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Article abstract

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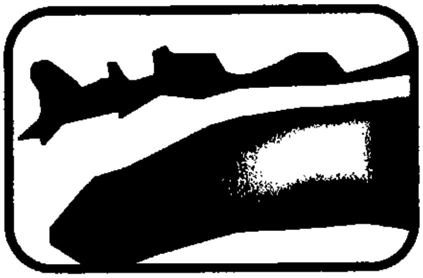

The Oak Ridges Moraine of Southern Ontario: A Ground-water Resource at Risk

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SUMMARY

Protection of ground-water resources is an emerging theme in many urban areas. In south-central Ontario, the Oak Ridges Moraine (~1400 km²) is a prominent glacial moraine complex on the rapidly urbanizing northern margin of the Greater Toronto Area and constitutes a major regional aquifer system. Given the pre-eminent economic importance of the region, the ground-water resource can be argued to have provincial significance, and there is much current debate regarding the impact of urbanization and other anthropogenic activities on ground-water quality and supply. Particular issues are the degree of acceptable future development and the definition of the most environmentally and hydrogeologically sensitive areas. This paper reviews what is currently understood of the geology and hydrogeology of the Oak Ridges Moraine, and provides an overview of quantitative modelling studies.

RÉSUMÉ

La protection des ressources en eau souterraine est une question qui commence à soulever l'intérêt dans un grand nombre de régions urbanisées. C'est le cas de la région métropolitaine de Toronto dans le centre-sud ontarien. Dans la partie nord de cette région, se trouve un important complexe glaciaire, la moraine de Oak Ridges (environ 1400 km²) lequel qui constitue un aquifère régional de première importance. Étant donné le poids de l'économie de la région, on peut comprendre que ses ressources hydriques prennent une importance provinciale, et cela soulève maintenant de nombreux débats sur les repercussions de l'urbanisation et d'autres activités anthropogéniques sur la qualité et le volume d'eau souterraine disponible. On s'attache en autres à définir un niveau de développement domiciliaire qui soit acceptable et à délimiter les régions les plus exposées tant sur le plan environnemental que hydrogéologique. Cet article passe en revue les connaissances actuelles sur la géologie et l'hydrogéologie de la moraine de Oak Ridges et présente un résumé des modèles quantifiés existants.

INTRODUCTION

Throughout the Great Lakes basin, the quantity and quality of ground waters have become serious issues for concern. In 1983, the Great Lakes Advisory Board of the International Joint Commission recognized major deficiencies in knowledge about the nature and extent of ground water within the basin. Concerns were also expressed that "existing estimates of ground-water flow based on general geology were inadequate."

In south-central Ontario, the Oak Ridges Moraine (ORM; ~1400 km²) is a prominent physiographic feature now being threatened by rapid and poorly planned urbanization on the northern fringe of the Greater Toronto Area (GTA). The moraine forms a west-east trending belt of undulating, kettled topography, between 5 km and 20 km wide, that extends for more than 140 km eastward from the Niagara Escarpment (Fig. 1A). The ORM extends across three regions (Peel, York, Durham) of the GTA and 14 townships (Fig. 1B), and accounts for more than 18% of the total GTA area. The moraine forms the surface-water drainage divide between Georgian Bay and Lake Ontario and provides baseflow to more than 30 major streams. The ORM is the focus of much current debate regarding the impact of urbanization and other anthropogenic activities on ground-water quality and supply, together with the degree of acceptable future development and definition of the most environmentally sensitive areas. The ORM aquifer is recognized as being of provincial importance given its strategic location adjacent to the rapidly growing GTA.

HISTORICAL OVERVIEW

The recent history of the ORM provides a classic illustration of unsustainable land use practices. The moraine is of considerable significance in the economic and social development of the province of Ontario; this history is briefly reviewed below and in Figure 2.

European Settlement

Permanent European settlement of the ORM started in 1783 when the British Government sought homes for Loyalists driven from the newly independent United States of America. Many settlers were part of religious groups such as Quakers, Amish, Hutterites and Mennonites from Pennsylvania (the plain folk), who were attracted by an exemption from military service issued by Lieutenant-Governor John Graves Simcoe in 1792. Quakers settled the townships of Uxbridge and Newmarket; Mennonites settled Altona. A growing influx of American settlers, who had dubious loyalty to the Crown, threatened the political security of the fledgling province of Upper Canada, and large-scale European migration was promoted after the War of 1812-1814. This coincided with the end of the Napoleonic Wars in Europe and the arrival of war veterans entitled to free lots of wild land; other arrivals to the ORM (described as "bold sweeping hills" by Catharine Parr Traill in 1836) included displaced Scottish Highlanders and craftsmen made redundant by mechanization in the factories of Britain. Men with military experience were favoured so as to enable the mustering of local militias. Settlement of the ORM was seen as a first line of defence for York (Toronto) with Yonge Street, the main north-south route across the ORM, primarily a military trail. Unfortunately, much land was obtained by Crown grants, not for immediate settlement, but for future sale for profit after it had been cleared of forest. Unbridled land speculation, inadequately taxed uncultivated land, the prevalent practice of squatting, and government corruption were leading causes of the Rebellion of 1837 when William Lyon Mackenzie and his Reformers marched south along Yonge Street to the skirmish at Montgomery's Farm.

Habitat Destruction and Loss of Sustainability

Municipal reforms of Lord Durham, following the Rebellion of 1837, ushered in several decades of prosperity across

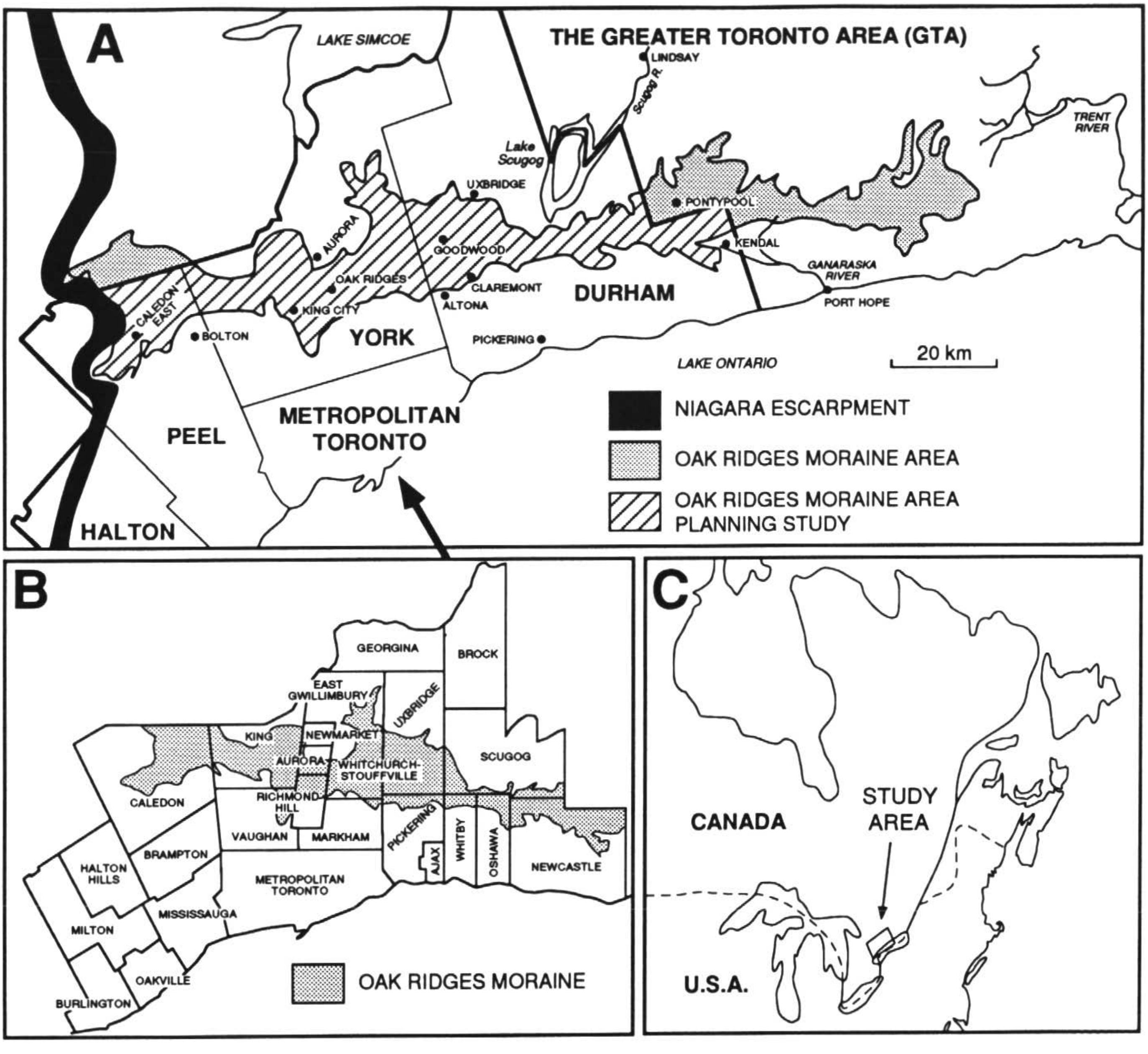

Figure 1 *Oak Ridges Moraine area showing (**A**) the five regions composing the Greater Toronto Area and (**B**) townships. The regional location is shown in (**C**). The area shown under Oak Ridges Moraine Area Planning Study area is the focus of the ORM Technical Working Committee, having the objective of formulating legislation to protect the natural resources of the area.*

the ORM (or Pickering Sandhills as it was widely known), accelerated by the introduction of steam-driven saw mills (1850), plank roads, and railways (the Northern Railway arrived in Aurora in 1853). The 1854 Reciprocity Treaty between Canada and the United States removed the duty from Canadian wheat and lumber and the so-called White Pine Clause that had previously reserved the cutting of pine for masts destined for the Royal Navy. The thick forest soils of the ORM were recognized for their agricultural potential, and wholesale forest clearance began. To avoid labour-intensive tree cutting, ring barking was used, whereby the trees were simply stripped of bark and allowed to rot. Because labour was expensive, logging and stumping bees were organized to haul logs into enormous piles for burning to supply potash fertilizer; the burning of 10 acres of forest typically produced about 5 barrels (2500 lbs) of potash (Johnson, 1973). Contemporary journals describe widespread devastation to the habitats of animals and indigenous people; Johnson (1973) remarks that the area was not so much settled as overrun. An excellent account of the harsh backwoods life at this time is provided by Susanna Moodie in *Roughing It in the Bush*, published in 1852. The largest man-made impact on the landscape at this time was the construction of a dam on the Scugog River at Lindsay and the creation of Lake Scugog in the late 1830s. A canal was also planned across the ORM, from Lake Simcoe to Lake Scucog across the Dividing Ridges to Whitby, but never built (Keefer, 1863).

Widespread clearance of the forest cover across the ORM resulted in environmental degradation, and ultimately, loss of sustainability in the latter half of the 19th century. The widespread practice of slash and burn resulted in rapid soil erosion, and created extensive tracts of derelict land of little agricultural value. Exposed soils, devoid of a thick cover of leaf litter, became frozen in winter, reducing recharge to underlying aquifers, creating rapid spring runoff and flooding along many creeks (*e.g.*, the Ganaraska watershed; Fig. 3). Large volumes of sediment accumulated along the lower reaches of rivers and in Lake Ontario (see Eyles, in press); springs dried up, requiring wells to be dug at great expense. Sustained agriculture became impossible on nutrient-starved sandy soils, and formerly cultivated areas were converted to grazing, resulting in intensification of soil loss from overgrazing, trampling and the widespread generation of sand dunes and blowouts.

The resident population of the ORM area peaked in 1861 (Fig. 2) and began to decline thereafter as attempts at agriculture proved futile; many small communities disappeared (Caddy, 1861). The McKinley Tariff, introduced by the United States in 1890, virtually shut off the lucrative United States market for squared timber and other commodities such as wheat. This coincided with the appearance of the destructive wheat midge and resulted in widespread economic depression and loss of population across the ORM (Johnson, 1973). Increased reliance on farm machinery, access to the rich soils of the Prairies facilitated by the completion of the Canadian Pacific Railroad in 1888, and the rapid growth of the city of Toronto further drained the ORM of its rural population (Johnson, 1973; Brown, 1978; Darroch and Soltow, 1994; Fig. 2).

