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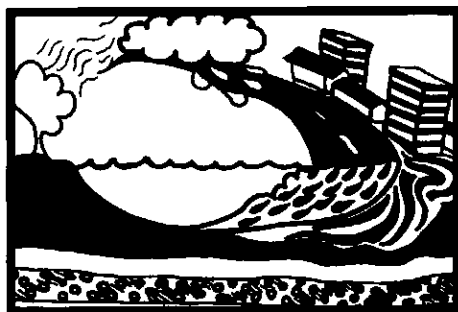
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Résumé de l'article

La gestion des répercussions environnementales de l'urbanisation sur les bassins de drainage constitue un problème de taille confrontant les collectivités canadiennes. Pour y faire face convenablement, les services de planification urbaine doivent pouvoir compter sur des données environnementales de qualité pour espérer pouvoir élaborer des politiques efficaces de réhabilitation et d'utilisation des sols. Le traitement de ce genre de problème exige que l'on adopte une approche multidisciplinaire intégrant une gamme de disciplines scientifiques, dont la géologie, la géochimie, la sédimentologie, l'hydrogéologie, l'hydrologie, la géophysique ainsi que l'hydro-écologie.

Des géoscientifiques de l'Université de Toronto et de l'Université McMaster travaillent de concert avec la ville de Pickering (Ontario) à la réhabilitation d'une lagune du lac Ontario et son bassin de drainage urbanisé (baie de Frenchman), lesquels sont soumis à de forts volumes d'eaux de ruissellement et à une érosion et un transport sédimentaire accrus. Dans l'ensemble du bassin de drainage, le cycle hydrologique a été considérablement changé par une « induration » des sols découlant de la construction de routes et d'édifices, limitant d'autant l'infiltration de l'eau et favorisant son ruissellement. Ces eaux de bassin de drainage « urbanisé » se déversent dans la lagune côtière peu profonde et quasi fermée de la baie de Frenchman, piégeant ainsi les sédiments à grains fins contaminés. Un gamme étendue de techniques géophysiques ont été mises à profit dans la lagune de la baie de Frenchman pour définir la géologie de la lagune, les caractéristiques physiques des sédiments du fond ainsi que la distribution des sédiments contaminés sur le fond.

ARTICLE



Geophysical and Sedimentological Assessment of Urban Impacts in a Lake Ontario Watershed and Lagoon: Frenchman's Bay, Pickering, Ontario

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SUMMARY

Managing the environmental impacts of urbanization on watersheds is a major problem facing Canadian communities. Meeting this challenge requires that municipal planning departments have access to good quality environmental information allowing them to develop effective land use plans and remediation policies. Managing such problems demands an interdisciplinary approach involving a range of scientific disciplines including geology, geochemistry, sedimentology, hydrogeology, hydrology, geophysics and aquatic ecology.

Geoscientists from the University of Toronto and McMaster University are working with the City of Pickering, Ontario on remediation of a Lake Ontario lagoon and urbanized watershed (Frenchman's Bay) experiencing large stormwater flows and enhanced sediment erosion and transportation. Throughout the watershed, the hydrological cycle has been dramatically changed as a result of 'hardening' by roads and buildings – greatly restricting infiltration and promoting surface runoff. The urban-impacted watershed empties into the shallow, semi-enclosed coastal lagoon of Frenchman's Bay – serving as a trap for fine-grained contaminated sediment. A wide range of geophysical techniques have been employed in Frenchman's Bay lagoon to determine the geology of the lagoon, physical characteristics of bottom sediments and the distribution of contaminated sediment on its floor.

SOMMAIRE

La gestion des répercussions environnementales de l'urbanisation sur les bassins de drainage constitue un problème de taille confrontant les collectivités canadiennes. Pour y faire face convenablement, les services de planification urbaine doivent pouvoir compter sur des données environnementales de qualité pour espérer pouvoir élaborer des politiques efficaces de réhabilitation et d'utilisation des sols. Le traitement de ce genre de problème exige que l'on adopte une approche multidisciplinaire intégrant une gamme de disciplines scientifiques, dont la géologie, la géochimie, la sédimentologie, l'hydrogéologie, l'hydrologie, la géophysique ainsi que l'hydro-écologie.

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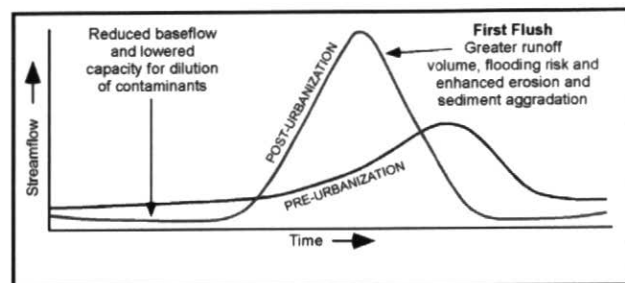
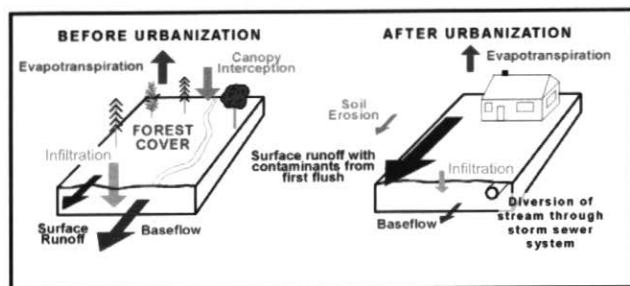
ville de Pickering (Ontario) à la réhabilitation d'une lagune du lac Ontario et son bassin de drainage urbanisé (baie de Frenchman), lesquels sont soumis à de forts volumes d'eaux de ruissellement et à une érosion et un transport sédimentaire accrus. Dans l'ensemble du bassin de drainage, le cycle hydrologique a été considérablement changé par une « induration » des sols découlant de la construction de routes et d'édifices, limitant d'autant l'infiltration de l'eau et favorisant son ruissellement. Ces eaux de bassin de drainage « urbanisé » se déversent dans la lagune côtière peu profonde et quasi fermée de la baie de Frenchman, piégeant ainsi les sédiments à grains fins contaminés. Un gamme étendue de techniques géophysiques ont été mises à profit dans la lagune de la baie de Frenchman pour définir la géologie de la lagune, les caractéristiques physiques des sédiments du fond ainsi que la distribution des sédiments contaminés sur le fond.

INTRODUCTION

More than 80% of Canadians live in urban areas, the highest percentage in the world, with the exception of Australia. Managing environmental impacts arising from rapid growth is a key challenge to many urban municipalities, particularly those in the Great Lakes where lake water is used both for public consumption and as a sink for waste waters. Near Toronto, wastewater and stormwater discharge into semi-enclosed coastal lagoons such as Frenchman's Bay in the City of Pickering (Fig. 1).

Ensuring the long-term sustainability of Frenchman's Bay and its watershed depends on controlling stormwater flows and the input of sediments and contaminants. This is fundamentally dependent on collection

A



B

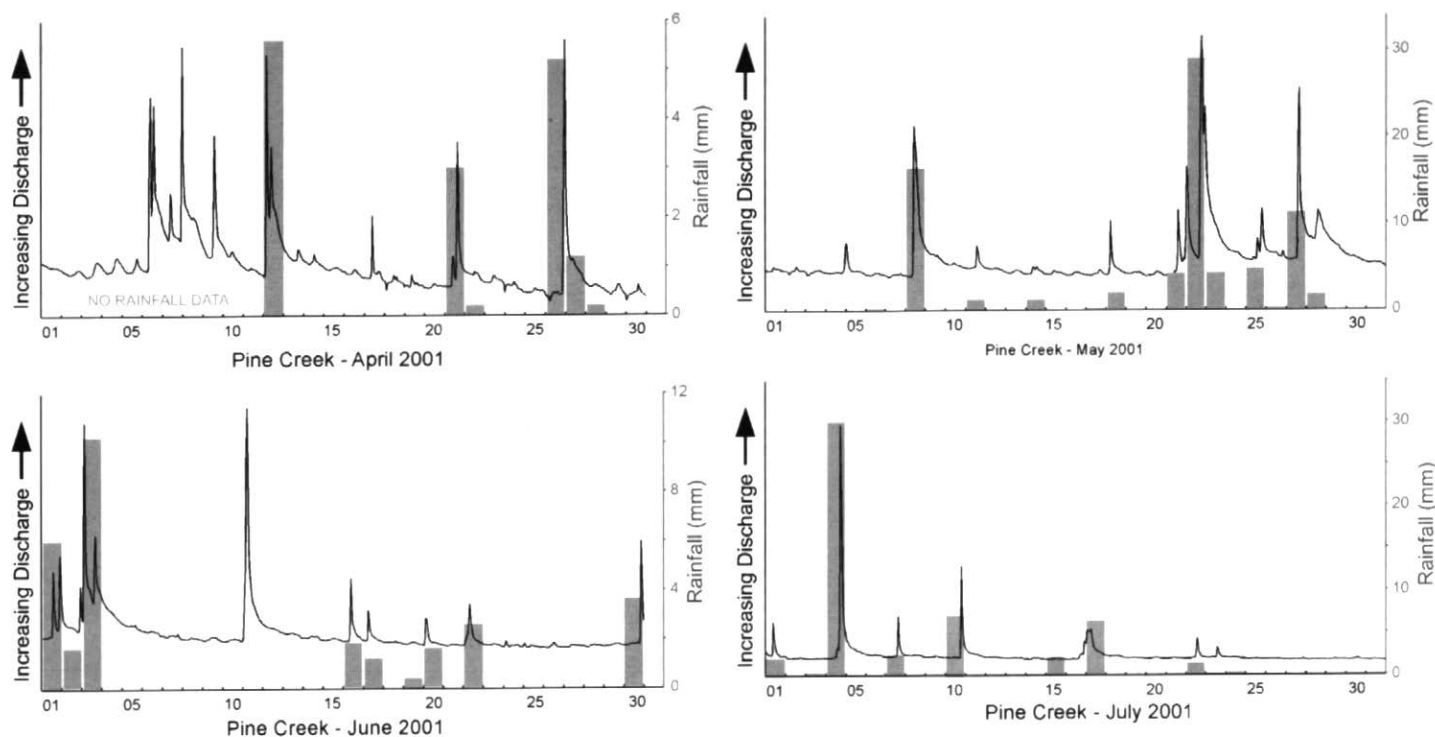


Figure 1 A. Impact of urbanization on the hydrological cycle in natural watersheds, showing the effects upon groundwaters and surface waters. Creeks draining into Frenchman's Bay exhibit a 'flashy' storm discharge typical of urban streams. B. Flow of Pine Creek April to September 2001, showing 'flashy' discharge typical of urban creeks. Grey bars are rainfall (scale at right in millimetres). Stormwater runoff results in loss of wetlands on the northern margin of the Frenchman's Bay (Fig. 2).

of field data regarding the geology and hydrogeology of the watershed, the nature of surface water flows, and patterns of sediment and water movement. Various reports have consistently commented on the lack of such information from the watershed, especially an absence of any 'predevelopment' data (Lemay and Mulamootil, 1981; Nelson, 1991; Persaud et al., 1987; Ontario Ministry of the Environment and Energy, 1997; Mayor's Task Force, 1998). The contribution of this paper is to

demonstrate the utility of using geophysical methods in identifying and mapping contaminated sediment – and its movement – within Frenchman's Bay.

