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Aller au sommaire du numéro

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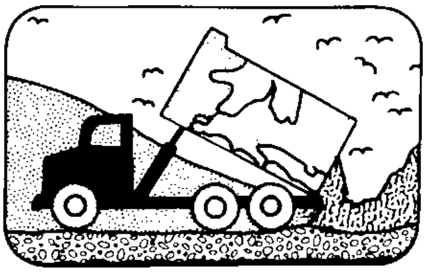
Résumé de l'article

Much of urbanized North America is experiencing major problems with regard to the management of municipal waste; production exceeds the capacity of management systems to handle waste by reuse, recycling, incineration and landfilling. The last is a multi-billion dollar a year industry and in volves a large research effort by various public and private agencies to minimize environmental degradation from leachate contamination of groundwaters. This paper presents the preliminary results of a long-term study aimed at establishing the regional. Quaternary glacial geology of existing and projected landfills in southern Ontario, and the groundwater contamination potential of such landfills. It can be shown that at least 300 landfills in southern Ontario are located in abandoned aggregate or bedrock quarries where little regard was given to ground water contamination. Many landfills contain toxic liquid and solid industrial wastes, but few data are available. Areas of fine-grained, impermeable glacial sediments, affording some degree of natural protection, have are stricted extent in southern Ontario; silt- and sand-rich tills predominate and, despite their massive, dense character, have significant bulk permeabilities. Projected sites canbe fully engineered and protected by "hydraulic traps", thereby minimizing groundwater impacts, but the presence of nearly 1200 sites that lack any engineering poses a significant threat to groundwater supplies. Groundwater flow paths and estimates of groundwater discharge to Lakes Erie and Ontario are very poorly understood; a pressing research need is to determine the effects of climate warming and lowering of the groundwater table on subsurface contaminant transport to the Great Lake basins through complex glacial stratigraphies.



The Geology of Garbage in Southern Ontario

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SUMMARY

Much of urbanized North America is experiencing major problems with regard to the management of municipal waste; production exceeds the capacity of management systems to handle waste by reuse, recycling, incineration and landfilling. The last is a multi-billion dollar a year industry and involves a large research effort by various public and private agencies to minimize environmental degradation from leachate contamination of groundwaters. This paper presents the preliminary results of a long-term study aimed at establishing the regional Quaternary glacial geology of existing and projected landfills in southern Ontario, and the groundwater contamination potential of such landfills. It can be shown that at least 300 landfills in southern Ontario are located in abandoned aggregate or bedrock quarries where little regard was given to groundwater contamination. Many landfills contain toxic liquid and solid industrial wastes, but few data are available. Areas of fine-grained, impermeable glacial sediments, affording some degree of natural protection, have a restricted extent in southern Ontario; silt- and sand-rich tills predominate and, despite their massive, dense character, have significant bulk permeabilities. Projected sites can be fully engineered and protected by "hydraulic traps", thereby minimizing groundwater impacts, but the presence of nearly 1200 sites that lack any engineering poses a significant threat to groundwater supplies. Groundwater flow paths and estimates of groundwater discharge to Lakes Erie and Ontario are very poorly understood; a pressing research need is to determine the effects of climate warming and lowering of the groundwater table on subsurface contaminant transport to the Great Lake basins through complex glacial stratigraphies.

INTRODUCTION

Canadians are world-class consumers, each generating 1.7 kg of garbage per day, the highest per capita figure in the world. Sweden, for comparison, produces 0.8 kg per person per day. In southern Ontario, which contains 35% of the Canadian population, a high level of consumption is associated with a waste management system that emphasizes the burial of municipal waste in landfills; less than 10% of the total waste stream is recycled. There are nearly 1200 active and inactive landfills within Quaternary sediments in southern Ontario; for all but a handful there are no available data as to contents, underlying geology, or potential for groundwater contamination by leachate plumes. Most of these sites were in use prior to enactment of the Protection of the Environment Act in 1971. The purpose of this article is to describe recent developments in waste management in southern Ontario where the distribution of Quaternary glacial sediments constrains the location and design of new landfills and determines the contamination potential of existing and abandoned sites. Here, we present a general picture of the glacial stratigraphy of the region and distribution of existing and abandoned landfill sites. Southern Ontario, in particular the Toronto region, is typical of many mid-latitude urban areas, and the data presented here regarding Quaternary geological constraints on the siting of landfills have some broader international significance.

MUNICIPAL WASTE MANAGEMENT IN THE TORONTO REGION

One out of every six Canadians lives in the Greater Toronto Area (GTA), a 6250 km^2 area which extends 125 km to the east of the Niagara Escarpment and northward from Lake Ontario to Lake Simcoe (Fig. 1). The area generates more than 20% of the national income, 44% of Ontario's gross provincial product of $249 billion, and contains 44% of Ontario's population in an area less than 1% of the total land area of the province. Population is growing at about 10% annually with a projected total of about 6 million by the year 2021. The region currently produces about 5 million tonnes of municipal waste each year, but there is not a single disposal facility for hazardous industrial waste. The area's existing landfill sites will be full by 1993 and there is a major research effort, involving government, university and the private sector, to find environmentally safe long-term sites. Garbage disposal is currently the focus of intense social and political debate.

The provision for new landfill capacity in

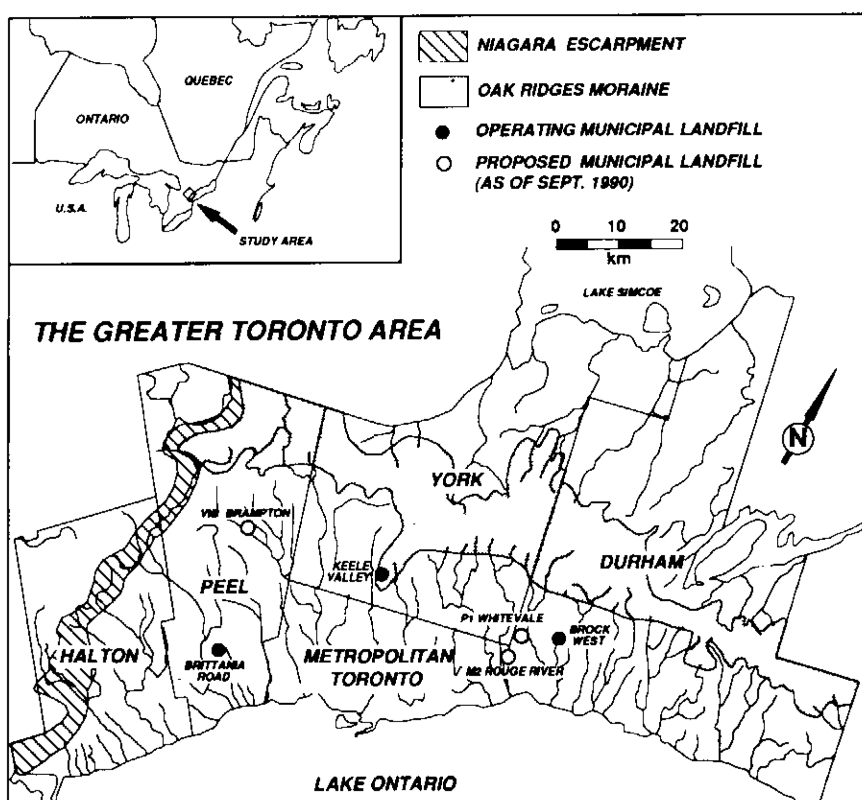

Figure 1 *Location map for Greater Toronto Area (GTA) showing currently operating and proposed interim municipal landfill sites and the five regional municipalities.*

the GTA, a political grouping which comprises the five regional municipalities of York, Durham, Peel, Halton and Metropolitan Toronto (Fig. 1), has lagged behind a steady increase in the generation of municipal waste. Each person in the GTA produces about 0.5 tonnes of municipal garbage each year, which is the *highest anywhere in the world*. This figure is increased to 1.49 tonnes per year for persons employed by industrial and commercial companies where light industrial waste is added to the residential waste stream. Figure 2 depicts volumes of municipal waste as currently produced every year in the five regional municipalities of the GTA. The total amount of landfill waste in 1989 was about 4.1 million tonnes. This volume is not easy to visualize. In 1989, Toronto opened a new domed stadium (Skydome); the total amount of municipal garbage produced by the GTA in 1989 was equivalent to the volume of four Skydomes (Fig. 3B). Due to a downturn in the economy, the total GTA waste production in the last three years has fallen. This is only a temporary abatement, however (see below). The present landfill sites handling this waste (Keele Valley, which is Canada's largest landfill, Brittania Road and Brock West; Fig. 1) will be full shortly after 1992 and even with planned waste diversion targets of 25% in place the GTA has insufficient landfill capacity to meet the needs of the area's 4 million people beyond 1993.

THE POLITICS OF WASTE MANAGEMENT

In response to the shortfall in landfill capacity, in March 1989, the five municipalities called for a long-term waste management system to be in place no later than 1996 and to be developed either by the private sector or public agencies. The main goal of the plan was to divert 50% of solid waste from landfills by reduction, reuse and recycling by the year 2000; the present figure is less than 10%. In addition, the five Regional Chairmen of Durham, Halton, Peel and York Regions and Metropolitan Toronto proposed a stand-by plan to deal with the shortfall in disposal capacity between 1992 and 1996. In that plan, each Region agreed to nominate one or more short-term, contingency waste disposal sites to serve the GTA in that period.