BIGSBY (1824)	"BOLD LINE OF HEIGHTS .. BREAKING INTO CONFUSED RIDGES AND HUMMOCKS"
1840	EUROPEAN SETTLEMENT & CLEARANCES
1861	PEAK OF POPULATION
TAYLOR (1913)	RECOGNITION OF INTERLOBATE ORIGIN BETWEEN NORTHERN AND SOUTHERN ICE MASSES
1920	INCREASED RUN-OFF FLOODING AND LOSS OF SUSTAINABILITY - POPULATION DECREASE REDUCED RECHARGE, LOWERED GROUNDWATER TABLE
CHAPMAN & PUTNAM (1943)	DETAILED PHYSIOGRAPHIC MAPPING
(1944)	DEPARTMENT OF PLANNING & DEVELOPMENT
1946	CONSERVATION AUTHORITIES ACT
CALEY, etc. 1940s	FIRST GROUND WATER STUDIES & FARM PONDS POLICY
1954	HURRICANE HAZEL: INCREASED ROLE FOR CONSERVATION AUTHORITIES
HEWITT, KARROW 1960s	SURFICIAL MAPPING: EVALUATION OF AGGREGATE RESOURCES
SINGER, SIBUL, etc. 1970s	GROUND WATER RESOURCES OF SELECTED WATERSHEDS
DUCKWORTH (1979)	SUBSURFACE STRATIGRAPHY
1980s	POPULATION RETURNS TO 1860 LEVELS
MTRCA (1989)	GREENSPACE STRATEGY
INTERA-KENTING (1990), CROMBIE COMMISSION (1990)	'ECOLOGICALLY-BASED WATERSHED PLANNING'
OAK RIDGES MORAINE TECHNICAL WORKING COMMITTEE (1994a,b)	OAK RIDGES MORAINE AREA STRATEGY FOR THE GREATER TORONTO AREA

Figure 2 *Important milestones in the post-European settlement history and study of the Oak Ridges Moraine.*

Early Conservation Measures

The lack of sustainability clearly evident in the ORM in the late 1930s, and comparison with American conservation efforts in the Tennessee Valley, prompted the first provincial steps in environmental conservation in Ontario; these were considered of national significance and regarded as blueprints for postwar work in other areas of the country (Coventry, 1945). The connection between deforestation, downstream flooding, and declining ground-water levels was realized and conservation projects were initiated in the Ganaraska watershed to curtail repeated flooding of Port Hope. Carman (1941, p. 12) reviewed the then state of the environment across the ORM and concluded that "past and present generations were wholly occupied with the immediate problem of making a living, and in so doing have mined their natural resources of forest, soil and water"; he urged the planting of protective forests. The Reforestation Act of 1921 had earlier empowered municipalities to buy and reforest barren land.

Carman (1941) first recognized the importance of the numerous kettle lakes that dot the ORM for retaining surface-water runoff and promoting ground-water recharge. Carman recognized that this type of topography trapped surface water that would normally run off to streams. His work prompted a wider appreciation of the need to store spring runoff, and by 1950 as many as 5000 farm ponds had been constructed to augment ground-water supplies (Richardson, 1944, 1974). The first major initiative in conservation was made in 1944 when George Drew, Premier of Ontario, established the Department of Planning and Development (Fig. 2) under the direction of geologist George Langford. The 1946 Conservation Authorities Act established a framework for protecting watersheds by provincial and municipal governments. The London Conference of 1944 had earlier set the agenda for this effort when R.F. Legget, another geologist, had emphasized that ground-water supplies were central to all renewable resources, and identified the need for an inventory of existing hydrogeological conditions. A number of ground-water supply papers were produced under the auspices of the Ontario Water Resources Commission (*e.g.*, Hainstock *et al.*, 1948, 1952). However, because of the $100 million destruction caused by Hurricane Hazel in 1954, when 300 million tonnes of rain fell on Toronto, emphasis shifted to surface-water hydrology and flood protection. Only recently has attention been refocussed on the hydrogeological significance of the Oak Ridges Moraine after a hiatus of 50 years. A long history of rural depopulation has now come to an end and the population at the present time (>200,000) exceeds the previous peak reached in 1861 (Fig. 2).

URBANIZATION AND THE OAK RIDGES MORAINE

The present-day population of the GTA is 4.2 million and is expected to increase to 6.5 million by 2021, with most of this growth taking place on the northern outskirts of Metropolitan Toronto along the southern flanks of the ORM (Fig. 1). As a result of rapid urbanization along the Yonge Street corridor, extending north to Aurora and Richmond Hill, developmental pressures on the Oak Ridges Moraine have greatly intensified. Poorly planned residential, recreational and industrial activity along the moraine is recognized as a direct threat to the area's ecological integrity (Crombie, 1990; Intera-Kenting, 1990; Kanter, 1990). The major concerns that need to be addressed include the effects of land use changes on aquifer recharge, present and potential impacts from landfills, the effects of extensive aggregate extraction and rural urbanization requiring septic systems on well-water supplies, large-scale withdrawal of ground water by golf courses, farms, fish hatcheries, and batch (ready-mix) aggregate operations, and the effects of widespread application of agro-chemicals and road de-icing agents. The ORM has more than 100 active licensed aggre-

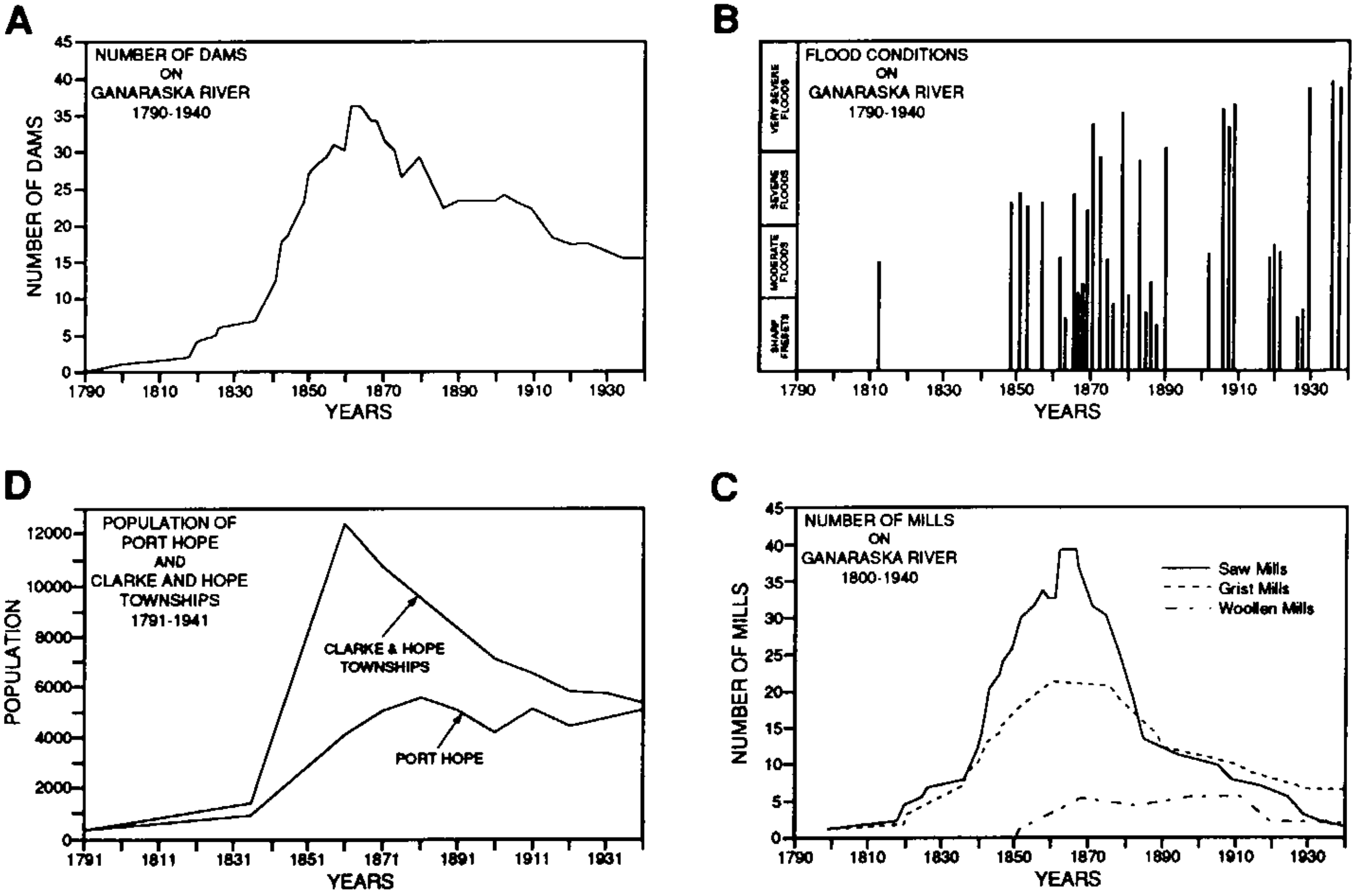

Figure 3 *Nineteenth-century environmental changes resulting from forest clearance across the Oak Ridges Moraine area; an example from the Ganaraska watershed (Fig. 1) (**A**) number of dams; (**B**) incidence of flooding; (**C**) population; (**D**) number of mills. Data from Richardson (1974). Note peak of population in 1860 and greatly increased incidence of flooding after 1850 when large-scale forest clearance began.*

gate operations, centred mostly in the town of Whitchurch-Stouffville and near Pontypool; average life expectancy of any one operation is about 16 years (Oak Ridges Moraine Technical Working Committee, 1994a). Licensees pay 8 cents per tonne per year of aggregate produced into a Rehabilitation Security Deposit System; a total of 486 ha has been rehabilitated to date. More than 1378 ha are classified as disturbed, *i.e.*, awaiting rehabilitation. Some 27 of the 95 active operators are authorized to excavate below the water table. This activity, together with large ground-water abstractions by batch plants producing ready-mix concrete for immediate delivery, are sources for concern. The key to evaluating the impact of aggregate extraction and many other activities is an understanding of the geological and hydrogeological complexity of the moraine.

Existing Water Usage

Within the ORM, about 60,000 people are dependent on about 30,000 private wells as listed by the Ontario Ministry of Environment and Energy, while the remaining population is dependent on municipal water (Lake Ontario and municipal ground-water production wells). To date, there has been no shortfall in supply within the ORM, but many areas are experiencing water quality problems related to septic tank operation and road salt. In the more heavily developed western half of the ORM, along the Yonge Street corridor, municipal water (from Lake Ontario) is supplied to about 70,000 people in Richmond Hill, and the remainder are supplied from municipal wells that draw on the Yonge Street aquifer and individual wells. In the east, municipal systems will shortly extend as far north as Brooklin, some 16 km north of Lake Ontario. Total municipal well production across the ORM is in the order of about 22 million $m^3 \cdot a^{-1}$, with greater than 50% of this total pumped from the Yonge Street aquifer alone. Other large users include farms, golf courses (about 60 in the ORM), and aggregate wash plants. As yet, a comprehensive water budget encompassing all users across the ORM has not been completed.

The provision of adequate sewage treatment systems is currently a severe restraint on development outside the Yonge Street corridor. Clearly, the further extension of municipal facilities, and the accompanying high-density urban development that follows, will require close regulation (see below). The York-Durham Sewage System (YDSS) services 140,000 residents of Richmond Hill, Aurora, Oak Ridges and Newmarket (Eyles, in press). Municipal communal systems service the communities of Stouffville and Uxbridge; the treatment plant for Stouffville (pop.: 18,500) discharges into a tributary of Duffins Creek, that for Uxbridge into the Nonquon River and, ultimately, Lake Scucog. King City (pop: 5000) is noteworthy as being the largest community in Ontario totally dependent on septic tanks, most of which are elderly and on small lots. Ironically, the shortfall in adequate sewage treatment facilities has had the beneficial effect of being a major impediment to urban growth. Extension of the YDSS has been suggested, but it is certain that this would promote rapid urbanization of the ORM. The provision of adequate facilities to handle sewage (whether private single dwelling, communal or municipal), and identification of the relative impact of each system on ground- and surface-water quality, are among the more pressing problems to be addressed, and will strongly influence the level and style of future development.

HYDROGEOLOGICAL SIGNIFICANCE OF THE OAK RIDGES MORAINE

Previous Work

Haefeli (1970) was the first to address the nature of large-scale ground-water flow in the region between Lake Simcoe and Lake Ontario and the role of the ORM in recharging the system. The first detailed evaluation of the ORM is that of Sibul *et al.* (1977) and Turner (1977) working for the Ontario Ministry of Environment. Based on the evaluation of many hundreds of water well records, Turner noted that yields of ground water were generally excellent and that the potential for the development of future high-capacity wells was good in most areas of the moraine. Sibul *et al.* (1977) recognized the role of the ORM in supplying baseflow to the head-water streams that source the tributaries of over 30 major rivers and creeks within the GTA.

