Hydrogeology of the Oak Ridges Moraine aquifer system: implications for protection and management from the Duffins Creek watershed

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Abstract: The Oak Ridges Moraine aquifer feeds the headwaters of major rivers in the Greater Toronto Area and is an important source of domestic water supply. Recognizing the rapid rate of urban growth in the region, there is a concern that changing land use along the moraine must be strictly controlled if groundwater is to be adequately protected. To date, efforts to incorporate groundwater protection into the land use planning process have been hampered by an inadequate quantitative hydrogeological understanding of the aquifer system. Focusing on the Duffins Creek watershed, comprehensive hydrogeological studies including a numerical flow model now provide a quantitative insight into the hydrogeologic function of the moraine. These studies demonstrate that 60% of the entire basin groundwater discharge to streams occurs along the south flank of the moraine, and 60% of this headwater discharge occurs below the 275 m above sea level contour, one of the commonly accepted planning boundaries of the moraine. The remaining discharge is contributed by aquifers within and underlying deposits that extend to the south of the moraine. While 75–80% of the watershed discharge to streams is received from the uppermost aquifer, 20–25% is contributed by deeper aquifers underlying the extensive Northern–Newmarket till aquitard. This work shows that the moraine sediments represent just one component of a regional flow system that extends beyond the morphological boundary of the moraine. This has important implications for groundwater protection, as it demonstrates the need for management strategies that incorporate the regional groundwater flow system and not the moraine in isolation.

Résumé : L'aquifère de la moraine de Oak Ridges alimente le cours supérieur de grandes rivières dans la région du Grand Toronto et constitue une importante source d'alimentation en eau domestique. Conscient du taux rapide de croissance urbaine dans la région, on croit que le changement d'utilisation des terres le long de la moraine doit être rigoureusement contrôlé afin de protéger adéquatement l'eau souterraine. À ce jour, les efforts pour inclure la protection de l'eau souterraine dans le processus de planification d'utilisation des terres ont été retardés par une connaissance quantitative hydrogéologique inadéquate du système d'aquifères. Ciblant le bassin hydrographique de Duffins Creek, des études hydrogéologiques complètes, incluant un modèle numérique de l'écoulement, fournissent maintenant un aperçu quantitatif de la fonction hydrogéologique de la moraine. Il démontre que 60 % de tout le débit souterrain du bassin a lieu le long du flanc sud de la moraine. Soixante pour cent de ce débit a lieu sous le niveau amsl de 275 m, soit l'une des limites couramment utilisées comme limite de planification pour la moraine de Oak Ridges. Le débit restant est contrôlé par des aquifères à l'intérieur et sous des dépôts qui se prolongent au sud de la moraine. Alors que 75 à 80 % du débit du bassin hydrographique vers les ruisseaux provient de l'aquifère supérieur, 20 à 25 % provient d'aquifères plus profonds sous la grande couche de till semi-perméable capacitive de Northern–Newmarket. Cette étude montre que les sédiments de la moraine ne représentent qu'une composante d'un système régional d'écoulement qui s'étend au-delà de la limite morphologique de la moraine. Cela représente des implications importantes pour la protection de l'eau souterraine car cela démontre le besoin d'avoir des stratégies de gestion qui incorporent le système régional d'écoulement de l'eau souterraine et non seulement la moraine.

[Traduit par la Rédaction]

Introduction

Throughout Canada, regional-scale understanding of groundwater flow systems is frequently lacking due to inadequate spatial and temporal data. Consequently, regional hydrogeology is rarely adequately incorporated into land use planning issues, an omission that puts both the quality and quantity of the resource at risk. In Ontario, for example, only morphologic features perceived to be "hydrogeologically sensitive" receive any serious attention (Howard 1997). This is unfortunate given that a conceptual regional hydrogeological model can often be developed for any potentially impacted system using

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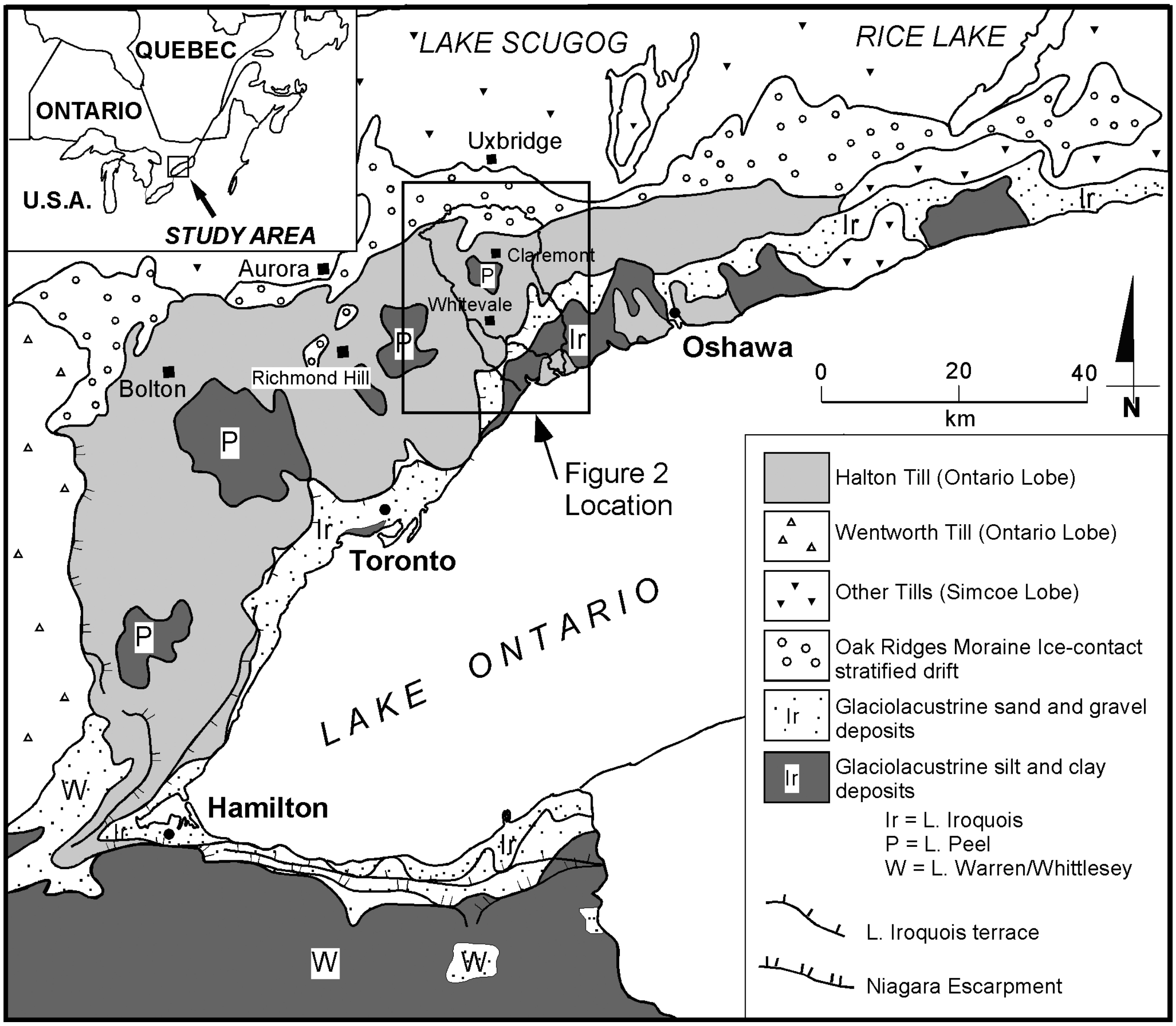
Fig. 1. Surficial geology of south-central Ontario, showing the extent of the Oak Ridges Moraine and location of the study area. Geology from Barnett et al. (1991).

