Flow system dynamics: isotopic tracer studies, south-central Ontario

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ABSTRACT
Tracers are useful for assessing flow and transport mechanisms on both local and regional scales, and can provide significant insight into regional flow system dynamics. The tracers utilized in this study include isotopes – specifically deuterium, oxygen-18 and tritium. Tritium tracer studies have utilized anthropogenic inputs provided by i) nuclear weapons testing which peaked in the 1960s and ii) local input since the early 1970s by fall-out from nuclear power generation. This paper summarizes the insight gained to date from isotopic tracers and the implications to flow system dynamics, particularly the hydraulic nature of aquitard units and erosional valley infill sequences.

RÉSUMÉ
Les traceurs sont utiles pour l'évaluation les flux et les mécanismes de transports aux échelles locales et régionales, et peut fournir la perspicacité significative dans la dynamique régionale des systèmes de flux hydrologiques. Les traceurs utilisés dans ce contexte incluent des paramètres chimiques inorganiques et des isotopes, particulièrement le Deutérium, l'Oxygène-18 et le Tritium. Les études de traceurs au Tritium ont eu recours aux apports (sous-produits) anthropiques associés aux essais associés aux missiles nucléaires qui ont culminés dans les années 1960, ainsi qu'aux apports locaux en provenance des stations de production d'énergie d'origine nucléaire à partir des années 1970. Cet article résume la connaissance acquise à ce jour grâce aux traceurs isotopiques et sa contribution à la dynamique des systèmes de flux, particulièrement en ce qui a trait à la dimension hydraulique des unités d'aquitards et aux séquences d'érosion-accumulation en zone de vallée.

1 INTRODUCTION

Water resources management is evolving, with an increased need for regional scientific understanding that spans political boundaries and can be incorporated into the planning process. Since 2001, a number of Municipalities and Conservation Authorities situated in south-central Ontario have been collaboratively conducting regional hydrogeologic investigations (see YPDT-CAMC study area in Figure 1). This regional understanding can then provide input and context for the range of issues that these agencies must address and allows for an integrated and consistent set of planning policies related to groundwater resource protection.

The technical hydrogeologic program of this collaborative involves three main components:

- Database of all geologic and water information including borehole, well, streamflow, climate, water use and water quality information;
- Three-dimensional hydrogeological interpretation; and
- Numerical flow modelling tools to help analyse the regional and local flow systems.

All components are updated and refined as new information and understanding is obtained. Further information may be found at www.ypdt-camc.ca.

Obtaining an adequate understanding of flow system dynamics is often hindered by the lack of a regionally dispersed long-term monitoring network. Many studies on prediction of regional aquifer/aquitard dynamics are conducted using numerical model derived estimates, or spatially and temporally limited tests (e.g. pump test, slug tests, laboratory tests on soil cores) which are not representative of the long-term bulk behaviour of the media. Field-based tracer studies provide a method for addressing both flow and transport mechanisms on both a local and regional scale. When combined with other physical and geophysical data, tracer studies can provide significant insight into regional flow system dynamics.

Isotopic tracer studies were initiated in the early 1990s in the Duffins Creek watershed (just east of Toronto) along the north shore of Lake Ontario to investigate the flow of groundwater through till aquitards encompassed within a three aquifer regional flow system (Gerber and Howard, 1996). Subsequent analysis has expanded the spatial distribution of sampling across south-central Ontario. The tracers utilized in this program include isotopes – specifically deuterium, oxygen-18 and tritium. Tritium tracer studies have utilized anthropogenic inputs provided by i) nuclear weapons testing which peaked in the 1960s, and ii) local input from nuclear power generation fall-out (since the early 1970s).

This paper summarizes the insight gained to date from isotopic tracers and the implications to flow system conceptualization and dynamics, particularly the hydraulic nature of aquitard units and erosional valley infill sequences. These features are interpreted to exert significant control over regional flow systems within the Great Lakes basin.

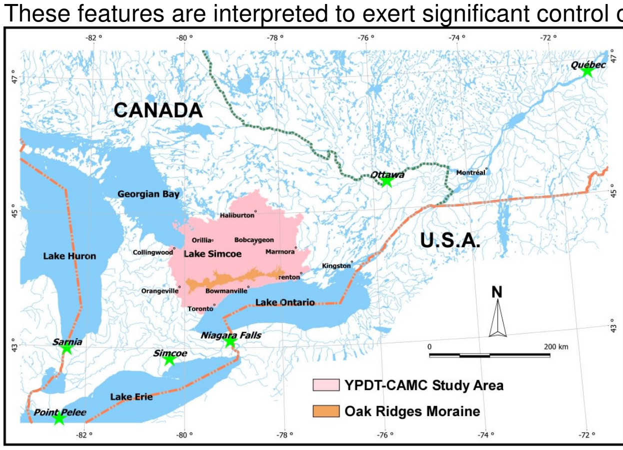

Figure 1: Location of study area - south central Ontario.

2 PHYSICAL SETTING

The Oak Ridges Moraine (ORM) is a 160-km long ridge of sand, silt and gravel deposits oriented in an approximately east-west direction north of Lake Ontario (Figure 2). This feature extends from the Niagara Escarpment in the west to the Trent River in the east. The aquifers within ORM deposits serve as a source of drinking water and provide groundwater discharge to headwater streams along the flanks of the moraine.

The bedrock geology consists of Paleozoic carbonate rocks in the east, north and western portions of the study area (Johnson *et al.*, 1992). The central study area is underlain largely by shale. The Paleozoic sequence onlaps Precambrian rocks situated to the north (Armstrong *et al.*, 1999). A major bedrock valley system, known as the Laurentian bedrock valley, trends from Lake Huron (Georgian Bay) to Lake Ontario in the Toronto area. Tributary valley systems to the Laurentian emanate from higher elevation areas along the Niagara Escarpment and Precambrian highlands to the northeast.

The Quaternary sediments that overlie bedrock across much of the study area represent deposition and erosional processes occurring over the last 135,000 years. This sequence consists of an alternating package of glacial (till and diamict) and interglacial sediments (lacustrine and fluvial). The thickest Quaternary sediment sequences, exceeding 200m thick, are associated with bedrock valley infill deposits and the Oak Ridges Moraine. Areas away from these two features are largely carbonate rock overlain by thin sediment.