While the hydrogeological importance of the ORM is well established in a strategic sense (Kanter, 1990), a comprehensive functional understanding is impeded by its hydrostratigraphic complexity. This difficulty was first recognized by Turner (1977) and Sibul *et al.* (1977), who were unable to establish the hydrogeological relationships between the Oak Ridges Aquifer Complex (term introduced by Turner, 1977) and other related aquifers identified locally at King City, Woodbridge, Nobleton, Richmond Hill, Aurora, Newmarket, Mount Albert, Uxbridge and Port Perry. Understanding the subsurface relationship between these aquifers is hampered by poor quality stratigraphic information contained in many well logs and the virtual absence of deep boreholes. The vast majority of wells penetrate to a depth of less than 75 m, which is less than one-third of the total thickness of glacial sediments in the ORM. In contrast to detailed mapping of surface sediments (*e.g.*, Gwyn, 1972, 1976a, b; White, 1975; Gwyn and Cowan, 1978; Duckworth, 1979; Sharpe and Finley, 1993), little is known of the deeper stratigraphy and sedimentology of the ORM. Provisional geophysical studies of the deep moraine stratigraphy and regional correlations of the most prominent glacial stratigraphic units were presented by Fligg and Rodriques (1983) and Eyles *et al.* (1985).

The work of Sibul *et al.* (1977) drew attention to the importance of hydrostratigraphic detail, particularly with respect to surface tills which locally drape the moraine and its flanks. The authors correctly recognized that the distribution and hydrogeological characteristics of surficial units influence the recharge characteristics of the aquifer and its susceptibility to contamination. More recently, the work of Howard and Beck (1986), Kaye (1986), and Proulx and Farvolden (1989) has resolved a number of specific issues concerning the hydrogeological role of the ORM. Howard and Beck (1986) were able to establish the hydraulic relationship between the ORM and 13 other aquifer systems in the Duffins Creek-Rouge River drainage basins. Kaye (1986) and Proulx and Farvolden (1989) were able to explain site-specific hydrogeological anomalies related to recharge and contaminant movement, anomalies that were notably complicated by the hydrostratigraphic complexity of the moraine and the local occurrence of perched aquifers isolated from underlying aquifer systems.

In 1989, the Metropolitan Toronto Re-

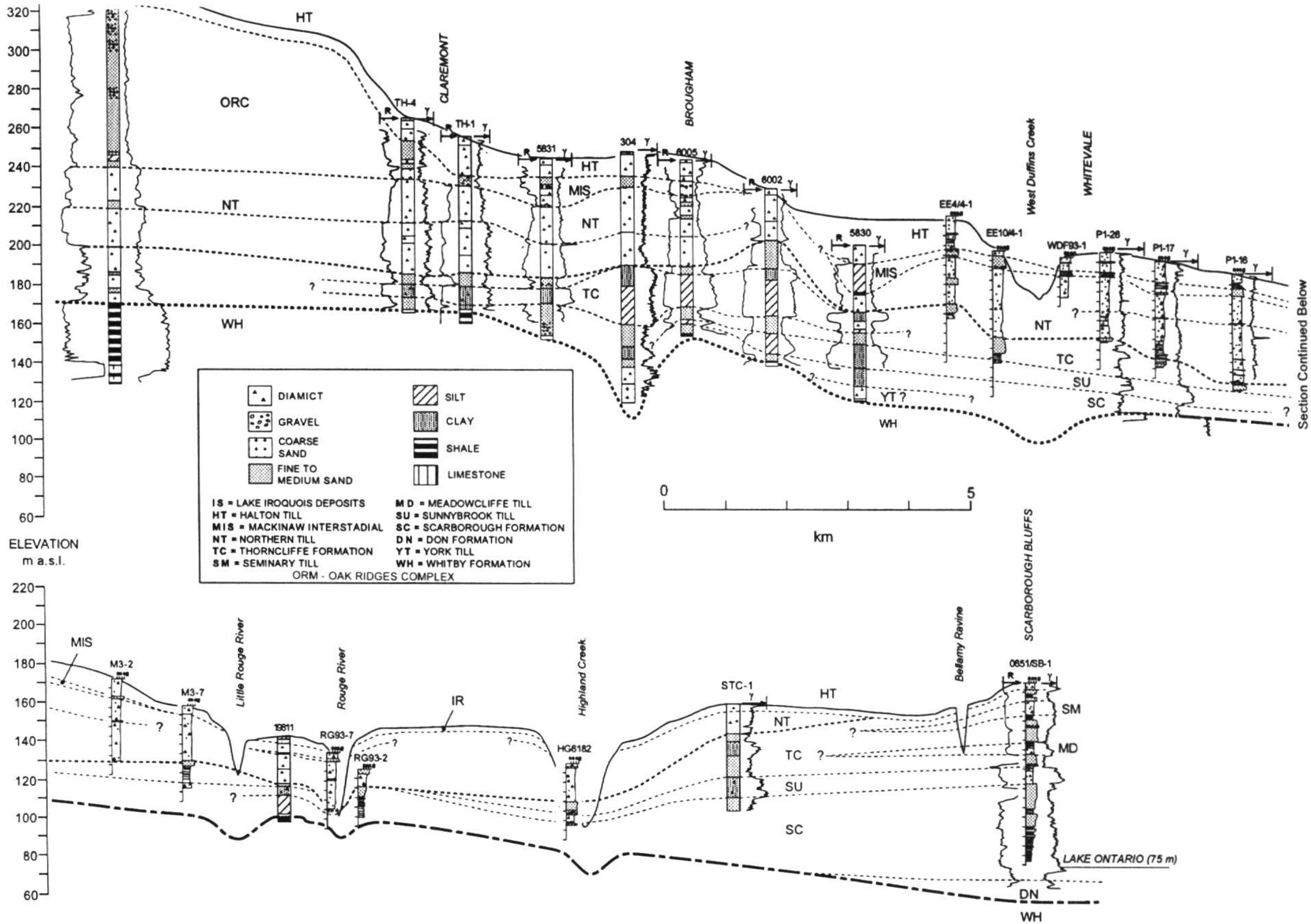

Figure 4 *Compilation of subsurface data from outcrop, downhole geophysical and drill core data from the crest of the ORM to Lake Ontario showing inferred distribution of principal Late Pleistocene stratigraphic units. For a highly simplified version see Figure 5. For location of section see Figure 10.*

gion Conservation Authority (MTRCA) released its Greenspace Strategy, which addressed the protection of the hydrology of the ORM. In this document, the ground-water component of the hydrological cycle was identified as being "poorly understood and an obstacle to the development of land use controls and management practices." A key requirement identified by the MTRCA was the development of ground-water management objectives that the authority could recommend to head-water municipalities. Also in 1989, the Greater Toronto Greenlands Strategy was initiated by the provincial government in an effort to protect the natural landscape. Background papers prepared for this document highlighted the hydrogeological significance of the ORM and recommended a comprehensive hydrogeological investigation of the entire ORM area. Similar sentiments were echoed in the "Interim Report of the Royal Commission on the Future of the Toronto Waterfront" (Crombie, 1990). The report argued that an adequate understanding of the waterfront region, its shoreline, rivers, wetlands and associated biota could only be established through study of the entire Toronto watershed area. The ORM was identified as "unique, varied and complex, under great stress and in need of comprehensive studies of its geology and hydrogeology" (Crombie, 1990).

The province of Ontario established the Oak Ridges Moraine Technical Working Committee (ORMTWC) in June 1991 to develop long-term strategies and legislation that would not only protect the biological and cultural integrity of the ORM, but would ensure abundant clean water, the maintenance of baseflow in head-water streams, storage in kettle lakes, and sustainable use of water by residents on and adjacent to the moraine (Oak Ridges Moraine Technical Working Committee, 1994a, b).

GEOLOGICAL FRAMEWORK OF THE OAK RIDGES MORAINE

The geology of the ORM was discussed as early as 1863 by Logan, but the first surficial geology map of the ORM was produced for the Ontario Research Foundation in 1951 by L.J. Chapman

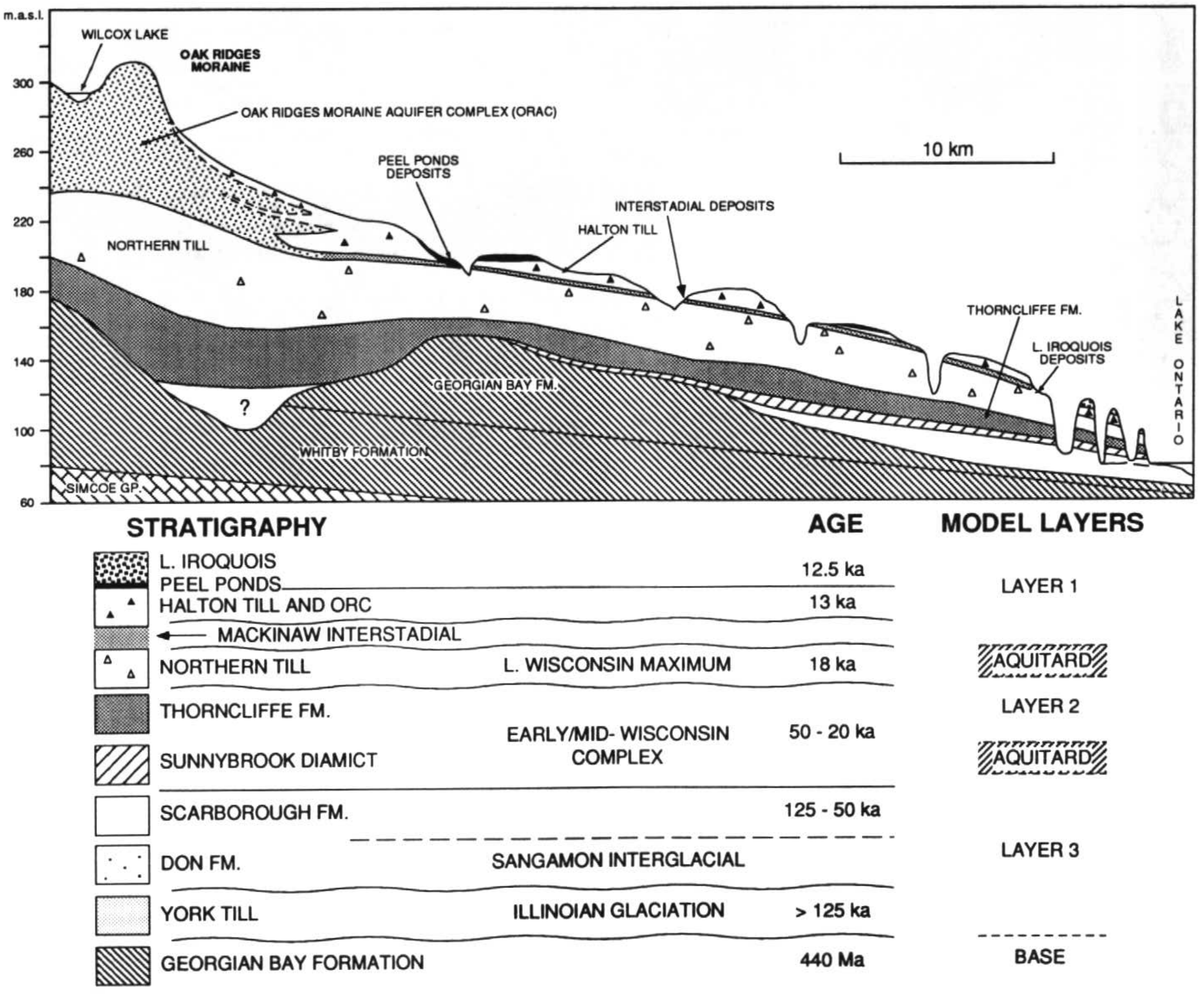

Figure 5 *Highly schematic north-south cross-section through the ORM south to Lake Ontario and component stratigraphy and hydrogeological behaviour. Layers 1, 2 and 3 identify modelled layers discussed in text (see Fig. 11).*

and D.F. Putnam. The deep stratigraphy of the ORM has only recently been explored using high-resolution seismic reflection surveys, drilling, geophysical borehole logging, coring, outcrop description, and queries of computerized water well records (*e.g.*, Fig. 4). The regional geology of the study area consists of thick Late Pleistocene glacial sediments (Fig. 5) resting on southwesterly dipping Lower Paleozoic strata which, in turn, cover a complexly structured basement of mid-Proterozoic age (Eyles, in press).