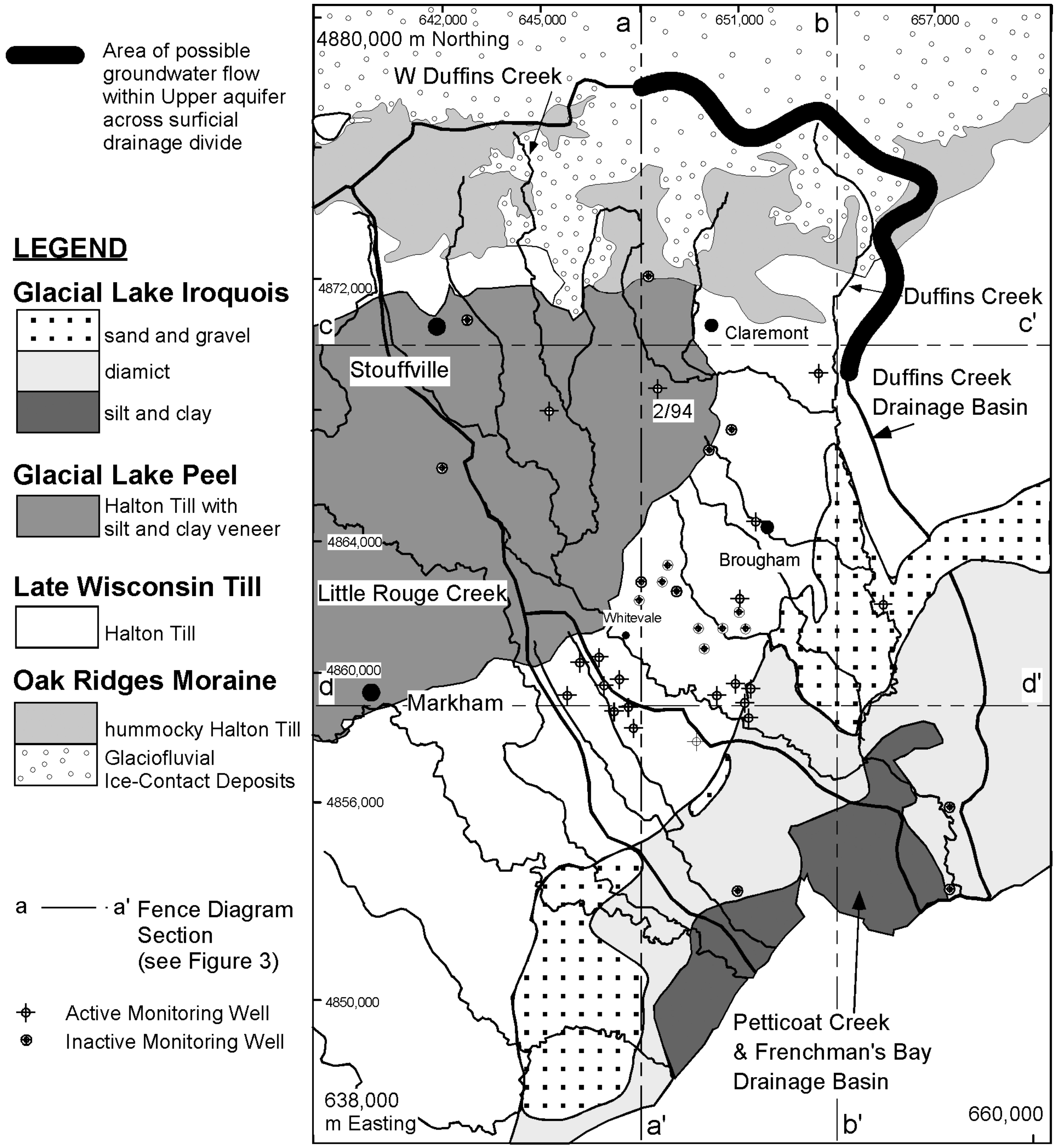


available water-well and stratigraphic data. With minor additional field data, these models can be tested, revised, and refined using numerical flow modeling techniques to provide a meaningful quantitative understanding of the system. This information can then be directly incorporated into the planning process and provide input for aquifer protection plans.

The value of this approach is illustrated here by applying it to the Oak Ridges Moraine of southern Ontario. This geomorphologic feature has been the subject of intense public and scientific debate regarding proposed urbanization. For planning purposes, the extent of the Oak Ridges Moraine is commonly defined by a combination of surficial geology and the 275 m above mean sea level (amsl) topographic contour (Intera Kenting Ltd. 1990; Hunter and Associates and Raven Beck Environmental Ltd. 1996), which generally coincides with a break in slope at the foot of the moraine ridge. Another initiative has defined the Oak Ridges Moraine Planning Area by the 245 m amsl topographic contour (Ontario Ministry of Natural Resources 1994). The moraine is widely considered as the major recharge zone for the area (Carman 1941; Haefeli 1970; Sibul et al. 1977; Turner 1978; Crombie 1990; Intera Kenting Ltd. 1990) and at issue is the assumption that land use change along the moraine will cause unacceptable impacts on both the quality and quantity of local groundwater. A historical account of land use change along the moraine and its associated impacts is provided by Howard et al. (1996).

In this paper, we present the findings of a detailed hydrogeological study of the Duffins Creek watershed (Fig. 1), part of the Lake Ontario catchment area. Using an existing steady-state, finite-difference numerical groundwater flow model described by Gerber and Howard (2000) for the area shown in Fig. 2, this work quantifies the hydrogeologic role of the moraine, describes its function as part of a regional groundwater flow system, and examines the implications of land use change along the moraine in the context of resource management and aquifer protection. The results of this study raise concerns for the adoption of groundwater protection strategies that consider the moraine in isolation and fail to consider the regional flow system that extends well beyond the morphological boundary of the moraine. The work presented has implications across Canada for the role of hydrogeology in regional land use planning issues and illustrates the need

Fig. 2. Duffins Creek study area. Surficial geology from Barnett et al. (1991). Oak Ridges Moraine deposits from Barnett (1996) and Barnett and McRae (1996). Glaciolacustrine deposits from J. Westgate (unpublished data on file with the Ontario Geological Survey). Lake Iroquois deposits from J. Westgate and Sharpe and Barnett (1997). Modified from Gerber and Howard (2000).

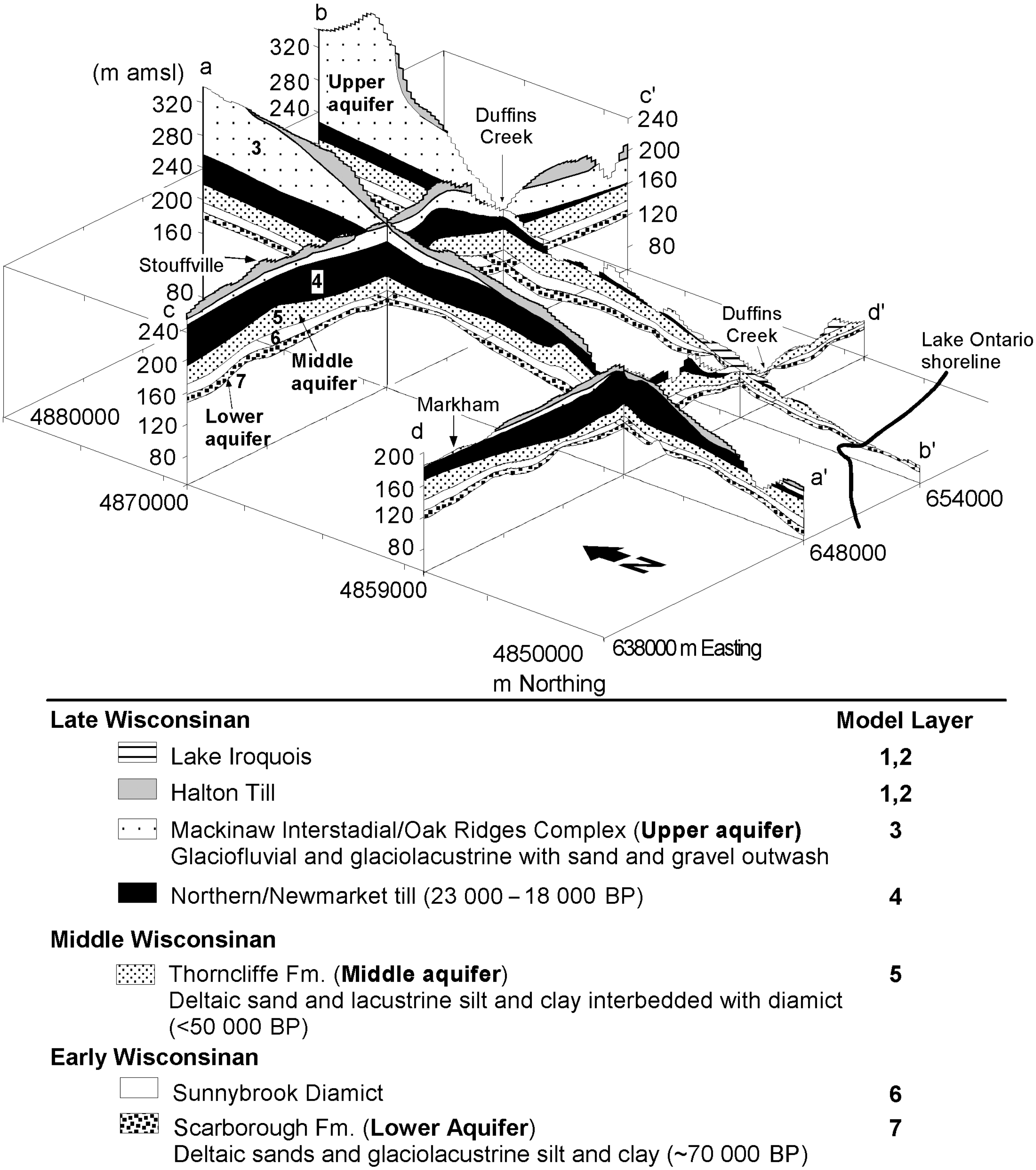


to perform studies at the watershed scale. This study, undertaken between 1996 and 2001, provides strong support for the recently published recommendations made in the Part Two report of the Walkerton Inquiry (O'Connor 2002). This report proposes that groundwater protection strategies be developed for all watersheds in Ontario, and that they incorporate water balance studies and flow models.

Geology and hydrogeology of the study area

The geology and topography of the study area are the legacy of a succession of glacial and interglacial events that led to deposition of Quaternary sediments on a bedrock surface consisting of Late Ordovician shales of the Whitby Formation (Johnson et al. 1992). This surface slopes southward from an approximate elevation of 180 m amsl beneath the Oak Ridges Moraine to approximately 50 m amsl at Lake Ontario (Russell and Stacey 2001). The bedrock surface exhibits considerable topography, consisting of north- to northwest-trending channels that extend beneath and south of the Oak Ridges Moraine (Ostry 1979; Eyles et al. 1993; Russell and Stacey 2001). Within the study area, the most pronounced bedrock

Fig. 3. Fence diagram of Quaternary deposits for the study area. See Fig. 2 for cross section locations. Layer numbers refer to numerical groundwater flow model layer number. See text for construction details and source data. Modified from Gerber and Howard (2000).



channels occur along the Duffins Creek valley and beneath Little Rouge Creek, located immediately west of the Duffins Creek watershed.