Appreciable thicknesses of unconsolidated sediment contain a three aquifer system with aquifer units occurring within lacustrine and fluvial deposits (Figure 3). Shallow aquifer systems occur within the Inter-Newmarket sediments (north of the Oak Ridges Moraine) and Oak Ridges Moraine and Mackinaw Interstadial sediments (along and south of the moraine). Deeper aquifer systems occur within deposits of the Thorncliffe and Scarborough Formations (or coeval equivalent) situated beneath the Lower Newmarket till (aka Northern till in the literature e.g. Gerber and Howard, 1996). These deeper aquifer systems pinch out along higher elevation bedrock areas in the north, east and western parts of the study area. Erosional channels have been cut into the stratigraphic package (Sharpe *et al.*, 2004), often completely through the Lower Newmarket till which leads to enhanced hydraulic connection between the shallow and deep aquifer systems (see Figure 2 for interpreted tunnel channel locations). Bedrock aquifers are utilized in areas where thin Quaternary sediments overlie carbonate rock. Further physical setting information and references are summarized in Earthfx (2006).

3 METHODS

This paper utilizes isotopic analyses from a number of piezometers installed as part of various investigations conducted at different times. The various sampling locations and associated references are shown on Figure 2 and listed in

Table 1. All investigations utilized a similar well development and sampling protocol with all analyses conducted at the same laboratory.

Piezometers were evacuated prior to sampling. To initially develop the wells which were drilled with mud rotary drilling methods, a minimum of ten well volumes were removed until the parameters pH, conductivity and temperature stabilized. Prior to each sampling event, three well volumes were removed or purging was conducted until pH, conductivity and temperature stabilized.

Isotope analyses were conducted at the University of Waterloo Environmental Isotope Laboratory using conventional preparation techniques. Results for oxygen-18 and deuterium are expressed as delta units (δ) in per mil (‰) where

$$\delta^2H \text{ (or } \delta^{18}O) = [(R_{sample}-R_{standard})/R_{standard}] \times 1000 \qquad [1]$$

R_{sample} and $R_{standard}$ refer to the ratio of ^2H to ^1H (hydrogen), or ^{18}O to ^{16}O (oxygen), in the sample and standard, respectively. All results were normalized to Vienna Standard Mean Ocean Water (V-SMOW = 0‰) with a precision of ± 2.0 ‰ for δ^2H and ± 0.2 ‰ for $\delta^{18}O$. Tritium (^3H) contents of water were measured by liquid scintillation counting after electrolytic enrichment of water (± 0.5 TU), or by direct counting (± 8 TU). One TU equals 1 ^3H atom per 10^{18} hydrogen atoms, or 0.118 decays per second per litre (dps/L). One dps/L equals 1 Bequerel/Litre (Bq/L).

4 PRECIPITATION INPUT

4.1 ^2H (deuterium) and ^{18}O Input

The stable isotopes ^2H and ^{18}O are considered conservative tracers for meteoric waters and are unlikely to be altered significantly by water-rock interaction at temperatures less than 50°C (Lawrence and Taylor, 1972). ^2H and ^{18}O in groundwater are strongly influenced by climatic conditions at the time of recharge and the isotopic composition of shallow groundwater usually reflects the average annual composition of local precipitation. Some systems are able to preserve a seasonally varying input (Fritz *et al.*, 1987). The degree of enrichment or depletion of these heavy isotopes partly depends on the average annual surface air temperature

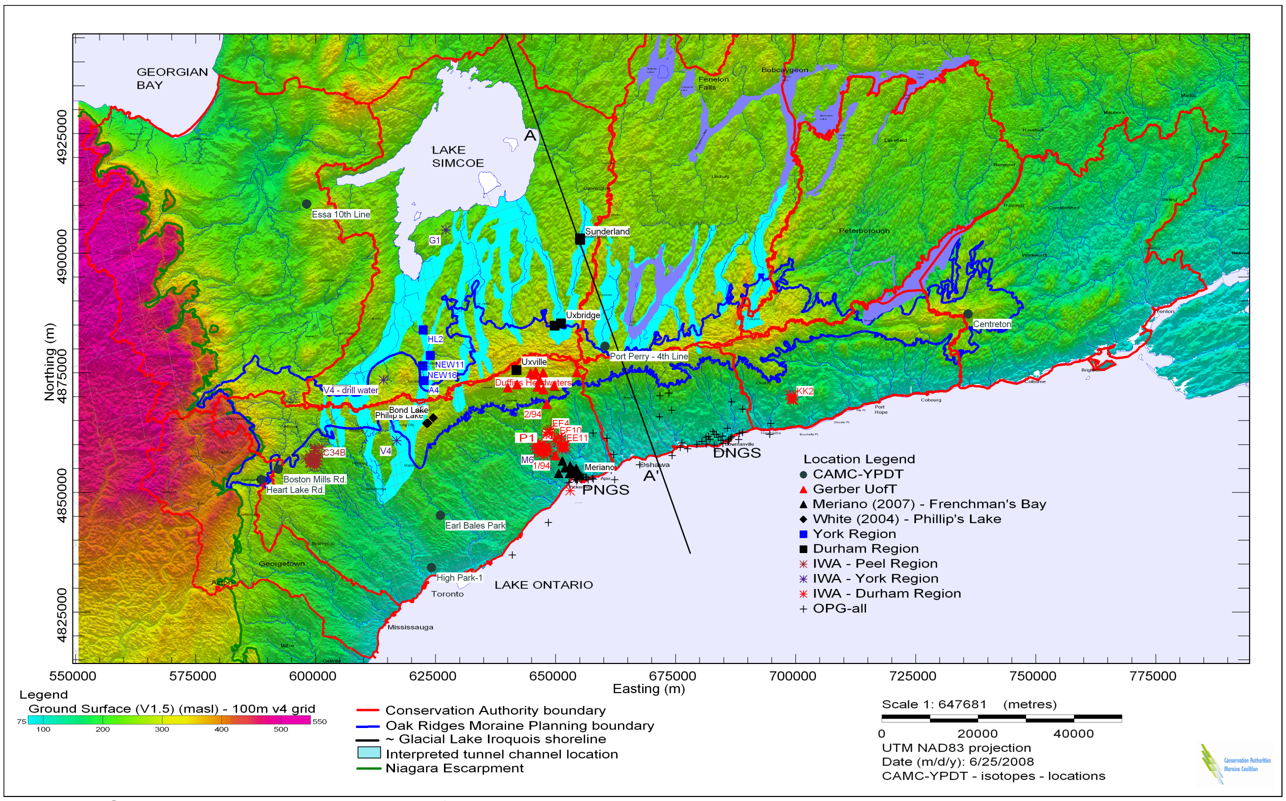

Figure 2: Study area showing ground surface topography, sample locations and cross section location.