Location of the Oak Ridges Moraine

Funk (1977) suggested that the west-east alignment of the ORM reflected the existence of an underlying ancestral bedrock drainage divide; recent data confirm this. The position of the ORM is controlled by the topography of the underlying Paleozoic bedrock surface, which shows a prominent west-east trending bedrock high (informally named the Pontypool ridge by Eyles *et al.*, 1993; Fig. 6). A narrow, northeast-trending bedrock valley punctures the ridge, extending northward to Lake Simcoe, as a result of selective erosion along fractured Paleozoic strata lying above a thrust zone in underlying mid-Proterozoic basement strata (the Central Metasedimentary Belt Boundary Zone; see Eyles, in press). To the west, the ORM rests on a thick Late Pleistocene stratigraphy, selectively preserved in a major bedrock low (the Laurentian Channel), that connects Georgian Bay and the Lake Ontario basin and which formerly carried the drainage from the upper Great Lakes to the St. Lawrence River (Spencer 1881, 1889; Fig. 6). The Laurentian Channel has played a fundamental role in allowing the preservation of a thick Late Pleistocene stratigraphy in southern Ontario that contains significant aquifers.

Glacial Stratigraphy of the Moraine

The deeper Late Pleistocene glacial strata infilling the Laurentian Channel and related bedrock channels below the ORM comprise strata from the Illinoian glaciation (York Till; >100 ka), the last (Sangamon) interglacial (Don Formation, *ca.* 80 ka) and the early and middle phases of the last (Wisconsin) glaciation (Scarborough Formation, Sunnybrook Diamict and Thorncliffe Formation; 60-45 ka; Fig. 5; Eyles, in press). Deltaic sands of the Thorncliffe Formation are a particularly distinct geophysical marker unit throughout the length of the Laurentian Channel (*e.g.*, Fligg,

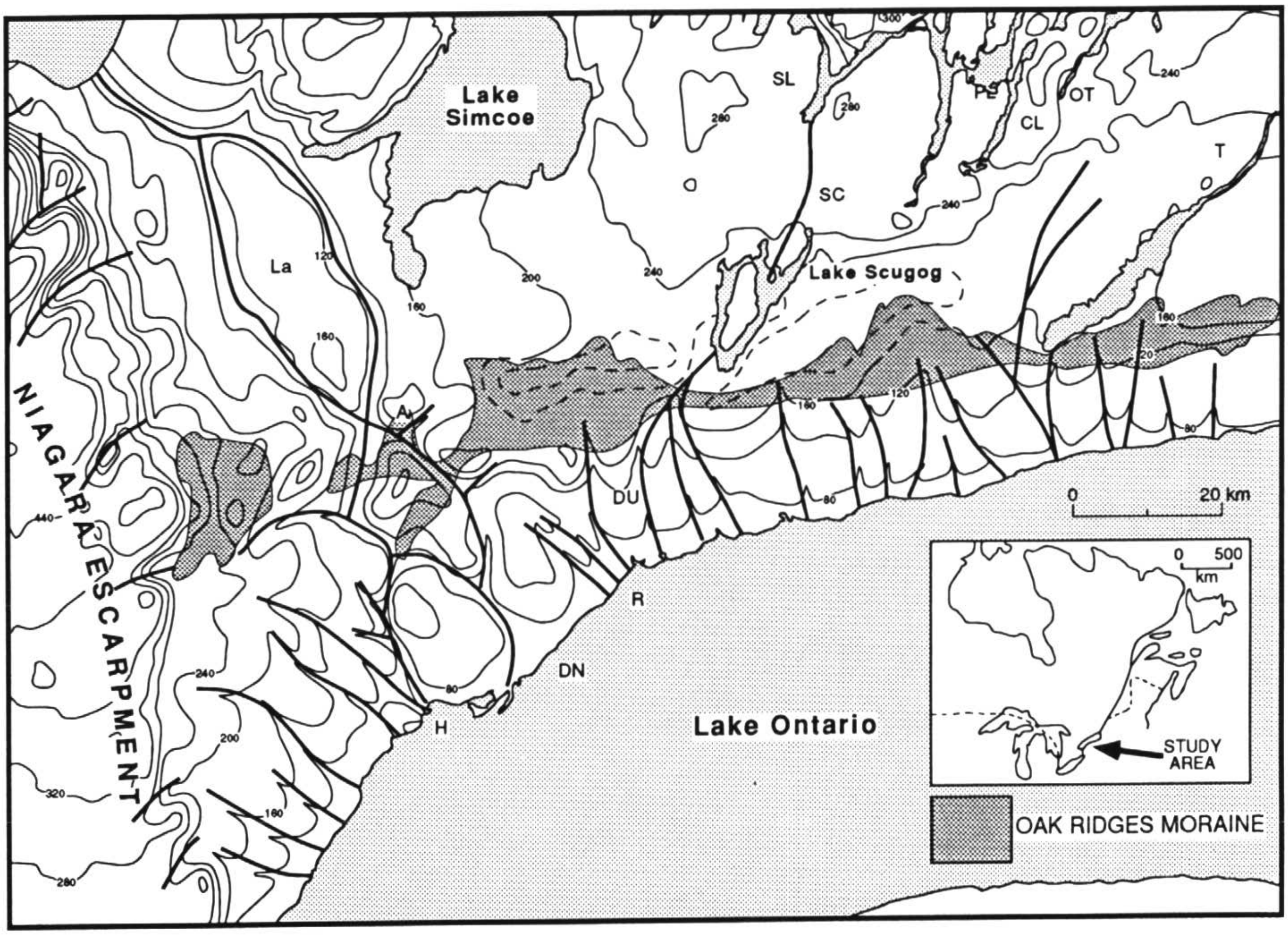

Figure 6 *The bedrock surface of south-central Ontario (after Eyles* et al., *1993). Dashed lines on bedrock contours indicate bedrock high (Pontypool ridge) which controls location of ORM. The bedrock surface shows several major channel systems; Dn, Don channel; Du, Duffins Creek channel; H, Humber channel; La, Laurentian channel; OT, Otanabee channel; R, Rouge River channels; Sc, Scugog channel; T, Trent channel. Lakes named are; BL, Balsam Lake; CL, Chemung Lake; PL, Pigeon Lake; SL, Sturgeon Lake. Lake Scugog is man-made (see text).*

1983) forming a regional aquifer system north, south and below the ORM (*e.g.*, Aravena and Wassenaar, 1993).

Late Wisconsin Events

During the main phase of the last (Late Wisconsin) glaciation (*ca.* 18 ka), the Laurentide Ice Sheet covered all of southern Ontario and extended well into New York State and Ohio (Karrow, 1989; Fig. 7A). This event resulted in deposition of the Northern till. The Northern till can be traced below the ORM and is equivalent to the Newmarket Till, mapped north of the ORM by Gwyn (1972), and the Bowmanville Till, mapped to the east by Brookfield *et al.* (1982; see also Singer, 1973, 1974; Gwyn, 1976a, b). The Northern till (up to 60 m thick) contains sheet-like sand and gravel interbeds that play a critical role in providing potential ground-water flow paths through otherwise impermeable till (Boyce *et al.*, 1995; Boyce and Koseoglu, in press; Eyles, in press; Eyles and Boyce, in press). Investigations using environmental isotopes (M.M. Dillon Ltd., 1990) and water balance investigations (Gerber and Howard, in press), suggest that a significant proportion of recharge to the confined ORM aquifer complex originates along the flanks of the ORM in areas mapped as till. Significant recharge to the deeper aquifers occurs outside the boundary of the ORM as demarcated by hummocky surface topography. This has important implications for protection of the hydrogeological integrity of the ORM and surrounding rivers and definition of the precise areas to be protected (see below).

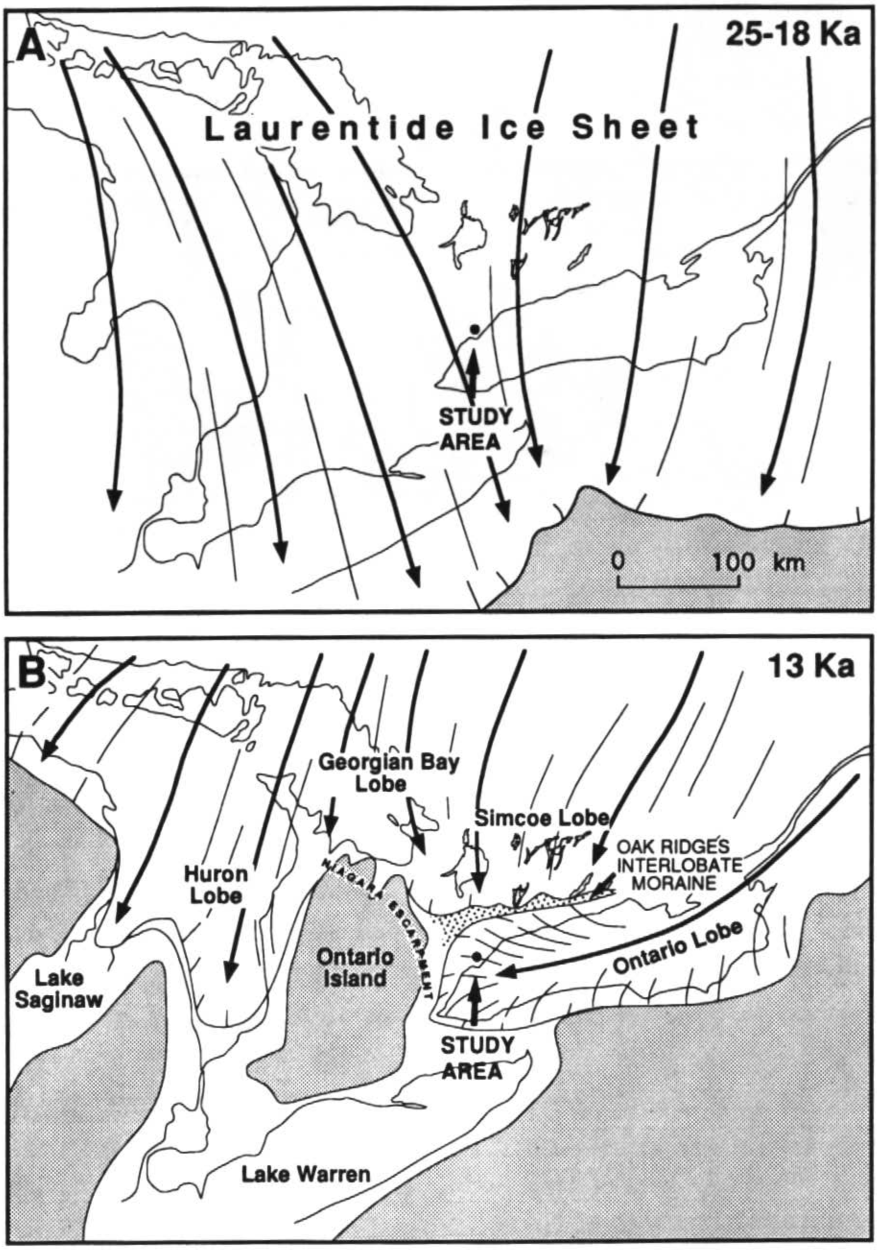

Figure 7 *Ice flow directions during* (**A**) *maximum extent of the late Wisconsin Laurentide Ice Sheet and deposition of Northern till (Figs. 4, 5, 8) and* (**B**) *during the Port Huron Stadial when the Halton Till and the ORM were deposited (after Boyce* et al., *1995).*

Formation of the Oak Ridges Moraine. Despite its thickness and wide geographic extent, the ORM records only a brief episode of glacial sedimentation at the close of the last glaciation. The ORM is classified as an interlobate moraine (Chapman and Putnam, 1984) and records sedimentation between two lobes of the Laurentide Ice Sheet during the Port Huron Stadial, sometime after 13 ka (Fig. 7B; Terasmae and Matthews, 1980). The moraine is, in fact, composed of glaciolacustrine fan-delta and outwash deposits that accumulated in an interlobate lake (Fig. 8), with water depths controlled by the elevation of overflow channels across the Niagara Escarpment in the west (*e.g.*, Duckworth, 1979; Chapman, 1985). This lake was dammed between the northwestward flowing Ontario lobe, which deposited the Halton Till south of the ORM, and the Simcoe Lobe to the north (Figs. 7, 8; Hewitt, 1969; Barnett *et al.*, 1991). Large volumes of dead ice were trapped within the lake and were buried by sediment; their later melt resulted in the many hundreds of kettle lakes that dot the moraine and impart the typical hummocky surface topography. The outer margins of the moraine show many steep slopes and deep gullies as a result of late-glacial melt-water erosion as the ice margins receded. The Halton Till is the most widespread late Wisconsin glacial unit at surface on the southern flank of the ORM (Fig. 7B). Regionally extensive sands and gravels lying between the base of the Halton Till and the Northern till were deposited during a brief ice-free episode in southern Ontario (Mackinaw Interstade; 13.3 ka; Fig. 5). The ORM area became ice free about 12 ka.