EFFECTS OF URBANIZATION

Urbanization creates major changes in natural ecosystems – most particularly to the hydrological cycle. Watersheds are 'hardened' by large areas of impermeable built landscape (Fig. 1A). Stream flows are drastically changed and natural channels are altered by erosion and downstream sedimentation. Peak

storm flows (Fig. 1B) are much greater than under natural conditions because nearly all precipitation flows off directly to creeks through pipes and drains. Infiltration of precipitation into the groundwater system is greatly reduced though offset by leakage, as yet poorly understood, from buried utilities such as sewers and water mains. As a consequence, the volume of groundwater discharging to creeks as baseflow during dry summer months is reduced and creates lowered water levels. At these times, river flow is

dependent on surface water contributions from surrounding streets and roofs. This water contains a wide range of contaminants and is warmed by flowing over artificial surfaces, proving lethal to aquatic organisms.

In Southern Ontario, urbanization has been extremely rapid and these problems are particularly acute due to the presence of numerous lagoons and wetlands at river outlets. Water and sediment exchange from these enclosed basins with the lake is restricted resulting in the accumulation of contaminated urban sediment (e.g., Nriagu et al., 1983; Kohli, 1979; Marsalek and Ng, 1989; Booth and Reinelt, 1993; Coakley and Mudroch, 1997). In addition, wetlands have been severely reduced in extent – both by enhanced wet-weather urban streamflow and by infilling as a result of construction – such that their function as habitat and nursery for many aquatic organisms is greatly impaired.

FRENCHMAN'S BAY PHYSICAL SETTING

The Frenchman's Bay watershed in south-central Ontario has a population of about 50,000 people and extends over some 20 km². More than 80% of the watershed is urbanized making it one of the most densely urbanized in Canada (Fig. 2). The limit of the watershed is defined by Petticoat Creek in the west and Duffins Creek in the east. The northern limit is abruptly defined by a steep bluff. This is the shoreline of a glacially dammed ancestral Lake Ontario (Glacial Lake Iroquois; Fig. 3). Within the watershed, four principal creeks; Amberlea (301 hectares, 13.5 % of watershed), Dunbarton (212 ha, 9.5%), Pine (677 ha, 30%) and Krosno (784 ha, 35%) drain into the semi-enclosed coastal lagoon of Frenchman's Bay on the northern shoreline of Lake Ontario (Fig. 4A, B). Small tributaries on the north, west and east margins of Frenchman's Bay have been extensively engineered by pipes and culverts to form stormwater 'sewersheds' (260 ha, 12%) that empty directly into the Bay (Fig. 3). Many tributaries and intermittent streams have been lost as a result of infilling and piping of their

valleys (Mayor's Task Force, 1998).

Frenchman's Bay lagoon extends over some 85 hectares (ha), and contains about 55 ha of open water having a maximum depth of 3.5 m. The bay is separated from Lake Ontario by a barrier beach some 900 m long and about 50 m wide and 2 m high, with a dredged entrance for boats to access marinas. Prominent aeolian dunes up to 1 m high are present on the surface of the barrier beach. On a short-term basis, water levels in Frenchman's Bay fluctuate in response to wind piling up water on lee shores (seiches) and flood discharges from the surrounding watershed. The mean water level in Lake Ontario is 74 m above sea level and is subject to small (1 m) seasonal

variations related to spring snow melt and longer (decadal) variations reflecting changing rainfall totals across the Great Lake basins. Over geological time (hundreds of years), water levels are rising (the present-day rate of lake-level rise is about 20 cm a century; Quinlan and Mulamootil, 1987; Pengelly and Tinkler, 1997) as the outlet of Lake Ontario near Kingston experiences a faster rate of uplift compared to the western end of Lake Ontario.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF FRENCHMAN'S BAY WATERSHED

Extensive geological investigations have been conducted adjacent to the Frenchman's Bay watershed in connection with the hydrogeology of the south slope of the Oak Ridges Moraine and several landfill sites (e.g., Westgate, 1979; Boyce et al., 1995; Howard et al., 1997; Eyles et al., 1997; Boyce and Eyles, 2000; Gerber and Howard, 2000). Much pertinent work has also taken place in the vicinity of Pickering Nuclear Generating Station (Gore and Storrie, Ltd., 2000a, b) with additional information from borehole records drilled during various construction projects (e.g., widening of Highway 401). The locations of more than 3600 boreholes are shown on Figure 5. The data set has been used to construct a west-east cross-section showing the layering within glacial sediments below the ground surface and the depth to bedrock (Fig. 6) as well as maps of bedrock topography and surficial drift thickness (Fig. 7). The data set is being used to develop a three-dimensional groundwater flow model for the regional study area between Frenchman's Bay and the Oak Ridges Moraine (e.g., Eyles et al., 1997; Meriano and Eyles, 2003; Gerber and Howard, 2002).

The Frenchman's Bay watershed is underlain by several layers of glacial sediment (Fig. 6) that formed as a result of glacial advance and retreat of the Laurentide Ice Sheet between 70,000 and 12,000 years ago. These sediments cover a gently sloping bedrock surface composed of Whitby Formation shale of Late Ordovician age (approximately 440 million years; Eyles, 2002; Ministry of Northern Development and Mines,



Figure 2 Loss of provincially significant wetland area at Frenchman's Bay. A - 1939; B - 1993. Note progressive fragmentation of wetland. This loss has resulted in exposure and erosion of underlying muds that remain in suspension in the water column accounting for discolouration of bay waters and lack of clarity.

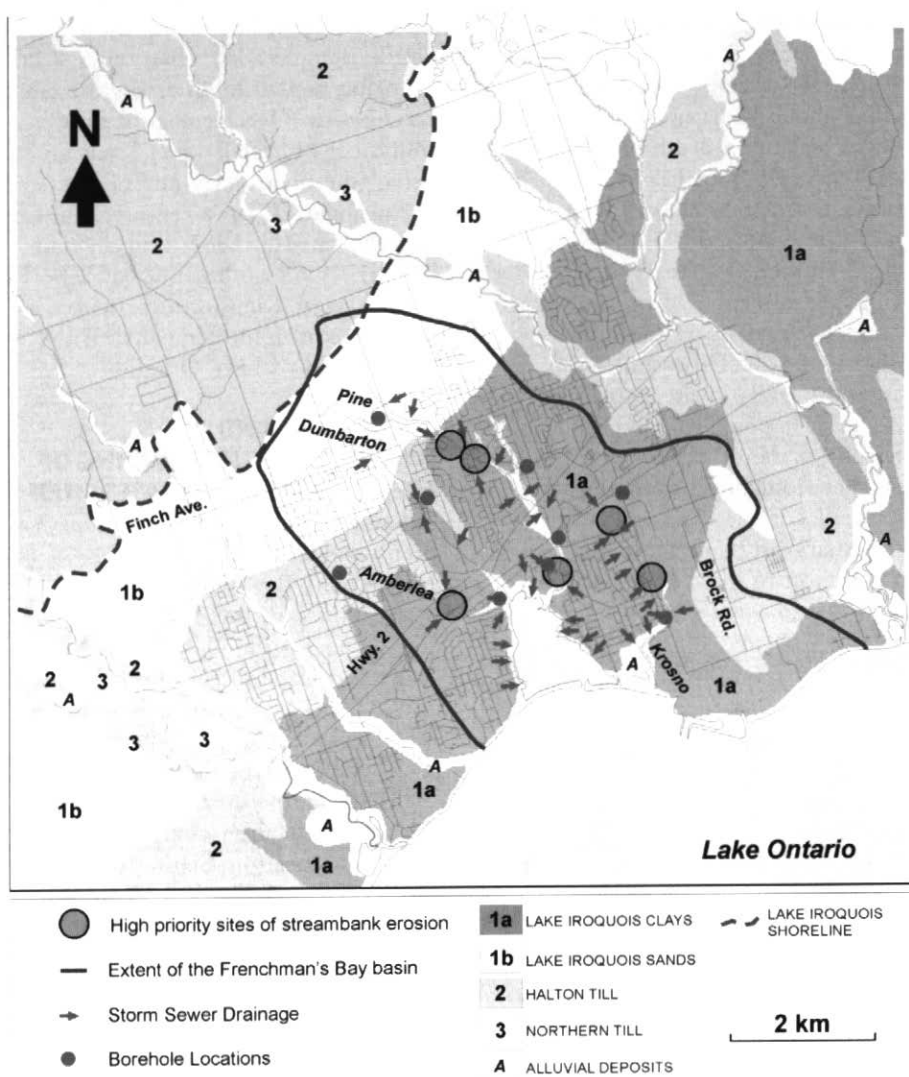


Figure 3 Geology of the Frenchman's Bay watershed (after Westgate, 1979). The watershed is sharply defined on its northern margin by the former shoreline of Glacial Lake Iroquois. Road network indicates the extent of urban development around the bay where pre-existing creeks were converted to storm sewersheds emptying directly into Frenchman's Bay. Sites with extensive erosion and the borehole network used for groundwater monitoring also shown.

Bedrock Geology of Ontario, Map 2544). The bedrock surface that underlies the watershed shows several ancient valleys that drained south to the deeper bedrock basin below Lake Ontario. Frenchman's Bay is situated over one prominent valley (Fig. 7). Outcrops of shale occur along the lower reaches of Amberlea Creek but are deeply buried by younger glacial sediments elsewhere. Glacial strata are overlain by younger postglacial sediments, which were deposited after the final retreat of the last ice sheet about 12,000 years ago. These sediments have accumulated principally in Frenchman's Bay lagoon. The most

recent sediments in the bay record the dramatic impact of human activities in the watershed beginning with indigenous peoples about 1000 years ago and then Europeans after 1840. These sediments are extremely contaminated as a result of urbanization of the watershed after 1960.

GLACIAL SEDIMENTS

Glacial deposits record two episodes of expansion and retreat of the Laurentide Ice Sheet (Northern Till and Halton Till; Fig. 6) during the last ice age. Locally, these tills are separated by sand and gravel, which record short-lived, ice-free conditions in the region. The surface of

the younger till (Halton Till) is marked by low, elongate hills (drumlins) oriented parallel to former ice flow direction – southeast-northwest – recording ice flows out of the deep bedrock depression now occupied by Lake Ontario northward toward to the Oak Ridges Moraine. These drumlins now protrude as 'islands' through a cover of Glacial Lake Iroquois nearshore sands and offshore clays and provide the only topographic relief in the lower Frenchman's Bay watershed, defining its eastern and western margins.