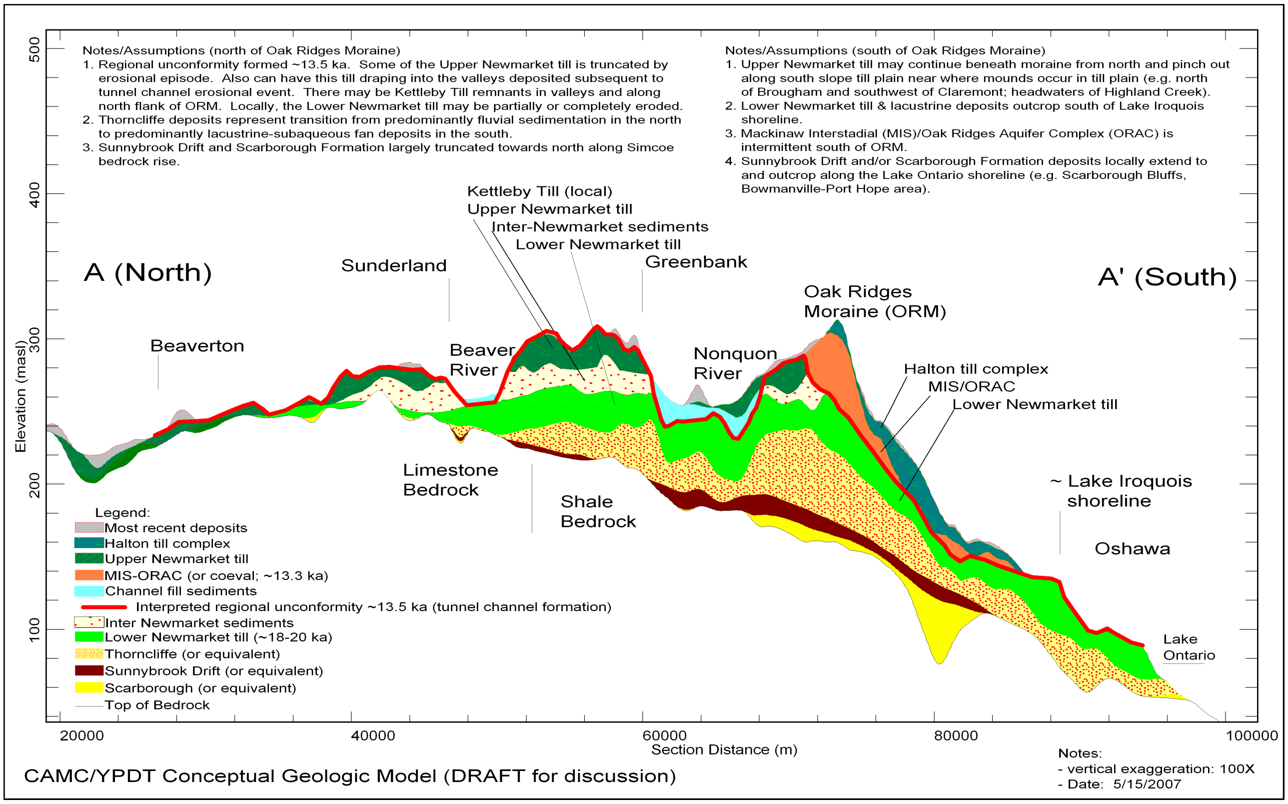

Figure 3: North-south cross section. See Figure 2 for section location.

Table 1: Summary of results of isotopic analyses (all analyses for samples since 1989).

Site		depth (m)	$\delta^{18}O$ (o/oo) min	$\delta^{18}O$ (o/oo) max	#	$\delta^{2}H$ (o/oo) min	$\delta^{2}H$ (o/oo) max	#	^{3}H (TU) min	^{3}H (TU) max	#	Source
Groundwater												
1/94	porewater		-10.35	-7.97	18	-71.98	-62.78	18	<6	259	10	Gerber & Howard, 1996
	groundwater		-10.83	-9.77	18	-74.14	-62.71	18	<0.8	205	8	Gerber & Howard, 1996
2/94	porewater		-11.67	-8.86	31	-80.71	-62.59	31	<0.8	48.5	27	Gerber & Howard, 1996
	groundwater		-11.82	-10.53	23	-80.22	-72.89	23	<0.8	19	5	Gerber & Howard, 1996
Frenchman's Bay			-10.17	-9.17	9	-65.55	-58.29	9	149	593	9	Meriano, 2007
Phillip's Lake			-11.73	-10.10	2	-81.76	-67.00	2	51.4	28.8	2	White, 2004
P1	porewater		-12.36	-9.44	25	-88.97	-48.71	25	8	43.5	22	M.M. Dillon, 1990; IWA, 1994a
	groundwater		-12.74	-7.84	65	-88.97	-60.68	37	<0.8	139.2	36	M.M. Dillon, 1990; IWA, 1994a
EE4			-11.33	-9.90	8	-76.73	-67.63	8	na	na	-	IWA, 1994b
EE10			-11.05	-9.37	6	-75.00	-63.94	6	na	na	-	IWA, 1994c
EE11			-10.96	-8.50	30	-78.78	-61.09	30	na	na	-	IWA, 1994g
KK2			-11.06	-9.54	13	na	na	-	na	na	-	IWA, 1994d
C34B - Bolton			-12.30	-8.98	64	-87.64	-60.46	64	<0.8	57.9	67	IWA, 1994i
G1 - Sutton			-11.04	-10.20	3	-74.67	-65.69	3	3.8	39	3	IWA, 1994f
M6 - Markham			-11.22	-10.42	3	-75.56	-70.77	3	2.4	42	3	IWA, 1994e
V4 - King City			-10.51	-10.46	2	-70.73	-69.56	2	70	85.6	2	IWA, 1994h
YPDT-CAMC	Essa 10th Line	86.3	-12.28	-12.07	2	-84.21	-82.25	2	5.2	8.3	2	this study
	High Park (Scar)	41.2	-10.24	-10.08	2	-68.44	-68.40	2	<0.8	<0.8	2	this study
	Boston Mills	160.0	-11.06	-	2	-76.59	-68.86	2	1.5	12.5	2	this study
	Earl Bales Park (HT)	8.9	-9.44	-	1	-64.41	-	1	38.1	-	1	this study
	Earl Bales Park (Scar)	99.9	-10.26	-	1	-70.17	-	1	3.5	-	1	this study
	Port Perry 4th Line (TC)	6.1	-10.50	-	1	-69.51	-	1	51.1	-	1	this study
	Port Perry 4th Line (Scar)	120.5	-14.53	-	1	-100.46	-	1	2.3	-	1	this study
	Heart Lake Rd (TC)	4.8	-10.90	-	1	-71.70	-	1	29.3	-	1	this study
	Heart Lake Rd (Scar)	171.1	-11.16	-11.04	2	-76.69	-73.60	2	<0.8	0.9	2	this study
	Centreton (Rice Lake; TF)	45.9	-11.20	-	1	-78.22	-	1	15.2	-	1	this study
	Centreton (Rice Lake; YT)	176.2	-11.11	-	1	-78.77	-	1	3.8	-	1	this study
Sunderland MW1		8.9	-11.90	-	1	-84.00	-	1	23.6	-	1	data provided by Durham Region
Sunderland MW2		11.2	-11.80	-	1	-84.00	-	1	22.2	-	1	data provided by Durham Region
Uxville MW1 & MW2 (ORAC)		53.8	-11.86	-	1	-83.14	-	1	15.7	17.7	2	data provided by Durham Region
Uxbridge MW5		70.1	-11.61	-	1	-80.09	-	1	6.9	7.7	2	data provided by Durham Region
Uxbridge MW6		55.3	-11.73	-	1	-79.38	-	1	<0.8	-	2	data provided by Durham Region
	subtotal				340			299			217	
Surface Water												
Phillip's Lake			-4.00	-3.70	2	-43.00	-42.00	2	80	95.3	2	White, 2004
Bond Lake			-5.00	-3.60	2	-47.00	-40.65	2	80.3	89.1	2	White, 2004
Lake Ontario at Pickering			-7.53	-6.48	11	-54.70	-47.71	11	63.1	117.9	6	Gerber & Howard, 1996; IWA, 1994b-g
Duffins Creek headwaters			-11.25	-7.89	12	-79.88	-58.04	12	22	51	12	R.E. Gerber, unpublished
Lindsay Creek (Bolton)			-1.74	-	1	-27.32	-	1	57.8	-	1	IWA, 1994i
Beaver River at Sunderland			-11.20	-11.00	2	-81.00	-80.00	2	na	na	-	data provided by Durham Region