RECHARGE AND THE REGIONAL WATER BALANCE OF THE ORM

Development of regional ground-water flow models depends on a quantitative understanding of aquifer recharge, discharge and the regional water balance; these components of the regional ground-water system of the ORM have been studied on the Beaverton River, Pefferlaw Brook, Black River, East Holland River, Rouge River, and Duffins Creek watersheds (Fig. 9). Several independent approaches have been used to perform the analysis, including separation of stream and spring flow measurements and estimates of direct recharge using soil moisture balance techniques. These techniques are widely used in regional assessments of ground-water regimes, and results are described in detail by Gerber and Howard (in press).

HYDROGEOLOGICAL MODELLING OF THE OAK RIDGES MORAINE

Ultimately, quantitative ground-water flow models can be used to evaluate the potential effects of changing land use, climate and competing resource management practices in the ORM watershed, and to understand the sensitivity and sustainability of the ground-water resource. At present, hydrogeological models are being used primarily to test specific hypotheses concerning the nature and extent of deep ground-water flow and the influence of surface tills on aquifer recharge.

Ground-water flow models are being developed as a two-stage process. During the first stage, modelling work has focussed on FLOWPATH, a finite-difference steady-state flow model that can simulate ground-water flow and perform particle tracking in heterogeneous, anisotropic aquifers of two dimensions (Franz and Guiguer, 1990). FLOWPATH has been used to model a sub-domain of the regional study area (Fig. 10), thereby providing important data regarding ground-water flow paths, flow rates, and contaminant transport. As part of the second stage of the modelling work, a multi-dimensional transient ground-water flow model is under development that incorporates FLOWPATH calibrations, but has been extended in three dimensions to cover the entire ORM area. The transient model is based on MODFLOW, a United States Geological Survey finite-difference model coded by McDonald and Harbaugh (1984). MODFLOW can be used to simulate steady-state, transient, confined and unconfined ground-water flow in three dimensions or as quasi three-dimensional flow. In addition, MODFLOW allows for spatial and temporal variation of boundary conditions and recharge, and specification of any number of injection or withdrawal wells. MODFLOW has been extensively used and tested and is widely accepted as a verified model.

The governing equation on which MODFLOW is based is given by Equation 1. This equation is a mathematical

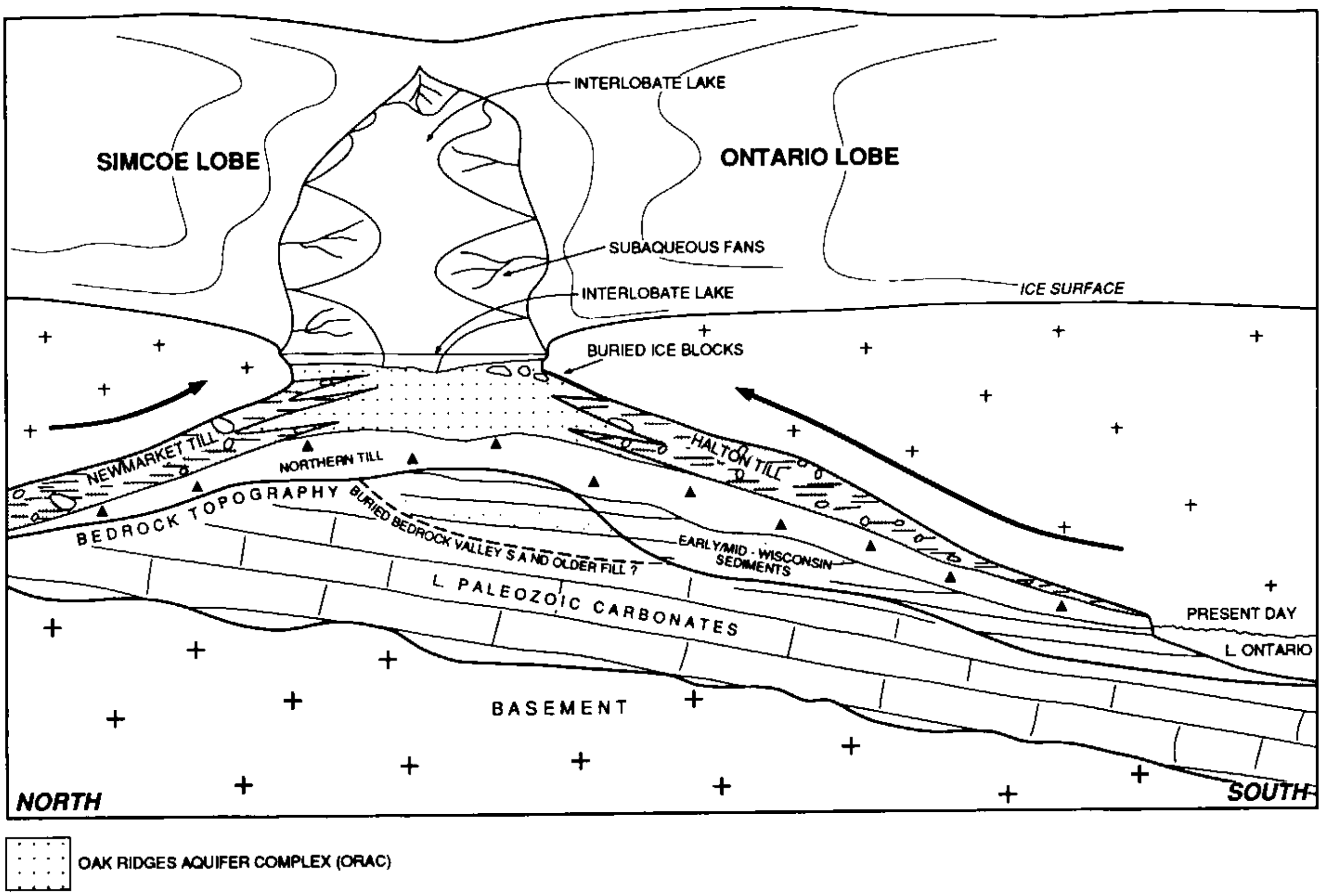

Figure 8 *Eastward looking, highly schematic view of formation of the interlobate Oak Ridges Moraine as a series of overlapping glaciolacustrine fans deposited in a large interlobate lake between Lake Simcoe and Lake Ontario ice lobes (see Fig. 7). Burial of stranded ice blocks below sediment results in the typical hummocky, kettled topography of much of the moraine. Lake level was controlled by the Niagara Escarpment in the west (Fig. 7B). The Northern till comprises an extensive aquitard below the ridge (Figs. 5, 11).*

representation of ground-water flow, which describes three-dimensional ground-water flow of constant density through porous media. K_{xx}, K_{yy}, K_{zz}, are values of hydraulic conductivity along the x, y and z co-ordinate axes, which are assumed to be aligned with the principal axes of hydraulic conductivity; h is the potentiometric head; W is the volumetric flux per unit volume and represents sources and/or sinks of water; S_s is the specific storage of the porous material; and t is time (Table 1). Hydraulic conductivity (K) is a measure of the ease with which water passes through a medium. The storage coefficient refers to the amount of water that an aquifer releases from, or takes into, storage. Equation 1 describes ground-water flow under non-equilibrium conditions in a heterogenous and anisotropic medium. The solution to this equation yields values of hydraulic head (water levels) at specific points and time.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t} \qquad (1)$$

MODFLOW employs the finite difference method to solve Equation 1; detailed derivation of this method is given by Rushton and Redshaw (1979). Essentially, the finite difference method involves approximating the partial derivatives ∂x, ∂y and ∂z by discretizing the problem domain into a large number of smaller subdomains, which are termed blocks or cells, and approximating the partial derivative ∂t using discrete time

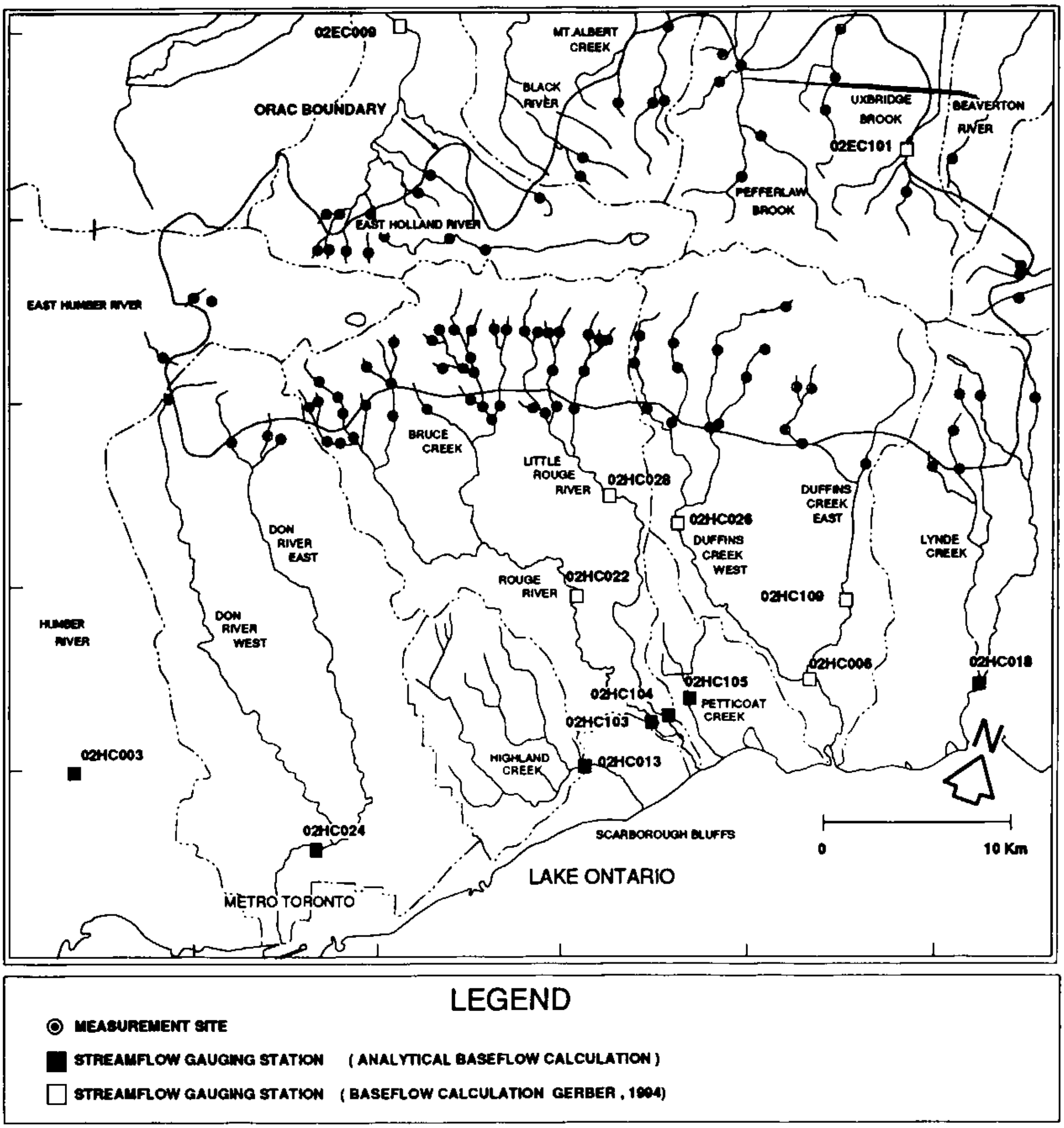

Figure 9 *Streamflow measurement sites and gauging stations.*

steps (Mercer and Faust, 1992). Each finite difference block contains a node, and the collection of blocks produces a rectangular grid. This grid is superimposed over the study area, and each block is assigned aquifer parameters appropriate to the field situation. To fully define the flow regime, internal sources, sinks and boundary conditions must also be specified.

For the purposes of MODFLOW, the regional ground-water flow regime of the ORM is defined as being bounded by Lake Ontario in the south, Lynde Creek in the east, the East Humber River to the west, and the furthest extent of the ORM to the north (Fig. 10). Aquifers in this region have been divided into a three-layer system consisting of an upper sand and gravel complex of the moraine proper (Oak Ridges Aquifer Complex; 200-325 masl), an intermediate aquifer (equivalent to the Thorncliffe Formation; 140-215 masl), and a lower aquifer defined between bedrock and 140 masl (Scarborough Formation; Figs. 5, 11). Model transmissivities were estimated on the basis of aquifer lithology and thickness; aquifer recharge and the regional water budget data were obtained using various methods described above (Table 1). Recharge zones are shown in Figure 12. A steady-state version of the model has been calibrated by comparing potentiometric heads and streamflows generated by the model with comparable field data.