The solid-waste program for the GTA was then managed by the Solid Waste Interim Steering Committee (SWISC). The Regional Municipality of Durham nominated the P1 Contingency Landfill Site ("the P1 Site"; Fig. 1) to provide interim waste capacity until long-term landfill sites are approved for use. The Regional Municipality of Peel nominated a site (VIB) near the city of Brampton, while Metropolitan Toronto nominated a controversial site (M2) on its eastern border in Scarborough, close to the Rouge Valley within an area now designated for a provincial park (Fig. 1). SWISC's comprehensive long-term solid-waste management programme for the GTA, planned to begin operation in 1996, was to be subject to a full Environmental Assessment Act process. This process is streamlined for interim, short-term sites (see below). Under the terms of the agreement arranged by SWISC with Durham Region, $20 million would be paid immediately and a further $21 million at the time of approval for site P1; this money would be available to fund recycling projects in Durham. An estimate of

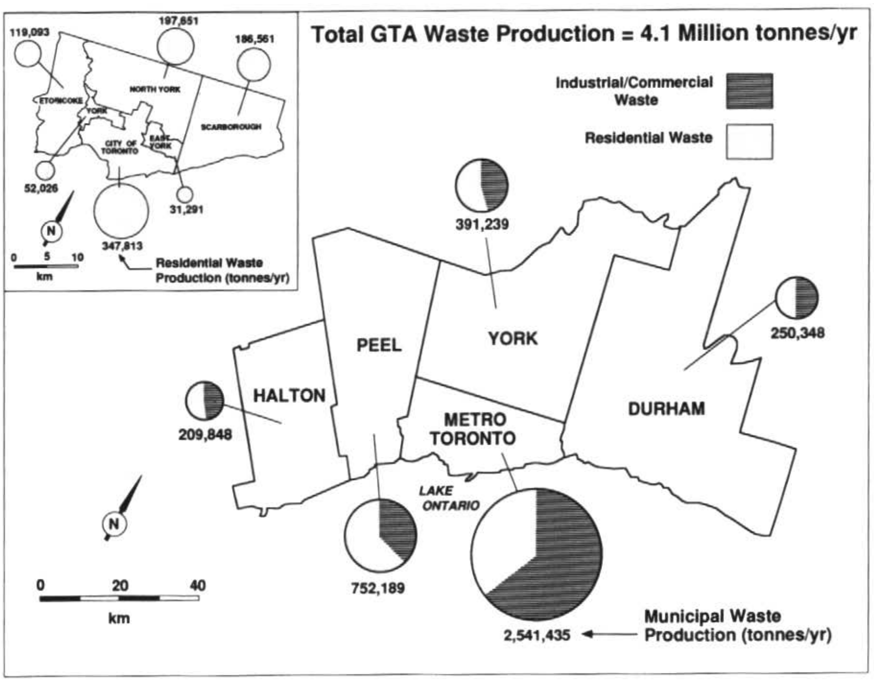

Figure 2 ***(upper left)*** *Municipal waste production in 1989 for the GTA and Metropolitan Toronto (inset) in tonnes per year.*

VOLUME OF SKY DOME = 1,557,435 m^3

CAPACITY = 1,090,204 tonnes of garbage

= 26% of GTA annual waste production

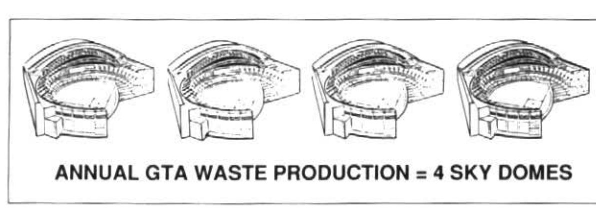

Figure 3 **(A)** ***(left)*** *Skydome as an interim landfill site; a cartoonist's view. (Courtesy of the Toronto Star.)* **(B)** ***(above)*** *Annual GTA municipal waste production expressed as Skydome volumes.*

capital expenditure on the landfill is about $51 million during a five-year period for construction, operation, closure and perpetual care; net revenue during that time would be about $210 million. Thus, there are significant financial benefits to be gained by having a landfill site approved. It should be noted, in addition, that commercial tipping fees at the existing landfill sites increased to $150/tonne in early 1990, representing a 700% increase since 1988; if garbage is separated into recyclable loads of material the fee is $75/tonne.

The wider political dimensions of solid-waste handling and control are expressed through the legal processes, whereby landfill sites are chosen under environmental protection legislation. In some cases, legal considerations are sufficiently important to override geological considerations of the respective merits of individual landfill sites. This is not the place to review in detail the existing environmental legislation in Ontario that governs landfill practice. An excellent review of legislation and compliance procedures is that of Phyper and Ibbotson (1991). In brief, the selection of landfill sites in Ontario is normally examined, approved and licensed under the Environmental Assessment Act (EAA), whereby the best site is located following an exhaustive screening process, taking into account potential impacts on the natural and human environment (*e.g.*, social, economic and cultural conditions; Fig. 4). The time required to complete such a process is at least five years and would substantially exceed the date of landfill exhaustion for the GTA, resulting in an intensified crisis with regard to waste disposal capacity. As a result, the municipalities of Peel and Durham applied to the Minister of the Environment in July 1990 for the V1B and P1 sites to be made *exempt* from the EAA. Approval would be sought, instead, under the Environmental Protection Act (EPA) which examines the environmental impact and suitability of specific sites chosen without undergoing the comprehensive screening process demanded by the EAA (Fig. 4). Part V of the EPA governs the approval of waste management facilities. When specific criteria — designed to minimize the impact on the natural environment only — are met, the required Certificate of Approval is granted. The EPA, therefore, has a much narrower definition than the EAA, and is widely known as a "fast-track" mechanism, compared with the lengthy and exhaustive evaluation required by EAA legislation.

This exception was granted through an order in cabinet by the then Liberal Government of David Peterson; with a cabinet order there was no debate in the Ontario Legislature. Certain restrictions were attached, however: namely, that the sites would be closed in 1996 and that 25% of the waste stream by weight would be diverted from the landfill (*i.e.*, recycled). A provincial election on September 6, 1990 was won by the New Democratic Party under Bob Rae. In the election campaign, Rae promised that, if elected, he would revoke the exemption and institute a full environmental assessment under EAA regulations for all future landfills in Ontario, including interim sites nominated by the GTA. Rae stated that, "unless we cut the number of landfills there'll be no action to cut waste", and "Creating landfills creates an incentive to use [them]". At the same time, the Mayor of Pickering announced a court battle to "delay, if not stop" use of the P1 site. Widespread concern with waste management may have been a factor in the election of Ontario's first NDP government, which was perceived as having a better and "greener" management programme.

In November 1990, the new Environment Minister Ruth Grier announced, not surprisingly, given the pre-election rhetoric, that she would shelve the Whitevale and Brampton interim sites, arguing that they were not needed despite strong opposition from the regional chairmen of the GTA. SWISC was dissolved and was to be replaced by a provincially established authority (the IWA; see below) with responsibility for new dump sites and technologies for recycling. One day after making this announcement, however, Grier confounded critics by making a turn-around and stating that, in the unlikely event new sites were needed, she would use her emergency powers to open the Whitevale and Brampton sites without any formal hearing, and would, furthermore, expand existing dumps (Britannia Road, Keele Valley, Brock West; Fig. 1), also without a hearing. In June 1991, Grier issued a Provincial Order to expand the Britannia Road site; the order is being defied by the Peel Region. At that time, a 6000 home subdivision was planned close to the Britannia Road dump site and Brock West could accept no further waste beyond 1992. Keele Valley could accept, under emergency expansion, about 14 million tonnes, sufficient for approximately three years, given the current annual production of garbage within the GTA. Any reduction in the waste stream by recycling and reuse would extend the capacity a little further. Critics say the new Provincial Government's waste management strategy consists simply of emergency powers. Strong words were spoken; Mississauga mayor Hazel McCallion called the Environment Minister a "meddling hypocrite".