Note: Repeat values not reported in this table.
na - not analyzed

(Dansgaard, 1964). More depleted values indicate meteoric waters which were recharged during the winter or during a period of cooler climate. Fritz *et al.* (1987) report $\delta^{18}O$ of shallow modern groundwaters for the study area to range from -9 to -12 ‰, which is similar to the long term average for the Ottawa IAEA precipitation monitoring station (IAEA, 1992).

When dealing with flow systems where groundwater may be hundreds to thousands of years old, the precipitation input to the system may have changed over time. For example, groundwater interpreted to be >10,000 years old in unfractured aquitards from various locations in North America are depleted in $\delta^{18}O$ relative to modern meteoric waters by at least 5 ‰ (Desaulniers *et al.*, 1981; Simpkins and Bradbury, 1992; Remenda *et al.*, 1994). Desaulniers *et al.* (1981) interpret $\delta^{18}O$ of -17 ‰ in deep clay till groundwater near Sarnia to represent waters 11,000 to 14,000 years old. Sklash *et al.* (1992) also report depletion down to -15 ‰ in clay till groundwater near Windsor with an interpreted age of at least 7,000 years. Edwards and Fritz (1986; 1988) have produced a paleoclimate reconstruction for southern Ontario using stable isotope ratios from fossil plant cellulose and lake marl. Their estimated $\delta^{18}O$ composition for meteoric water recharged more than 11,000 years ago of -16.6 ‰ is comparable to deep clay till groundwater near Sarnia and Windsor.

4.2 3H (tritium) Input

Tritium is a radioactive isotope of hydrogen (half-life of 12.43 years) which is produced naturally in the upper atmosphere by cosmic-ray bombardment. Since 1953, tritium has also been produced anthropogenically by thermonuclear weapons testing and fall-out from nuclear power plants, the result being that the tritium content of precipitation has increased by several orders of magnitude. Prior to 1953, the tritium content of precipitation was <25 TU (Faure, 1986). Brown (1961) estimated a pre-1953 concentration of 15 TU for precipitation in the Ottawa valley region. Fall-out from nuclear weapons testing peaked during 1963 (IAEA, 1992). Tritium levels within groundwater above 1 TU are generally interpreted to indicate mixing with at least some post-1952 precipitation (e.g. Ruland *et al.*, 1991).

Figure 4 illustrates average annual tritium concentrations in precipitation at the Ottawa IAEA station and select Ontario Hydro Pickering Nuclear Generating Station monitoring locations (OPG, 2007). Data from the Ottawa IAEA station reflect natural cosmogenic generation, nuclear weapons testing fallout which peaked in 1963 and perhaps minor Chalk River nuclear power generation fall-out (now off-line). Current tritium levels have declined to pre-1953 concentrations as estimated by Brown (1961). Radioactive decay and mixing within the shallow groundwater zone by lower concentration precipitation since 1966 is expected to have diluted the bomb peak signal to values well below 100 TU. Monitoring stations located up to 12km from the Pickering Nuclear Generating Station contain elevated levels of ^{3}H from reactor fall-out that gets incorporated into the local precipitation. For at least the local area, elevated levels of ^{3}H in groundwater will represent recharge since 1953 (weapons testing) or recharge since the early 1970's (nuclear generating station fall-out).

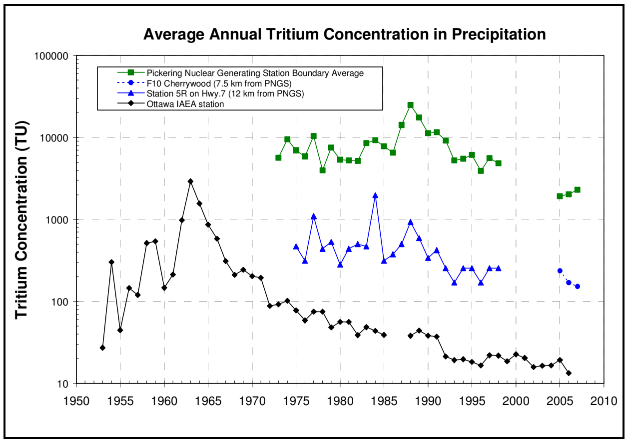

Figure 4: Measured tritium concentration in precipitation.