The Quaternary succession ranging in thickness from 0 (absent) to 200 m was deposited over the last 125 000 years and consists of alternating diamict and fluvial–lacustrine deltaic units (Eyles 1997) (Fig. 3) forming aquitards and aquifers, respectively. The three-dimensional (3D) arrangement of geologic units shown in Fig. 3 is constructed from borehole and water-well record information (see Gerber and Howard 2000 for details). A more detailed treatment of the geology can be found in Sharpe et al. (2002), Pugin et al. (1999), Barnett et al. (1998), Eyles (1997), and Boyce et al. (1995).

Within the study area the groundwater flow system can be subdivided on the basis of geology into three overburden aquifers: the Upper, Middle, and Lower aquifers (Fig. 3). This refines the previous classification of “shallow” and "deep" aquifers (Sibul et al. 1977) which was based on relative elevations of water-well screen clusters. From a quantity and quality perspective, the shale bedrock does not contain viable aquifers (Sibul et al. 1977).

Groundwater flow within all three aquifers is predominantly south towards Lake Ontario at regional horizontal hydraulic gradients ranging from 0.001 to 0.01 (Gerber and Howard 2000). Under natural undisturbed conditions, groundwater discharge occurs to streams and rivers. The Upper aquifer is unconfined in areas of surficial sand in the northern part of the basin and becomes confined towards the south when overlain by the Halton Till. Direct recharge due to the infiltration of precipitation occurs over most of the study area. The Middle and Lower aquifers are generally confined and recharged by downward vertical leakage through the aquitards.

Groundwater flow system analysis

To provide a quantitative understanding of the regional groundwater flow system and in particular to investigate the role of the Oak Ridges Moraine above 275 m amsl, a steady-state numerical groundwater flow model for the Duffins Creek drainage basin (herein referred to as the model) was used. The model was subsequently utilized to assess the groundwater management implications of reducing direct recharge along the Oak Ridges Moraine as a consequence of urban development.

Numerical model design and calibration

The calibrated numerical flow model for the study area was developed in a previous investigation (Gerber and Howard 2000) to estimate the regional bulk hydraulic conductivity of the Northern–Newmarket till aquitard, which separates the Upper aquifer from the deeper aquifers. The model was constructed using Visual MODFLOW (Waterloo Hydrogeologic, Inc. 1996), which provides a graphical user interface for the 3D finite-difference code MODFLOW (McDonald and Harbaugh 1988). Model details, including calibration and boundary conditions, are included in Gerber and Howard (2000) and only briefly summarized here. The model encapsulates the 3D framework of the geologic deposits shown in Fig. 3 using nine model layers with a grid discretization of 200 m × 200 m cells (110 columns and 150 rows). The configuration of the geologic layers was prepared using borehole data extracted from approximately 7000 Ontario Ministry of the Environment (MOE) water-well records, supplemented by borehole data collected from landfill (M.M. Dillon Limited 1990, 1994*a*, 1994*b*, 1994*c*, 1994*d*; Fenco MacLaren Inc. 1994), regional water resource (Sibul et al. 1977), and aquitard investigations (Gerber and Howard 1996; Boyce 1997; Gerber 1999).

Other inputs to the steady-state model include recharge and hydraulic conductivity estimates for the various geologic units. Table 1 summarizes the calibrated recharge values for the model and includes a comparison of these values with estimates obtained from streamflow separation and soil moisture balance methods (Gerber 1994; M.M. Dillon Limited 1994*d*; Gerber and Howard 1997), and regional groundwater flow modeling (M.M. Dillon Limited 1990, 1994*d*; Smart 1994). Hydraulic conductivity (K) estimates for all hydrogeologic units were obtained from slug testing, pumping tests, and specific capacity analysis. Model-calibrated estimates of hydraulic conductivity are compared with field estimates and other published values in Gerber and Howard (2000). Hydraulic conductivity anisotropy for all layers was set as $K_x = K_y$, and horizontal hydraulic conductivity was set as 10 times vertical hydraulic conductivity, i.e., K_h (K_{xy}) = $10K_v$ (K_z), consistent with values for similar deposits to the west of the study area near Waterloo (Martin and Frind 1998).

The model was calibrated to observed hydraulic heads (112 monitoring wells at 38 locations shown in Fig. 2) and estimates of groundwater discharge to streams at 17 locations (Figs. 4, 5). Model-calculated hydraulic head distributions were also calibrated to hydraulic head distributions produced from MOE water-well records in areas where monitoring wells were not available (Gerber and Howard 2000). The calibration was achieved by trial and error and involved varying recharge and hydraulic conductivity values independently within the range of estimated values until the observed heads and groundwater discharge to streams were reproduced. The root mean square (RMS) error for the calibrated heads within all three aquifers is 3.5 m. Although not calibration targets, the model spatial distribution of groundwater discharge to streams proved to be consistent with field observations of low streamflow in the summer (Hinton 1996; Kenney et al. 1996); also, model estimates of spring and aquifer discharge to Lake Ontario (700 m^3/d) compared favourably with estimates from Haefeli (1972) and Ostry (1979) (600 m^3/d).

Although the model was calibrated at steady state to the estimated annual average groundwater discharge to streams and the average annual values of hydraulic head for the period of record, it is recognized that both groundwater recharge and groundwater discharge to streams vary seasonally and from year to year depending on climatic and antecedent conditions. For the study area, groundwater recharge occurs mainly in the spring during snowmelt and in the late fall when soil moisture deficits are satisfied and evapotranspiration rates are low. It is during these seasons that the water table and aquifer hydraulic head values are highest, hydraulic gradients are greatest, and groundwater discharge to streams reaches a maximum. Groundwater discharge to streams is at a minimum when the water table and hydraulic head configuration are at their lowest. Figure 6 shows a long-term streamflow hydrograph for a site near the mouth of Duffins Creek. Flows are plotted logarithmically. Peaks on the hydrograph represent runoff in response to rain or snowmelt events, and groundwater discharge is shown by a gradual response to long-term changes in the groundwater flow system. The analysis presented here deals with an "average" groundwater flow system condition as shown by the broken line on the hydrograph (Fig. 6). With calibration to average hydraulic head and groundwater discharge conditions, the model was used to provide a quantitative understanding of the regional flow system and its annual water balance and test the sensitivity of this system to possible changes in the annual direct recharge condition resulting from urbanization. The extremes of high and low flow will be discussed in a separate paper when more transient data have been collected.

Role of the regional aquitard

As demonstrated by Gerber and Howard (2000), the groundwater flow system is largely controlled by the Northern till

Table 1. (A) Summary of unit recharge rates (mm/year) from other studies and (B) numerical model calibrated recharge for the study area.

(A) Unit recharge rates (mm/year)

	Gerber 1994	Meriano 1999	Hunter and Associates 1996[a]	Smart 1994	Singer 1981	M.M. Dillon Limited 1994d		M.M. Dillon Limited 1990 (3D)
						2D	3D	
Oak Ridges Moraine								
Ice contact	300–400	400	300–400	350	280–380			
Hummocky till		335						
Halton Till Plain	150–250	150–200		170–250	150–200	126	189	100–150
Glacial Lake Peel								
Silty clay		35		50				
Sand		200						
Glacial Lake Iroquois								
Sand and gravel		200		150				
Clay and silt				0–40	50–100			
Diamict					50–100			
Urban		50		0–40				

(B) Model-calibrated recharge for the study area

	Total area (km^2)	Recharge area (km^2)[b]	Percentage of recharge area	Recharge[c]		Percentage of recharge
				mm/year	m^3/d	
Duffins basin	282					
Petticoat basin	54					
Oak Ridges Moraine						
Ice contact	40	35	13	400	38 800	31
Hummocky till	39	36	13	325	31 800	25
Halton Till Plain	111	85	30	150	34 900	27
Glacial Lake Peel	58	50	18	50	6 800	5
Glacial Lake Iroquois						
Sand and gravel	24	20	7	200	10 800	9
Silt and clay	34	32	11	25	2 200	2
Diamict	30	25	9	25	1 700	1
Total	336	282	100		127 000	100