The situation was made more complex when Metropolitan Toronto announced, in early December 1990, that it planned to dump its wastes in an abandoned open pit mine at Kirkland Lake, 530 km north of Toronto. In response, the Minister of the Environment once more affirmed that the Province, not Metro, was now responsible for waste management. In some quarters, reaction to Metro's proposal was generally negative; significant reduction in waste volumes could only come about if waste were a local responsibility and not simply a problem to be exported. Kirkland Lake Mayor Joe Mavrinac, conscious of the jobs the proposal would create in his community, called it "a sweet deal". In early 1991, Grier killed the proposal to export garbage to Kirkland Lake. At present, communities that could profit from accepting Metro's garbage are stalled; other communities who do not want landfills in their midst are equally frustrated. Ironically — some would say hypocritically — Metro continues to export up to 500,000 tonnes of waste annually to the United States. As a result, Metro expects to lose $60 million in disposal fee revenues to the United States, where tipping fees are much less. There is no shortage of United States dumps, which are subject to less rigorous environmental controls and are willing to take Canadian garbage for $40 per tonne compared with $150 per tonne in Metro. Much of the waste is

THE ENVIRONMENTAL ASSESSMENT ACT (EAA)	THE ENVIRONMENTAL PROTECTION ACT (EPA)
• Comprehensive screening process applied to assess alternative landfill sites • Considers impacts on the natural environment (e.g., social, economic and cultural conditions) • The EAA uses a broader definition of "environment" than the EPA	• Under Part V of the Act, a certificate for operating a landfill can be granted if environmental criteria are met for a specific site • Purpose of the Act is to provide for the protection and conservation of the natural environment

Figure 4 *Province of Ontario Acts as they relate to the landfill site selection process.*

incinerated, and airborne pollutants are exported back to Ontario where incineration is banned.

While many countries, such as Japan, Denmark and Sweden, extol the environmental virtues of incineration, they lack the geological conditions necessary for landfills. Indeed, the considerable thickness of glacial "drift" in southern Ontario has promoted the disposal of waste in landfill sites, and lies at the root of the current problem. Incineration is not an option for Ontario and is a touchy area in United States/Canada relations. As late as 1987, 140,000 tonnes of garbage were incinerated each year in Ontario, but this practice was discontinued in 1988. Ontario was the first province or state in North America to ban the development of new solid-waste incineration facilities; the only communities in Ontario still using incineration are Hamilton and London. In 1991, Environment Minister Ruth Grier issued a lawsuit against the City of Detroit to force the city to add state-of-the-art emission control systems to its incinerator. Michigan lawyers are currently seeking to prove that Ontario issued writs with "unclean hands", citing that Ontario incinerators do not have the most up-to-date emission controls. Furthermore, the province exports waste to other United States incinerators that lack modern emission controls. United States lawyers are seeking as much as $3 million in costs. If their defence is successful, it may force Ontario to upgrade its existing incinerator facilities.

RECENT DEVELOPMENTS

The most recent development in Ontario has been the establishment in 1991 of the Interim Waste Authority Ltd. (IWA). The IWA is a Crown agency which reports to the GTA. The minister with responsibility for the GTA has directed that the search for the area's long-term waste disposal sites be confined within the GTA, to promote the government's "conserver society" objectives. The IWA is the first agency to outline in a single document the proposed planning process, site selection criteria, and public consultation plan. An extensive public consultation strategy has been devised by the IWA.

Bill 143, which is the enabling legislation behind the IWA, was introduced to the Ontario legislature in November 1991 and met with stiff opposition. Part of the bill consists of widely supported waste reduction measures, with regard to packaging, for example, but the remainder of the bill's provisions would entrench the government's power to unilaterally extend existing dumps without rigorous environmental assessments. Essentially, the IWA would become both the proponent of any new landfill and the approval agency, which places the Environment Minister as head of the IWA, in a conflict of interest. Bill 143 is expected to be passed in the spring of 1992. The IWA is currently in the process of identifying provisional sites for detailed site investigation. One such candidate site is twice the size (about 300 hectares) of the existing Keele Valley dump, which is already the largest in Canada. Targeted to open in 1996, the proposed "super" landfill would serve Metro and York; Durham and Peel would be served by separate sites.

With the severe recession now affecting waste production, the garbage crisis has eased temporarily; Brock West, for example, may be open until 1996 given the decrease in the dimensions of the waste stream. Better-than-expected compaction at the landfill and

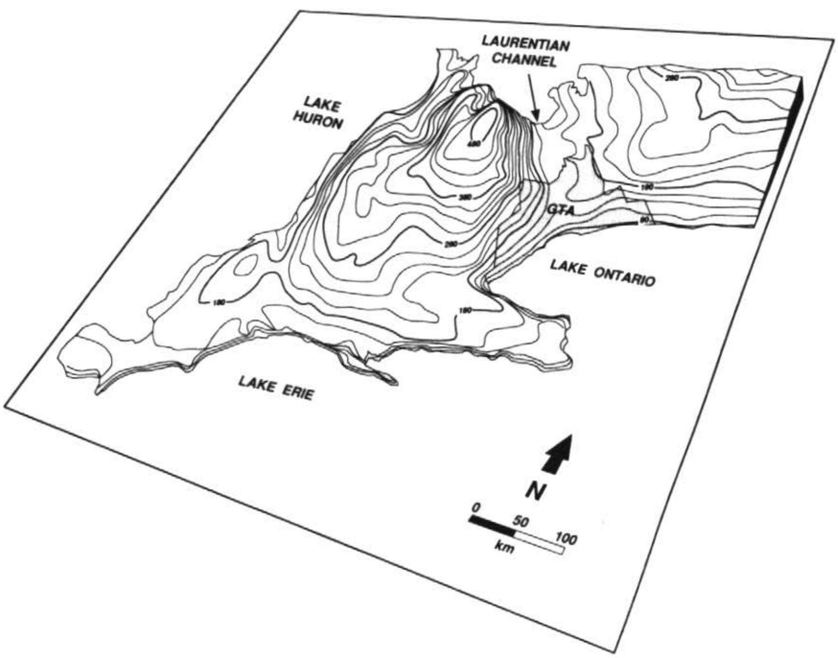

Figure 5 **(A)** *Generalized bedrock topography in southern Ontario reconstructed from Geographical Information System referencing more than 10,000 borehole records and other outcrop data. Contour interval 25 m.*

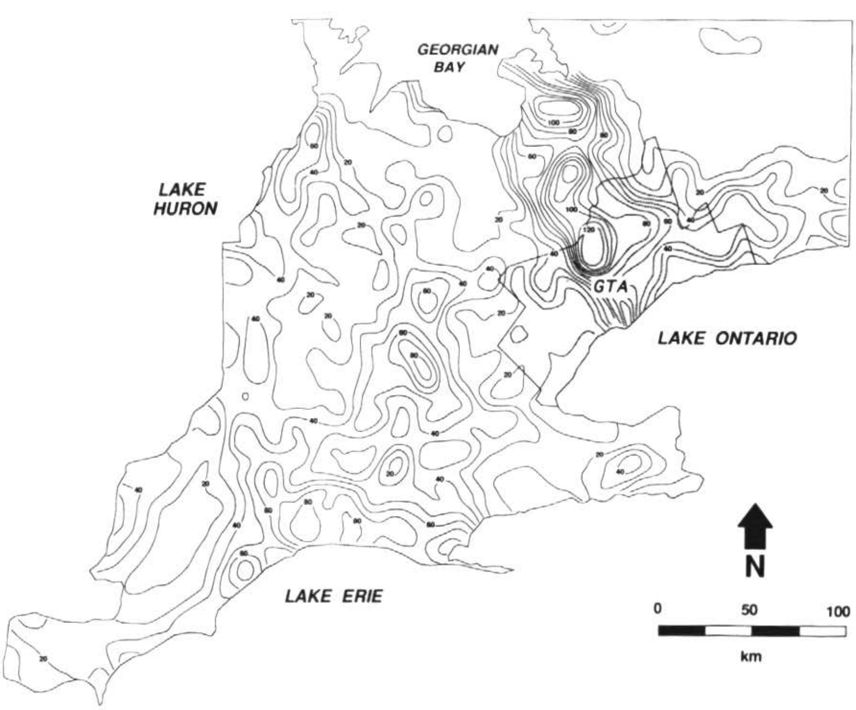

Figure 5 **(B)** *Generalized drift thickness map for same area as in A. Contour interval 10 m.*

improved waste reduction initiatives have also helped. The volume of waste dumped in Metro's landfills (Fig. 2) dropped by 31% in 1991 and the trend is continuing. The biggest decrease is in excavated fill materials, reflecting a slump in the construction industry. It is probably safe to assume that all existing Metro-area dumps will be expanded and will continue to be used until 1996.

Outside the GTA, centralized waste management plans are lacking and there are few records of the types of waste placed in closed or open landfills; typically, waste management falls under the responsibility of assorted departments such as Public Works, Planning and Civil Engineering. A major problem is the lack of provincial or federal funding with which to begin preliminary work on comprehensive waste management plans. One of the goals of this paper was to establish an accurate assessment of the volume of waste generated by Ontario residents, but this proved impossible for all but the GTA. Accurate records of waste generation rates, volumes and types are not available at the local level and this has to be a major objective of the new Provincial authority set up by the NDP.

The situation in southern Ontario, where different waste management strategies continue to be major topics of political and social debate, is typical of the "garbage crisis" facing most communities in North America. Despite differences in competing waste management strategies, landfill sites remain a necessary option. There is, consequently, an urgent demand for detailed systematic terrain studies to identify Quaternary geological constraints on projected landfill sites, and the groundwater contamination potential of existing and abandoned landfills.

