)	Simulated Baseflow (m^3/d)	%Error
Rouge River	55865.5	57472.6	+2.9
Little Rouge Creek	19910.4	21200.5	+6.5
Highland Creek	25929.1	14113.0	-45.6

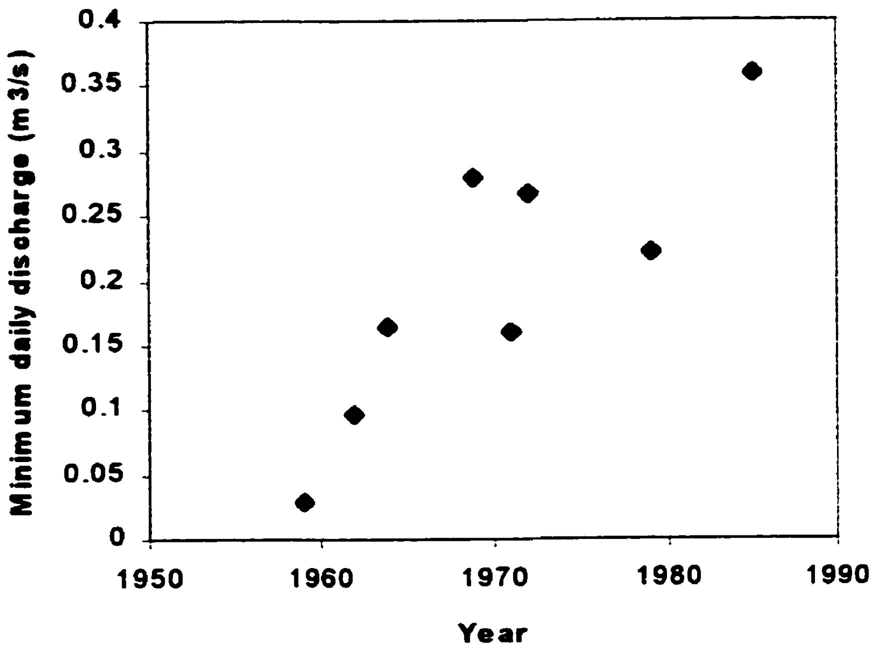


Figure 30. Historical minimum daily discharge values for Highland Creek, Station No. 02HC013.

5.6 Sensitivity Analysis

Trial and error calibration of a numerical model results in optimization of many of the parameters, where different sets of data may in fact produce identical results (Anderson and Woessner, 1992). The sensitivity of the model with respect to boundary conditions was evaluated by performing calibration runs in which calibrated values for recharge and GHB parameters were changed while other model parameters were kept constant. Magnitude of change in hydraulic head as represented by RMS (root mean square) and seepage to selected stream segments (Rouge River and Little Rouge Creek) were used to compare the sensitivity simulations to the calibrated solution.

The effects of change in recharge on simulated results were examined by varying the recharge to the basin within ±20%. The calibrated model was very sensitive to changes in recharge. Simulation runs had poor performance when recharge was increased; and failed to converge when recharge to the catchment was decreased by more than 5%. A 20% increase in basin recharge caused the RMS of the resulting model to increase by 0.85 m (10.5%) and caused a significant increase in the simulated baseflow to the Rouge River and the Little Rouge Creek. In addition, the uncertainty in model prediction for these stream segments increased from +2.9% to +22% for the Rouge River and from +6.5% to +28% for the Little Rouge Creek. Increasing the groundwater recharge by 20% also resulted in a substantial rise of water table in the upper portion of the watershed. This is due to the presence of low permeability deposits such as Markham Clays where an increase in recharge causes considerable rise in the water table.

The sensitivity of the model with respect to GHB was tested by removing these boundaries from layer 4 (Middle Aquifer). Their removal resulted in a rise in calculated hydraulic heads and 0.77 m (9.5%) increase in RMS. The head estimates particularly increased along the lower half of the western boundary where the flux was previously leaving the basin and decreased near the southeastern margin where the flux was entering the basin. Baseflow to the Little Rouge Creek increased slightly, by only 53 m^3/d, but increased by

2,000 m3/d to the Rouge River (from 57,500 m^3/d to 59,500 m^3/d; +2.9% error to +7% error).