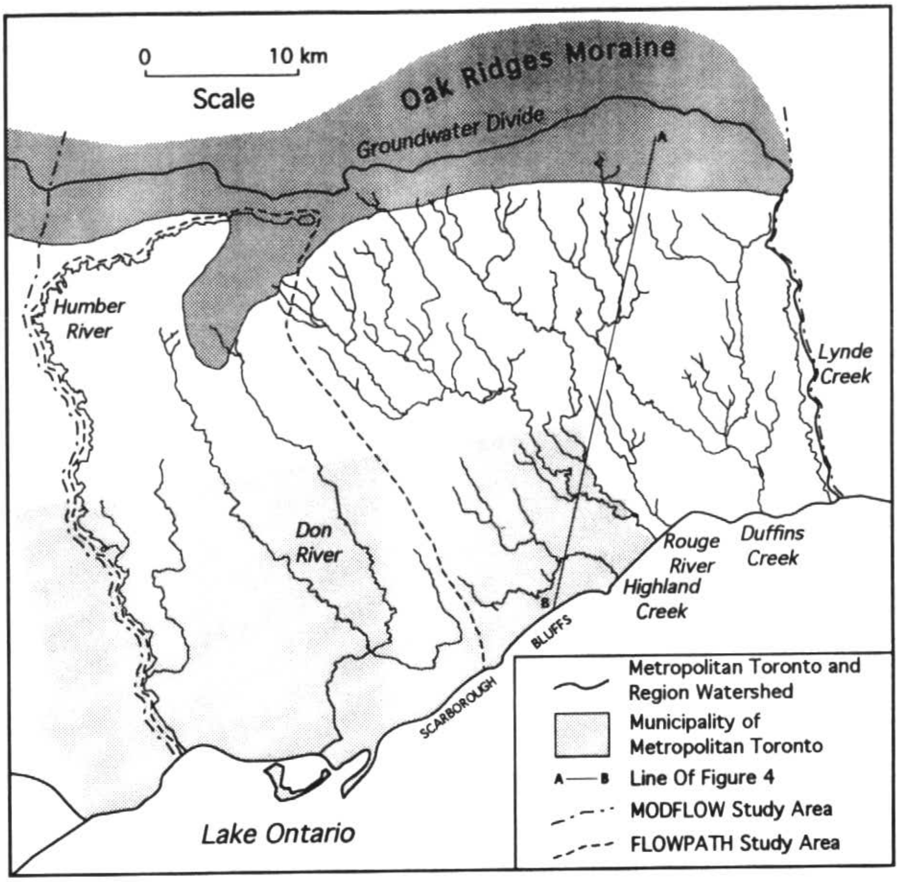

Figure 10 *MODFLOW and FLOWPATH study areas (from Smart, 1994). The line of section for Figure 4 is also shown.*

Table 1 Input parameters for transient ground-water flow modelling (MODFLOW). All model units are in metres (L) and days (T); recharge has been converted to mm·a^{-1} to maintain consistency with recharge estimates in the study area (Gerber and Howard, in press).

Parameter	Dimensions	Range
Hydraulic Conductivity (K_x,K_y)	L/T	0.1-10
Transmissivity (T_x, T_y)	L^2/T	1.0-4000
Specific Yield (Sy, unconfined aquifer)	dimensionless	0.25-0.06
Storativity (S, confined aquifer)	dimensionless	0.005-0.00001
Layer Thickness Unconfined (bottom elevation) Confined (top and bottom elevation)	L	10-80
Recharge	L/T	0 mm·a^{-1}-450 mm·a^{-1}
Leakance	T^{-1}	1.0×10^{-1}-1.0×10^{-8}

Potentiometric Surface

The potentiometric surface of the Oak Ridges Aquifer Complex (ORAC; Fig. 12A) is a subdued replica of the surface topography of the moraine, and ranges from 320 masl in elevation at the centre of the complex to 220 masl along the flanks. Water levels are highest in the east, where the drainage basin divide separates the Rouge River Basin and the Duffins Creek Basin to the south from drainage basins to the north, and far northwest, where a drainage basin divide separates the Humber River basin from the Holland River basin. These high water levels are roughly coincident with the crest of the ORM, and form the regional ground-water divide. Local highs up to 290 masl occur at the northern extent of the Don River drainage basin, and are due to perched aquifer systems situated above the regional ORAC water table.

The regional horizontal hydraulic gradient averages 0.012. Horizontal gradients range from 0.004 near the centre of the complex to 0.025 at discharge points such as East Duffins Creek and the East Holland River. Ground-water contours deflect around tributaries of major streams originating on the moraine, indicating a significant contribution of ground water to these streams. Along the northern and southern boundaries of the ORAC, regional horizontal gradients increase to 0.017. Ground-water contours are grouped closer together in these areas, due to a decrease in transmissivity resulting from aquifer deposits interfingering with the less permeable Halton and Northern tills that flank the ORM (*e.g.*, Fig. 4).

Simulated Water Levels in the Oak Ridges Aquifer Complex

The steady-state model was calibrated, in part, by comparing model heads (Fig. 13B) with the observed potentiometric surface (Fig. 13A). A good correlation is obtained. Model heads rise from 230 masl along the southern boundary of layer 1 to 320 masl at the centre. A ground-water divide runs generally east-west across the moraine, and this is also well represented by the model data. In general, regional hydraulic gradients are well reproduced, but increased gradients observed near the northern and southern boundaries of the complex are not well represented. The highest gradients are observed at discharge points such as East Duffins Creek and the East Holland River, and most contours deflect around streams in sympathy with the field data. Since no effort was made to simulate the perched aquifer systems, local water level highs in the north Don River basin are not reproduced by the model.

The quality of the simulation can also be established by a statistical analysis of the field heads and model heads. The difference between these values is known as the residual head. In general, a good calibration is achieved if 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. The mean error for the ORAC model layer (layer 1) is -0.5 m, and the standard deviation is 8 m, which are both within acceptable limits. Model heads are plotted against field heads in Figure 14; a perfect calibration is achieved when points fall along the 1:1 line. It can be seen from the figure that most data points fall close to the straight line, with a few anomalous highs. Most of these anomalies are caused by perched water tables or by high gradients along the northern and southern boundaries of the ORAC, which are not well simulated by the model.

Simulated Flow in the Oak Ridges Aquifer Complex

A fundamental element of the calibration process has been to determine whether the model generates the correct ground-water flux. Commonly, this is achieved by comparing model outflows with baseflow observed in receiving streams (Table 2). The influence of receiving streams on regional flow is shown by the ground-water flowlines on Figure 15. Under steady-state ground-water flow conditions, the total ground-water inflow to the model is balanced by ground-water outflow. To estimate outflow, more than 100 stream and spring flow measurements were taken around the boundary of the ORM during a summer dry spell. Flow measurements were subject to error depending on the size, cross-sectional shape, and flow conditions of the stream. However, comparisons to permanent stream gauge stations in the Holland River, Black River, and Mt. Albert Creek basins suggest that the estimates are within ±30%. In basins containing only a few headwater tributaries, errors of this magnitude are small in comparison to total ground-water fluxes. However, measurement errors become much more significant in basins such as the Rouge River and Duffins Creek, which are fed by many tributaries. For this reason, while many streamflow measurements were taken in the Rouge and Duffins basins, greater reliance is placed on gauging station data for estimating outflows in these basins.

Model outflows are compared with field outflow estimates in Figure 16. A good correlation is generally observed, with the exception of East Duffins Creek, where it is suspected that additional inflows are being received from neighbouring basins to the east, possibly as a result of the buried bedrock channels shown in Figure 6. Under steady-state conditions, total ground-water outflows will match the incoming recharge. Based on recharge calculations, baseflow studies, and model behaviour, total recharge to the model layer 1 is 5.55×10^5 $m^3 \cdot d^{-1}$ and model outflow to streams, springs and marshes is 2.55×10^5 $m^3 \cdot d^{-1}$. The remaining 3.00×10^5 $m^3 \cdot d^{-1}$ represents the amount of water which must infiltrate or leak *via* the Northern till to deeper aquifers contained within bedrock channels.

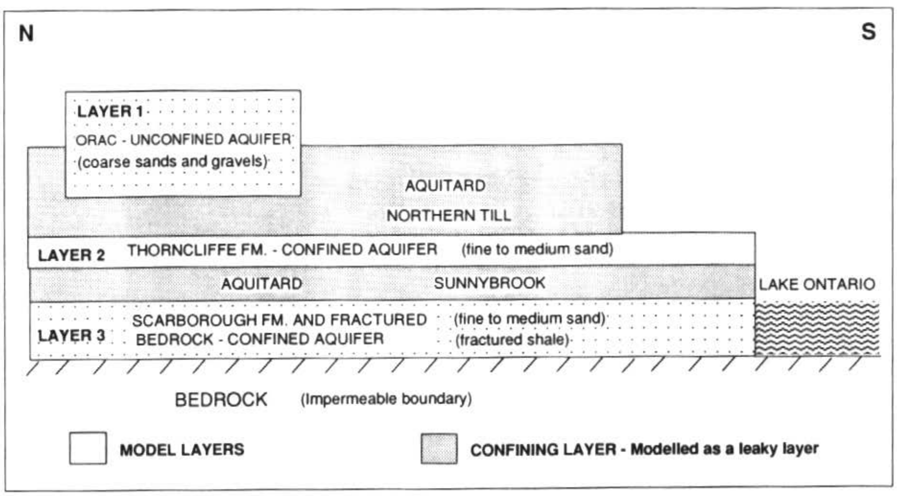

Figure 11 *Design of quasi three-dimensional ground-water flow model based on north-south stratigraphy shown in Figure 5 (from Smart, 1994). The figure identifies model layers only and does not attempt to portray thickness or extent (see Fig. 4).*

Model Leakance

The model is referred to as a quasi three-dimensional ground-water flow model because intervening aquitard layers are not explicitly represented. A quasi three-dimensional model uses a leakage term, referred to as leakance, to simulate the effects of an aquitard layer.

Model leakance is used to simulate the behaviour of an aquitard, *i.e.*, a layer that has a lower hydraulic conductivity than overlying or underlying aquifers. Leakance and "leakage" are related, but differ in the following manner: leakance is equal to the hydraulic conductivity of an aquitard divided by the thickness of the aquitard, whereas leakage refers to the rate at which water is transmitted across the aquitard (as a volume per unit time).

Leakance was used to simulate the influence of the Northern till. This unit has been widely used as a substrata for landfills, but problems are emerging with higher-than-expected ground-water flows through the till (see Boyce and Koseoglu, in press; Eyles, in press; Eyles and Boyce, in press; Gerber and Howard, in press). Leakance values were estimated using hydraulic conductivity values typical of till deposits and using an arbitrary aquitard thickness of 10 m. Hydraulic conductivity values typical of till deposits range from 1×10^{-1} $m{\cdot}d^{-1}$ (1×10^{-4} $cm{\cdot}s^{-1}$) to 1×10^{-6} $m{\cdot}d^{-1}$ (1×10^{-9} $cm{\cdot}s^{-1}$) (Freeze and Cherry, 1979). Based on these hydraulic conductivity estimates and an aquitard thickness of 10 m, the leakance values used during the calibration of the model ranged from $1\times10^{-1}{\cdot}d^{-1}$ to $1\times10^{-8}{\cdot}d^{-1}$ (Table 1).

In order to calibrate the model, two leakance zones, which are within an order of magnitude, were used: one with a value of $2.5\times10^{-5}{\cdot}d^{-1}$ and the other with a value of $1\times10^{-4}{\cdot}d^{-1}$. In general, the lower leakance value was applied to the central portion of layer 1, and the higher leakance value was applied to the perimeter of layer 1. These leakance values convert to a hydraulic conductivity of 2.5×10^{-4} $m{\cdot}d^{-1}$ (2.8×10^{-7} $cm{\cdot}s^{-1}$) for the central portion and 1×10^{-3} $m{\cdot}d^{-1}$ (1×10^{-6} $cm{\cdot}s^{-1}$) for the edges of layer 1, based on a 10-m aquitard thickness. This range is in good agreement with the known hydraulic conductivity of the Northern till underlying the ORAC, and allows for reliable estimates of the amount of recharge received by aquifers underlying the ORAC as vertical leakage to be made. This deep infiltration, spread over the 849 km^2 area of the ORAC, is equal to an average infiltration rate of 129 $mm{\cdot}a^{-1}$.