QUATERNARY GEOLOGICAL SETTING OF THE TORONTO REGION

Recent reviews of the Quaternary stratigraphy of southern Ontario and the Toronto region have been presented by Karrow (1984), Eyles (1987) and Eyles and Williams (1992). The form of the bedrock surface (Fig. 5A) has exerted a significant control on the thickness and preservation of Quaternary sediments; a prominent bedrock channel (Laurentian River Channel) contains the thickest drift cover in the area (Fig. 5B). The channel fill is composed of Illinoian (?) glacial and Sangamon interglacial sediments buried below last glaciation (Wisconsin) deposits (Fig. 6). Deposits of the last glaciation are of prime interest in landfill evaluation, given that they comprise the dominant surface materials across the region, and given the shallow (<15 m) depths of excavation employed in landfill construction. Close to the Niagara Escarpment and on the Pre-cambrian Shield to the northeast, the reduced thickness of glacial drift (<10 m) necessitates that consideration be given to the hydrogeological properties of bedrock (Fig. 7). The lithologic character and, consequently, the hydraulic properties of bedrock, vary considerably across the region. The most significant bedrock aquifers occur in limestones and dolostones (*e.g.*, Guelph-Amabel Formation; Fig. 7), and are generally restricted to the upper 5–10 m fractured parts of the formations (Novakovic and Farvolden, 1974). Modelling the presence of these fractured zones is particularly problematic in establishing groundwater flows. Even in areas of thick (>100 m) drift cover, *e.g.*, along

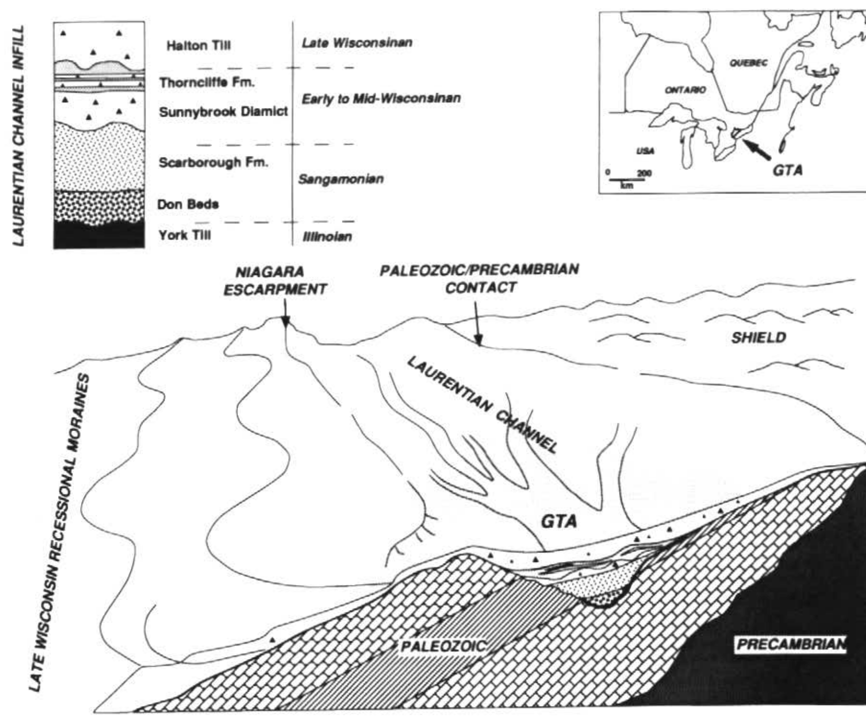

Figure 6 *Schematic representation of Quaternary stratigraphy preserved within Laurentian Channel (based on Eyles and Williams, 1992).*

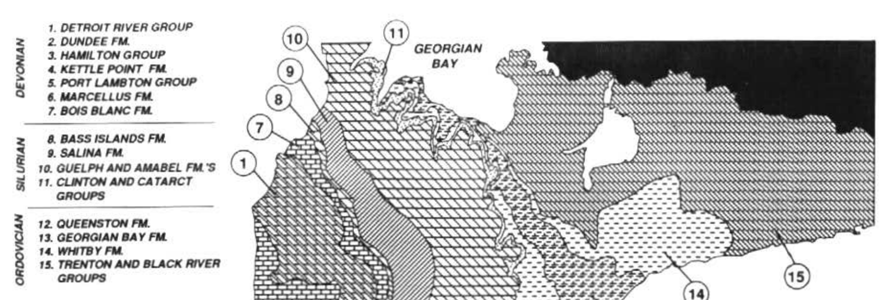

Figure 7 *Bedrock geology map of southern Ontario showing dominant lithology of strata (after Freeman, 1978).*

the Laurentian Channel (Figs. 5B and 6), the hydrogeological characteristics of both Quaternary and underlying bedrock strata are an important consideration in modelling the potential movement of leachates from landfills under "worst-case" scenarios, involving either complete failure of engineered leachate collection systems or sustained leakage from abandoned landfills in areas of inappropriate (*i.e.*, highly permeable) substrates (see below).

The surficial Quaternary map of southern Ontario (1:1,000,000 scale), first published by Chapman and Putnam (1966) with subsequent modifications by the Ontario Waste Management Corporation (1986) and the Ontario Geological Survey (Barnett *et al.*, 1991), is a valuable tool in the first stages of screening potential landfill sites. However, maps of surficial geology show only the character and distribution of surface sediments and thus provide no data as to the deeper stratigraphy. The hydrogeological assessment of potential landfill sites is dependent upon detailed knowledge of the distribution and geometry of sediments in the subsurface, and their physical properties. Mapping of aquifers, water quality and groundwater yields has been conducted by the Ontario Ministry of the Environment, but the coverage is not exhaustive and in places is based on dated information. In response to the need for integrated geological and hydrogeological data required for such applied investigations, a centralized geoscience databank and data analysis system was recently established at the Scarborough Campus of the University of Toronto under joint funding from the Great Lakes University Research Fund (GLURF) and the Natural Sciences and Engineering Research Council (NSERC). The facility, comprising three dedicated PC-486 workstations running SPANS GIS, multi-gigabyte capacity tape and disk storage devices and full-size digitizing and scanning facilities, permits the integration, storage, retrieval and regional-scale analysis of large volumes of environment-related information. Although a wealth of environment-related data has been accumulated by government, private sector and universities in Ontario, no comprehensive framework for the collection, assessment and management of this information previously existed.

The rationale, operation and use of the facility is being described elsewhere, but it is now possible to generate bedrock topography, drift thickness and generalized stratigraphic summaries for most areas of southern Ontario. Work is in hand using the GIS system to produce "landsystem" maps linking the stratigraphy and engineering characteristics of different terrain types (*e.g.*, Eyles and Dearman, 1981; Eyles, 1983). This process serves as a first level "screen" on the location of landfill sites, and identifies terrains where landfill sites are undesirable and where there is a high potential for groundwater contamination.

Figure 8 shows the distribution of near-surface (<15 m) Quaternary sediments in southern Ontario grouped according to dominant lithology (*i.e.*, permeability). Low-permeability glaciolacustrine silts and clays are generally considered to be favourable substrates for landfill sites, but have limited areal extent in southern Ontario. These sediments record various stages in the development of high-level, proglacial lakes. Fine-grained, matrix-dominant and coarser clast-dominant tills are the predominant surficial materials in the region. Matrix-dominant tills are characterized by higher silt and clay contents (>80%) and low to moderate permeability. These sediments afford some degree of natural containment and attenuation of landfill leachates (see below). On the other hand, sand-rich (>50%) clast-dominant tills may not be suitable for landfill purposes, owing to their stratigraphic complexity and moderate

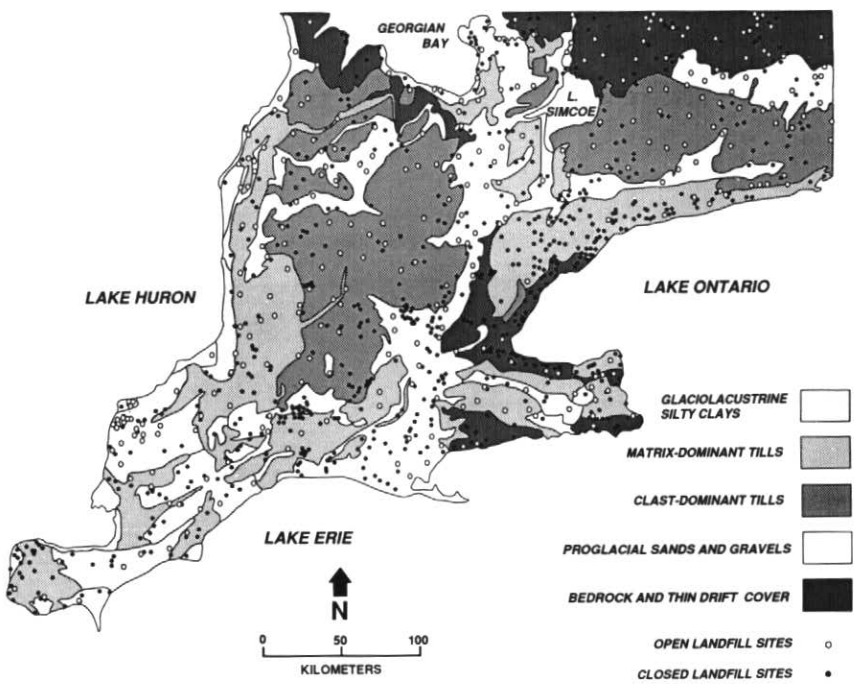

Figure 8 *Location of open (n=311) and closed (n=868) landfill sites and distribution of Quaternary sediment types in southern Ontario (after Chapman and Putnam, 1966; Ontario Waste Management Corporation, 1986; Ontario Ministry of the Environment, 1991).*