The last glacial sediments to be deposited in the Frenchman's Bay watershed accumulated about 12,500 years ago as the Laurentide Ice Sheet withdrew from Southern Ontario. At this time, much of the area was flooded by the waters of Glacial Lake Iroquois – a short lived, high-level ancestral Lake Ontario that stood some 50 m above the modern lake level. The lake was created as a result of the Laurentide Ice Sheet continuing to block the St. Lawrence River as it withdrew eastward from central Canada. The subsequent drainage of Lake Iroquois, some 12,000 years ago, left a prominent shoreline bluff inland together with deposits of lacustrine clay and sand across much of the Frenchman's Bay watershed (Fig. 3). Creeks have their headwaters in small cedar swamps and intermittent streamflows emerging from groundwater springs at the base of the Iroquois shoreline bluff.

Thick Pleistocene glacial sediments south of the ORM host multiple aquifers in which regional groundwater flow is toward Lake Ontario and Frenchman's Bay (Gerber and Howard, 2002; Fig. 7). The thickness of glacial sediment within the Frenchman's Bay watershed is however, greatly reduced south of the Glacial Lake Iroquois shoreline where a single aquifer is present (Fig. 7C). The bluff forms the major groundwater discharge zone in the watershed and is the source for the creeks that flow to Frenchman's Bay. A groundwater-monitoring network has been set up in the watershed (Fig. 3) to identify sources of recharge and contaminants. Groundwater in the watershed is locally recharged by direct infiltration of

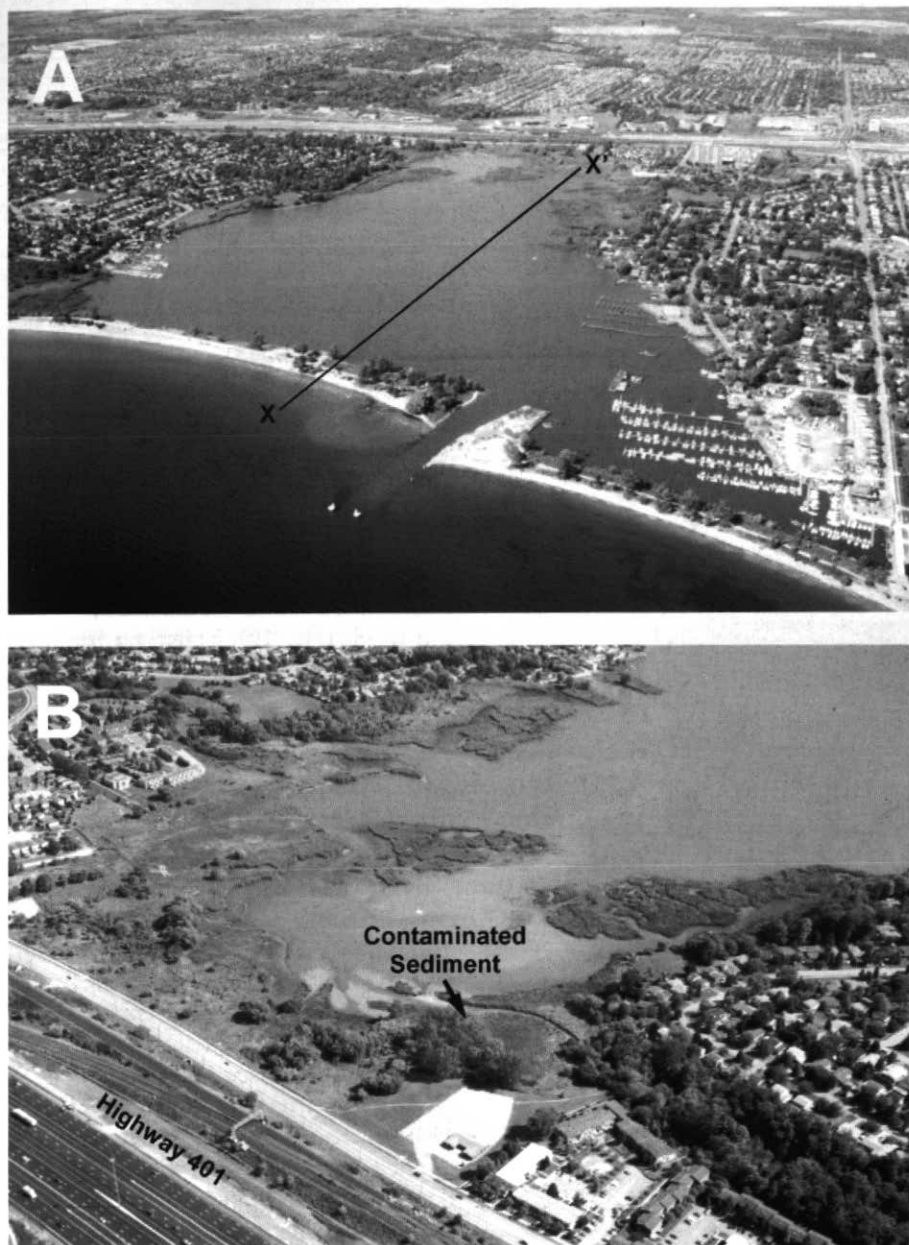


Figure 4 A. Frenchman's Bay. Note discolouration of water and reduced water clarity compared to that of Lake Ontario in foreground. This reflects elevated levels of suspended sediment resulting from the erosion and resuspension of organic-rich fine-grained mud at the northern margin of the bay. X-X' is the line of section shown in Figure 10. B. Northern margin of Frenchman's Bay showing extensive exposures of mud. Formerly, this area was occupied by wetlands that have been eroded by uncontrolled stormwaters emerging from the mouths of Dunbarton, Amberlea and Pine creeks. The mud is the result, principally, of deforestation in the watershed beginning in the 1840s (European Settlement Layer). Contaminants sourced from the surrounding urban area are accumulating here. Arrow shows location of magnetic susceptibility mapping of contaminated sediment (Fig. 12D).

precipitation over the permeable portion of the watershed (approximately 20% of the area). Other sources of recharge include leaking water mains, sanitary sewers and irrigation water from gardens and parks.

AGE AND FORMATION OF FRENCHMAN'S BAY AND SEDIMENT INFILL

A wide range of geophysical techniques – shown schematically in Figure 8 – were employed in this study to

determine the nature of bottom sediments and the distribution of contaminated sediment in Frenchman's Bay lagoon. In addition, cores were taken enabling direct recovery of sediments below the floor of the Bay and to identify the age of the lagoon. A radiocarbon date of 2750 ± 70 years before present was obtained from peat at the base of the lagoonal infill sediments (McCarthy, 1986; McCarthy and McAndrews, 1988). This indicates that the lagoon, as a physiographic feature, is no older than about 3000 years.

A ground-penetrating radar survey was conducted across the barrier beach separating Frenchman's Bay from Lake Ontario. This was completed to identify the geology of the outermost part of the lagoon. A PulseEKKO IV unit was used with 1000 V pulsers and a 50 MHz antenna permitting a vertical resolution of about 1.5 m. Application of ground-penetrating radar (GPR) to exploration of the shallow subsurface has been described in several recent papers (e.g., Beres et al., 1999; Vandenberghe and van Overmeeren, 1999). Figure 9A shows prominent reflectors within the barrier beach identifying stratified sand and gravel at depth. These layers record upward growth and migration of the beach over the past 3000 years as the level of Lake Ontario has slowly increased. The line was collected parallel to the long axis of the barrier beach and also shows the presence of several, small, buried and now infilled channels in the subsurface. These likely record major storms and the erosion and washing over of the barrier beach by large storm waves from Lake Ontario.

Much of the infill of Frenchman's Bay lagoon consists of massive to laminated marl (Fig. 10). The term 'marl' refers to any fine sediment enriched in CaCO_3 (calcium carbonate, the mineral calcite). Marl sediments are typical of enclosed lagoons with clear water and extensive areas of submergent aquatic vegetation such as *Myriophyllum*. These plants secrete CaCO_3 , which slowly accumulates on the lagoon floor to form a chalky deposit. Marl sediments in Frenchman's Bay record pristine environmental

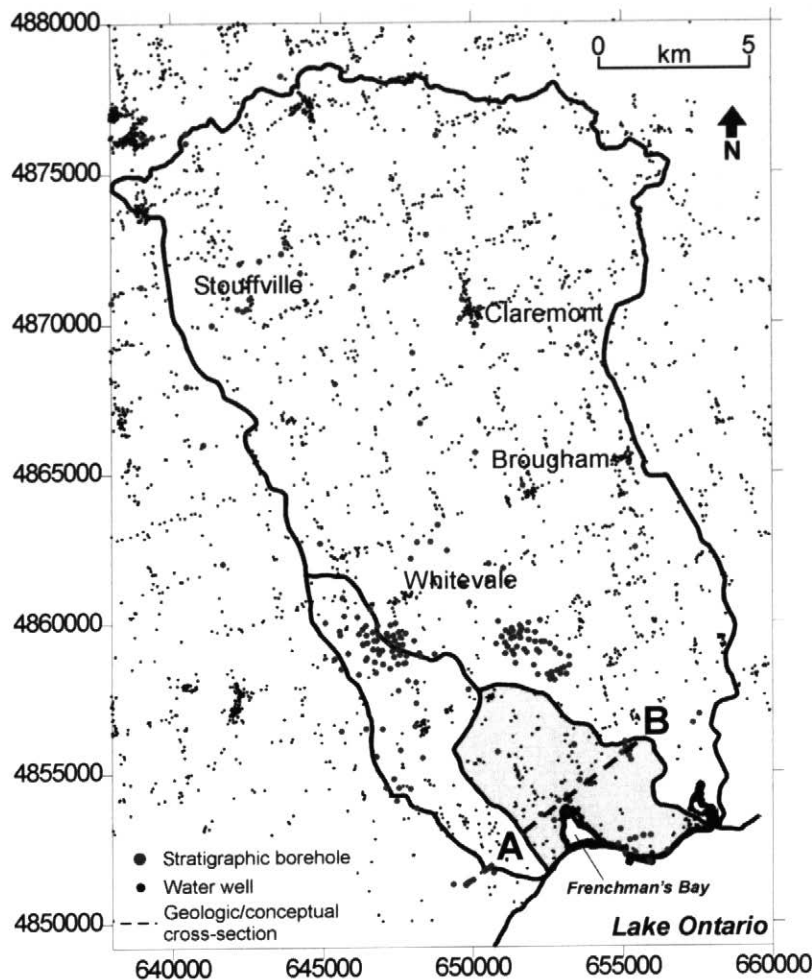


Figure 5 Distribution of ~3600 boreholes used in this study to construct regional cross-sections through the Frenchman's Bay watershed (highlighted) and surrounding area (Fig. 6), glacial sediment thickness and the topography of the bedrock surface under glacial sediments (Fig. 7C, D).