The results of the sensitivity analysis indicate the calibrated model was very sensitive to changes in recharge, therefore, the uncertainty in their calibrated values is small. The model was found to be less sensitive to GHB boundaries in the Middle Aquifer, perhaps, because lateral flow is not the principle process by which groundwater enters and leaves the RRHC watershed. In the calibrated solution only about 2% (2,900 m^3/d) of the total recharge enters the basin as lateral flow, mainly from southeast margin of the Middle Aquifer, while approximately 4% (5,800 m3/d) of the total discharge occurs as lateral flow from the western boundary of the Middle Aquifer into the adjacent Don watershed basin.

6.0 QUANTIFICATION OF GROUNDWATER SYSTEM

Water balance calculations using ZONEBUDGET indicate that a total recharge of more than 149,000 m^3/d enters the groundwater system at an average infiltration rate of 109 mm/a. The recharge to the Upper Aquifer takes place at the crest of the ORM at steady-state values of 56,000 m^3/d, more than 37% of the basin recharge, and along the south flank of the ORM at 50,000 m^3/d, 33% of basin recharge. Recharge to the Upper Aquifer through Lake Markham deposits amounts to 27,000 m^3/d or about 18% of the total basin recharge. Recharge to the lower aquifers occurs as either direct recharge from the upper to lower aquifers in areas with no aquitard or as leakage in areas with an aquitard. The magnitude and direction of leakage depends on the thickness and the vertical hydraulic conductivity of the confining layers, and on vertical hydraulic gradient between these layers (Christensen et al., 1998).

The simulated groundwater balance for the Middle Aquifer indicates that leakage from the Upper Aquifer through the Upper Aquitard (Northern Till) amounts to almost 74% of the total inflows to this aquifer (29 mm/a). This value compares to 35 mm/a of vertical leakage through the Northern Till in the Duffins Creek watershed reported by Gerber (1998). The Lower Aquifer also receives leakage through the Middle Aquitard (Sunnybrook Diamict). The head difference between the middle and lower aquifers is almost negligible towards the north, however, a downward hydraulic gradient exists in the south, which amounts to 76% of the total inflows entering this aquifer as downward leakage.

83% (124,191 m^3/d) of all the recharge to the RRHC watershed discharges into streams and creeks. Aquifer contributions to gauged/calibrated stream segments have been summarized in Table 7. The headwaters of the Rouge River and Little Rouge Creek receive 40% of the basin recharge via the Upper Aquifer Complex as their baseflow (60,000 m^3/d (Table 7). Seepage estimations from various deposits within the RRHC watershed have been listed in Table 8. The contribution of the ORM and Halton Till deposits (Upper Aquifer) to baseflow in RRHC watershed amounts to 64% (80,000 m^3/d) of the total baseflow received in the basin (Table 8). Seepage to streams and creeks from the Middle and Lower Aquifers account for 12% and 13% of the total basin baseflow respectively (Table 8). Baseflow contributions from the Lower Aquifer are inconsistent with Gerber (1998), where he reports a seepage of only 2-3% from the lower aquifer into Duffins Creek. The inconsistency may be the result of thick Scarborough Formation discharging directly into lower reaches of Rouge River and Highland Creek in the southern region of the watershed.

Seepage to Lake Ontario is simulated at approximately 7,400 m^3/d or about 5% of the total recharge. This estimate is 6,700 m^3/d greater than the calculated seepage (700 m^3/d) using estimates of mean transmissivity for the Rouge River drainage basin as determined by Haefeli (1972). The discrepancy may be due to increased transmissivities where up to 40 m of deltaic sands of the Scarborough Formation outcrop along the topographic break at the Scarborough Bluffs (Figure 16C). 92% of simulated seepage to Lake Ontario occurs along this section of the bluffs, west of East Point.