A relatively high infiltration rate (156 $mm{\cdot}a^{-1}$) in the Holland River basin contrasts with a low infiltration rate (41 $mm{\cdot}a^{-1}$) obtained for the Pefferlaw drainage basin. The high downward movement of ground water in the Holland River basin is facilitated by a high recharge to the ORAC and the under-

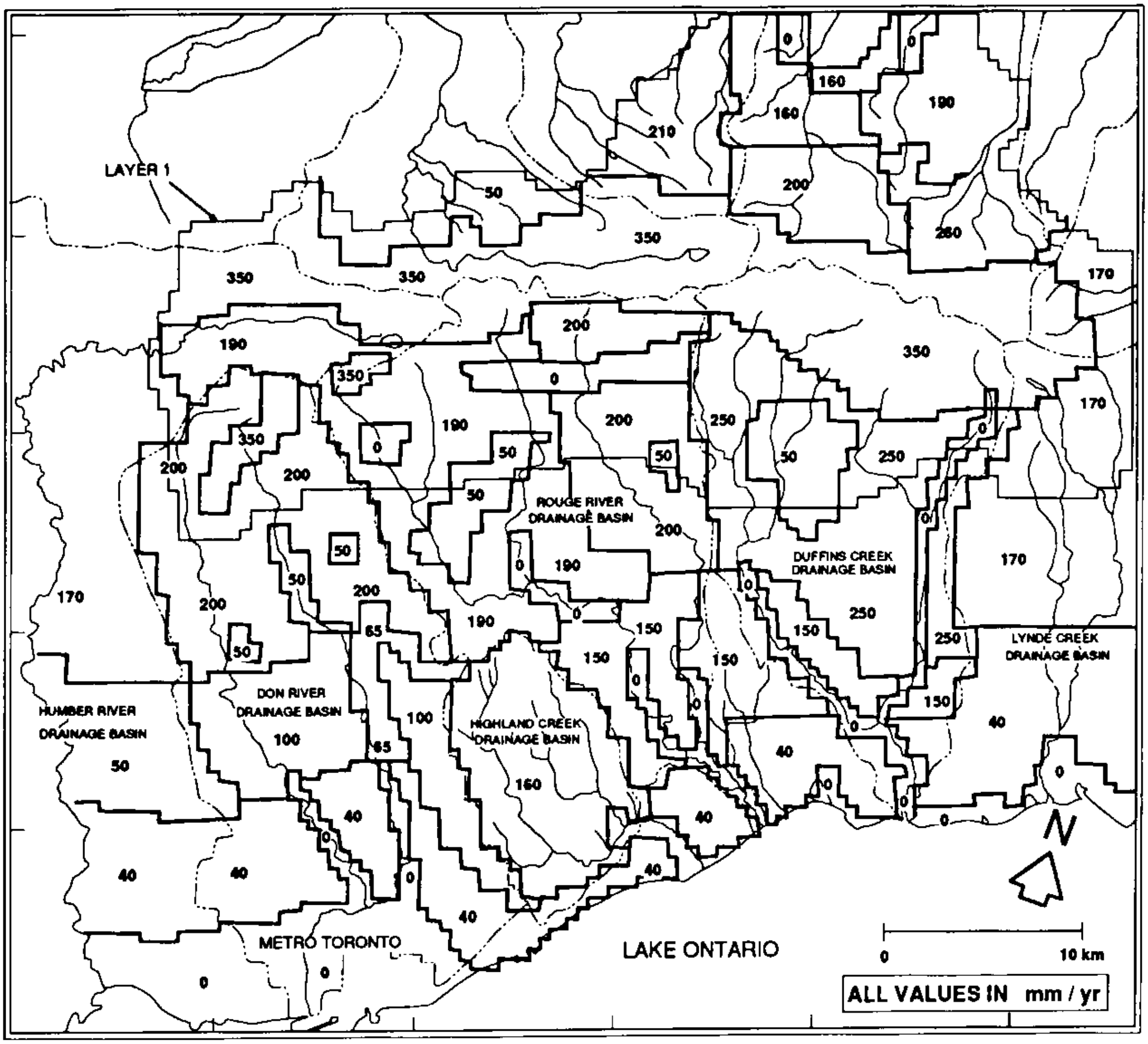

Figure 12 *Recharge zones and values used in ground-water flow model.*

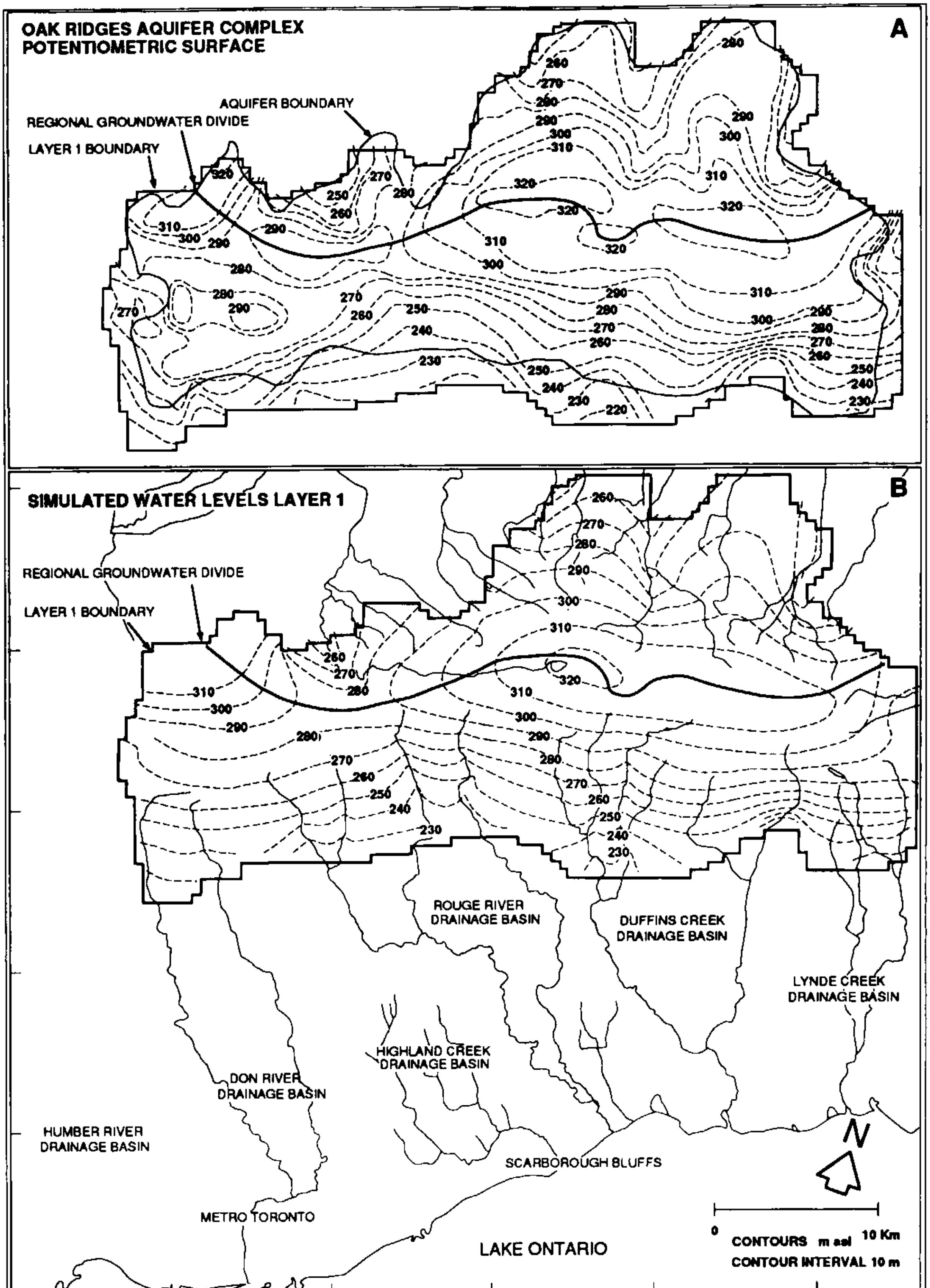

Figure 13 (**A**) *Potentiometric surface for the Oak Ridges Aquifer Complex (layer 1; Fig. 11);* (**B**) *Modelled surface. See text for details.*

drainage resulting from steep vertical gradients between the aquifer complex and deep aquifers below the groundwater divide area. Low vertical infiltration in the Pefferlaw basin is probably the result of lower vertical gradients between the ORAC and deep aquifers, and from upward gradients from deep aquifers discharging to the Pefferlaw River. These data emphasize the need for a detailed understanding of the subsurface geology across the entire ORM area in order to more closely constrain the modelling exercise.

MODEL PREDICTION FOR EXPANDED URBANIZATION

Predictive transient simulations were used to estimate the drawdown and aerial cone of depression that may result if urbanization expands onto the ORAC. The transient simulation presented here was carried out to study the effects of simultaneously increasing municipal water abstractions to the maximum capacity of the wells and decreasing recharge by 5%. In some situations, recharge losses due to urbanization can be as much as 50%, which, for example, would decrease recharge in a temperate climate from 300 $mm \cdot a^{-1}$ to 150 $mm \cdot a^{-1}$ (Smart, 1994).

Recharge losses can be supplemented with the use of soak aways and infiltration ponds; however, recent studies in the Oak Ridges Moraine area indicate that, even with these protective measures, recharge will be depleted by at least 5% (Gore and Storie, 1993). For the purposes of this simulation, recharge was decreased for layer 1 by 5%, representing moderate urbanization with population densities approximately equivalent to the Aurora-Newmarket area. The model was allowed to reach a new steady state in response to the stress. In practice, it may take tens of years to reach the predicted drawdowns. The decline in water levels and the cone of depression surrounding the municipal wells are shown in Figure 17. Water levels are predicted to decline up to a maximum of 5 m, which occurs at the community of Oak Ridges, and 1 m to 3 m in outlying areas. A second simulation, in which recharge to layer 1 was decreased by 10% and municipal water abstractions were raised to twice the existing maximum capacity of the wells, caused a widespread decline of water levels. A maximum decline of 19 m was observed in the community of Oak Ridges; in several other areas, water level depressions approached 11 m. As anticipated, both simulations caused a significant reduction in the discharge of groundwater to head-water streams originating along the flanks of the moraine. It should be noted that the model has not been fully calibrated in transient mode due to a lack of long-term data. However, predicted drawdowns are consistent with observed declines in the Aurora-Newmarket area (International Water Consultants, 1991).

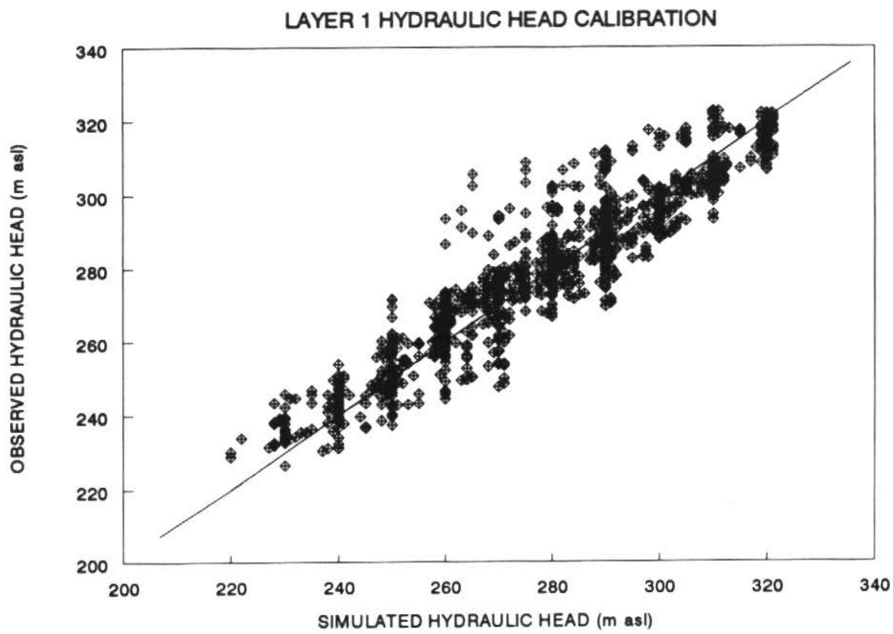

Figure 14 *Observed hydraulic head plotted against simulated head. See text for details.*

Table 2 Ground-water inflows and outflows; all values in $m^3 \cdot d^{-1}$. Measured and calculated outflows in italics.