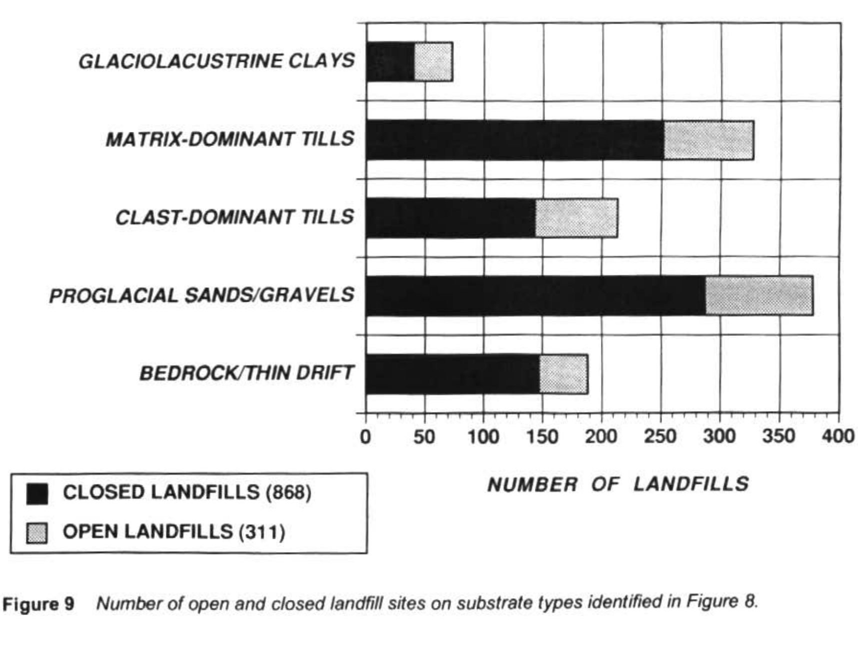

Figure 9 *Number of open and closed landfill sites on substrate types identified in Figure 8.*

to high hydraulic conductivity. Lenticular sand and gravel horizons associated with these tills locally constitute significant overburden aquifers with yields sufficient for domestic and municipal use. Proglacial sands and gravels are widespread across the region and delineate former outwash plains, meltwater spillways, and morainal belts built at the margins of Late Wisconsinan ice sheets. The thickness of these deposits is considerable (*e.g.*, >100 m along the Oak Ridges moraine; Fig. 1) and they constitute major areas of groundwater recharge. More than 90% of overburden wells in southern Ontario are developed in these deposits. Although it is not out of the question to site a small attenuation type landfill in a sand body in southern Ontario, in general, these substrates are unsuitable as landfill sites, given their hydrogeologic importance as recharge areas and their high potential for contaminant migration.

DISTRIBUTION OF LANDFILL SITES AND POTENTIAL FOR GROUNDWATER CONTAMINATION

Figure 8 shows the location of 1183 open and closed landfill sites in southern Ontario, superimposed on the map of surficial geology. These are landfills whose location is known to the Ministry of Environment; it has been estimated that several hundred remain to be discovered. Figure 9 gives a breakdown of the number of open and closed sites on each Quaternary sediment type and shows that the greatest number (380) are located on areas of sand and gravel. This is a reflection of the use of abandoned pits and quarries for landfilling; most sites are located in former aggregate or bedrock quarries and are consequently associated with either sand-rich substrates or fractured bedrock in which leachate plumes are likely to develop (see below). There is, therefore, a crisis with regard to locating new landfill sites and also in assessing the extent of groundwater contamination at landfill sites used prior to enactment of the Environmental Protection Act in 1971. As late as 1977, the definition of a sanitary landfill made no mention of mandatory preventive measures to restrict or even assess groundwater contamination. For most of these abandoned sites, there are little or no data regarding the commencement of filling, type of waste (many handled industrial and municipal solid and liquid waste), or volume since no records were kept.

Landfills constructed after 1986 are required to satisfy Ontario Ministry of Environment (MOE) Guidelines on Reasonable Use (Ontario Ministry of the Environment, 1986), which are the basis for groundwater quality management in Ontario. The policy established procedures to determine the reasonable use of, and allowable impacts on, groundwater in the vicinity of a landfill. The burying of waste is only acceptable if leachates dilute sufficiently beyond the landfill boundary to meet drinking water and recreational water quality standards. The guidelines specify that water quality cannot be degraded by more than 50% of the difference between natural (*i.e.*, background) levels and Provincial drinking water requirements. These guidelines are meant to ensure that landfills have a negligible impact on both groundwater quantity and quality under expected operating and failure conditions. It can be assumed that many sites identified on Figure 8 fail to satisfy MOE Reasonable Use guidelines since they occur in inappropriate substrates (Fig. 9). This is well-illustrated by the municipal dump in Cobourg, which is generating a contaminant plume well-defined by elevated levels of chlorides moving away from the site in the subsurface within "shoe-string" sand bodies enclosed within till (Fig. 10). The leading edge of the plume is advancing at about 30 m per year. Expansion plans were denied in 1989 because the dump failed to comply with Reasonable Use guidelines (Environmental Assessment Board, 1989).

A major problem is that only limited testing has been done in the vicinity of pre-existing landfills. A massive and costly effort is required to delineate the location and dimensions of subsurface leachate plumes derived from these sites. Development around such sites is already being hindered by the cost of remediation and by legal disputes as to responsibility for these costs. However, a far greater problem is intense urban development that has already taken place in the vicinity of abandoned landfills, such as the case with the Upper Ottawa Street landfill in Hamilton where health problems in both former workers and current residents were identified by a Ministry of Health enquiry in 1986 (Fig. 11). Non-intrusive techniques, *i.e.*, geophysical methods, for exploring the stra-

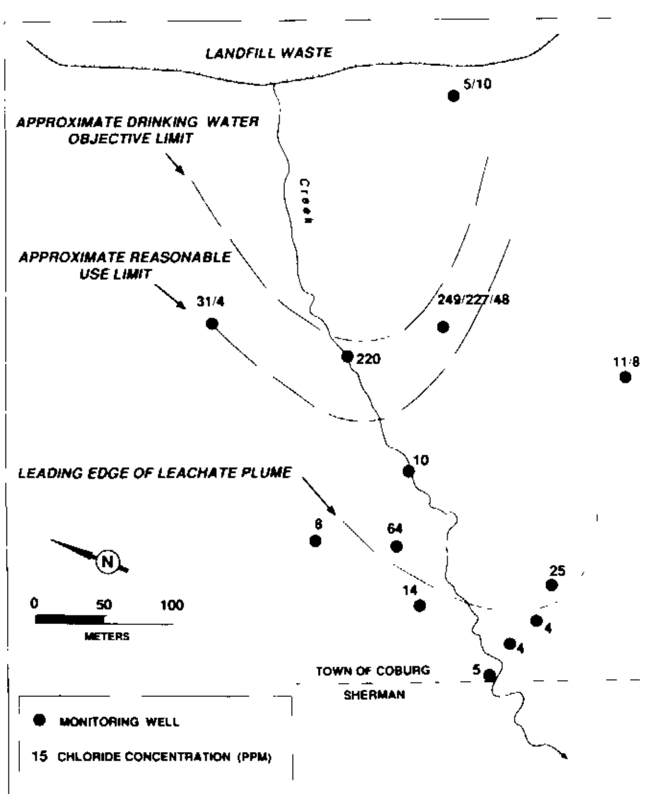

Figure 10 ***(left)*** *Subsurface leachate plume defined by elevated chloride levels derived from Cobourg municipal landfill. Figures are in ppm (after Environmental Assessment Board, 1989).*

Figure 11 ***(below)*** *Summary of Ontario Ministry of Health Report (1986) on the Upper Ottawa Street landfill in Hamilton.*

- **hundreds of boreholes required to obtain complete picture of waste contained in landfill**
- **leachate mounding and leachate springs a major problem**
- **chronic respiratory problems in residents and former landfill workers**
- **workers exposed to unknown levels of carcinogenic chemicals**
- **health registry for incidence of cancer to be set up**

tigraphy of old landfills are gaining more importance given the dangers of drilling on landfills where the subsurface stratigraphy and contents are unknown. The consensus is that it is better to leave the waste in the ground than to risk further environmental damage as a result of disturbance and removal to other sites. The "archeology" of abandoned landfills is an emerging sub-discipline of Quaternary Geology (*e.g.*, Rathje, 1991).