Table 7. **Simulated aquifer contributions to gauged stream segments.**
(%) = **Percentage of total baseflow to stream segment.**

	Rouge River (m^3/d)	Little Rouge Creek (m^3/d)	Highland Creek (m^3/d)
Upper Aquifer	45788.3 *(79.7%)*	19950.6 *(94%)*	8020.4 *(56.8%)*
Middle Aquifer	8933.9 *(15.5%)*	0	2687.7 *(19%)*
Lower Aquifer	0	0	3396.0 *(24%)*

Table 8. Simulated baseflow contribution from various deposits to rivers in RRHC watershed.
(%)= Percentage of total basin baseflow.

Deposit	Baseflow to Rouge River and Little Rouge Cr. (m^3/d)		Baseflow to Highland Cr. (m^3/d)	
Halton Till	1036.6	*(0.83%)*	3379.64	*(2.72%)*
ORMC	67916.49	*(54.69%)*	7298.67	*(5.88%)*
Northern Till	414.59	*(0.33%)*	1443.72	*(1.16%)*
Thorncliffe Fm.	11754.3	*(9.46%)*	3213.83	*(2.59%)*
Sunnybrook Diamict	3.87	*(0.003 %)*	0.07	
Scarborough Fm.	11751.7	*(9.46%)*	4682.15	*(3.77%)*
Lake Markham Deposits	10574.34	*(8.52%)*	-	-
Lake Iroquois Deposits	-	-	721.03	*(0.58%)*

7.0 SUMMARY AND CONCLUSIONS

Knowledge of the relationships between aquifer geometry, groundwater flow, recharge and distribution of surface discharge patterns is a key element in identifying long-term solutions to potential effects of urbanization on surface and ground waters. Methodology was developed to construct a conceptual model that provides a basic understanding of the complex glacial hydrogeology of the study area. The study recognized three principle aquifer systems consisting of an upper sand and gravel complex (Upper Aquifer ≈ 150 – 340 m a.s.l), an intermediate aquifer (Middle Aquifer ≈ 120 – 240 m a.s.l) and a lower aquifer defined between bedrock and ≈ 150 m a.s.l (Lower Aquifer). The aquifers are separated by finer grained diamict units. The conceptual hydrogeologic model of the groundwater flow system, formulated from the available geological and hydrogeological data, formed the basis for the construction of a groundwater flow model. The model was calibrated under steady-state conditions to point water level data, kriged heads and streamflow measurements. The model reproduces the measured hydraulic heads, and the simulated baseflows are within an acceptable range of measured values with the exception of Highland Creek. At Highland Creek, failure to partition the baseflow component of streamflow from the urban sources of water is believed to result in a 45% underestimation of simulated baseflow in this highly urbanized catchment. The following conclusions can be inferred from the model results:

- A total recharge of 149,000 m^3/d over the 500 km^2 watershed enters the groundwater system at an average infiltration rate of 109 mm/a.
- 70% of total recharge to the RRHC watershed enters the groundwater flow system as direct infiltration through the ORM and the South Slope of the ORM (Halton Till plain) at rates of 335-400 mm/a and 150-200 mm/a respectively.
- 83% (124,191 m^3/d) of all the recharge to RRHC watershed discharges into streams and creeks as baseflow. The ORM and Halton Till deposits supply 64% (80,000 m^3/d) of the entire basin baseflow.

- Vertical leakage through the confining layers appears to be the primary source of recharge/leakage to the deeper aquifers in the watershed. Vertical leakage through the Northern Till to the Middle Aquifer (29 mm/a) and through the Sunnybrook Diamict to the Lower Aquifer (21 mm/a) amount to 76% of all the inflows to these aquifers.
- Groundwater flow in aquifers is generally southward, towards Lake Ontario, with local deflections towards the streams. Approximately 4% of recharge is exported from the watershed into the Don drainage basin to the west, while only about 2% of the total recharge is imported into the study area, mainly from the neighboring basin to the east (West Duffins Creek).