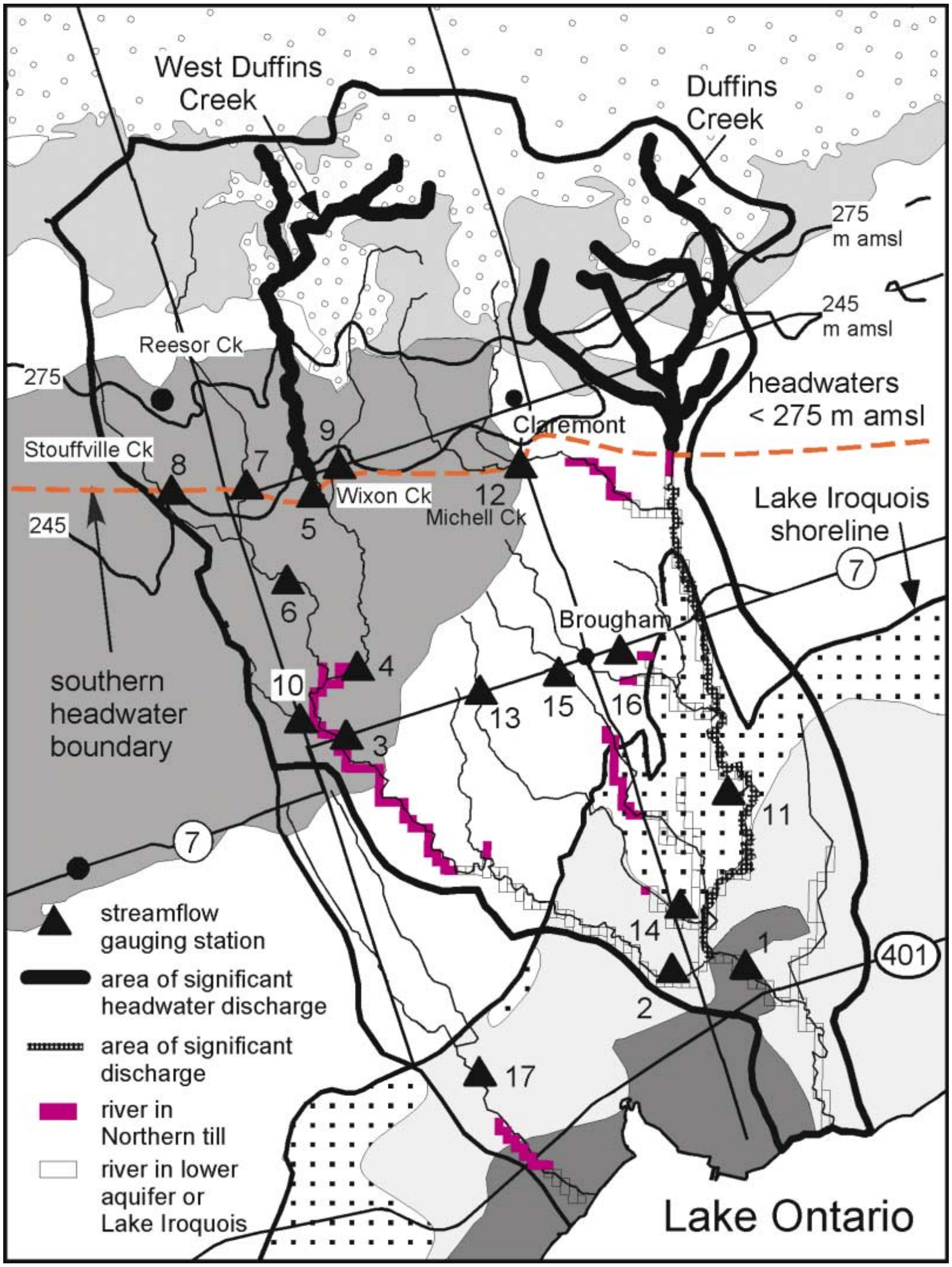
Note: See Fig. 2 for deposit locations.
[a]Hunter and Associates and Raven Beck Environmental Ltd. (1996) estimate for Oak Ridges Moraine >275 m amsl.
[b]Total area minus area of river and river valley cells where discharge occurs.
[c]Unit recharge rates from Gerber and Howard (2000).

aquitard, a relatively low permeability unit that separates the Upper aquifer from the two deeper aquifers. The regional bulk Northern till vertical K_v is estimated to range from 5×10^{-9} to 5×10^{-10} m/s, with a regional vertical downward Darcy flux or an average unit leakage rate of 35–40 mm/year over the study area. This vertical leakage is the primary source of recharge to the Middle and Lower aquifers and represents less than 27% of direct recharge to the Upper aquifer and water table via the Oak Ridges Moraine and Halton Till deposits. Although total groundwater flux to the deeper aquifers is relatively low, the presence of tritiated water (Gerber and Howard 1996) indicates that vertical downward groundwater flow velocities through the Northern till may be quite high, on the order of 1 m/year or less. These high velocities are attributed to the presence of heterogeneities within the till which impart an internal aquitard stratigraphy consisting of tabular till beds (elements) separated by laterally continuous, sheet-like sands and gravels (interbeds) and boulder pavements. Individual till elements contain sedimentary heterogeneities over several length scales, including discontinuous sand and gravel lenses, thin (<2 cm) sand dykes, diapirs, and zones of complexly deformed lacustrine sediments. Locally, the till matrix shows zones of horizontal and vertical fracturing and subvertical shear planes (Gerber et al. 2001). The presence of hydraulic interconnections or interaction between shallow and deep aquifers is consistent with groundwater hydrochemistry patterns outlined by Howard and Beck (1986). It should be noted that breaches through the Northern–Newmarket till are reported to occur within south-central Ontario which may allow for increased recharge to the underlying aquifers depending on the channel-fill sediments (Sharpe et al. 2002). Within the study area, the Northern–Newmarket till has been eroded over much of the southeastern part of the basin south of the Lake Iroquois shoreline. This area largely functions as a groundwater discharge area for the deep aquifers. Using the terminology of Sharpe et al. (2002), recharge to the deep aquifers within the study area can be considered to occur through the Newmarket till upland hydrogeological terrain.

Recharge, leakage, and groundwater travel times

Although the Oak Ridges Moraine forms a major recharge

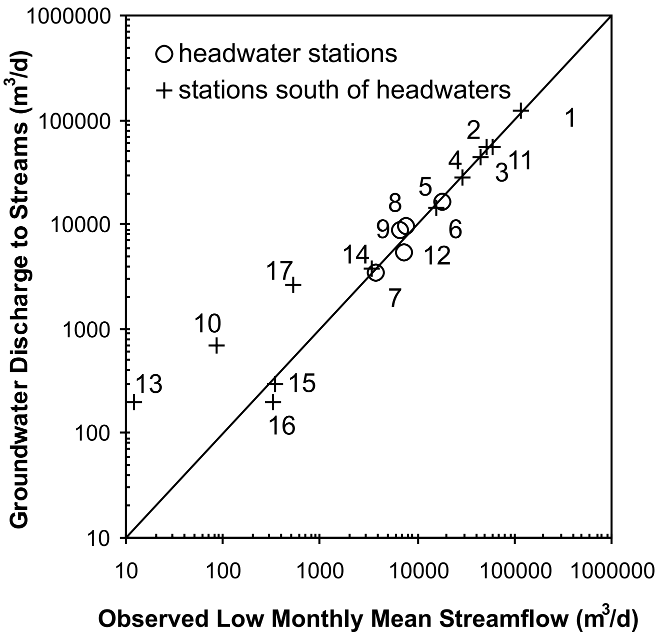
Fig. 4. Significant groundwater discharge zones. Surficial geology legend as in Fig. 2.



zone within the study area, significant recharge also occurs through surficial deposits situated south of the moraine. Oak Ridges Moraine and associated hummocky till deposits cover 24% of the study area (26% of the recharge area) and account for an estimated 56% of the direct recharge (Table 1B). Another area of significant recharge is the Halton Till plain, which covers 30% of the recharge area and accounts for 27% of the direct recharge for the basin. The calibrated unit recharge rate of 150 mm/year for the Halton Till compares favorably with model-calibrated values for other southern Ontario surficial tills used in investigations relating to the Waterloo Moraine (180–220 mm/year; Martin and Frind 1998) and the Oro Moraine (180 mm/year; Beckers and Frind 2001). To place these unit recharge rates into perspective, the average total precipitation at Stouffville (Stouffville water pollution control plant (WPCP) station 6158084) for the period 1972–1991 is 864 mm/year (W. Dnes, Meteorological Service of Canada, personal communication, 2001). A brief summary of the water balance for the study area is included in Table 2.

Groundwater and surface-water divides are rarely coincident in natural systems; thus the basin water balance must consider the potential for the flow of groundwater across drainage basin

Fig. 5. Numerical flow model calculated groundwater discharge to streams versus observed low monthly mean streamflow from Water Survey of Canada (1992). Gauging station locations shown in Fig. 4.



divides, leading to a form of indirect recharge (inflow) or groundwater outflow. For the study area, direct recharge via precipitation and vertical leakage through aquitards represent the dominant influence on groundwater discharge to streams. In the calibrated model, for example, over 90% (114 500 m^3/d) of the total direct recharge to the groundwater flow system (127 000 m^3/d) discharges to rivers in the basin, with discharge from springs in river valleys contributing an additional 7% (9000 m^3/d). This leaves a net groundwater outflow out of the basin of approximately 3500 m^3/d (<3%).

For the Upper aquifer, satisfactory model calibration was achieved when groundwater was allowed to enter across surface drainage divides in the northeast part of the study area near the headwaters of Duffins Creek as shown in Fig. 2. This area was noted for its anomalous water chemistry by Howard and Beck (1986) and was identified as a possible location of trans-boundary flow on the basis of water balance studies (Gerber 1994; Gerber and Howard 1997) and measurement of low-flow streamflow conditions (Hinton 1996). Although it is generally acknowledged that groundwater may enter and leave the basin in this area, the model-calculated net influx to the Upper aquifer of 5000 m^3/d represents just 4% of the total basin groundwater discharge to streams.

A net outward groundwater flux of 8500 m^3/d occurs from the Middle and Lower aquifers and is equivalent to 7% of the total direct recharge. The majority of this outward flux occurs toward the west into the Rouge River drainage basin and is consistent with the findings of a numerical groundwater flow system analysis conducted for the Rouge River basin (Meriano 1999).