Leachate composition within subsurface plumes and surface springs varies widely according to rate of water infiltration and the age, composition, thickness, and state of consolidation of the waste, and the way it was handled when placed in the landfill. Compacted waste is generally assumed to have a hydraulic conductivity of 10^{-2} cm•s^{-1} and a density of 600 kg•m^{-3}; the average composition of municipal waste is shown in Table 1. Initially, large volumes of volatile fatty acids are produced, resulting in leachates characterized by high levels of total organic carbon and high biological and chemical oxygen demand. Thereafter, the proportion of proteins rises and organic pollutants resulting from insecticides and solvents can be detected. Inorganic components include dissolved ions (*e.g.*, chloride), nutrients (*i.e.*, phosphorous and nitrogen compounds), and metals, principally iron. Iron-rich springs occur on the sideslopes of many landfills as a result of leachate mounding (see below).

Table 1 Typical composition of municipal waste produced by Canadian urban communities (from Bird and Hale, 1978).

COMPONENT		WET WEIGHT (%)
Paper:		
Kraft Paper	**9.51**	
Newsprint	**9.33**	
Fine Paper	**7.91**	
Other Paper	**12.13**	
		38.88
Glass:		
Beer Containers	**0.04**	
Returnable Softdrink	**0.23**	
Non-Returnable Softdrink	**1.30**	
Liquor and Wine	**1.50**	
Food Containers	**1.98**	
Other Containers	**0.28**	
Flat and Cullet	**1.17**	
		6.50
Ferrous Metals:		
Beer Cans	**0.01**	
Softdrink Cans	**0.85**	
Food Cans	**2.53**	
Other	**1.95**	
		5.34
Non-Ferrous Metals:		
Aluminum	**0.77**	
Other	**0.04**	
		0.81
Plastics:		
Containers	**0.88**	
Sheet, Film and Other	**3.98**	
		4.86
Ceramics and Rubble		**1.77**
Lumber		**3.36**
Putrescible		**30.55**
Textiles, Leather, Rubber		**3.55**
Yard Wastes, Brush		**3.30**
Soil		**0.77**
Petroleum/Chemical Mixes		**0.31**
	Total	**100.00**

The migration of leachate in the subsurface is governed by a number of hydrogeological and hydrochemical mechanisms (*e.g., Macfarlane et al.*, 1983). Briefly, advection is the component of migration accomplished by the physical movement of water through the substrate; the rate is normally equal to the average groundwater velocity as determined by Darcy's Law. Thus, the grain size, porosity and presence or absence of fractures (see below) are of importance. *Diffusion* describes the movement of chemicals from areas of high to low concentration and will be significant even in clayey materials where advection is at a minimum. It is the dominant process when average linear groundwater velocities are less than a few centimetres per year. *Mechanical dispersion* of leachate occurs when particles in a sediment force groundwater to deviate from a linear flow vector. *Adsorption* may remove leachate components by binding them to the surface of clay minerals. This process is significant in southern Ontario where nitrates are adsorbed by clays. In addition, heavy metals are rapidly removed from solution by precipitation in carbonate-rich glacial sediments. *Biodegradation* of leachate will occur as a result of microbial action by bacteria present in glacial sediments. Biological decomposition of organic material produces gas composed of methane (~45%) and carbon dioxide (55%), which can migrate off-site and present an explosive hazard to adjacent buildings. New landfills employ a gas collection system consisting of horizontal perforated pipes at different levels of the landfill; one tonne of waste produces about 6 m^3 of gas each year. Methane quality is typically low (300-500 BTUs per cubic foot), but can be employed as an energy source. Bacopoulos (1988) reports that the Keele Valley site has the potential to produce 803,000,000 m^3 of methane during the next 30 years with a potential revenue generation of $158,000,000 in 1983 dollars. Several sites are now using methane for local power production.

Given the requirements of the MOE "Reasonable Use" criteria (Ontario Ministry of the Environment, 1986), landfills are ideally sited in areas of relatively thick, impermeable sediments where there is a high degree of natural protection afforded by attenuation of leachate within the property boundaries of the landfill (*e.g.*, Fig. 12A). The widespread use of liners (Fig. 12B) composed of compacted clay, till or synthetic materials only started in 1986, but, even so, leachate can migrate off-site if the liner is not overlain by a drainage layer that can be pumped. In the absence of any drainage system, leachate "mounding" within the landfill results in overland transport of leachate from springs on the sideslopes of the landfill (Fig. 12B). The efficiency of clay liners in fine-grained sediments is also affected by diffusion, which transports leachate from areas of high concentration to low (*e.g.*, Desaulniers *et al.*, 1981; see above; Fig. 12B). A further problem in clay-rich soils is caused by the presence of fracture systems. These are of particular significance in the clay plains of southwest Ontario near Sarnia and Windsor (*e.g.*, Ruland *et al.*, 1988; D'Astous *et al.*, 1989; Rowe, 1990) and have been investigated in most detail in the vicinity of hazardous industrial waste sites close to the St. Clair River. Fracture systems are generated in Quaternary sediments by many processes, such as glaciotectonism below ice sheets, desiccation accompanying drawdown of the water table during Holocene dry climates, cold climate (periglacial) processes, and neotectonic movement of underlying bedrock. Fractures in glacial sediments are identified by weathering "haloes", and active groundwater flow is recorded by the presence of post-1953 tritiated water, and elevated ratios of $^{18}O/^{16}O$ compared to *in situ* porewaters in surrounding matrix. The latter, in contrast, are relatively enriched in ^{16}O, reflecting the original glacial meltwater source at the time of deposition. The presence of vertical fractures is not easily identified by conventional drilling, and it is common practice to drill angled boreholes and dig test pits when fracturing is suspected (Fig. 13).

Despite the considerations discussed above, fine-grained sediments nonetheless afford some degree of natural protection of groundwaters from leachate contamination. Given the intense scrutiny that projected sites will undergo in the future, new landfill sites will only be approved if they are fully engineered (see below). Fine-grained sediments are generally favoured as landfill substrates since they afford "fall-back" protection should the engineered leachate collection system fail. Unfortunately, clay-rich sediments are not evenly distributed throughout southern Ontario (Fig. 8); within the GTA, where 50% of the province's waste is generated, silt and sand-rich tills predominate. In this area, there is especial concern with the groundwater regimen in massive dense subglacially deposited tills.

GEOLOGICAL CONSTRAINTS ON LANDFILLING IN THE TORONTO WATERSHED

The Toronto Watershed encompasses the drainage areas within the GTA lying to the south of the groundwater divide formed by the hydrogeologically complex Oak Ridges moraine (375 km²; Fig. 1). The moraine runs west-east from the Niagara Escarpment to Belleville for 160 km, reaching a maximum elevation of 400 m a.s.l. and varying 4-20 km in north-south extent. The moraine formed as a series of coalesced outwash fans built out into a narrow body of water dammed between a northern ice mass (Lake Simcoe lobe), one to the south, moving out of Lake Ontario (Lake Ontario lobe), and the Niagara Escarpment to the west. The moraine constitutes the major recharge area for groundwaters moving south to Lake Ontario, but the system is being increasingly affected by urban development, by a past history of extensive mining for aggregates, and by poor farming practices. The Keele Valley landfill site uses an old gravel quarry on the south side of the moraine. The Vaughan Township landfill, about 0.5 km north of Keele Valley, is associated with a well-defined chloride plume (*e.g.*, Fig. 10) up to 500 m wide and more than 1500 m in length that is associated with chloride levels in excess of 60 mg•L^{-1} at the property boundary (Bacopoulos, 1988).

Southward from the Oak Ridges moraine, the dominant surficial sediment is the Halton Till, which forms a low-relief drumlinized and fluted plain with an average elevation of 120 m a.s.l. This till plain was deposited below the Lake Ontario ice lobe as it flowed to the northwest to abut the moraine. In the last several years, many millions of dollars have been spent on detailing subsurface geological and hydrogeological characteristics of the Halton Till. The P1 interim landfill site, at Whitevale in Durham Region in north Pickering (Fig. 1), is located on this unit and is representative of ground conditions found across a large proportion of the Toronto Watershed. The P1 Site is approximately 275 hectares (680 acres) in size and was planned to be used for the disposal of an estimated 6 million tonnes or 8.6 million m³ of domestic, commercial and non-hazardous, solid industrial waste in a filling area of 40 hectares (100 acres). The annual filling rate was projected at 1.2 million tonnes (1.7 million m³).