5 RESULTS

5.1 $\delta^{2}H$ and $\delta^{18}O$

Craig (1961) showed that $\delta^{2}H$ and $\delta^{18}O$ are linearly correlated along a meteoric water line which can be defined globally ($\delta^{2}H = 8\ \delta^{18}O + 10$) and locally for each geographic region. Meteoric waters which deviate from this line are interpreted as having been modified by evaporation, mixing with non-meteoric waters or biologic transformations (Fontes, 1980; IAEA, 1981). Figure 5 shows a plot of $\delta^{2}H$ versus $\delta^{18}O$ for select samples along with a comparison to both the GMWL and the Ottawa Meteoric Water Line (OMWL; $\delta^{2}H = 7.63\ \delta^{18}O + 6.53$, Fritz *et al.*, 1987). Drilling fluid for the various investigations (a potential contaminant to the natural groundwater isotopic results) has been obtained from Lake Ontario, and displays $\delta^{2}H$ and $\delta^{18}O$ concentrations which lie on an evaporation trend away from the meteoric water line (slope of 4 to 6) consistent with the surface water source. These values compare favourably to values obtained for the Niagara River and St. Lawrence River at the western and eastern ends of Lake Ontario by Yang *et al.* (1996). They also compare to the Lake Erie evaporation trend reported in Huddart *et al.* (1999) and the Duffins stream headwaters samples, also shown on Figure 5. Note that not all samples are plotted on Figure 5, however the range of results for all analyses listed on Table 1 are covered in this figure.

As mentioned previously, $\delta^{18}O$ of shallow modern groundwaters for the study area are expected to range from -9 to -12 ‰ (Fritz *et al.*, 1987). An apparent trend illustrated on Figure 5 is a depletion trend in shallow groundwaters moving north from Lake Ontario. Results from sites close to Lake Ontario (e.g. Frenchman's Bay; Earl Bales Park) contain $\delta^{18}O$ values in the -9 to -10 ‰ range. Further north Site 1/94 at -10 ‰, and even further north at Site 2/94 and the Duffins headwaters (unevaporated) are at -11 to -12 ‰, the latter similar to average values in precipitation recorded at the Ottawa IAEA station. Results from the stream source area within the Humber River watershed are also similar (Hinton *et al.*, 1998). In shallow groundwater at a site on the shore of Lake Erie at Point Pelee the concentration of -9 ‰ is similar to that near Frenchman's Bay (Figure 1; Huddart *et al.*, 1999). This means that the $\delta^{18}O$ precipitation input across the study area likely varies depending on location and distance from Lake Ontario with average inputs similar to those measured at the Ottawa IAEA along and north of the Oak Ridges Moraine and a more enriched input closer to Lake Ontario. This reflects the incorporation of evaporated Great Lakes waters into the vapour mass, and ultimately into the precipitation, as described in Gat *et al.* (1994) and Fritz *et al.* (1987).

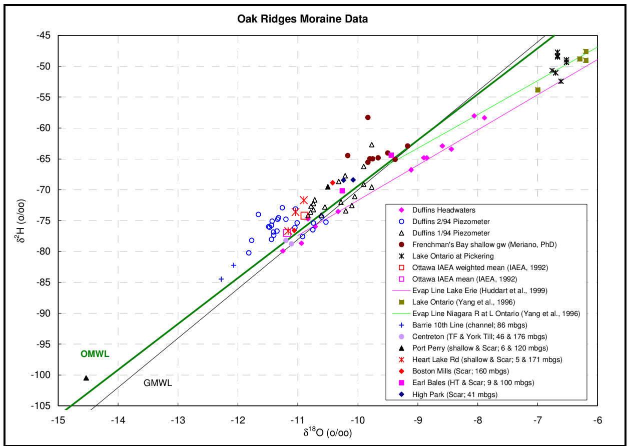

Figure 5: δ^2H versus δ^{18}O for select samples.

5.2 Deuterium Excess

The stable isotopic signature of precipitation (and shallow groundwater) often reflects the origin of the vapour masses that influence local climate. The Deuterium excess (d) is a parameter often considered to reveal the origin of these vapour masses. The d is defined as

$$d = \delta^2H - 8\delta^{18}O \qquad [2]$$

and will have values near 10 if precipitation follows the Global Meteoric Water Line (GMWL). A consistent vapour source (e.g. Pacific Ocean, Arctic Ocean, Gulf of Mexico or Atlantic Ocean) controlling local climate would lead to invariant d values. Local conditions and mixing of vapour sources throughout the year; however, lead to variation in the local vapour masses (and hence precipitation) leading to locally varying meteoric water lines and variable d values. The main controls over d include i) humidity (higher humidity – lower d); ii) snow and ice formation (lower T – higher d) and iii) evaporation from surface water bodies whereby increased evaporation will lead to a higher d value in the resultant evaporated water and local precipitation (Fritz *et al*., 1987; Gat *et al*., 1994).

Within the study area the meteorological regime is generally controlled by mixing of air masses originating over the Gulf of Mexico and the Atlantic Ocean. Winter precipitation can be influenced by Arctic air (higher d) and summer can be influenced by Pacific air masses (lower d) (Fritz *et al*., 1987). The annual average d for precipitation as measured at the IAEA Ottawa and Simcoe stations are 12.2 and 11.5, respectively, with summer values being lower than winter values (Fritz *et al*., 1987).

The d estimates for groundwater and Lake Ontario water from this study are shown on Figure 6. The results follow a negatively sloped line trending towards the results for Lake Ontario. This indicates that the resultant recharge from precipitation is from a vapour mass that is affected by evaporation from surface water, in this case the Great Lakes. This is consistent with Gat *et al*. (1994), who estimate that the local vapour mass within the summer and autumn months contains approximately 4.6 to 15.7% water content evaporated from the Great Lakes during the summer. It should be noted that Gat *et al*. assumed only Pacific air mass precipitation contribution to the local area. These results are also consistent with the apparent trend of δ^{18}O depletion within shallow groundwaters northward from Lake Ontario.

The above discussion assumes that mixing within the subsurface largely removes the variation in isotopic signatures that occurs within the precipitation input. The groundwater signature then reflects long term climatic averages and conditions that persist for extended periods throughout the time of recharge. Figure 7 illustrates results of δ^{18}O and d for four sampling events conducted since 1995 at Sites 1/94 and 2/94. Preliminary interpretation suggests that a seasonal component may be preserved within the groundwater regime at both of these sites given the variation in δ^{18}O outside of the precision range (± 0.2 ‰). This suggests that perhaps the flow system is much more active than previously assumed; however, further testing is necessary.

5.3 Tritium

Howard and Beck (1986) completed hydrochemical studies in the south-central part of the study area and concluded that shallow and deep aquifer systems were interconnected regionally and received a significant component of recharge via overlying till units. This was later confirmed by Gerber and Howard (1996) and Gerber (1999).