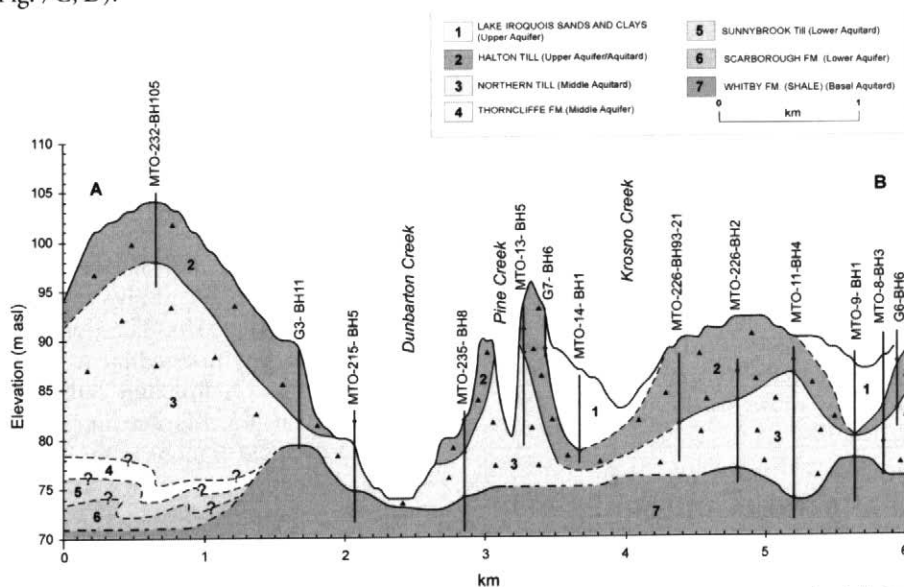


Figure 6 West-east-oriented geological cross-section of the Frenchman's Bay watershed (A-B, Fig. 5). Geological layers control the movement of groundwater and act as hydrostratigraphic units (i.e. aquifers or aquitards). Note topographic highs underlain by tills (drumlines) and inter-drumlin areas where Glacial Lake Iroquois sediments are thickest.

conditions where water clarity is unaffected by suspended sediment allowing the growth of submergent aquatic vegetation. These sediments record a watershed uninfluenced by human activity. Marl deposition in Frenchman's Bay lagoon was abruptly terminated about 1840 when Europeans began to deforest the surrounding watershed, releasing large volumes of soil to creeks where it was then transported to Frenchman's Bay.

EUROPEAN SETTLEMENT LAYER

The uppermost sediment layer in Frenchman's Bay lagoon is in places more than 1.5 m thick and consists of a black-coloured, foul-smelling mud, rich in wood debris, partly decomposed organic matter, and the pollen of grass and weeds (Fig. 10). This layer has been recognized by many other investigators below the floor of Lake Ontario. It is the product of European settlement and widespread forest clearances and subsequent soil erosion after 1840. Weninger and McAndrews (1989) established that as a consequence of deforestation, sedimentation rates in coastal lagoons of the Humber River in Toronto increased more than tenfold over natural pre-existing conditions. All of the lower portions of rivers in Southern Ontario contain thick accumulations of sediment recording dramatic environmental changes after 1840; increased incidence of flooding resulted from the partial filling of many floodplains with sediment (Eyles, 1997).

The European Settlement Layer is thickest in the northern reaches of Frenchman's Bay and has been exposed by erosion of wetlands at the mouths of Amberlea, Dunbarton and Pine creeks. The upper part of the European Settlement Layer also records the later impact of urban runoff commencing in the 1960s in the form of elevated levels of contaminants. Chemical analysis of sediment in the lagoon shows that Ontario Ministry of Environment Provincial Sediment Quality Guidelines are exceeded for many parameters such as total keldahl nitrogen (TKN), phosphorus, cadmium, lead, copper, mercury, zinc, cyanide, oil and grease, and total organic carbon.

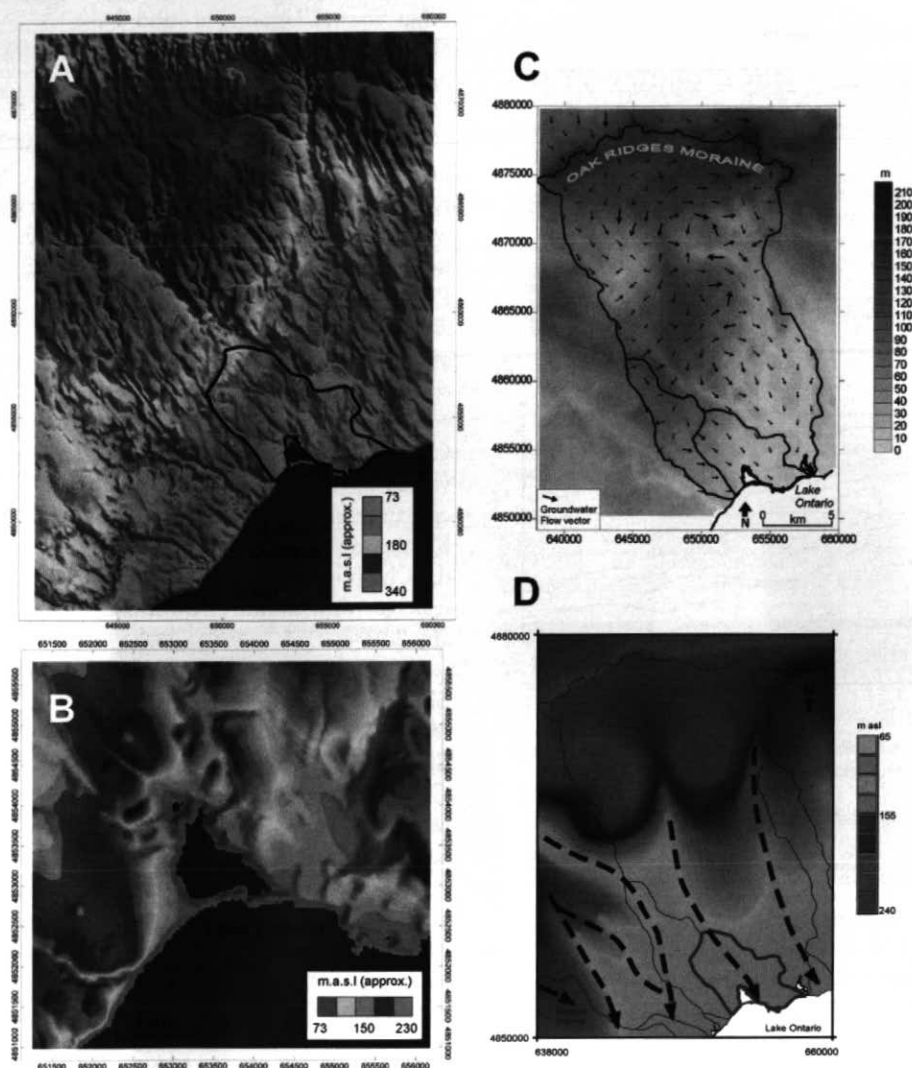


Figure 7 A, B. Surface topography from Oak Ridges Moraine south to Lake Ontario and Frenchman's Bay Watershed (dark line). C. Thickness of glacial deposits in the study region. Frenchman's Bay watershed is highlighted. Sediment thickness declines from north from the Oak Ridges Moraine southwards to the Frenchman's Bay watershed. Arrows indicate general direction of groundwater flow for the region. D. Bedrock topography below the south slope of the Oak Ridges Moraine and Frenchman's Bay watershed (highlighted). The bedrock surface shows several shallow channels (dashed lines) infilled by glacial and postglacial sediments. Elevation shown in metres above sea level.

HYDROLOGICAL IMPACT OF URBAN DEVELOPMENT

Frenchman's Bay watershed exhibits many symptoms typical of urbanized catchments blanketed by impermeable roads and buildings. Rainwater is captured by drains and pipes that collect and divert such flows to the nearest creek (Fig. 11C). During large storms, surface flow in the four principal creeks (Amberlea, Dunbarton, Krosno and Pine) is greatly increased above historic pre-urban conditions (Fig. 1A).

The 'flashy' and substantial wet-weather discharge shown by Pine Creek

(and all creeks that drain to Frenchman's Bay) has resulted in erosion of its banks and the downstream movement of sediment. This is an acute problem in the Frenchman's Bay watershed because fine suspended sediment enters the bay and reduces water clarity. Consequently, attention has been focused on mapping the watershed and identifying sites of streambank erosion (e.g., Fig. 3), which produces turbid conditions in the Bay and results in its characteristic muddy brown colour (Fig. 11D). In turn, suspended sediment reduces light penetrating to the floor of the bay, restricts the growth of aquatic plants and impacts the habitat of aquatic organisms such as fish. Typically, erosion sites are located at the exits of culverts, pipes and concrete channels where large pools have been cut in the floors and sidewalls of the creeks as a result of scouring by focused stormflows (Fig. 11B, C).

Enhanced flows of water and sediment have destroyed large areas of the fringing wetlands on the northern side of the lagoon resulting in the exposure of extensive mudflats where Amberlea and Dunbarton creeks enter the bay (Fig. 4B). Mid-nineteenth century wharves once accessible to boats are now surrounded by exposed mud and shallow water.

Analysis of water quality in the lagoon shows elevated levels of chloride (from road salt), suspended solids, turbidity, fecal coliform, total phosphorus, metals (such as cadmium, lead, nickel, zinc and copper) and various organic chemicals such as hydrocarbons and nitrates similar to

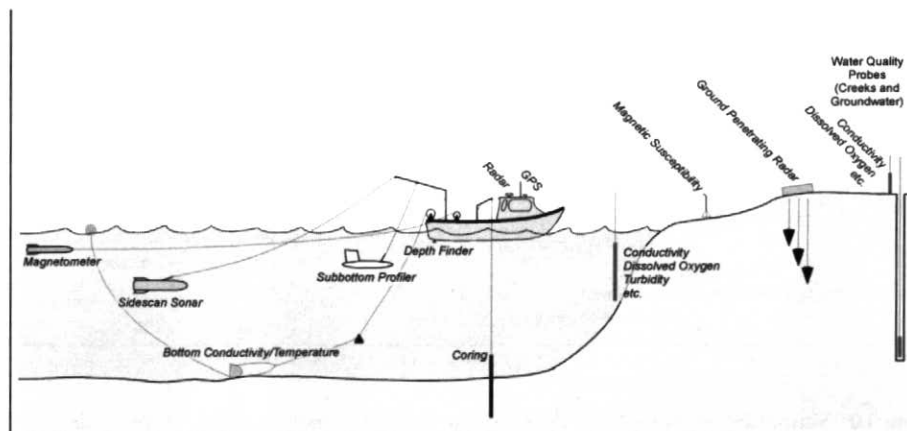


Figure 8 Geophysical instruments and techniques used by the study team in Frenchman's Bay and surrounding watershed.