As established from a number of landfill site investigations in the GTA, the Halton Till is a very dense, generally massive sandy silt, occasionally silty-sand till (Fig. 14; average 47% sand, 33% silt, 20% clay), 5–50 m thick that rests on a regional unconformity cut across older Quaternary deposits (Fig. 6). The unit typically shows a low-relief and drumlinized surface, and site investigations have provided very useful data as to the geology and origin of drumlins (Boyce and Eyles, 1991). The variation in thickness of this massive till across the Toronto Watershed area is of particular interest to landfill site evaluation, given its apparent suitability as a landfill substrate and its ability to provide

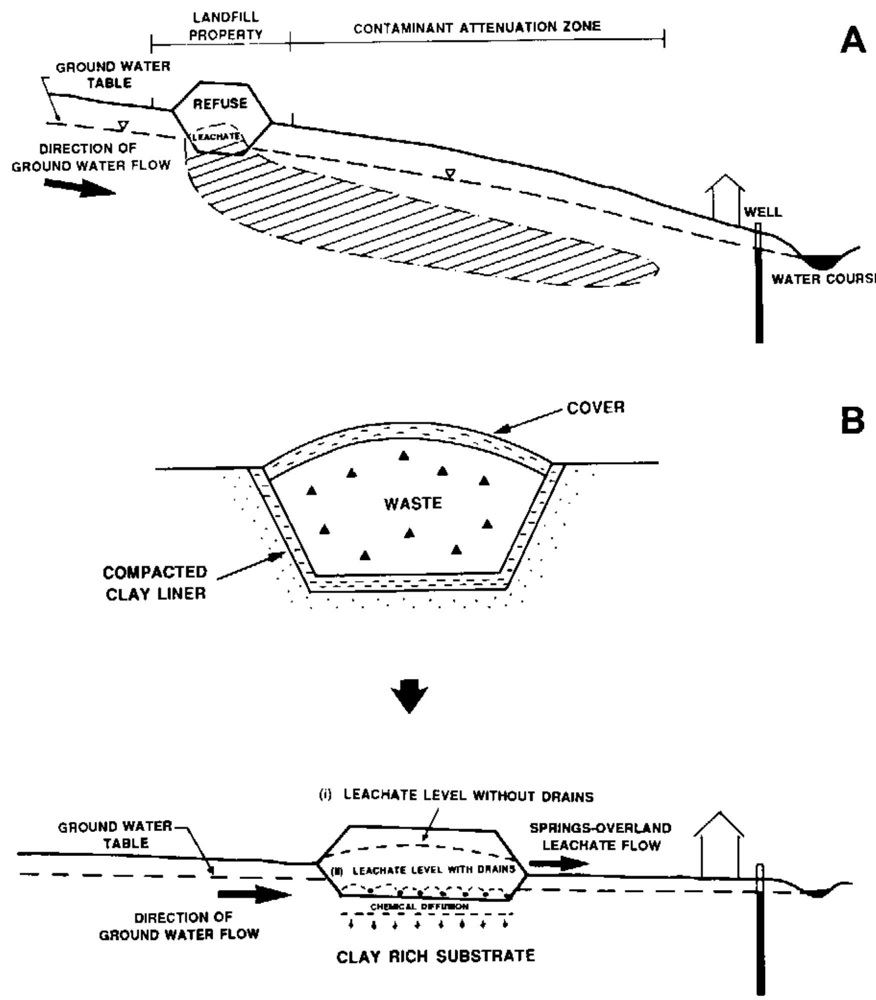

Figure 12 (A) *Unlined landfill, typical of many sites shown on Figure 9, with leachate plume.* (B) *Lined landfill showing leachate level without (i) and with (ii) drains. (Modified from Rowe, 1988).*

natural containment of leachate (*e.g.*, Fig. 12A).

The apparently massive Halton Till unit, on closer resolution, shows a crude internal stratigraphy in the form of horizontal cobble and boulder concentrations that can be traced, in many cases, for more than several hundred metres. These concentrations are particularly evident on downhole geophysical logs employing natural gamma tools run through steel drill rods (Dillon Ltd., 1990). Boulder concentrations give rise to a distinct "spike" on gamma logs as a result of high contents of granitic rocks containing mica. Regional data suggest that the Halton Till comprises, for the most part, a "deformation till" that was transported and emplaced as a result of the pervasive shearing of subglacial sediments. The massive "concrete-like" appearance of this unit (Fig. 14) is the result of incorporation, mixing and complete assimilation of proglacial sediments overrun by the ice sheet (Boulton and Hindmarsh, 1987; Boyce and Eyles, 1991). Boulder concentrations define increments of till deposited successively below the ice sheet by "freezing" (dewatering) of the base of the deforming layer.

A survey of existing water wells in the Toronto Watershed shows that the Halton Till is an aquitard, *i.e.*, not capable of yielding the minimum supply of 45 $L \cdot min^{-1}$ to a well. This, combined with its generally massive, dense structure, indicates its suitability as a landfill substrate and, consequently, there are many landfills sited on this till (Fig. 8). However, several sites have well-defined leachate plumes moving outward in underlying sediments, and deep fracturing has been invoked (see below). Detailed geochemical investigation has recently shown that the Halton Till, in fact, contains an active groundwater flow system and that there is often a direct hydraulic connection through the massive till from aquifers above and below. Plots of relative concentrations of anions and cations identify different water types in the Halton Till and their likely sources. Near-surface horizons (<15 m) are characterized by calcium bicarbonate waters typical of freshly recharged ground water, where dissolution of dolomite and calcite by mildly acidic recharge waters is the predominant hydrogeochemical process (Howard and Beck, 1986). Because of cation exchange, there is a transition to sodium bicarbonate waters below 15 m; site investigations at Whitevale (Dillon Ltd., 1990) showed the presence of sodium and sulphate at depth in the Halton Till resulting from contamination by superphosphate fertilizers, further indicating a direct hydraulic connection into the massive dense Halton Till. Reduction of sulphate resulted in the noticeable presence of hydrogen sulphide gas during drilling operations (R. Gerber, pers. comm., 1989-1991). The additional presence of nitrate and phosphate in Halton Till porewaters also confirms an active groundwater system. These data show that the Halton Till does not necessarily afford adequate protection against leachate migration below the base of a landfill site. The situation is rendered more complex given that groundwater paths through the till are poorly understood. This may involve flow through the horizons containing boulder concentrations and till sub-units with variable consolidation characteristics under high vertical gradients maintained by downward seepage from surficial aquifers.

Figure 13 *Test pit through Halton Till.*

CASE HISTORIES

Problems associated with landfills sited on the Halton Till are clearly illustrated by three sites on the eastern margin of Metropolitan Toronto. The Stouffville landfill (1962–85) is situated on the Oak Ridges moraine. The site is underlain by approximately 10 m of Halton Till resting on thick (up to 100 m) sands and gravels (Oak Ridges Aquifer Complex; Turner, 1977) which, in turn, rest on much older fine-grained, predominantly glaciolacustrine sediments. Disposal of liquid industrial waste (oil from gas stations, sulphuric acid, calcium hydroxide, hydrochloric acid, and other unknown wastes) began in 1962. Until 1970, this waste was placed directly, without any treatment, in abandoned pits or "lagoons" excavated in the Halton Till. The site received solid industrial and municipal waste until it was closed in 1985 and is estimated to contain a total of approximately 10 million tonnes of waste. The coarse-grained sediments (Oak Ridges Aquifer Complex) below the Halton Till behaved essentially as a drain, drawing surface waters from the landfill through the Halton Till and into underlying sands and gravels. The present situation is characterized by a plume of contaminants, delineated by elevated chloride levels (up to 122 $mg \cdot L^{-1}$), extending about 1 km southwestward from the site and advancing at a velocity of about 40 m per year. No significant off-site contamination occurs by lateral flow through the Halton Till, but permeable "windows" through the till allow vertical transport of contaminants from the lagoons (Proulx and Farvolden, 1989).

The Brock West (1975 to present) and Beare Road (1969–85) landfills in Pickering and Scarborough, respectively, are typical of many abandoned landfills in the Metro area; they partially occupy abandoned aggregate quarries in shoreline deposits of glacial Lake Iroquois which rest on the Halton Till. Lake Iroquois was a high-level ancestral Lake Ontario dammed by ice along the St. Lawrence River Valley during final retreat of the Late Wisconsinan Ice Sheet. It drained at about 12 ka. The abandoned Lake Iroquois cliff line is a major morphological feature around the margin of Lake Ontario, and nearshore deposits have been mined extensively for aggregates. These sand and gravel deposits represent significant pathways for contaminant migration at both Brock West and Beare Road and leachate has been detected at depths greater than 30 m within the underlying Halton Till; fracturing is suspected (Hydrology Consultants Ltd., 1981). The Beare Road landfill closed in 1985 and is not lined. The Brock West site features an engineered bentonite-sand liner containing spaced leachate collection pipes, which is underlain by a groundwater drainage system to depress the groundwater table below the liner. The liner is a 10 cm thick sand approximately 10% by weight bentonite and compacted to 90% Standard Proctor Density; effective hydraulic conductivity is about 1.5×10^{-8} cm•s^{-1} (Trow Ltd., 1987). Until 1981, leachate collection pipes were made of tar-coated galvanized steel, but these were rapidly corroded by leachate, and thick-walled polyethylene is now used. Leachate capture, as of 1986, was less than 5% of surface precipitation infiltrating the waste mound, suggesting that much of the infiltrating water is retained by the waste. This situation will continue until the site reaches field capacity; thereafter a larger volume of leachate will be collected, but a larger volume is also expected to infiltrate the liner. The role of the liner at Brock West is simply to reduce the loading of leachate on the underlying groundwater flow system. About 50% of rainfall infiltration is anticipated to pass through the liner, but Trow Ltd. (1987) concluded that insufficient data are available to predict detailed impacts on groundwater quality.