All shallow groundwater samples contain tritiated water indicating recharge since the early 1950's (bomb testing source) and/or recharge since the early 1970s (nuclear reactor source). Many concentrations are above the naturally produced tritium levels of 15 TU as recorded at the Ottawa IAEA station suggesting an anthropogenic input that produced elevated levels of tritium in precipitation since the 1970's (Figure 4). The young tritiated groundwaters found in the shallow system have migrated to deep aquifers at Port Perry, Boston Mills and Barrie (Essa 10th Line) which represent tunnel channel locations (i.e. absence of Lower Newmarket till) and at Site P1 and Earl Bales park where the Lower Newmarket till is present. Some of these deep samples may represent contamination with drilling fluid, although all samples lie on the meteoric water line and do not appear to indicate mixing with an evaporated (i.e. Lake Ontario) drilling fluid source (Figure 5). Contamination by drilling and installation fluids may persist, at least in aquitards, for years as discussed by Remenda and van der Kamp (1996). Future sampling and analysis will further test the results presented.

5.4 Apparent Groundwater Age

Groundwater age dating utilizing ^{14}C has been conducted on deep confined groundwater (47-175 mbgs) contained within the "Alliston Aquifer Complex" (Aravena and Wassenaar, 1993; Aravena *et al*., 1995). The "Alliston Aquifer Complex" is described by the authors to occur immediately above bedrock within deep unconsolidated sediments in the area to the west of Lake Simcoe, roughly coincident with the Laurentian bedrock valley. It is considered to be coeval to deposits of the Scarborough Formation. The results from the Aravena studies indicate that a significant part of the deep aquifer groundwater is less than 13,000 years old, with an older component in the central part of the aquifer estimated to be 15-23,000 years old. The younger "modern" groundwater is found in wells 47 to 59 m deep situated along the western edge of the aquifer where recharge is expected to occur. This groundwater is tritiated and has $\delta^{18}O$ signatures that range from -10.8 to -12.4 ‰. The deeper, older waters have $\delta^{18}O$ signatures ranging from -13.5 to -14.7 ‰. In comparison, York Region has periodically (since 1985) analysed for ^{14}C waters from four municipal wells screened within the deep aquifer system (Holland Landing PW2 (72mbgs); Newmarket PW11 (79 mbgs); Newmarket PW16 (107 mbgs) and Aurora PW4 (101 mbgs)). Estimated ^{14}C age dates range from 1,800 to 9,600 years old; however, these estimates have not been corrected for methanogenesis affects on the carbon pools within the aquifer. These corrections can be significant as discussed in Aravena *et al*. (1995), leading to reduced age estimates. Analyses for $\delta^{2}H$ and $\delta^{18}O$ are currently being conducted for these wells. Previous analyses of deep groundwater (>80 mbgs) for nearby wells within York Region have $\delta^{18}O$ signatures ranging from -10 to -15.22 ‰; however, ^{3}H analyses were not conducted for these samples (Husain *et al*., 2007).

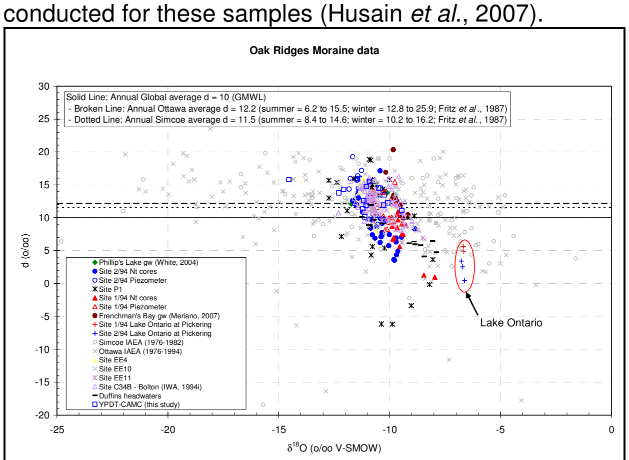

Figure 6: Deuterium excess (d) versus $\delta^{18}O$.

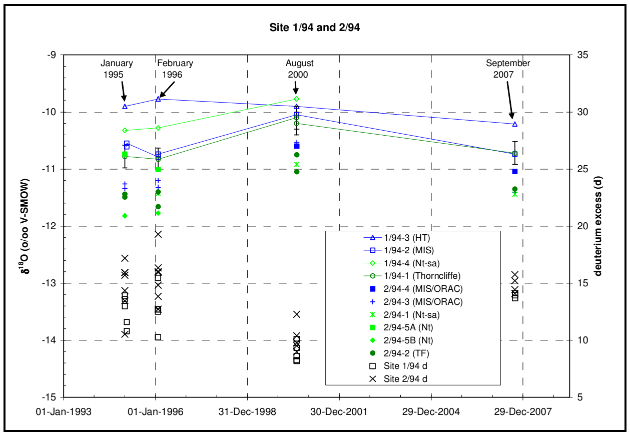

Figure 7: Site 1/94 and 2/94 δ18O and d versus time.

Groundwater δ^{18}O signatures analysed for this study range from -7.84 to -14.53 ‰ (

Table 1; Figure 5). Given the "Alliston Aquifer Complex" results discussed above one might assume that the most depleted δ^{18}O value found in a deep well near Port Perry would represent water that is thousands of years old, and the most enriched waters (Frenchman's Bay) represent recharge from modern meteoric precipitation.

Depletion trends (δ^{18}O) with depth would be expected where aquitards effectively separate overlying shallow and underlying deeper aquifer systems. In such systems shallow groundwater migration to the deeper aquifer system would be impeded by intervening low hydraulic conductivity aquitards resulting in little mixing of waters at depth. Figure8 illustrates tritium concentrations versus δ^{18}O results summarized for this study. As expected, the highest tritium concentrations occur within shallow groundwaters at Frenchman's Bay (Meriano, 2007) situated adjacent to the Pickering Nuclear Generating Station. However, even the most depleted δ^{18}O value obtained in the deep Port Perry location also contains tritium, suggesting an active flow system with mixing of older and very recent water. It is also noted that many of the "modern" δ^{18}O signature waters do not contain tritium suggesting recharge prior to the 1950's. The deep tritiated waters encountered to date occur in areas where the Lower Newmarket till has been eroded (e.g. in an interpreted tunnel channel at Port Perry); and in deep aquifers where the till is present (e.g. Site P1, Earl Bales Park). In the deep aquifer system at all locations, whether the Lower Newmarket till aquitard is present or absent, the presence of a mix of older and younger waters is consistent with the observed lack of a significant δ^{18}O depletion trend with depth at all sites tested to date. Mixing of older and younger waters in the deep aquifers is also consistent with the lack of a depletion trend through the Lower Newmarket till (aka Northern till) at five sites as discussed by Gerber *et al* (2001).