In general, the model gives a reasonable depiction of the overall groundwater flow system and budget. However, due to lack of hydraulic head data for the most northerly parts of the Middle and Lower Aquifers, the simulation results for these regions should be considered preliminary. Inaccurate estimates of head values are likely where data interpolation is performed between distant wells where only few measured data are available. Refinement of the model in these regions will be possible by additional measurements of hydraulic head in the deeper aquifers.

Streamflow measurements, where available, are used in waterbalance calculations and flux calibrations of groundwater flow models. In most cases, stream baseflows are considered to represent groundwater recharge. In smaller urbanized basins, such as Highland Creek, stream baseflows may not be appropriate for estimating groundwater recharge because the baseflow component of streamflow cannot readily be distinguished from the urban sources of water.

The trial-and-error calibration of the groundwater flow model presented herein aided our understanding of the hydraulic behavior of the RRHC aquifer systems. Although the sensitivity analysis performed reduces the possibility of such calibration producing a non-unique solution, the geologic and hydrogeologic expertise and preferences of the modeler may, in fact, influence the calibration to produce a non-unique solution. As a result, further evaluation of parameterization and calibration is recommended by use of automated inverse modeling and continued monitoring. The importance of sound professional judgement in developing the conceptual model cannot be overemphasized, as the estimations/predictions of the groundwater flow model is only as accurate as the conceptual model permits.

Dramatic growth and population increases in the RRHC watershed provided the motivation for acquiring a firm understanding of the geology and hydrogeology in the area. North of the city, the South Slope of the ORM is undergoing rapid urbanization and there are concerns for the quality of ground and surface waters. Many municipalities are struggling to cope with urban planning in the absence of adequate baseline data and groundwater flow models. As a result, official plans are being formulated with little regard for environmental impacts. Urban development has been fueled to a large degree by easy access to drinking water from Lake Ontario, which has been the reason for the neglect of groundwater issues. Much of the South Slope area is underlain by permeable sediments such as the Halton Till which provide little protection for underlying aquifers.

The RRHC groundwater flow model provides better insight to the hydraulic behavior of the aquifer systems in the watershed. A land use map summarizing the primary activities that may contribute contaminants to the subsurface was also developed for the study area. Together, they provide an ideal basis for establishing potential chemical loadings on the groundwater system and defining contaminant migration routes to Lake Ontario. The results of this study will allow for a proactive management of groundwater and surface water resources and will provide insights for optimal development of water resources towards a conjunctive use of ground and surface waters as the area continues to urbanize.

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9.0 APPENDIX A RECORDED MEAN DISCHARGE VALUES.

Table A1. Mean discharge values for Rouge River, Station No. 02HC022 (drainage area 186 km2), 1980-1990.

Mean Discharges (m^3/s)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean (Annual)
1980	1.76	0.45	4.58	4.93	0.97	0.54	1.33	0.49	0.63	1.12	0.99	1.79	1.63
1981	0.25	5.04	1.07	1.03	1.21	0.71	0.53	0.99	2.19	2.63	2.00	1.11	1.56
1982	1.02	0.43	6.62	4.10	0.62	2.28	0.91	0.74	1.11	1.25	3.13	3.54	2.15
1983	1.43	2.38	2.76	3.43	2.96	0.50	0.30	0.42	0.46	0.80	2.00	1.93	1.61
1984	0.47	5.98	4.37	2.83	1.86	0.82	0.50	0.81	1.17	0.58	1.71	1.75	1.90
1985	0.75	5.01	5.85	3.25	0.75	0.78	0.43	1.08	0.79	0.92	4.70	1.53	2.15
1986	1.34	1.04	6.04	1.57	0.82	1.43	0.55	5.38	6.64	2.38	1.35	2.36	2.58
1987	1.28	0.71	4.14	2.75	0.52	0.86	0.75	0.42	0.65	0.61	1.53	2.33	1.38
1988	0.89	0.83	2.28	1.60	1.13	0.39	0.43	0.32	0.60	0.94	1.36	0.59	0.95
1989	1.20	0.53	1.73	1.18	1.41	1.50	0.32	1.06	0.88	1.00	2.68	0.59	1.17
1990	1.74	2.44	4.79	3.14	1.39	1.44	1.08	1.17	0.64	2.53	1.80	4.52	2.22
Mean (Monthly)	1.10	2.26	4.02	2.71	1.24	1.02	0.65	1.17	1.43	1.34	2.11	2.00	1.76

Table A2. Mean discharge values for Little Rouge Creek, Station No. 02HC028 (drainage area 77.7 km2), 1980-1990.