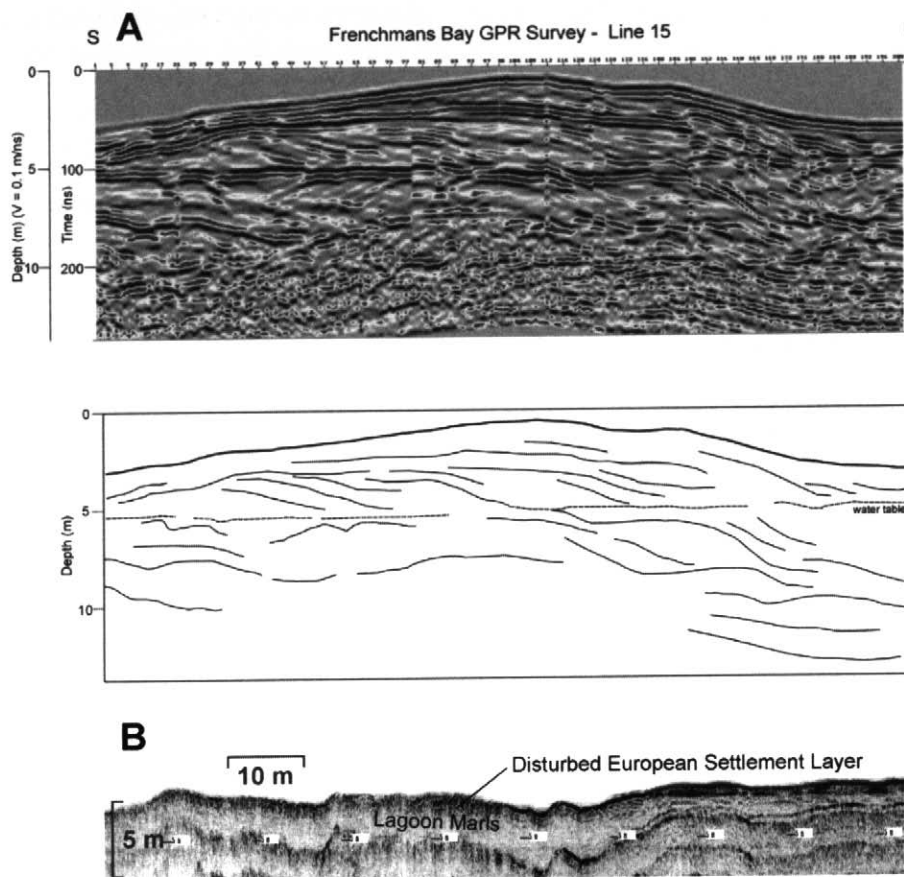


Figure 9 A. Ground-penetrating radar profile collected across the spit at the mouth of the Bay. Profile clearly shows internal layering of the beach at depth, recording upward growth and migration of the beach system during its 3000 year history. B. Results of sub-bottom profiling at Frenchman's Bay.

other coastal lagoons around Lake Ontario that are impacted by urbanization (e.g., Chow-Fraser et al., 1996, 1998; McDonald et al., 1997; Chow-Fraser, 1999; Crosbie and Chow-Fraser, 1999). These values are a typically an order of magnitude higher when compared to those from pristine wetlands (such as Presqu'île Provincial Park) defining the Bay as a degraded aquatic environment. In the summer and fall of 2002 and early 2003, concentrations of *E. coli* and total coliforms in the Krosno Creek, Pine Creek and Frenchman's Bay reached values up to 300 times the accepted concentrations set by Provincial Water Quality Objectives (PWQO). These data highlight the possible influence of leakage from sanitary sewers (Eyles et al., 2003).

SEDIMENT DEPOSITION AND MAPPING OF CONTAMINATED SEDIMENT IN FRENCHMAN'S BAY

Given concerns with the fate of sediment in Frenchman's Bay – in particular the distribution of contaminated sediment – the movement and deposition of sediment across the floor of the bay was investigated using a range of water- and land-based geophysical techniques (Fig. 8).

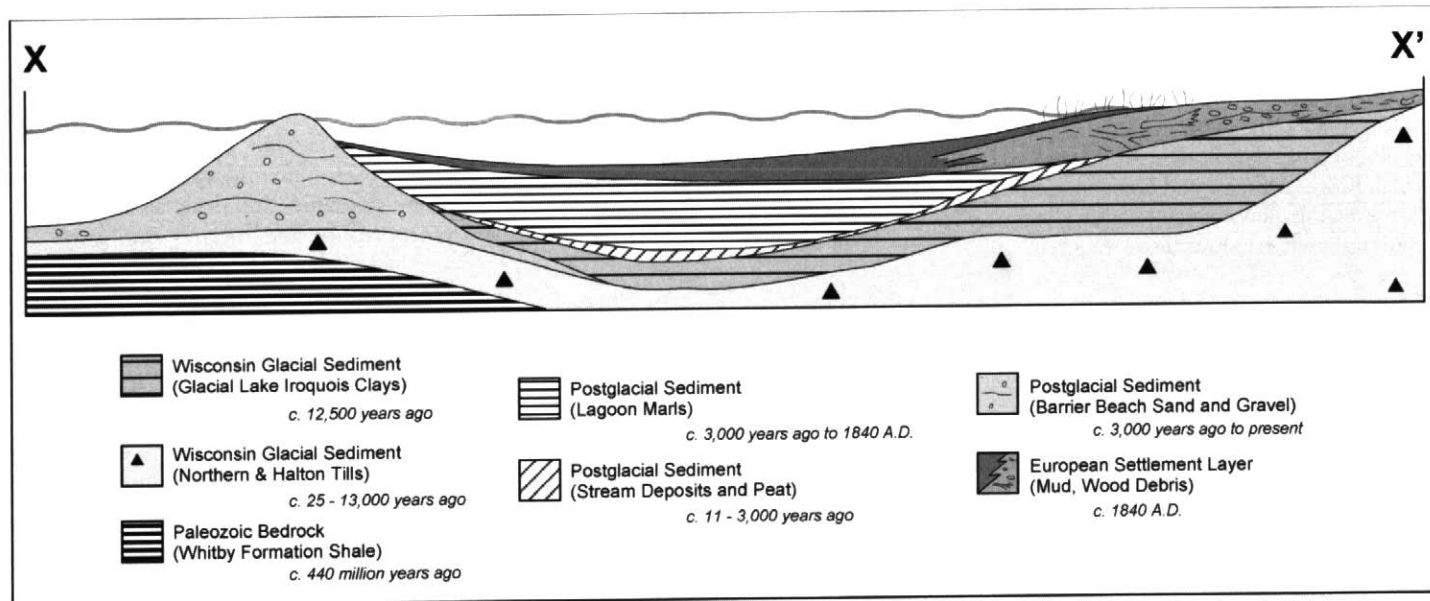


Figure 10 Simplified stratigraphy of the sediment infill of Frenchman's Bay as determined by sub-bottom profiling, coring and ground penetrating radar (Fig. 9). The European Settlement Layer consists of mud with abundant wood debris and is thickest in the northern margin of the bay.

WATER DEPTHS

Existing navigation charts for Frenchman's Bay are dated and show insufficient detail for the purpose of mapping the distribution of contaminated sediment. Bathymetric data were acquired in Frenchman's Bay using a Garmin 200 kHz echo sounder. Survey navigation and positional data were obtained using an on-board Differential Global Positioning System (DGPS) with a horizontal positioning error of < 3 m. The detailed bathymetric map (Fig. 12A) shows that water depths in Frenchman's Bay vary from less than 0.5 m to a maximum of 3.5 m within a north-south-trending basin. The southwestern perimeter of this basin has a remarkable linear boundary and has likely been modified by dredging. Other areas of dredging activity include a west-east channel that connects the lagoon entrance to the central basin and an area of distinctly hummocky bottom topography on the eastern lagoon floor that may be the result of the dumping of dredgate from marina operations widening the entrance of Frenchman's Bay.

SIDE-SCAN SONAR IMAGERY

The bottom features of portions of Frenchman's Bay lagoon were mapped in part by side-scan sonar using a Shark Marine Technologies Sport-Scan 881 operating at 600kHz (Fig. 13). This technique produces, essentially, a photograph-like image of the lagoon floor using high-frequency sound waves. This initial survey showed that much useful information can be determined with regard to the type and distribution of sediment and submerged aquatic vegetation, the effects of dredging and boating activity, and bottom water currents.

WATER CIRCULATION

Circulation and sediment transport in Frenchman's Bay is dictated by the interaction of relatively cold lake water moving into the bay from Lake Ontario with warm water entering the bay from the surrounding urban catchment. In order to identify how these waters interact and move through Frenchman's Bay during different weather conditions, systematic measurements of bottom