Although much of the recharge to the Oak Ridges Moraine discharges along the south slope, creating headwaters for the various streams, some recharge moves vertically downwards to the deeper aquifers and follows significantly longer travel paths. The results of numerical model groundwater particle tracking shown in Fig. 7 suggest that recharge remote from headwater streams and closer to the regional drainage divide is more likely to move vertically downward and recharge the deeper aquifers. This is consistent with regional groundwater flow modeling conducted by Smart (1994). Deep vertical leakage can also occur beneath the Halton Till and Glacial Lake Peel plains where recharge is remote from streams.

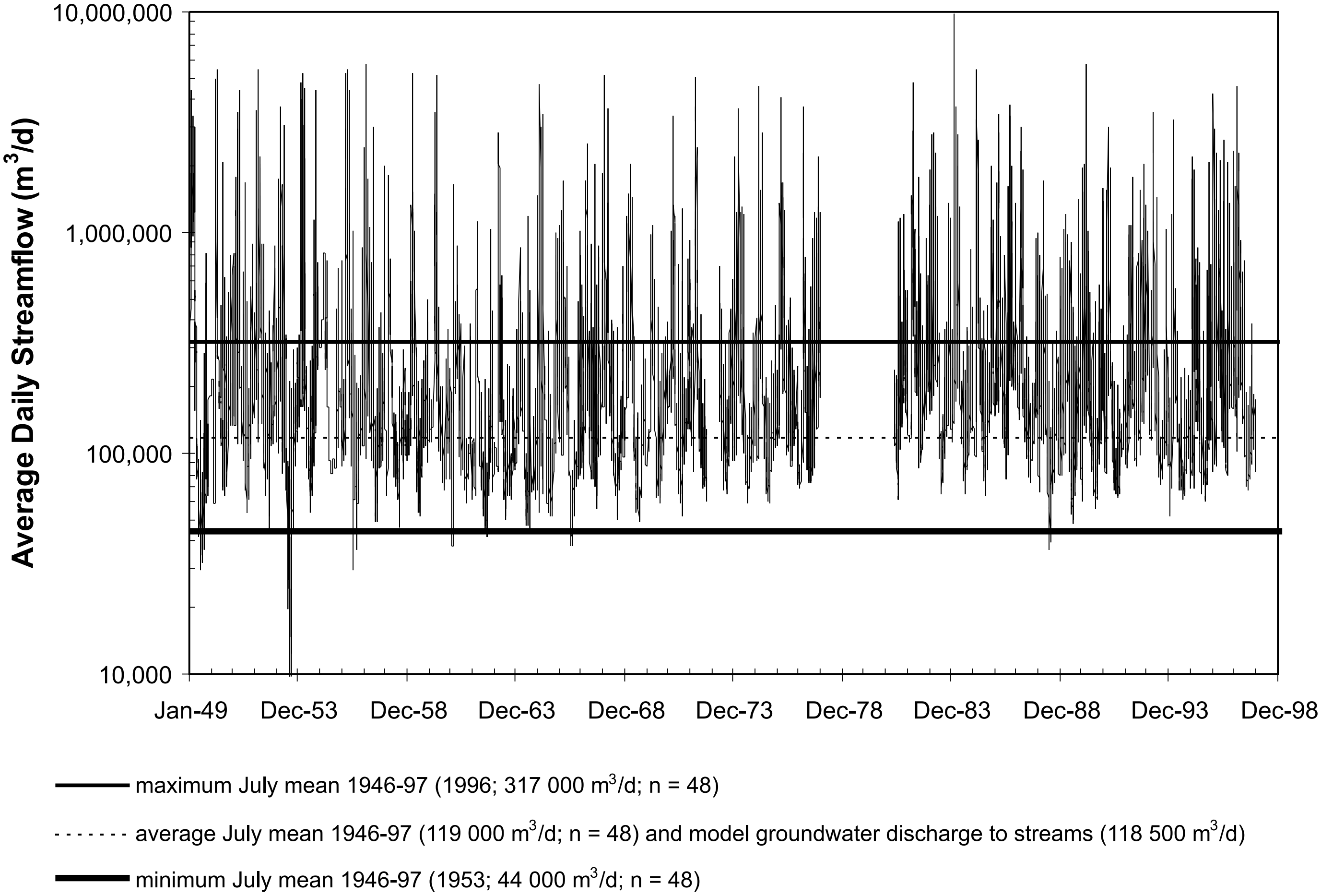
Figure 7 shows groundwater flow paths estimated using MODPATH (Pollock 1989), a particle-tracking routine that utilizes flow system output calculated by MODFLOW. Porosities for each model layer used in the MODPATH calculations were 0.30, except for the Halton Till, Lake Peel, and shale bedrock (0.2) and the Northern till (0.15) deposits. Estimated particle travel times for the traces or paths shown in Fig. 7 range from 7 to 1000 years. The shorter travel times are associated with groundwater discharge from the Upper aquifer, and the longer travel times with groundwater that moves vertically downward through the Northern till and discharges from the Middle aquifer into West Duffins Creek. Recharge occurring close to the divide along the crest of the moraine may ultimately enter the Lower aquifer and reemerge in the lower reaches of Duffins Creek after a travel time of ~2500 years. This suggests that permanent changes in the quality of the aquifer recharge will not be fully realized in receiving streams for a time period spanning years to millennia. Note that the processes that affect solute transport and concentrations such as dilution, dispersion, retardation, transformations, and attenuation mechanisms have not been incorporated here. Also note that anthropogenically induced changes in the hydraulic head and ultimately groundwater discharge within the groundwater flow system will be realized over a much shorter time frame, as this represents a pressure response that propagates much more quickly throughout the system. The particle traces shown in Fig. 7 are therefore considered order of magnitude estimates and are provided simply to give an indication of the interaction of the various components of the groundwater flow system.

Groundwater discharge to streams

The Oak Ridges Moraine (Fig. 2) forms the major recharge zone within the study area, accounting for approximately 70 000 m^3/d, or 56%, of the total direct recharge. As outlined in Fig. 8 and Table 3, only 30 000 m^3/d emerges in the headwaters above 275 m amsl, representing just 43% of the Oak Ridges Moraine recharge and 24% of the total system recharge. The remaining water (*i*) moves in the Upper aquifer and discharges to headwaters immediately below 275 m amsl; (*ii*) moves within the Upper aquifer and enters streams situated within the South Slope physiographic region, well to the south of the headwater area; (*iii*) moves within the Upper aquifer to discharge as springs along deep river valleys where the river has eroded into or beneath the Northern till; (*iv*) enters the Middle and Lower aquifers and reemerges as groundwater discharge to streams in the southern part of the study area; and (*v*) moves within all aquifers to discharge at Lake Ontario.

The headwater discharge zone exists along a topographic break in slope to the south of the moraine where the Upper aquifer thins and is semiconfined by the Halton Till. For discussion purposes, the headwater areas have been split

Fig. 6. Hydrograph of streamflow for gauging station 1 near the mouth of Duffins Creek. Discharge is shown logarithmically. See Fig. 4 for gauging station location.



into those stream reaches above and below the 275 m amsl topographic contour, a commonly applied planning boundary for the southern part of the Oak Ridges Moraine. Another Oak Ridges Moraine planning boundary occurs along the 245 m amsl topographic contour (Fig. 4). This boundary generally conforms to the southern boundary of the headwater area, with the exception of Duffins Creek. From a hydrogeologic standpoint, the choice of either planning boundary is irrelevant.

The numerical model suggests that discharge to headwater streams in the study area (stations 8, 7, 5, 9, 12, and Duffins Creek above the Michell Creek – Duffins Creek confluence; Fig. 4) accounts for approximately 72 300 m^3/d or 60% of the entire basin groundwater discharge to streams. Two of these headwater areas, West Duffins Creek and Duffins Creek, receive Upper aquifer discharge accounting for approximately 16 and 28%, respectively (total 44%), of the entire basin groundwater discharge to streams. Similar patterns were described by Hinton (1996), who measured discharge to these two stream reaches at 39% of the total basin low streamflow condition. The model estimate of discharge is higher by 5% because it considers slightly longer stream reaches for these two areas. Significantly, these two headwater areas correspond to surficial glaciofluvial ice-contact deposits along the Oak Ridges Moraine (Fig. 4), which are also the largest remaining tracts of forested land within the study area. It is estimated that 95 000 m^3/d or 77% of the total basin groundwater discharge emerges from the Upper aquifer.

Another area of significant groundwater discharge occurs along Duffins Creek southeast of Claremont, where all three aquifer systems discharge (Fig. 4). Discharge along this reach is mainly provided from the Middle and Lower aquifers (80%), with only 20% of the discharge occurring from the Upper aquifer. As estimated by the model, approximately 21% of the total basin discharge occurs from the Middle aquifer.

In an analysis of regional groundwater flow systems in Alberta, Toth (1963) suggested that deep regional groundwater flow is generally unimportant as far as contributions to the major stream in a basin are concerned because (*i*) groundwater flow rates are low, and (*ii*) a large portion of recharge water (~90%) never reaches this part of the flow system. This finding is consistent with the results of this study which suggest that the groundwater discharge contribution from the Lower aquifer, which occurs in the southern part of the study area, accounts for only 2% of total basin groundwater discharge.