Mean Discharges (m^3/s)													
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Mean (Annual)**
1980	0.79	0.13	2.04	2.54	0.39	0.21	0.43	0.20	0.26	0.54	0.49	0.98	0.75
1981	0.26	1.59	0.56	0.53	0.70	0.26	0.15	0.55	1.12	1.40	1.09	0.51	0.73
1982	1.23	0.29	3.82	1.23	0.31	1.04	0.52	0.30	0.44	0.62	2.08	2.06	1.16
1983	0.75	1.24	1.44	1.78	1.46	0.28	0.13	0.19	0.21	0.34	1.05	1.11	0.83
1984	0.40	3.62	2.32	1.55	1.01	0.28	0.19	0.22	0.48	0.32	0.90	1.08	1.03
1985	0.40	2.43	3.37	1.79	0.38	0.34	0.17	0.30	0.28	0.38	2.45	0.80	1.09
1986	0.64	0.62	3.92	0.85	0.42	0.61	0.20	1.92	3.13	1.23	0.68	1.06	1.27
1987	0.57	0.19	2.74	1.63	0.36	0.30	0.25	0.17	0.23	0.25	0.75	1.33	0.73
1988	0.48	0.64	2.51	1.19	0.79	0.14	0.10	0.13	0.21	0.35	0.68	0.40	0.64
1989	0.52	0.27	0.95	0.82	0.95	0.51	0.09	0.32	0.32	0.40	1.88	0.27	0.61
1990	1.00	1.53	2.74	1.73	0.56	0.34	0.31	0.41	0.23	1.15	0.98	2.17	1.09
Mean (Monthly)	0.64	1.14	2.40	1.42	0.67	0.39	0.23	0.43	0.63	0.63	1.18	1.07	0.90

Table A3. Mean discharge values for Highland Creek, Station No. 02HC013 (drainage area 86.2 km2), 1980-1990.

Mean Discharges (m^3/s)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean (Annual)
1980	0.71	0.42	3.69	2.09	0.98	1.22	1.03	0.67	0.77	1.20	0.86	0.99	1.22
1981	0.47	3.06	0.58	0.72	1.18	0.91	1.00	1.25	1.34	1.72	1.23	0.65	1.18
1982	1.13	0.70	3.94	1.69	1.01	1.65	0.62	1.26	1.37	0.70	1.82	1.68	1.46
1983	1.01	1.34	1.66	2.01	1.89	0.79	0.62	1.35	0.91	1.37	2.00	1.71	1.39
1984	0.45	3.23	2.08	2.01	1.65	1.23	1.08	1.13	1.62	0.67	1.29	1.03	1.46
1985	0.53	3.27	2.50	1.42	1.25	0.75	0.74	1.69	0.98	1.00	3.48	0.92	1.54
1986	0.82	0.72	2.27	1.09	1.24	1.09	1.05	3.49	3.45	1.48	0.93	2.02	1.64
1987	0.86	0.65	1.55	1.54	1.03	0.87	1.10	0.67	1.37	0.72	1.51	1.43	1.11
1988	NA	NA	1.24	1.42	1.07	0.68	1.15	0.69	1.23	1.56	1.43	0.95	1.14
1989	0.69	0.50	1.04	0.92	1.26	1.31	0.56	1.27	1.27	1.53	1.90	0.54	1.07
1990	1.42	1.84	1.71	1.21	1.58	1.35	1.19	1.42	0.78	1.68	0.86	2.53	1.46
Mean (Monthly)	0.81	1.57	2.02	1.47	1.29	1.08	0.92	1.35	1.37	1.24	1.57	1.31	1.33