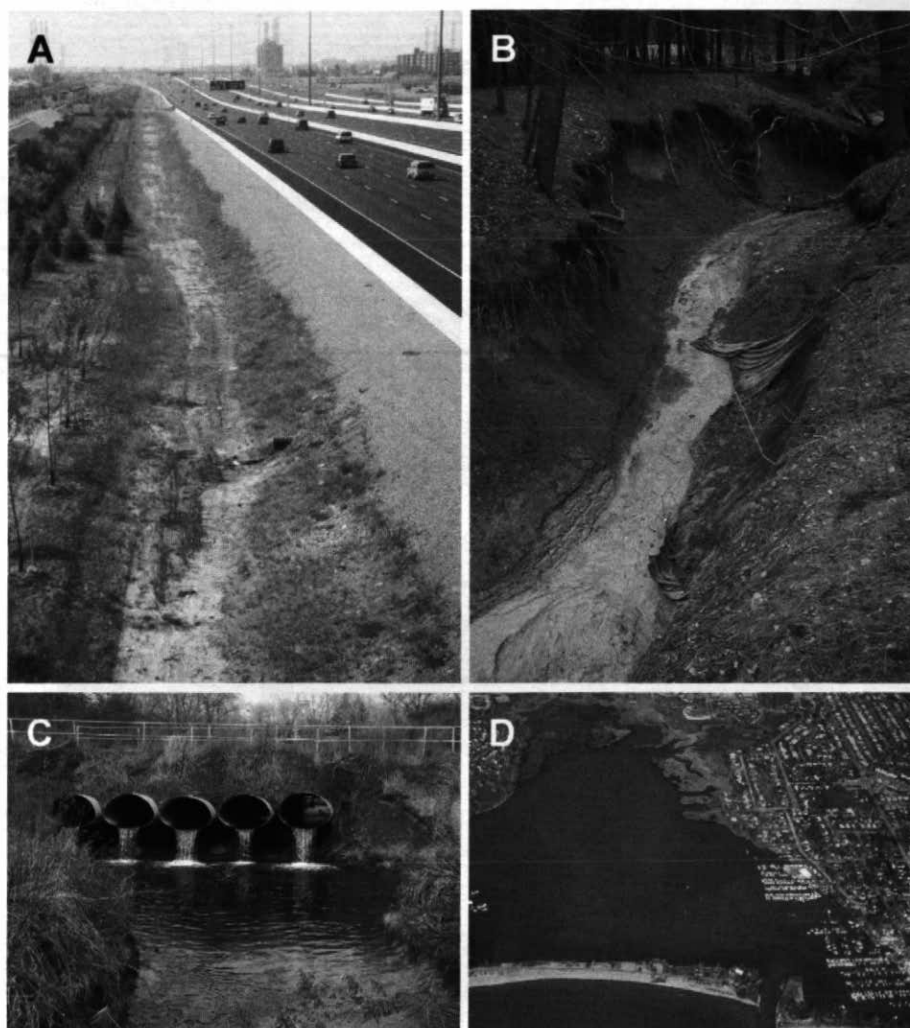
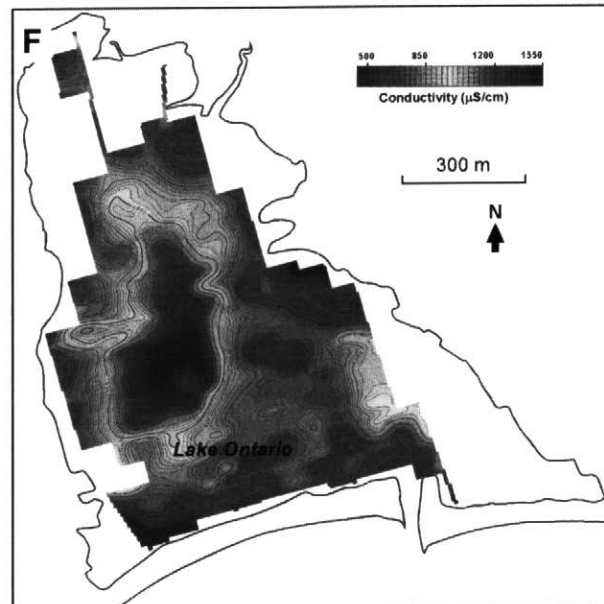
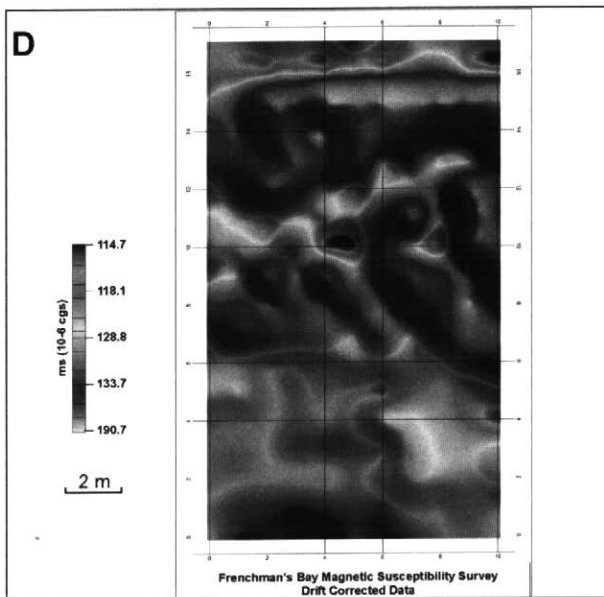
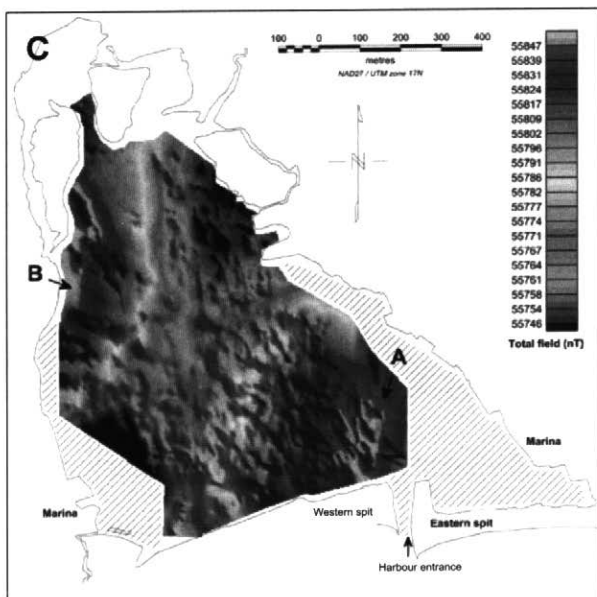
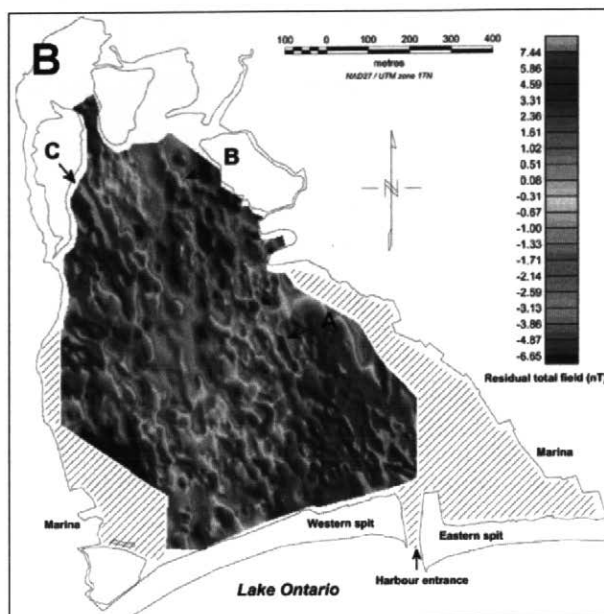
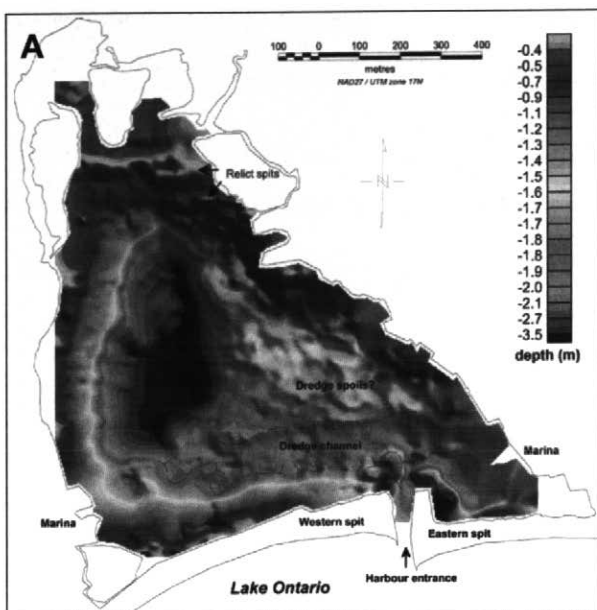


Figure 11 A. Shallow infiltration ditch on south side of Highway 401; this traps surface runoff from the highway but contaminants, such as road salt, enter the groundwater flow system, eventually draining into Frenchman's bay. B. Site in upper watershed where fine-grained deposits of Glacial Lake Iroquois are undergoing erosion and fine-grained suspended sediment is being transported to Frenchman's Bay. C. Culverts on Pine Creek and resultant downstream plunge pool. Fine-grained sediment is being eroded and deposited in Frenchman's Bay. D. Plume of suspended fine-grained sediment entering Frenchman's Bay as a result of erosion in the surrounding watershed due to uncontrolled stormwater runoff. Photograph courtesy of S. McQueen.

water temperature were conducted using a Geonics EM-38 ground conductivity meter towed at a speed of 5 km/h along the floor of the bay. Conductivity is a measure of how easily an electrical current passes through sediment and is, in part, controlled by water temperature (about 2% change per degree C) allowing the determination of bottom water temperature.

The results of the EM-38 survey (Fig. 12E) show that bottom water temperature is highest at the northern

end of Frenchman's Bay, close to creek inputs, and is lowest in the southeast portion of the lagoon close to the entrance to Lake Ontario. Summer data suggest that water circulation in the lagoon is anticlockwise. Warm creek waters ($>18^{\circ}\text{C}$) entering the bay along its northern margin move south and then eastward parallel to the barrier beach toward the entrance with Lake Ontario. Colder ($<13^{\circ}\text{C}$) water from Lake Ontario moves north through the entrance and along the eastern margin of the bay to mix with warmer lagoonal



waters. Aerial photographs taken of the bay after a major storm event show a plume of suspended sediment entering the bay from Krosno Creek and being moved northward (Fig. 11D). In this way contaminated sediment entering the bay from creeks along its northern margin are spread along its western edge (Fig. 12B, C). In protected semi-enclosed embayments such as Frenchman's Bay, frequent mixing with water from Lake Ontario, which could otherwise ameliorate negative effects of urbanization on water quality and suspended sediment, is minimized.

TRANSPORT AND DEPOSITION OF FINE SEDIMENT

A Geonics EM-38 conductivity meter was used to measure the potential of bottom sediments to conduct an electrical charge (Fig. 12F). These data, when collected systematically across the bay, allow broad mapping of sediment grain size on the floor of the lagoon using the well-known relationship between conductivity and grain size. Generally speaking, sands are characterized by a conductivity of less than 500 uS/cm, silts and clays show elevated conductivities.

Sediment conductivity data collected as part of an earlier survey of the lagoon by Geomar Geophysics Ltd. (1991) indicate a good relationship between water depth and grain size (Fig. 12). Data demonstrate that fine-grained sediment derived from the surrounding watershed is accumulating in the deeper water portions of Frenchman's Bay. The deepest parts of

the lagoon are associated with highly conductive clay-sized sediments (>1200 uS/cm). Lower values (between 600 and 900 uS/cm) occur over most of the bay where silt-sized sediment predominates in water depths of less than 2 m. Much lower conductivities (< 600 uS/cm) occur in shallow water sands close to the barrier beach, in water depths less than 1 m.

CONTAMINANTS IN SEDIMENT: MAGNETIC MAPPING TECHNIQUES

The uppermost sediment layer in Frenchman's Bay lagoon (European Settlement Layer, Fig. 10) is enriched in contaminants and fine-grained magnetic particles, which are a fingerprint of contaminated sediments sourced from the surrounding urban areas. Urban and industrial activities release significant amounts of airborne pollution as dust. Dust particles include ferromagnetic minerals such as iron oxide (magnetite), hematite, pyrrhotite and goethite. Magnetite is produced by power plants, cement manufacturers and, in particular, vehicles as a result of exhaust emissions and the wear of exhaust systems and tires. Magnetic dust particles accumulate in soils and are also washed from roads and impermeable surfaces into creeks and water bodies (e.g., Charlesworth and Lees, 1997; Hay et al., 1997). Magnetic properties of sediments can therefore be used as a tool in mapping urban-impacted contaminated sediment. Mapping of magnetic properties of sediment can be done simply and rapidly and is, thus, an inexpensive

means of determining the spatial distribution of urban-sourced sediments and other chemical pollutants in water bodies or on land (e.g., Flanders, 1994; Petrovsky and Ellwood, 1999; Boyce et al., 2001; Petrovsky et al., 2001). Studies in Southern Ontario have shown a strong correlation between magnetic content in sediment and contaminants such as heavy metals (such as cadmium, lead, nickel, zinc and copper) and various organic chemicals (Versteeg et al., 1995, 1997).