In summary, the study area can be subdivided into two general hydrogeologic settings (Table 3). One setting is characterized as a net recharge zone where direct recharge exceeds groundwater discharge. The Headwaters >275 m amsl and South Slope areas of Halton Till are net recharge areas.

Table 2. Annual water balance summary for the Duffins basin.

Parameter	Unit rate (mm/year)	Data source
Precipitation		
Rain	709	Stouffville WPCP station 6158084 (1972–1991)
Snowmelt	155[a]	Stouffville WPCP station 6158084 (1972–1991)
Total	864	Stouffville WPCP station 6158084 (1972–1991)
Potential evapotranspiration	608[a]	Stouffville WPCP station 6158084 (1972–1991)
	584–610	Brown et al. 1980
Actual evapotranspiration	533–559	Brown et al. 1980
	552	Morton 1983
Streamflow	357	1949–1997 (n = 43 years[b]); Duffins Creek at Pickering (02HC006/049; 250 km^2)

Note: Stouffville municipal groundwater pumping = 4170 m^3/d in 1990 (6 mm/year over drainage area of 250 km^2). Precipitation data from the Meteorological Service of Canada, and streamflow data from the Water Survey of Canada. Snowmelt reported as water equivalent.

[a]Calculated using the method of Johnstone and Louie (1983).

[b]Missing years 1972, 1973, 1978, 1979, 1980, 1981.

The second hydrogeologic setting is a net discharge zone where groundwater discharge exceeds direct recharge. The Headwaters <275 m amsl, South Slope Glacial Lake Peel, and Glacial Lake Iroquois regions function as net discharge zones. Upper aquifer discharge to rivers over the South Slope region totals 13 500 m^3/d (Fig. 8). Table 3 shows that the total discharge to rivers over the South Slope is 21 700 m^3/d. The remaining 8200 m^3/d of river discharge over the South Slope Halton Till region represents deeper aquifer discharge which is realized at the break in topographic slope that characterizes the transition from South Slope to Glacial Lake Iroquois regions. The Glacial Lake Iroquois shoreline used in this analysis is that of Chapman and Putnam (1984), based on broad physiographic regions. As shown in Fig. 4, some river reaches have eroded into the deeper aquifer system to the north of the Glacial Lake Iroquois shoreline.

Subsurface extent of the Oak Ridges Moraine

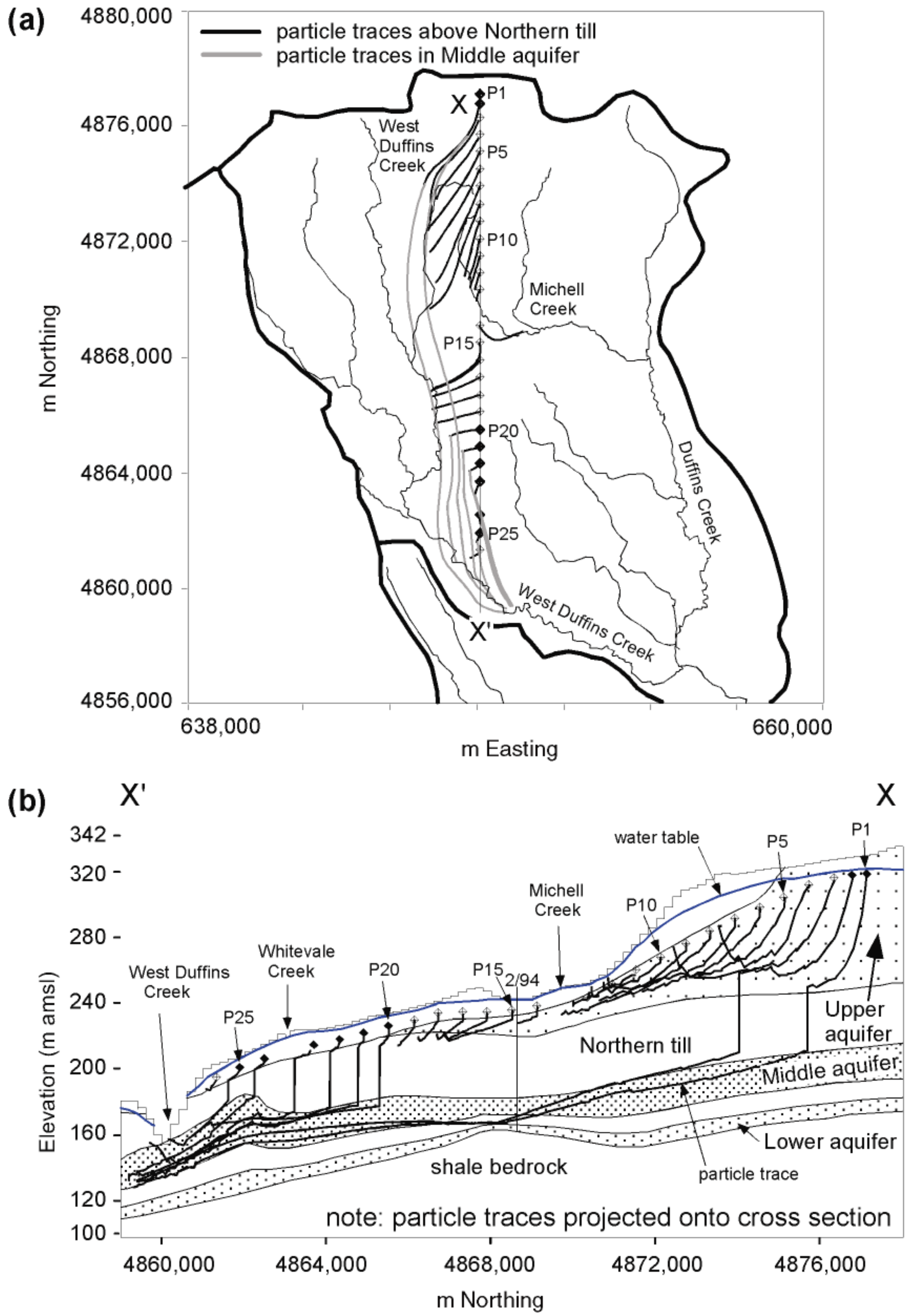
As outlined by Turner (1978), the Oak Ridges Moraine deposits extend within the subsurface to the south well beyond their surface outcrop (Fig. 3). In this area, known as the South Slope physiographic region (Chapman and Putnam 1984), deposits of the Oak Ridges Moraine are overlain by Halton Till and Glacial Lake Peel deposits.

The South Slope of the Oak Ridges Moraine is generally considered to be a groundwater discharge area, with shallow groundwater being released to headwater streams. Water-level fluctuations within the Upper aquifer along the south slope at site 2/94 are shown in Fig. 9 (see Figs. 2 and 7 for location). The key observation is that the presence of water levels above ground surface for parts of the year, particularly during the spring, confirms the potential for groundwater discharge with recharge water originating up-gradient within the Upper aquifer. Figure 9 also shows that during the spring vertical hydraulic gradients between sand bodies within the Upper aquifer are downwards. During the late summer and fall, water levels are below the ground surface and hydraulic gradients between sand bodies within the Upper aquifer are vertically upwards. This seasonal pattern differed in 2000, where a vertically downward hydraulic gradient between sand bodies within the Upper aquifer was maintained throughout the year. The reason for this behaviour is open to debate but it likely reflects a general lowering of hydraulic head in the shallower parts of the Upper aquifer system as a result of drought conditions and local discharge while deeper heads are maintained by lateral groundwater flow in the lower parts of the Upper aquifer system. This problem will be resolved when longer term transient data are available.

Implications for aquifer management and protection

Current attempts to develop strategies for groundwater protection and management in the region have focused exclusively on the Oak Ridges Moraine, probably in recognition of the relatively high unit recharge rate through its often sandy soils. For example, as a general planning principle, Hunter and Associates and Raven Beck Environmental Ltd. (1996) have suggested that the moraine above 275 m amsl, due to its recharge function, should be protected from major high-density urban and transportation development. The corollary, of course, is that major land use change below the 275 m amsl elevation contour would be acceptable, the implications being that the moraine above 275 m amsl is the dominant control on the groundwater flow system. To test these guiding principles, the groundwater flow model was used to explore the effects of changing recharge as a result of land use change above and below the 275 m amsl topographic contour. In effect, this analysis compares the importance of changing direct recharge over Oak Ridges Moraine ice-contact stratified drift and hummocky till deposits (greater than 275 m amsl) to a change in recharge via Halton Till below the 275 m amsl contour. Four scenarios were considered: (*i*) reduce unit direct recharge to Oak Ridges Moraine deposits by

Fig. 7. Groundwater particle tracking (*a*) plan and (*b*) section. Note that the particle traces are projected onto the section.



25 mm/year, (*ii*) reduce unit direct recharge to Oak Ridges Moraine deposits by 50 mm/year, (*iii*) reduce unit direct recharge to the Halton Till by 25 mm/year, and (*iv*) reduce unit direct recharge to the Halton Till by 50 mm/year. Oak Ridges Moraine deposits in this analysis include the hummocky Halton Till and ice-contact deposits shown in Fig. 2. The Halton Till area considered in this analysis occurs to the south of both the Oak Ridges Moraine and the Glacial

Fig. 8. Summary of present configuration of average groundwater discharge for the study area. Quantities are from numerical groundwater flow model.