These examples clearly illustrate the potential uncertainties associated with landfill sites located on the Halton Till where some degree of natural containment was incorrectly assumed to be provided by underlying tills. Higher than expected values of effective porosity for massive dense tills and complex hydrogeological conditions appear typical for the Halton Till, which underlies a large area of the Toronto Watershed (Fig. 8). Consequently, it can be concluded that landfills placed on this unit, despite its massive, dense character, cannot be relied upon to provide natural containment of leachate; fully engineered landfills are therefore required for new sites. The Halton Till is similar in textural characteristics and appearance to many till sheets deposited below continental ice sheets, and active groundwater systems may be a general characteristic of such tills. Laboratory determinations of permeability should be treated with caution, and greater reliance placed on field investigations such as pumping tests and hydrochemical sampling which provide information about bulk (*i.e.*, effective) permeability.

THE FUTURE: FULLY ENGINEERED LANDFILLS

An engineered containment system consists essentially of a compacted clay liner and, increasingly, an engineered drainage layer that can be naturally pressurized by ground waters in underlying deposits. In this way, groundwater flow paths are directed into the landfill, thereby ensuring no significant outward movement of contaminants. This is termed a "hydraulic trap" (Rowe, 1988). The basis of the system lies in ensuring that the level of leachate within the landfill is below the height of the water table in sediments surrounding the site; an inward flow of groundwater results. A typical "state-of-the-art" engineered containment system is shown in Figure 15. The collection system is designed to prevent leachate mounding (*e.g.*, Fig. 12B) and to collect leachate produced by infiltration of surface waters. The system consists of drains (Fig. 15: A) and an associated granular layer (Fig. 15: B) which directs leachate to a point where it can be pumped out. This collection system overlies a compacted clay liner (Fig. 15: C), the upper surface being protected by a geotextile separator layer (Fig. 15: D), which in turn overlies a lower granular unit (Fig. 15: E) resting on a second geotextile layer (Fig. 15: F). The purpose of the lower granular unit is to provide a hydraulic control layer whereby water could be added if there were significant drawdown of the groundwater head in underlying sediments, which might occur if the aquifer were developed and pumped, or as a result of climate warming (see below). Monitoring of water quality in the hydraulic control layer also provides an early warning system should the design fail; if contamination is detected, then the layer can be slowly pumped and the effluent treated municipally. Ideally the "hydraulic-trap" is self-regulating, but provision for a "hydraulic control layer" ensures flexibility in the event of partial or complete failure.

While the modern landfill can be said to be fully engineered, there are several geological constraints that must be met. The base contours of the landfill (typically 5–15 m below existing surface elevations) must be sufficiently low to ensure that groundwater flows into the fill. Base contours should also, however, be high enough to ensure a maximum thickness of low-permeability glacial

Figure 14 *Typical appearance of Halton Till in core sample.* **(left)** *Massive, sandy-silt till.* **(right)** *Pebble-rich, silty-sand till.*

sediments under the site. Base contours placed at too low an elevation could not only reduce the thickness of underlying sediments, but could also result in problems of liquefaction during construction of the landfill.

The life of an engineered containment system is usually estimated to be about 50 years, and significant deterioration of performance can be expected after this time. However, there is no experience of operating an engineered landfill for long time periods. The contaminating lifespan of a landfill is defined by the Ministry of the Environment as "the period of time during which the landfill will produce contaminants at levels that could have unacceptable impact if they were discharged into the surrounding environment" (Ontario Ministry of the Environment, 1986). No long-term field studies have been conducted, however, and research is based on small-scale cells (lysimeters) in which variables are carefully monitored. Given that there is a finite mass of contaminants in the landfill, leachate concentration levels through time take the form of an exponential first-order decay similar to radioactive decay; a half-life is the time taken to reduce the initial concentration by 50%. Therefore, it is important for the containment system to operate effectively for as long as possible while contaminants are removed by the leachate collection system or biodegrade, volatilize or become immobile (see above).

It is beyond the scope of this paper to discuss the details of contaminant transport modelling, but it is common practice in Ontario to apply criteria established for Reasonable Use guidelines to "critical" contaminants, such as dichloromethane and chloride, which are not easily attenuated by movement through soil. Initial source concentrations for chloride are typically ~ 2000 mg $\cdot L^{-1}$, with a half-life of 25 years. Corresponding data for dichloromethane is 6000 $\mu g \cdot L^{-1}$ with a half-life of 10 years. Dilution of contaminants in aquifers underlying the landfill cannot be relied on to meet reasonable use criteria because the dynamics of the groundwater flow system are often not sufficiently well known. The only solution, therefore, is to increase the service life of the engineered systems. There may, in addition, be significant problems in connection with future changes in climate.

Future climate variability is a major concern to communities on glaciated terrains surrounding the Great Lakes. The Great Lakes Science Advisory Board (Groundwater Contamination Task Force, 1985) found groundwater pathways to represent a significant route of contamination transport to the Great Lakes and, "existing estimates of groundwater flow based on general geology to be inadequate". More recently, the Great Lakes Water Quality Board (International Joint Commission USA and Canada, 1987) concluded that one of the most pressing research needs was to determine the effect of changing climate and lake levels on pollutant transport to the Great Lakes. Predictions of climate warming suggest that Great Lakes levels will decrease, groundwater levels will drop by several metres, and there will be a reduction in aquifer recharge. Similar warm conditions were experienced in the early postglacial in southern Ontario during the Hypsithermal. During this time of increased warmth (Hypsithermal; *ca.* 9000–6000 y.b.p.) water tables were lowered by decreased recharge and increased evaporation. This resulted in fracturing of surface sediments (*e.g.*, Soderman and Kim, 1970). Significant man-made changes in climate are expected within the lifetime of landfill sites (*ca.* 50 yrs), emphasizing the need for detailed predictive modelling of groundwater flows through glacial sediments. A first step in this process is the production of detailed stratigraphic syntheses that show the three-dimensional character and distribution of sediment in the subsurface. This process is essentially akin to reservoir modelling in hydrocarbon exploration and is dependent on the construction of large computer data banks and manipulation of subsurface data

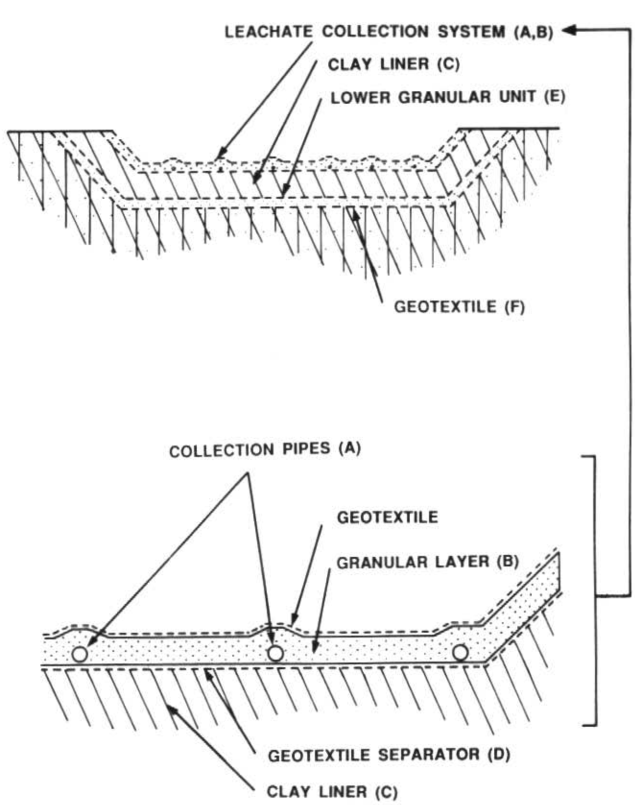

Figure 15 *Elements of a fully engineered hydraulic trap landfill after Maclaren Plansearch Ltd. (1990).*

Figure 16 *Garbage on the move: recent landslide of April 1991, at Brimley Road along Scarborough Bluffs, involving the downslope failure of municipal waste dumped in a lakeside ravine in the 1950s and 1960s.*

using GIS technology.

Finally, it can be concluded that glacial sediments may not provide sufficient natural protection from contamination of underlying groundwater resources by a landfill; fully engineered sites, employing "hydraulic trap" designs, are essential. We stress the need for establishing the location and detailed inventories of abandoned and existing landfill sites in glaciated terrains combining details of age, contents and local glacial geologic and hydrogeologic information in order to identify the potential for groundwater contamination. As if to emphasize this need, in mid-April 1991, a massive landslide took place along Brimley Road, along the Lake Ontario shoreline in Scarborough, involving the downslope collapse of municipal waste dumped in the area in the 1950s and early 1960s. The slide was 125 m long, 7 m deep, and more than 30 m wide, and released significant volumes of leachate during the sliding event (Fig. 16). The total cost of clean-up to the taxpayer was more than $2.1 million. Regardless of future political developments and trends in waste management policies, properly designed and operated landfills remain a necessary option for the foreseeable future. The glacial geology of southern Ontario is similar to many mid-latitude urban areas and the geological data and conclusions presented here with regard to landfill siting and groundwater contamination potential may have some broader significance.

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