A survey of the magnetic properties of sediment on the floor of Frenchman's Bay was conducted by boat employing the methodology used in other water bodies in Southern Ontario (Versteeg et al., 1997). Total magnetic field surveys were acquired with a Marine Magnetics Overhauser magnetometer towed at a depth of 0.5 m and a speed of 5 knots. During the survey, the magnetometer was cycled at 4Hz (with approximate horizontal sample intervals of 2 m). A second, base-station magnetometer was deployed onshore to record diurnal magnetic field variations throughout the survey period. Post-cruise processing of magnetic data involved corrections for diurnal variations, tie-line levelling, upward continuation (to 10 m) and regional residual separation. Other corrections included removal of magnetic variations (up to 5 nT) associated with changes in water depth. A total of 85 track line kilometres of magnetic data were collected along a series of west-east tracklines; several north-south axial lines were also recorded.

Figure 12 A. Shaded relief bathymetric map of Frenchman's Bay completed using differential GPS and an echo sounder. Maximum water depths (3.5 m) occur within an enclosed north-south-oriented basin on the western side of the lagoon. Bathymetry data also identify a dredged channel and hummocky topography adjacent to the channel most likely representing an area of dredge spoil. B. Residual magnetic field data from Frenchman's Bay. This data set provides a higher resolution image of the distribution of sediment having an elevated content of magnetic minerals. While the same overall pattern remains, other smaller anomalies can be identified (e.g. A, B, C in Fig. 12B). C. Total magnetic field data. These data suggest two principal locations where sediment is accumulating in Frenchman's Bay with a sufficiently elevated magnetic content to indicate the presence of contaminated sediment. Site A may reflect either an urban source in the southeast corner of the bay or the entry of coarser sand-sized sediment containing magnetite. Area B likely reflects the southward transport of contaminated mud from the northern reaches of the Bay where creeks flow into the lagoon. D. Results of a land-based magnetic susceptibility survey at the mouth of Dunbarton and Amberlea creeks showing elevated levels of magnetic content typically associated with sediment containing urban contaminants. E. Distribution of bottom water temperature in Frenchman's Bay as determined by conductivity survey (shown in F). Warmest temperature reflects the entry of warm urban waters at the northern end of the bay (Fig. 3) and presence of cold water in the deep-water basin on the west side of the bay and entering the southeast corner of the bay from Lake Ontario. Data suggest an anticlockwise flow of water in the lagoon. F. Conductivity of bottom sediments on the floor of Frenchman's Bay. Highly conductive sediment is represented by silt and clay, lower conductivity sediment by sand. Fine-grained sediment is preferentially being deposited in the relatively deep-water basin in the western half of the bay. This sediment has likely originated along the northern part of the Bay by the erosion of exposed mud by stormwaters (Fig. 4B).

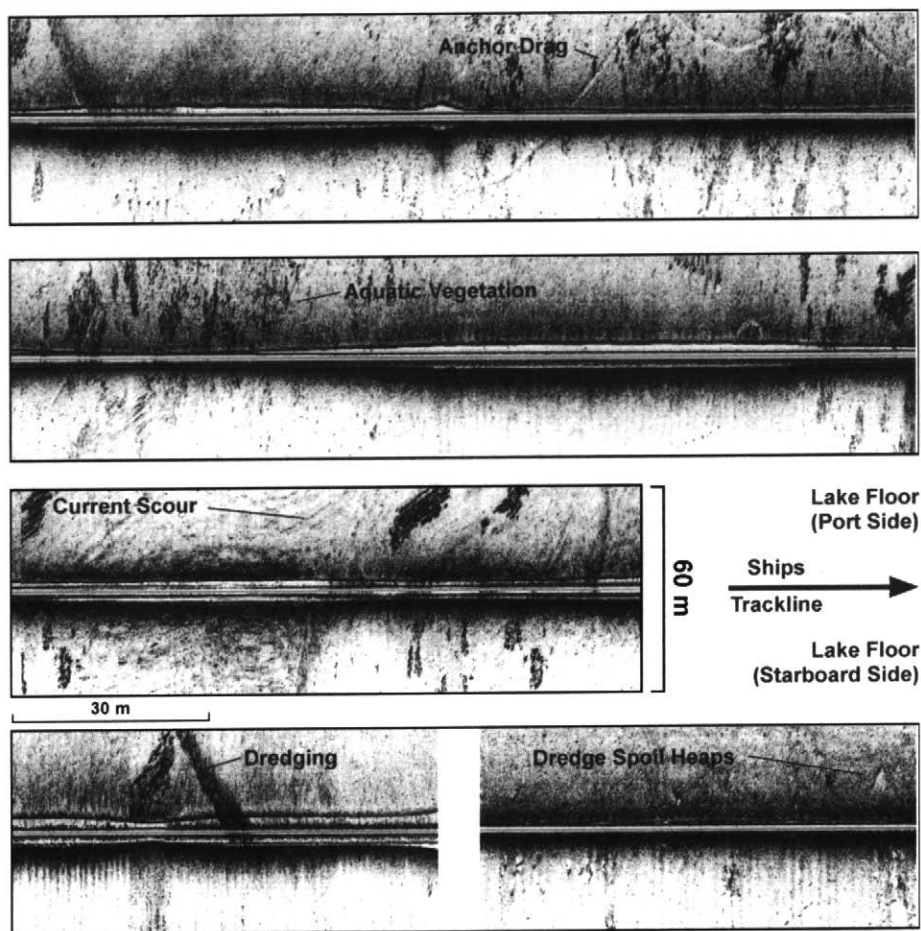


Figure 13 Examples of high-resolution side-scan sonar images of part of Frenchman's Bay showing effects of dredging, dumping of dredgate, anchor drag marks, effects of scour by bottom currents and clumps of aquatic vegetation on the lake floor.

The final processed magnetic field maps of total and residual magnetic fields (Fig. 12B, C) show silt-sized sediments containing elevated levels of magnetic minerals in the northwest and southeast parts of Frenchman's Bay. The greatly increased magnetic intensity shown by sediment in the northwest portion of the lagoon reflects the influx of urban-impacted sediment from Amberlea, Dunbarton and Pine creeks. This sediment is then being moved southward as part of the anticlockwise movement of water within the Bay. The high magnetic intensity of sediments in the southeastern corner of the lagoon is not surprising given the long history of commercial activity in Frenchman's Bay.

Other linear northwest-trending magnetic anomalies within the bay can be noted (Fig. 12B, C). Those on the west side of the bay appear to be

sourced from individual storm sewershed outfalls. These are being investigated further by detailed mapping of magnetic susceptibility.

MAGNETIC SUSCEPTIBILITY MAPPING

Magnetic susceptibility is the term that refers to the ease at which sediments are magnetized when subjected to a magnetic field. Their ability to become magnetized reflects the composition and amount of magnetic minerals present in the sediment. Boat-based magnetic susceptibility data from Frenchman's Bay were acquired using a Marine Magnetics Overhauser magnetometer (described above). Susceptibility data confirm the presence of two principal areas of urban-impacted sediment in Frenchman's Bay as identified by mapping of total and residual magnetic fields (e.g., Fig. 12B, C). In addition,

land-based data were also collected on foot using a Bartington MS-2 Magnetic Susceptibility Meter placed directly on the soil surface. Measurements were made at 0.5 m intervals as part of a survey at the mouth of Amberlea and Dunbarton creeks (location shown on Fig. 4B). This locality shows higher-than-background levels of magnetic susceptibility, indicating an urban source of contaminated sediment (Fig. 12D).

SEISMIC PROFILING

Seismic data were collected for the bay employing an Edgetech high-resolution XStar digital sub-bottom seismic reflection profiling system with an SB216S towfish operating with a swept frequency of 2-15 kHz. The instrument was towed approximately 0.5 m below the water surface at a speed of 3 knots. Navigational fixes were through a Lowrance GPS system with DGPS antenna.

Seismic sub-bottom profiling (Fig. 9B) shows two principal reflectors in the postglacial sediment layers within Frenchman's Bay consisting of lagoon marls, and a European Settlement Layer (as shown in Fig. 10). This corresponds to information from the coring operation.

Sub-bottom profiling provides an additional method for mapping the distribution of contaminated sediment in water bodies. The reflection coefficient can be calculated from seismic data and is related to the characteristics of the bottom sediment. The term reflection coefficient is a quantitative measure of the amount of acoustic energy that is reflected back to the surface from the lake floor during a seismic reflection survey. Contaminated sediment with its enhanced component of magnetite tends to have relatively high (and variable) reflection coefficient as it (generally) has a higher gas content.

DISCUSSION

The example of Frenchman's Bay illustrates a situation typical of many urban impacted watersheds in need of remediation where there is a lack of quantitative baseline data regarding both existing and predevelopment

conditions. Urban development proceeded rapidly in the 1960s and 1970s, largely in ignorance of environmental impacts and the need to monitor environmental conditions. Instruments such as waterwell loggers and stream-flow loggers have now been installed and are providing key data regarding the flux of surface and subsurface waters and their chemistry.

This paper provides a case history illustrating the many geophysical techniques and data sets increasingly being used in urban environmental investigations. The production and movement of contaminated sediment is of especial interest. Of the various geophysical techniques described here, the mapping of such sediment using magnetic properties is perhaps the most useful. This technique clearly identifies the distribution of sediment contaminated by urban activity.

Conventional remediation techniques include the construction of storm water retention ponds designed to retain surplus floodwaters and sediment. Normally, these would be placed along the valleys of creeks but in the case of the heavily urbanized Frenchman's Bay watershed, such remediation is not straightforward. A major consideration is the lack of space along crowded floodplains in which to construct appropriate stormwater retention ponds that trap water and contaminated sediment. These facilities are now required for new developments but the retrofitting of older urban areas such as in the Frenchman's Bay watershed is problematic. A difficulty is that the lagoon is impacted by contaminated water and sediment derived from major transportation corridors upstream on which large volumes of road salt are applied each winter, together with leaking utilities such as sewers. A wealth of hydrologic and hydro-geological data have now been collected in all seasons that identifies the large Highway 401 transportation corridor as the single largest influence on water quality in the watershed and Frenchman's Bay (Eyles et al., 2003). This is expressed as elevated values of conductivity and turbidity in winter associated with the application of road salt, and high levels of suspended solids

and dissolved nutrients in summer that promote the growth of algae in the Bay. Controlling this source is the focus of current remediation, involving the design and installation of a large constructed wetland system *downstream* of the 401 corridor along the northern margins of the Bay. This system will contain several retention ponds to control the influx of poor quality urban runoff and improve water quality and fish habitat in Frenchman's Bay.