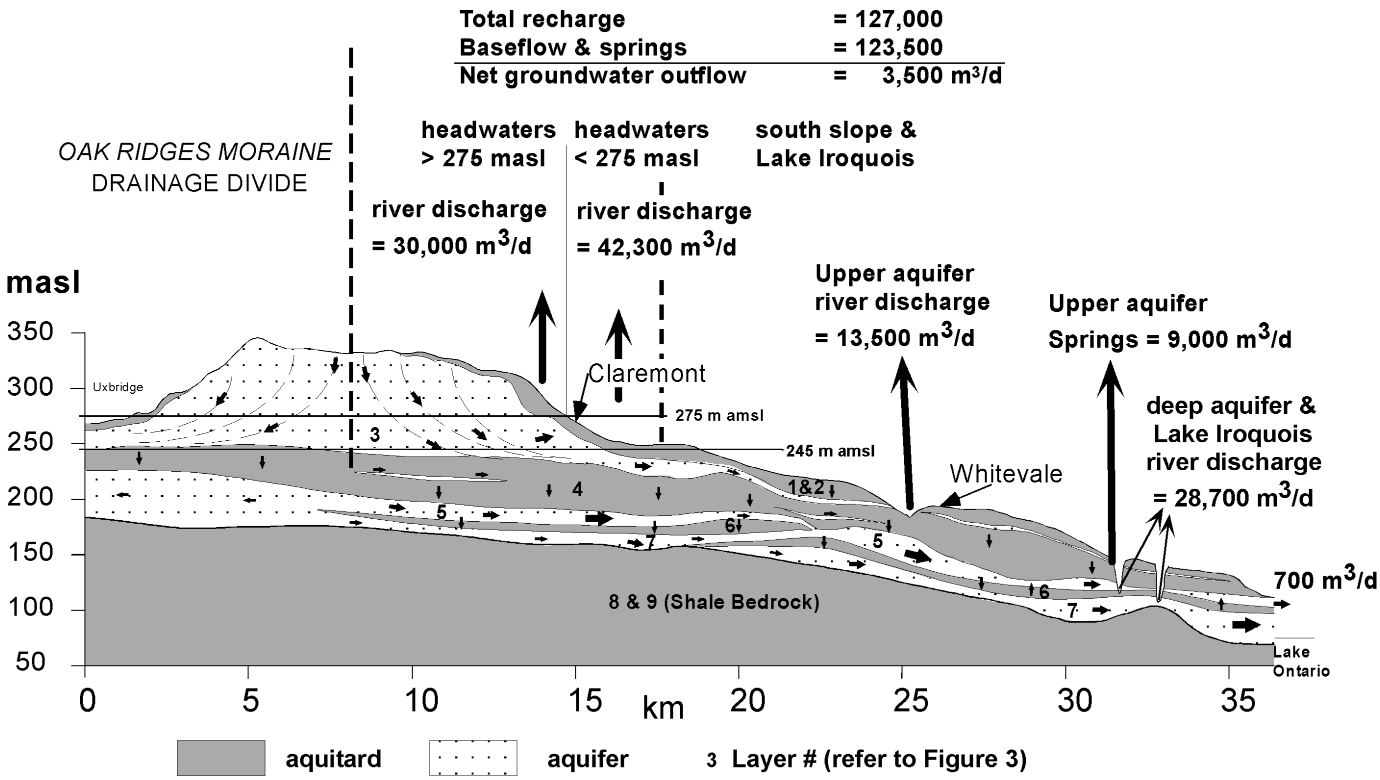


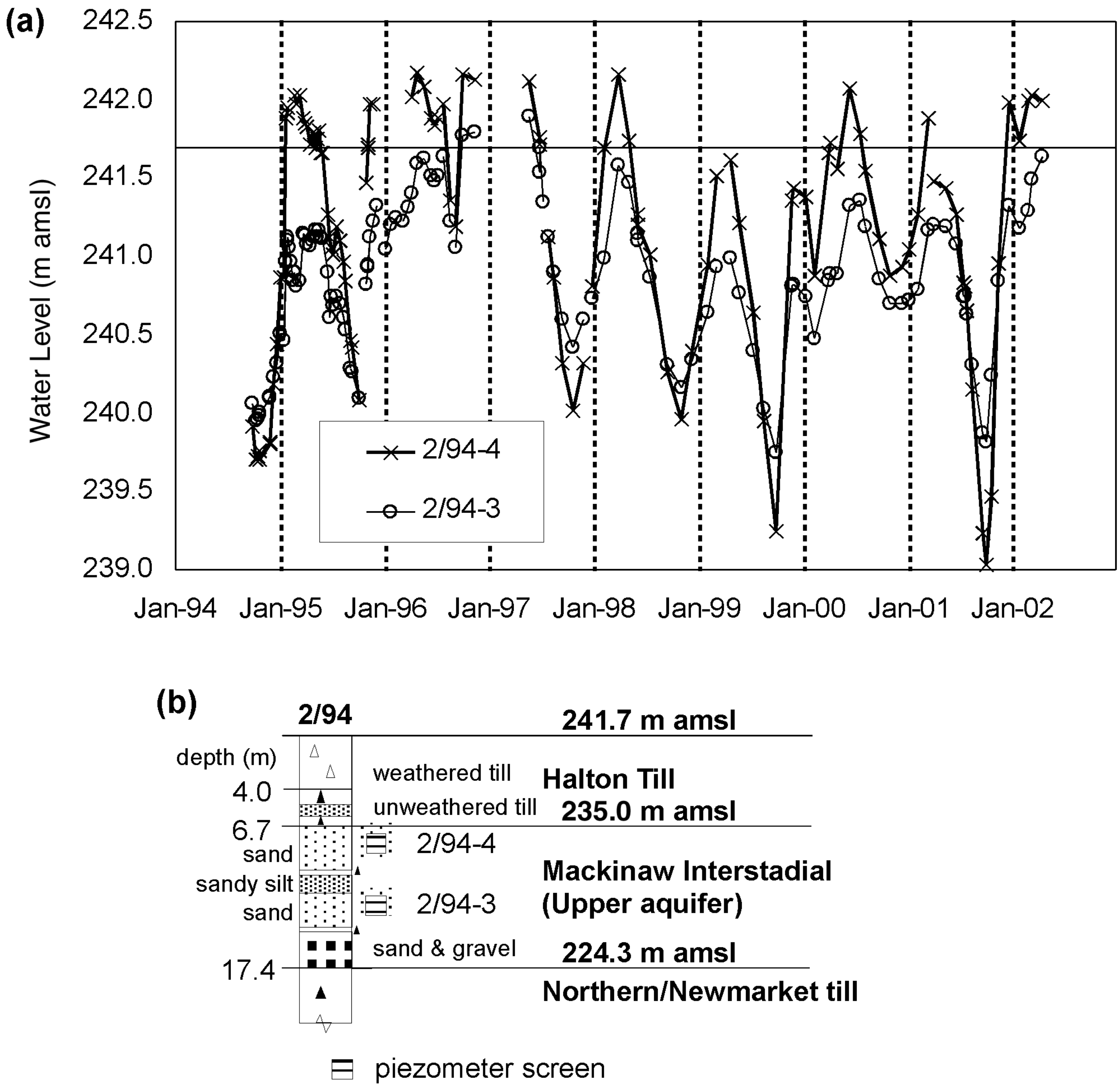
Table 3. Recharge and discharge per surficial geology and hydrogeologic regime.

Hydrogeologic regime	Surficial geology	IN (m³/d; recharge)	OUT (m³/d) Springs	OUT (m³/d) Rivers	IN–OUT (m³/d)
Headwaters >275 m amsl	Oak Ridges Moraine deposits	36 200	0	16 600	19 600
	Hummocky Halton Till	27 900	0	7 200	20 700
	Halton Till	4 200	0	6 200	–2 000
	Glacial Lake Peel	200	0	0	200
Subtotal		68 500	0	30 000	38 500[a]
Headwaters <275 m amsl	Oak Ridges Moraine deposits	2 600	0	9 500	–6 900
	Hummocky Halton Till	3 900	0	8 800	–4 900
	Halton Till	6 100	0	16 000	–9 900
	Glacial Lake Peel	2 100	0	8 000	–5 900
Subtotal		14 700	0	42 300	–27 600[b]
South Slope	Halton Till	24 600	5 500	15 500	3 600[a]
	Glacial Lake Peel	4 500	1 000	6 200	–2 700[b]
Subtotal		29 100	6 500	21 700	900
Glacial Lake Iroquois	Lake Iroquois	14 700	2 500	20 500	–8 300[b]
Total		127 000	9 000	114 500	3 500[c]

[a]Net recharge.
[b]Net discharge.
[c]Net groundwater outflow from watershed.

Lake Peel deposits. The area of Halton Till north of the Lake Peel plain was not considered in this analysis to enable similar areas of Halton Till and Oak Ridges Moraine deposits to be used (Fig. 2). The values of 25 and 50 mm/year represent typical estimated reductions in direct recharge that result from the introduction of impervious surfaces in medium- to low-density housing developments. A water balance for the Duffins basin has been completed for the period 1986–2000 using the method of Graham et al. (1997). An analysis of urbanization impacts on the water balance assuming a 50%

Fig. 9. (*a*) Hydrograph of hydraulic heads for the Upper aquifer at site 2/94. See Fig. 2 for site location and Fig. 7 for location within regional stratigraphy. (*b*) Detail of shallow deposits at site 2/94 and depth of piezometers. m amsl, metres above mean sea level.