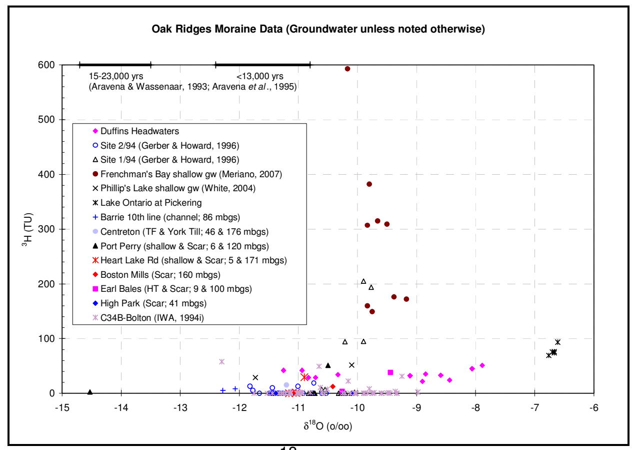

Figure 8: Tritium versus δ^{18}O for select samples.

6 SUMMARY AND CONCLUSION

This paper has summarized some of the insight gained to date from isotopic tracers and the implications to flow system conceptualization and dynamics, for a large study area situated along the north shore of Lake Ontario in south-central Ontario. This review of isotopic tracers forms part of an overall program of regional conceptual model development, refinement and testing that also incorporates numerical modelling output.

Results suggest a spatially varying precipitation input for the stable isotopes in groundwater recharge with values near Lake Ontario being more enriched (δ^{18}O signatures range -9 to -10 ‰) and more northerly shallow groundwater values being more depleted (-10 to -12 ‰). Deep aquifer waters at two locations near Lake Ontario (High Park and Earl Bales park) contain δ^{18}O depleted by approximately 1 ‰ compared to shallow groundwater and may represent recharge from upgradient within the flow system, ultimately along the ORM.

Elevated ^{3}H concentrations were observed within shallow groundwater, again with concentrations highest near Lake Ontario and the nuclear power plant source, and declining northward. Shallow groundwater at all locations analysed contains some ^{3}H. Some (but not all) locations show tritiated waters within deep aquifers, suggesting widespread mixing at depth with more recent recharge. The Lower Newmarket till aquitard may not effectively separate the shallow part of the groundwater system from the deeper part of the groundwater flow system at all locations. In some cases this aquitard has been eroded to varying degrees, possibly by tunnel channel activity beneath glacial ice. Tritium in deep aquifers has been found both in locations where the Lower Newmarket till is intact and in areas where it has been eroded, suggesting a relatively active flow system with mixing largely determined by vertical hydraulic gradients (i.e. some tunnel locations are characterized by upward flow).

This study has assumed that a) there is no contamination from drilling fluids, b) that there are no seasonal precipitation isotopic trends preserved in the groundwater flow system, and c) that groundwater concentrations will reflect long term precipitation averages. Preliminary results suggest these assumptions may not be true. Future sampling will aim to test this hypothesis, and will also incorporate other data related to geologic and groundwater quality that utilize other water chemistry information and tracers (e.g. ^{14}C, CFC) to continually advance and refine the flow system conceptual model.

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REFERENCES

Aravena, R. and Wassenaar, L.I. 1993. Dissolved organic carbon and methane in a regional confined aquifer, southern Ontario, Canada: Carbon isotope evidence for associated subsurface sources. Applied Geochemistry, 8, 483-493.

Aravena, R., Wassenaar, L.I. and Plummer, L.N. 1995. Estimating 14C groundwater ages in a methanogenic aquifer. Water Resources Research, 31 (9), 2307-2317.

Armstrong, D.K., 1999. Results of the Paleozoic Drilling Project, Northern Lake Simcoe Area, South-Central Ontario. Ontario Geological Survey Open File Report 59999, 121p.

Brown, R.M. 1961. Hydrology of tritium in the Ottawa Valley. Geochimica et Cosmochimica Acta, 21:199-216.

Craig, H. 1961. Isotopic variations in meteoric waters. Science, 133: 1702-1703.

Dansgaard, W. 1964. Stable isotopes in precipitation. Tellus, 16(4): 436-468.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D. Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjornsdottir, A.E., Jouzel, J. and Bond, G. 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature, 364, 218-220.

D'Astous, A.Y., Ruland, W.W., Bruce, J.R.G., Cherry, J.A. and Gillham, R.W. 1989. Fracture effects in the shallow groundwater zone in weathered Sarnia-area clay. Canadian Geotechnical Journal, 26: 43-56.

Desaulniers, D.E., Cherry, J.A. and Fritz, P. 1981. Origin, age and movement of pore water in argillaceous Quaternary deposits at four sites in southwestern Ontario. Journal of Hydrology, 50: 231-257.

Earthfx Incorporated, 2006. Final Report, Groundwater Modelling of the Oak Ridges Moraine Area Including Yonge Street Aquifer and Toronto and Region Conservation Watersheds, Report prepared for York-Peel-Durham Toronto Groundwater Management Strategic Study, available at www.ypdt-camc.ca, 244p.

Edwards, T.W.D. and Fritz, P. 1986. Assessing meteoric water composition and relative humidity from 18O and 2H in wood cellulose: paleoclimatic implications for southern Ontario, Canada. Applied Geochemistry, 1: 715-723.

Edwards, T.W.D. and Fritz, P. 1988. Stable-Isotope paleoclimate record for southern Ontario, Canada: comparison of results from marl and wood. Canadian Journal of Earth Sciences, 25: 1397-1406.

Eyles, N. 1997. Environmental Geology of a Supercity: The Greater Toronto Area. In Environmental Geology of Urban Area, Geological Association of Canada, Geotext 3, edited by N. Eyles, 7-80.

Faure, G. 1986. Principles of isotope geology, second edition. John Wiley and Sons, Inc.

Fontes, J.C. 1980. Chapter 3. Environmental isotopes in groundwater hydrology. In Handbook of Environmental Isotope Geochemistry. Edited by P. Fritz and J.Ch. Fontes, Elsevier Scientific Publishing Company.

Fritz, P., Drimmie, R.J., Frape, S.K. and O'Shea, K. 1987. The isotopic composition of precipitation and groundwater in Canada. Proceedings of an international symposium on the use of isotope techniques in water resources development, IAEA-SM-299/17, pp. 539-550.