Environmental investigations in urban areas offer exciting challenges to geoscientists because of the wide range of disciplines need to be brought together and focussed on any one investigation. In the present study for example, geophysicists, sedimentologists and hydrogeologists are working alongside biologists to assess contamination in a heavily urbanized watershed. In turn, data and recommendations must be conveyed to municipal planners. Access to good-quality geological information is fundamental to such investigations. A key element is to develop a good understanding of the geology and hydrogeology of the watershed and in turn, where and how sediment is produced, transported and deposited. Essentially, this entire approach represents the extension and application of basin analysis techniques long used by geologists, to urban watersheds. With a national population now increasingly clustered in urban areas, basin analysis techniques will be of increasing importance to the ways in which we plan our communities.

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REFERENCES

- Beres, M., Huggenberger, P., Green, A.G. and Horstmeyer, H., 1999, Using two- and

- three-dimensional radar methods to characterize glaciofluvial architecture: *Sedimentary Geology*, v. 129, p. 1-24.
- Booth, D. and Reinelt, L., 1993, Consequences of urbanization on aquatic ecosystems, measured effects, degradation thresholds and corrective strategies: *Proceedings, Watershed Management*, March 21-21, Alexandria, Virginia, p. 545-550.
- Boyce, J.I. and Eyles, N., 2000, Architectural element analysis applied to glacial deposits: internal geometry of a Late Pleistocene drumlinized till sheet, Ontario, Canada: *Geological Society of America, Bulletin*, v. 112, p. 98-118.
- Boyce, J., Eyles, N. and Pugin, A. 1995, Seismic reflection, borehole and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto: *Canadian Journal of Earth Sciences*, v. 32, p. 1331-1349.
- Boyce, J., Pozza, M. and Morris, W., 2001, High resolution magnetic mapping of contaminated sediments in urbanized environments: *The Leading Edge*, v. 20, p. 886-890.
- Charlesworth, S.M. and Lees, J.A. 1997, The use of mineral magnetic measurements in polluted urban lakes and deposited dusts: *Physics and Chemistry of the Earth*, v. 22, p. 203-206.
- Chow-Fraser, P. 1999, Seasonal, interannual and spatial variability in the concentrations of total suspended solids in a degraded coastal wetland of Lake Ontario: *Journal of Great Lakes Research* v. 25, p. 799-813.
- Chow-Fraser, P., Crosbie, B., Bryant, D. and McCarry, B., 1996, Potential contribution of nutrients and polycyclic aromatic hydrocarbons from the creeks of Cootes Paradise Marsh: *Water Quality Research Journal of Canada*, v. 31, p. 485-503.
- Chow-Fraser, P., Loughheed, V.L., Crosbie, B., LeThiec, V., Simser, L., and Lord, J. 1998, Long-term response of the biotic community to fluctuating water levels and changes in water quality in Cootes Paradise Marsh, a degraded coastal wetland of Lake Ontario: *Wetland Ecological Management*, v. 6, p. 19-42.
- Coakley, J.P. and Mudroch, A. 1997, Contaminated sediment in urban Great Lakes waterfronts, *in* Eyles, N., ed., *Environmental Geology of Urban Areas*. Geological Association of Canada, *Geotext* No. 3, p. 227-240.
- Crosbie, B. and Chow-Fraser, P., 1999, Percent land use in the watershed determines the water- and sediment-quality of 21 wetlands in the Great Lakes basin: *Canadian Journal of Fisheries and Aquatic Science*, v. 56, p. 1781-1791.
- Eyles, N., 1997, *Environmental Geology of a Supercity: the Greater Toronto Area*, *in* Eyles, N., ed., 1997, *Environmental Geology of Urban Areas*: Geological Association of Canada, *Geotext* No. 3, p. 7-80.

- Eyles, N. 2002, Ontario Rocks: 3 Billion Years of Environmental Change: Fitzhenry and Whiteside, Toronto, 339 p.
- Eyles, N., Boyce, J. and Gerber, R., 1997, Hydrogeological study of the North Pickering Development Corporation Lands and the Duffins Creek Watershed: Final Report to North Pickering Development Corporation, 28 p.
- Eyles, N., Chow-Fraser, P., Boyce, J.I., Meriano, M., Seilheimer, T., and Doughty, M., 2003, Remediation of an Urban-Impacted Watershed and Lagoon - Frenchman's Bay, City of Pickering: Final Report to Ontario Innovation Trust and City of Pickering, 96 p. (<http://envsci.utoronto.ca/publications>)
- Flanders, P.J., 1994, Collection, measurements and analysis of airborne magnetic particulates from pollution in the environment: *Journal of Applied Physics*, v. 75, p. 5931-5936.
- Geomar Geophysics Ltd., 1991, Electromagnetic sediment conductivity study of Frenchman's Bay, Lake Ontario: Unpublished Report prepared for Metropolitan Toronto and Region Conservation Authority, 16 p.
- Gerber, R. and Howard, K., 2000, Recharge through a regional till aquitard: Three-dimensional flow model water balance approach: *Groundwater*, v. 38, p. 410-422.
- Gerber, R. and Howard, K., 2002, Hydrogeology of the Oak Ridges Moraine aquifer system: Implications for protection and management from the Duffins Creek Watershed: *Canadian Journal of Earth Sciences*, v. 39, p. 1333-1348.
- Gore and Storrie Ltd. 2000a, Site-wide Groundwater Monitoring System; Pickering Nuclear Generating Station: Final Report for Ontario Power Generation, 276 p. and maps.
- Gore and Storrie Ltd., 2000b, Tritium In Groundwater: Final Report for Ontario Power Generation, 115 p. and maps.
- Hay, K.L., Dearing, J.A., Baban, S. and Loveland, P.J., 1997, A preliminary attempt to identify atmospherically-derived pollution particles in English topsoils from magnetic susceptibility measurements: *Physics and Chemistry of the Earth*, v. 22, p. 207-210.
- Howard, K., Eyles, N., Smart, P., Boyce, J.I., Gerber, R., Salvatori, S. and Doughty, M., 1997, The Oak Ridges Moraine of Southern Ontario: A groundwater resource at risk, *in* Eyles, N., ed., *Environmental Geology of Urban Areas: Geotext No. 3*, Geological Association of Canada, p. 153-172.
- Kohli, B., 1979, Mass exchange between Hamilton Harbour and Lake Ontario: *Journal of Great Lakes Research*, v. 5, p. 36-44.
- Lemay, M.H. and Mulamootil, G., 1981, A limnological survey of eight waterfront marshes: *Urban Ecology*, v. 5, p. 55-67.
- Marsalek, J. and Ng, H., 1989, Evaluation of pollution loadings from urban nonpoint sources: Methodology and applications: *Journal of Great Lakes Research*, v. 15, p. 444-451.
- Mayor Arthur's Task Force on the Pickering Waterfront 2001, Final Report 1998, 151 p.
- McCarthy, F., 1986, Late Holocene waterlevels in Lake Ontario: Evidence from Grenadier Pond and Frenchman's Bay: M.Sc. Thesis, University of Toronto.
- McCarthy, F. and McAndrews, J.H., 1988, Water levels in Lake Ontario 4320-2000 years BP: evidence from Grenadier Pond, Toronto, Ontario, Canada: *Journal of Paleolimnology*, v. 1, p. 99-113.
- McDonald, G., Chow-Fraser, P., Baskin, S., Clearwater, S., Crosbie, B., Croke, S., Lougheed, V., McFarlane, W. and Taylor, L., 1997, The effects of highway stormwater runoff pollutants on aquatic life: Unpublished Report, S Ontario Ministry of Transportation, 36 p.
- Meriano M. and Eyles N., 2003, Groundwater flow through Pleistocene glacial deposits in the rapidly urbanizing Rouge River-Highland Creek watershed, City of Scarborough, southern Ontario: *Hydrogeology Journal*, v. 11, p. 288-303.
- Ministry of Northern Development and Mines, 1992, Bedrock Geology of Ontario, Map 2544.
- Nelson, J.G., 1991, Urbanization, Conservation and Sustainable Development, The Case of Frenchman's Bay, Toronto, Ontario: Technical Paper 5, Heritage Resources Centre, University of Waterloo, 103 p.
- Nriagu, J., Wong, H.K.T. and Snodgrass, W.J., 1983, Historical records of metal pollution in sediments of Toronto and Hamilton harbours, *Journal of Great Lakes Research*, v. 9, p. 365-373.
- Ontario Ministry of Environment and Energy (MOEE), 1997, Environmental Conditions at Frenchman's Bay: Letter from D. Boyd, Great Lakes Nearshore Monitoring and Assessment to N. Eyles dated 11 August 1997.
- Pengelly, J.W., Tinkler, K.J., 1997, 12,600 years of lake level changes, changing sills, ephemeral lakes and Niagara Gorge erosion in the Niagara Peninsula and eastern Lake Erie Basin: *Journal of Paleolimnology*, v. 17, p. 377-402.
- Persaud, D. and Lomas, T.D. and Hayton, A., 1987, The In-Place Pollutants Program: Water Resources Branch Ontario Ministry of the Environment, 96 p.
- Petrovsky, E., Kapics, A., Jordunova, N. and Boruvika, L., 2001, Magnetic properties of alluvial soils contaminated with lead, zinc and cadmium: *Journal of Applied Geophysics*, v. 48, p. 127-136.
- Petrovsky, E., and Ellwood, B.B. 1999, Magnetic monitoring of air-land- and water-pollution, *in* Maher, B. A. and Thompson, R., ed., *Quaternary Climates, Environments and Magnetism: Cambridge University Press*, p. 279-322.
- Quinlan, C. and Mulamootil, G., 1987, The effects of water level fluctuations on three Lake Ontario shoreline marshes: *Canadian Water Resources Journal*, v. 12, p. 66-77.
- Vandenberghe, J. and van Overmeeren, R.A., 1999, Ground penetrating radar images of selected fluvial deposits in the Netherlands: *Sedimentary Geology*, v. 128, p. 245-270.
- Versteeg, K.J., Morris, W.A., and Rukavina, N.A., 1995, The utility of magnetic properties as a proxy for mapping contamination in Hamilton Harbour sediments: *Journal of Great Lakes Research*, v. 21, p. 71-83.
- Versteeg, K.J., Morris, W.A., and Rukavina, N.A., 1997, Mapping contaminated sediment in Hamilton Harbour, Ontario, *in* Eyles, N., ed., *Environmental Geology of Urban Areas: Geological Association of Canada, Geotext No. 3*, p. 241-248.
- Weninger, J.M. and McAndrews, J., 1989, Late Holocene aggradation in the lower Humber River valley, Toronto, Ontario: *Canadian Journal of Earth Sciences*, v. 26, p. 1842-1849.
- Westgate, J.A., 1979, Surficial Geology of the Markham Sheet, Scale 1:50,000: Unpublished map, Ontario Geological Survey.

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