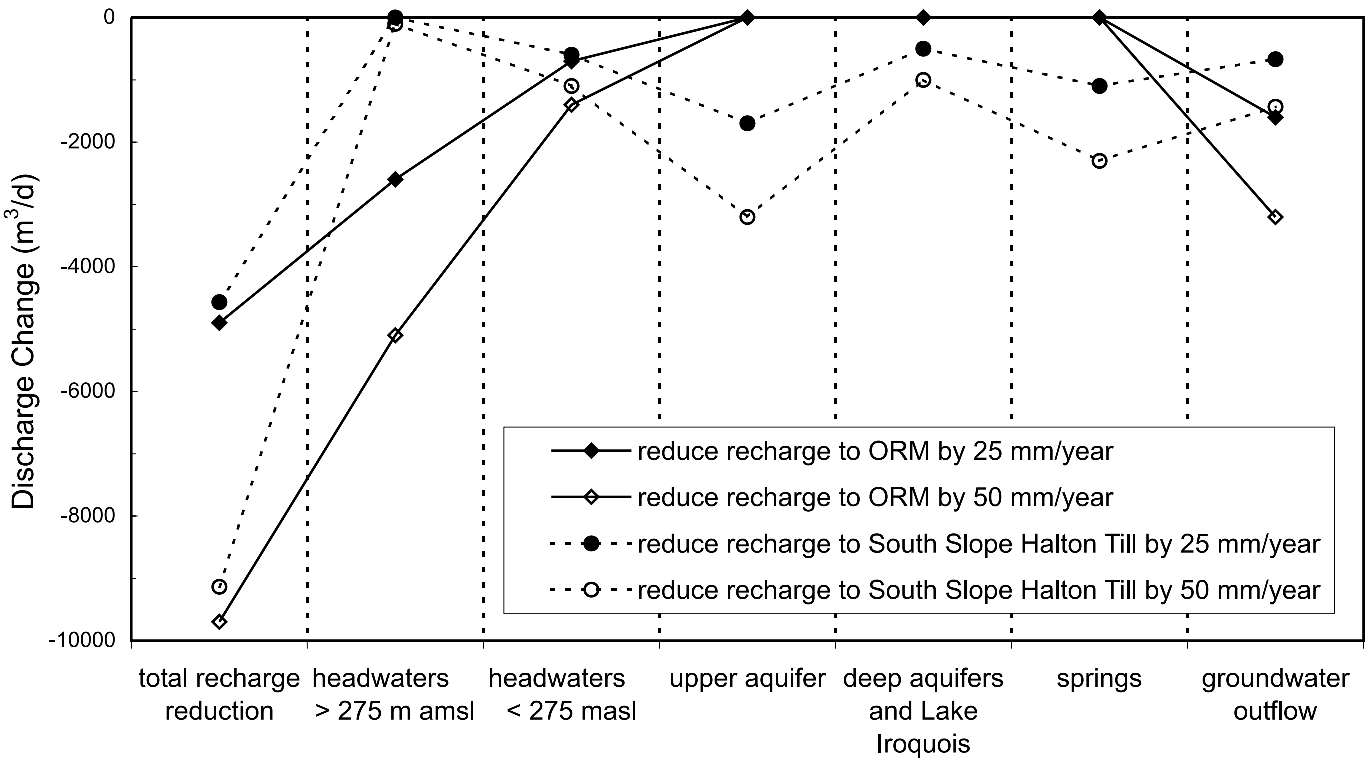


increase in impervious surfaces over open lands off of the Oak Ridges Moraine estimated an average reduction of direct groundwater recharge of 50 mm/year. This corresponds to an increase in impervious surfaces for the Duffins basin of 17%, from an existing 4% to a total of 21%. This does not incorporate the effects of use of infiltration basins nor the effects of leaking pipe networks associated with water supply and sewage removal systems which impact urban recharge (Lerner 2002). Note that this analysis focuses on groundwater quantity only and does not consider groundwater quality or temperature changes that may also result from land use change.

The changes to the groundwater balance for the four recharge-reduction scenarios are shown in Fig. 10. The results show how the location of the direct recharge reduction influences the spatial distribution of groundwater discharge. For recharge reductions over the Oak Ridges Moraine, discharge reductions are most significant for headwater stream reaches above 275 m amsl, with lesser effects on headwater streams below 275 m amsl. There are no significant discharge reductions from the Upper aquifer south of the headwater areas or where discharge is realized from the lower aquifers for the two Oak Ridges Moraine recharge-reduction scenarios tested. Note that the headwater areas referred to here include stream reaches above gauging stations 8 (Stouffville Creek), 7 (Reesor Creek), 5 (West Duffins Creek), 9 (Wixon Creek), 12 (Michell Creek), and Duffins Creek above the confluence with Michell Creek (Fig. 4).

Reducing unit recharge rates over Halton Till south of the Oak Ridges Moraine by 25 and 50 mm/year affects groundwater

Fig. 10. Recharge reduction influence on groundwater discharge. ORM, Oak Ridges Moraine..



discharge in a larger area including headwaters below 275 m amsl, Upper aquifer discharge to rivers and springs south of the Oak Ridges Moraine, and discharge from lower aquifers in the southern part of the basin. A reduction in discharge from the lower aquifers occurs because of a reduction in the downward vertical hydraulic gradient and hence reduced vertical leakage to these aquifers. The hydraulic head reduction in the Upper aquifer induced by reduced recharge is larger for the area of Halton Till than for the Oak Ridges Moraine deposits, for similar unit rate recharge reductions, because of the lower hydraulic conductivity of the Halton Till deposits. The corresponding hydraulic head drop in the Middle aquifer beneath the Halton Till is up to 1 m for a recharge reduction of 25 mm/year and up to 2.5 m for a recharge reduction of 50 mm/year. It should be noted that much of the discharge from the deeper aquifers occurs over a more restricted area (Fig. 4) compared to Upper aquifer and headwater discharge. This restricted area along Duffins Creek, just above the confluence with West Duffins Creek, acts as a drain for the deeper aquifers that slope into the bedrock valley situated beneath Duffins Creek.

Overall, discharge from the Upper aquifer in the headwater area accounts for approximately 60% of the entire basin groundwater discharge, with less than 25% of the entire basin discharge realized above the 275 m amsl contour. While over 85% of the headwater discharge in West Duffins Creek occurs above the 275 m amsl contour, greater than 85% of discharge to Duffins Creek occurs below the 275 m amsl contour.

Conclusions

The Oak Ridges Moraine of south-central Ontario contains a major aquifer system that feeds the headwaters for all major rivers in the Greater Toronto Area. Recognizing the rapid rate of urban growth in the region, there is a concern that changing land use along the moraine may impact the quality and quantity of associated groundwater resources. To date, efforts to incorporate groundwater protection into the land use planning process have been hampered by an inadequate quantitative hydrogeological understanding of the entire aquifer system.

Focusing on the Duffins Creek watershed, this study demonstrates that groundwater discharge along the south flank of the moraine contributes 60% of the entire basin discharge. The majority of this water discharges below the 275 m amsl contour, one of the commonly accepted boundaries of the Oak Ridges Moraine for planning purposes. The remaining discharge is contributed by aquifers within and underlying the deposits extending to the south. While approximately 77% of the entire basin discharge is realized by discharge from the Upper aquifer, 23% is contributed by deeper aquifers underlying the extensive Northern–Newmarket till aquitard which discharge near and south of the Glacial Lake Iroquois shoreline.

Conclusions that have significant implications on land use and groundwater flow system management are as follows:

(1) The majority of the study area is a groundwater recharge zone. Discharge zones are associated with stream reaches and areas along the south flank of the Oak Ridges Moraine. Only 44% of the recharge occurring within the Oak Ridges Moraine planning boundary, as delineated here by the 275 m amsl elevation contour, is realized as discharge within this boundary. Nearly 60% of the recharge discharges below the 275 m amsl planning boundary; thus its quality becomes subject to land use activities external to the moraine.

(2) Groundwater discharge is not uniform over the study

area but is localized over a few areas, largely controlled by geology and topography. These areas include the headwaters of West Duffins and Duffins creeks and the lower reach of Duffins Creek between the confluence with Michell Creek and West Duffins Creek. Also, recharge exhibits spatial variability depending on surficial soils, ground cover, and flow-system hydraulics.

(3) In assessing potential impacts to the groundwater flow system, the sensitivity analysis must consider all aquifers in the system and should not simply be limited to geologic features, such as the Oak Ridges Moraine, which are believed to contribute the majority of the recharge.

(4) The South Slope of the Oak Ridges Moraine is hydrogeologically complex, with spatially and temporally variant vertical hydraulic gradient directions. Simplified planning areas based on ground surface elevation (e.g., 275 m amsl) or the surface expression of a geologic–morphologic feature are misleading at best and likely will not provide adequate aerial coverage of the most sensitive parts of the flow system.

(5) Travel-time analysis suggests that sustained changes in the chemical quality of the aquifer recharge will take years to thousands of years to be fully realized in discharge areas. Hydraulic response times are expected to be orders of magnitude more rapid and will depend on location within the flow system.

This study shows that the Oak Ridges Moraine sediments represent just one component of a dynamic regional flow system that extends well beyond the morphological boundary of the moraine. This has important implications for groundwater protection, as it demonstrates the need for management strategies that incorporate regional groundwater flow systems at the watershed scale and not simply a morphologic or geologic feature (in this case a moraine) in isolation.

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