	INFLOWS			OUTFLOWS		
	RECHARGE	LEAKAGE	RIVER AND DRAIN BOUNDARY	LEAKAGE	GENERAL HEAD BOUNDARY	CONSTANT HEAD BOUNDARY
LAYER 1	555,000	255,000	300,000 *267,000*			
LAYER 2	283,800	300,000	350,400	158,000	75,400 *75,600*	
LAYER 3	85,200		211,000		18,000 *16,000*	14,200 *7,500*
Total Simulated Baseflow	816,400			Total Calculated Baseflow		*770,600*

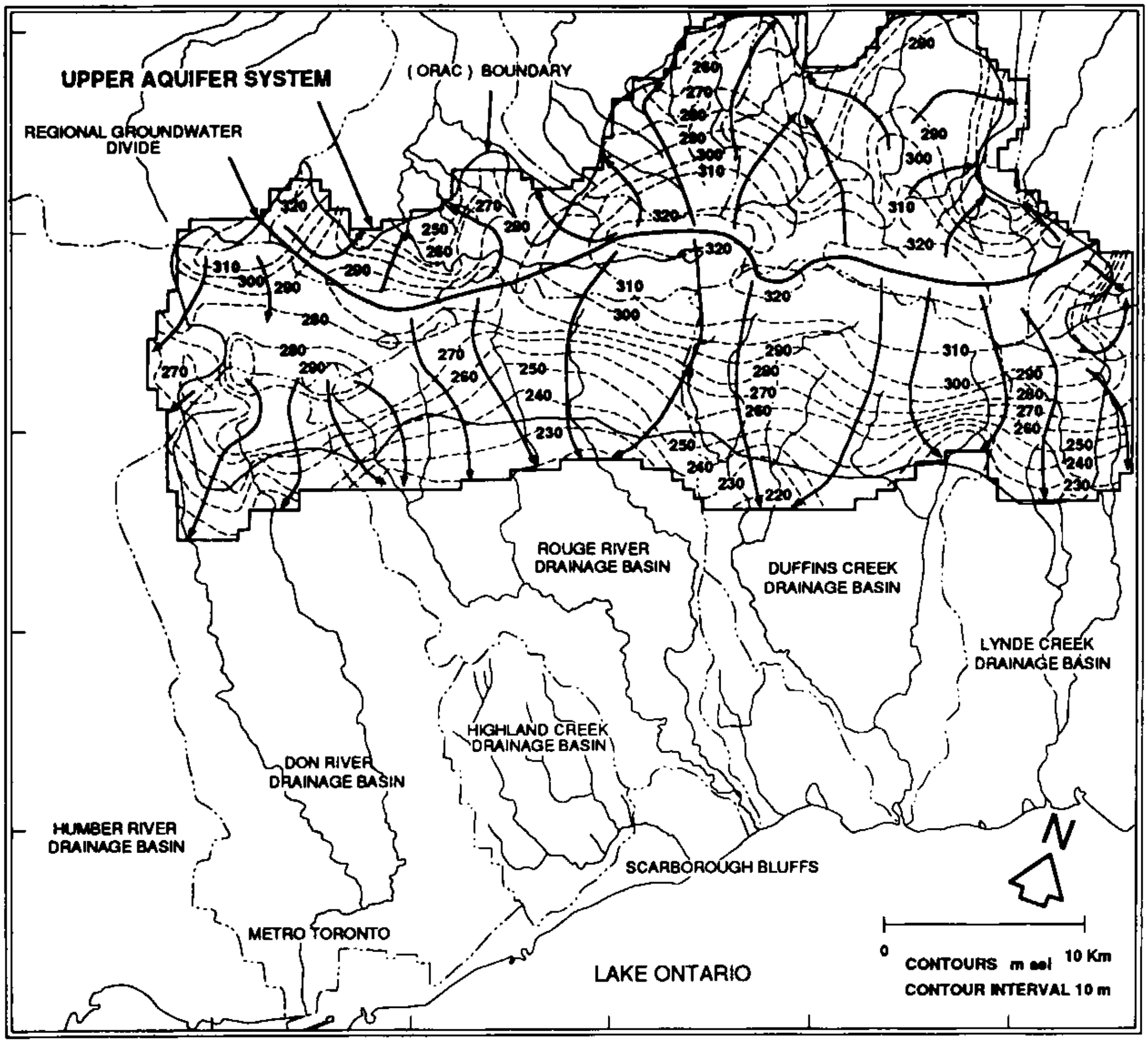

Figure 15 *Regional flowlines for the Oak Ridges Aquifer Complex (layer 1; Figs. 5, 11).*

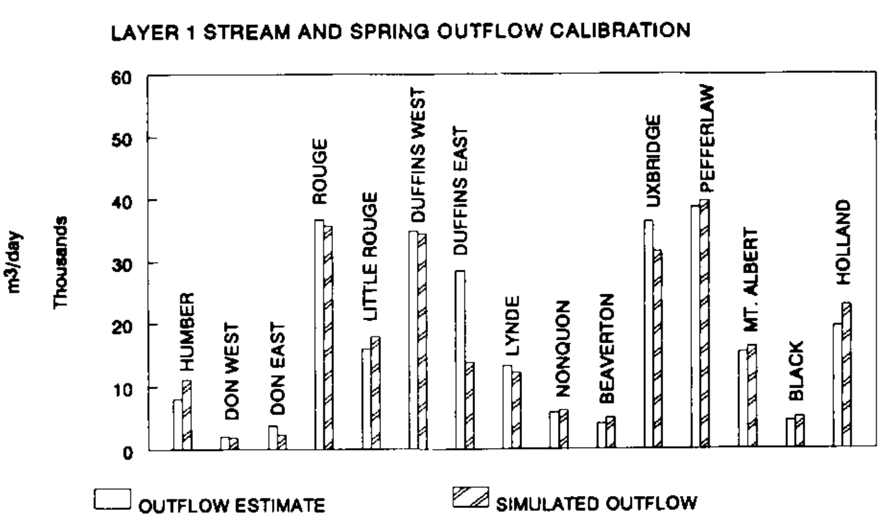

Figure 16 *A comparison of model outflows with field-based estimates.*

The model also allows estimates to be made of travel times for pollutants that enter the ORAC from septic systems and landfills and from other land uses. Smart (1994) showed that conservative inorganic contaminants (*i.e.*, those such as chloride or nitrate) which undergo no adsorption by binding to soil particles, and which travel at the average linear flow velocity of ground water released close to the ground-water divide, take more than 800 years to discharge to streams on the south slope of the ORM.

DISCUSSION

Work completed to date demonstrates the existence of a regionally extensive hydrostratigraphy within the Oak Ridges Moraine, comprising three principal aquifer systems. These include an upper sand and gravel complex (Oak Ridges Aquifer Complex (ORAC; 200-325 masl), an intermediate aquifer (equivalent to the Thorncliffe Formation; 140-215 masl), and a lower aquifer defined between bedrock and 140 masl (Scarborough Formation). Water balance and modelling studies suggest the deeper aquifers systems are recharged by the ORAC, close to the crest of the ridge, but also by recharge through the Halton and Northern tills along the moraine flanks. This finding has very important implications for managing the extent and density of urban development outside the topographically defined limits of the moraine proper.

Ground-water Management

The central issue with regard to ground-water resource management is precisely what area should be included within the ORM and be protected from further development. Interim definition of the ORM, as currently proposed by the Ontario Ministry of Natural Resources (OMNR), is arbitrarily based on the 275 masl contour because it encloses most of the hummocky, ice-contact deposits that make up the central geographical core of the moraine. Implicit in this definition is the assumption that this geographical zone includes the bulk of the Oak Ridges Aquifer Complex (ORAC), and that restricted urban development in this area will safeguard deeper aquifers. This assumption is difficult to sustain because there is good evidence that the ORM aquifer receives recharge through flanking till deposits both to the north, *via* deep bedrock channels that underdrain the moraine, and along the south slope from Richmond Hill east to Pickering. This area contains the head waters of the Don, Rouge and Duffins rivers, where the most intense developmental pressures are likely to be felt in response to proximity to the planned west-east 407 highway from Markham to Whitby and the proposed development of Seaton, a planned community of 90,000 people, in North Pickering (see Seaton Advisory Committee, 1994; Eyles, in press).

An important goal must be to develop the regional ground-water flow model into fully operational transient mode, thereby permitting the impact of various land use changes to be evaluated. The reliability of such a model will depend heavily on the ability, in the interim, to refine hydrogeological knowledge in several key areas. While the hydrogeological behaviour of the ORAC is generally well established, and geo-

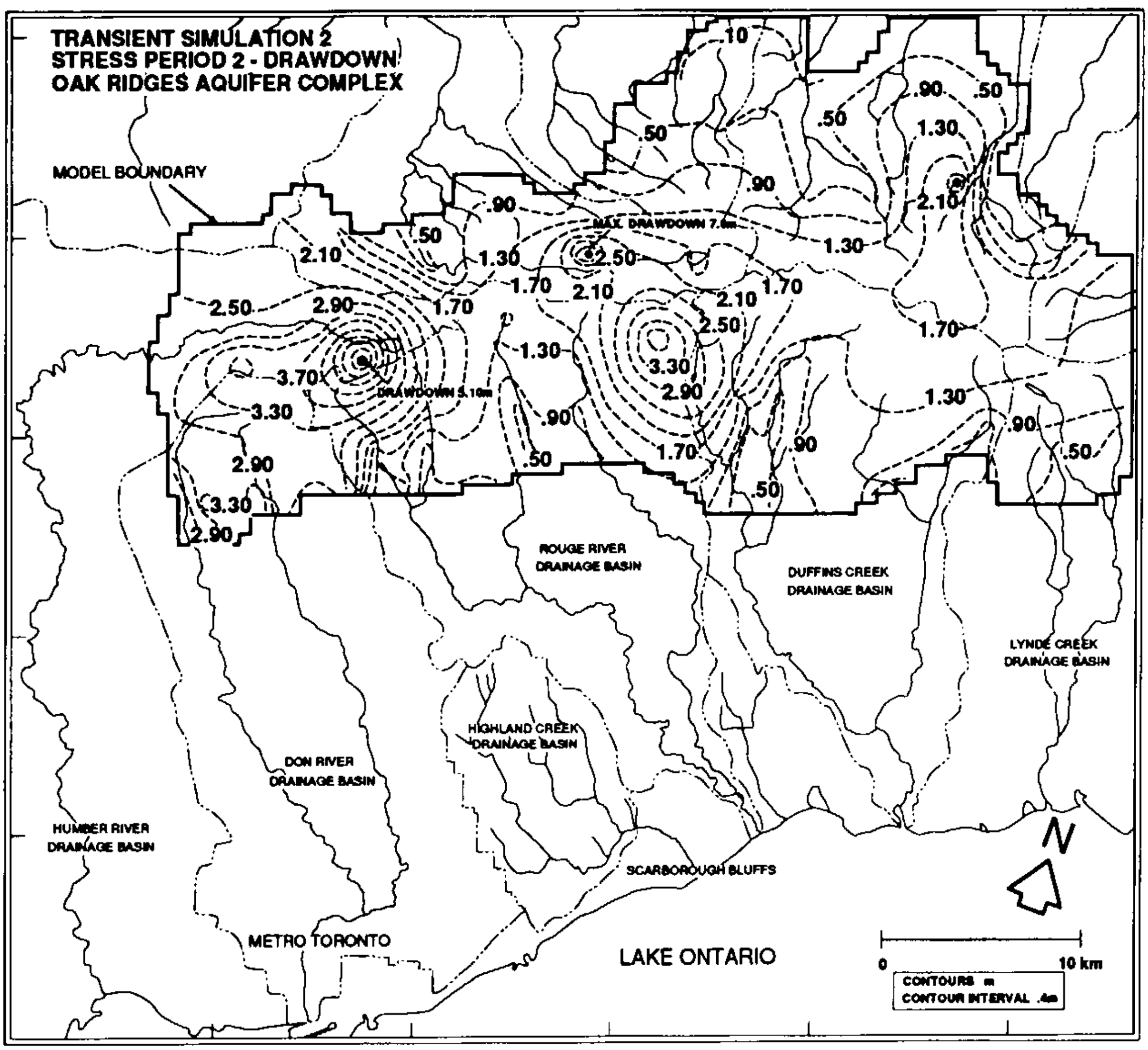

Figure 17 *Drawdown in the Oak Ridges Aquifer Complex resulting from increased municipal well abstraction.*

physical data are beginning to provide insight into the deeper stratigraphy, further hydrochemical and potentiometric data are required for the deeper aquifer units. In addition, while the till and clay deposits flanking the moraine are capable of transmitting significant quantities of water, further work is required to determine the nature of transmission, the velocities of flow, and the regional variability of these sediments. This knowledge is critical both for understanding contaminant impact potential and for quantifying the rates at which deeper aquifers are replenished *via* overlying aquitards. There remains a significant risk that the rate of urban development along and adjacent to the moraine will outpace the ability to make reliable predictions of potential impacts.

ACKNOWLEDGEMENTS

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