Gat, J.R., Bowser, C.J. and Kendall, C. 1994. The contribution of evaporation from the Great Lakes to the continental atmosphere: estimate based on stable isotope data. Geophysical Research Letters, 21 (7), 557-560.

Gerber, R.E., 1999. Hydrogeologic behavior of the Northern till aquitard near Toronto, Ontario. Ph.D. thesis, University of Toronto, 172p.

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

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

Hinton, M., Russell, H.A.J., Bowen, G.S. and Ahad, J.M.E. 1998. Groundwater discharge in the Humber River watershed. In proceedings of the “Groundwater In A Watershed Context” Symposium, Canadian Centre for Inland Waters, Burlington, Ontario, Canada. December 2-4.

Howard, K.W.F and Beck, P. 1986. Hydrochemical interpretation of groundwater flow systems in Quaternary sediments of southern Ontario. Canadian Journal of Earth Sciences, 23: 938-947.

Huddart, P.A., Longstaffe, F.J. and Crowe, A.S. 1999. δD and $\delta^{18}O$ evidence for inputs to groundwater at a wetland coastal boundary in the southern Great Lakes region of Canada. Journal of Hydrology, 214, 18-31.

Husain, M., Lee, T., Khazaei, E., Kemp, W. and Ariza, L. 2007. Source Water Protection: Geochemical and Isotope Trends in Major Water Supply Aquifers within the Oak Ridges Moraine Complex as Indicators of Source Water Quality and its Response to Stresses. In Proceedings of Joint CGS-IAH/CNC Annual Conference, OttawaGeo2007, 183-190.

International Atomic Energy Agency. 1981. Stable isotope hydrology: deuterium and oxygen-18 in the water cycle. Technical Report Series No. 210, Vienna.

International Atomic Energy Agency. 1992. Statistical treatment of data on environmental isotopes in precipitation. Technical reports series, ISSN 0074-1914, ISBN 9200-100892-9, Vienna.

Interim Waste Authority. 1994a. EA document IV, geology/hydrogeology, technical appendix 1: Site T1 for Durham Region landfill site search. Prepared by M.M. Dillon Limited, February, 1994, 90 p.

Interim Waste Authority. 1994b. EA document IV, geology/hydrogeology, technical appendix 2: Site EE4 for Durham Region landfill site search. Prepared by M.M. Dillon Limited, February, 1994, 70 p.

Interim Waste Authority. 1994c. EA document IV, geology/hydrogeology, technical appendix 3: Site EE10 for Durham Region landfill site search. Prepared by M.M. Dillon Limited, February, 1994.

Interim Waste Authority. 1994d. EA document IV, geology/hydrogeology, technical appendix 5: Site KK2 for Durham Region landfill site search. Prepared by M.M. Dillon Limited, February, 1994.

Interim Waste Authority, 1994e. IWA landfill site search, Metro/York Region, Step 6 hydrogeological report Site M6. Prepared by Fenco MacLaren Inc, February 1994, 58p.

Interim Waste Authority. 1994f. IWA landfill site search, Metro/York Region. Step 6 Hydrogeological Report, Sites G1B, G1C. Prepared by Fenco MacLaren Inc., February, 1994.

Interim Waste Authority. 1994g. IWA landfill site search, Durham Region. Detailed Assessment of the Proposed Site EE11, Appendix C Geology/Hydrogeology. Prepared by M.M. Dillon Limited, October, 1994, 197p.

Interim Waste Authority. 1994h. IWA landfill site search, Metro/York Region. Detailed Assessment of the Proposed Site V4A, Appendix C Geology/Hydrogeology. Prepared by Fenco MacLaren Inc., November, 1994.

Interim Waste Authority. 1994i. IWA landfill site search, Peel Region. Detailed Assessment of the Proposed Site C-34B, Appendix C Geology/Hydrogeology. Prepared by Golder Associates Limited, November, 1994.

Johnson, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G., and Rutka, M.A., 1992. Paleozoic and Mesozoic Geology of Ontario in Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2. p.907 – 1008.

Lawrence, J.R. and Taylor Jr, H.P. 1972. Hydrogen and oxygen isotope systematics in weathering profiles. Geochimica et Cosmochimica Acta, 36: 1377-1393.

Meriano, M. 2007. Groundwater-surface water interaction in Frenchman's Bay watershed, Ontario: implications for urban recharge, contaminant storage and migration. Unpublished Ph.D. Thesis, University of Toronto, 217p.

MM Dillon Limited. 1990. Regional Municipality of Durham Contingency Landfill Site Assessment Technical Support Volume B, Technical Report, Hydrogeology. September 1990. Published by Ontario Ministry of the Attorney General. 588p.

Ontario Power Generation. 2007. 2006 Results of Radiological Environmental Monitoring Programs. December 17.

Remenda, V.H., Cherry, J.A. and Edwards, T.W.D. 1994. Isotopic composition of old ground water from Lake Agassiz: implications for Late Pleistocene climate. Science, 266: 1975-1978.

Remenda, V.H. and van der Kamp, G. 1996. Contamination from sand-bentonite seal in monitoring wells installed in aquitards. Ground Water, 35(1): 39-46.

Ruland, W.W., Cherry, J.A. and Feenstra, S. 1991. The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario. Ground Water, 29(3): 405-417.

Sharpe, D., Pugin, A., Pullan, S. and Shaw, J. 2004. Regional unconformities and the sedimentary architecture of the Oak Ridges Moraine area, southern Ontario. Canadian Journal of Earth Sciences, 41, 183-198.

Simpkins, W.W. and Bradbury, K.R. 1992. Groundwater flow, velocity, and age in a thick, fine-grained till unit in southeastern Wisconsin. Journal of Hydrology, 132:, 283-319.

Sklash, M., Ainslie, A., Ibrahim, I. and Chekiri, K. 1992. Is there rapid recharge through 30 m of clayey till in Essex County, Ontario? Proceedings, Modern Trends in Hydrogeology, 1992 Conference of the Canadian National Chapter, International Association of Hydrogeologists, May 11 to 13, pp. 461-467.

White, T.L. 2004. The Hydrogeological Function of Kettle Lakes on the Oak Ridges Moraine, Ontario, Canada. Unpublished M.Sc. Thesis, University of Toronto.

Yang, C., Telmer, K. and Veizer, J. 1996. Chemical dynamics of the "St. Lawrence" riverine system: δD_{H2O}, $\delta^{18}O_{H2O}$, $\delta^{13}C_{DIC}$, $\delta^{34}S_{sulfate}$, and dissolved $^{87}Sr/^{86}Sr$. Geochimica et Cosmochimica Acta, 5, 851-866.