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ORIGINAL ARTICLE

Impacts of European settlement (1840–present) in a Great Lake watershed and lagoon: Frenchman's Bay, Lake Ontario, Canada

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Abstract The northern shore of Lake Ontario is one of the longest settled parts of Canada beginning around 1795. Accelerated settlement and deforestation after 1840 resulted in massive soil loss from easily-eroded Pleistocene glacial landscapes and the siltation of creeks and lagoons. Channel capacity was reduced but river flow was enhanced by diminished infiltration resulting in straightening of meandering channels, accelerated erosion of stream banks, increased incidence of downstream flooding and large influxes of mud to Lake Ontario. Conservation measures after World War II were successful but rapid urban sprawl after 1970 hardened watersheds and badly impacted the quality and quantity of surface and ground waters flowing to Lake Ontario. The Frenchman's Bay watershed (27 km^2) 50 km east of Toronto is one of the country's most urbanized (pop: 100,000; 76 % urban cover) and is crossed by Canada's busiest highway (Highway 401). The watershed drains to Lake Ontario through a coastal lagoon (Frenchman's Bay) in which pre-settlement postglacial carbonate is abruptly overlain by a 'European settlement' mud layer rich in weed pollen and organic debris; the uppermost 'urban' part of this deposit shows elevated level of metals and other contaminants. This layer records soil loss after 1840 and more recently, the influx of contaminated urban waters and sediment. Some 7,600 tonnes of road salt have been applied to the lagoon watershed each year producing spikes of brackish surface runoff during winter thaws. Some 50 % of the total salt applied to the entire watershed is conveyed directly to Frenchman's Bay Lagoon via surface runoff; the rest enters the groundwater system resulting in year-round brackish baseflow to creeks. Chloride continues to be stored in underlying aquifers such that the system has yet to reach a steady-state discharge. Future salinity of baseflow reaching the lagoon can be expected to increase by about 40 %. Rapid migration of contaminated groundwater is facilitated by the widespread presence of thick (<8 m) coarse-grained and heterogeneous fill materials of the built landscape. The watershed is experiencing ongoing changes in land use as urban infilling proceeds. The aquatic ecology of inflowing creeks to the lagoon has been greatly impacted resulting in major loss of wetlands and submergent vegetation and distinct changes in the structure of fish populations. This is the most detailed study of an urban watershed in Canada; lack of knowledge elsewhere is a constraint on the design and testing of mitigation measures and is a major impediment to assessing the impact of ongoing climate change on urban water resources, and the effects of urban runoff on Great Lakes water quality.

Keywords Urban watersheds · Great Lakes · Road salt · Seasonal runoff

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Introduction

What is now the 'environment' was once regarded in North America as a cheap inexhaustible resource to be exploited by early settlers wrestling a living from a wild 'untamed' land. Canadians had an inexhaustible supply of 'geography' (some said too much). Southern Ontario is one of the

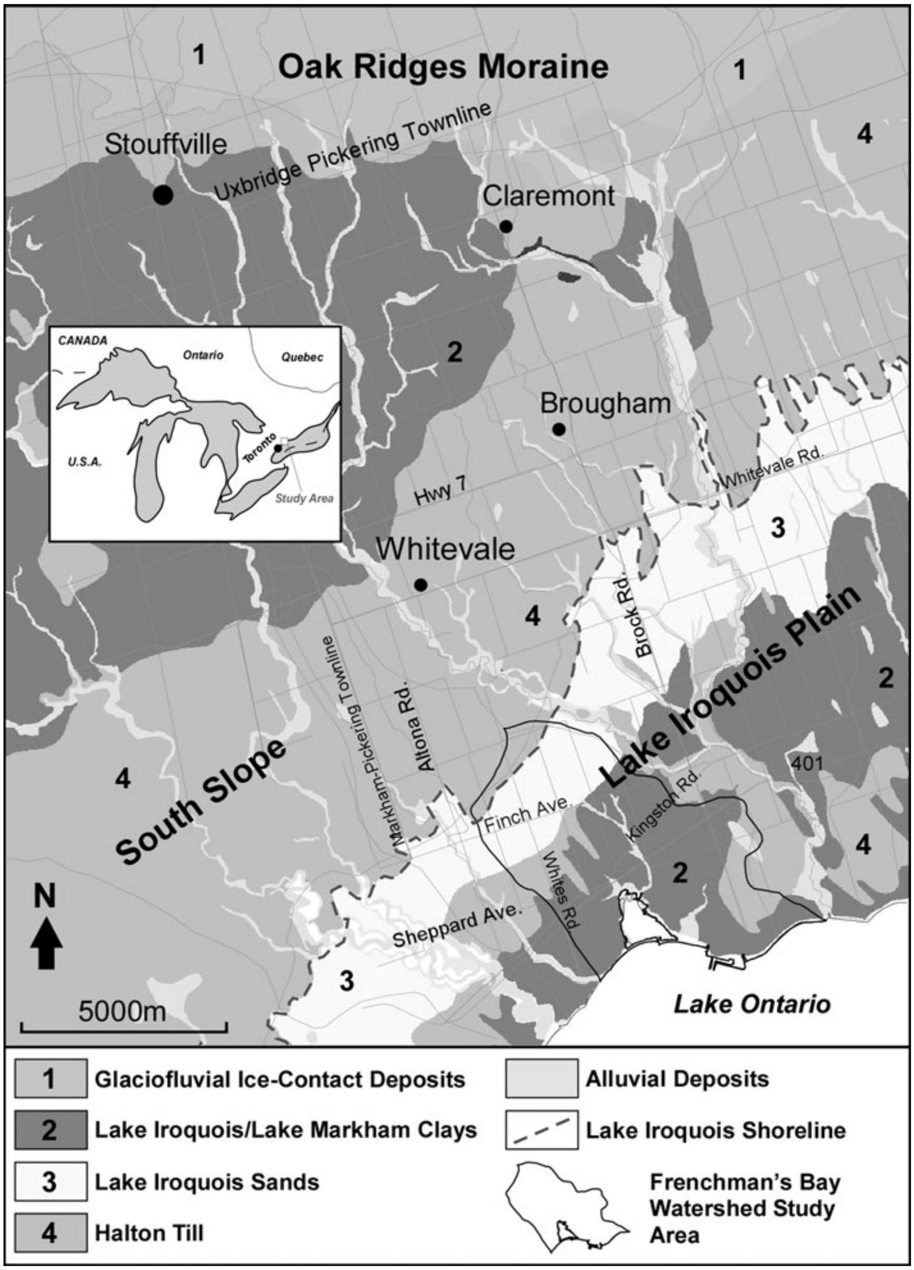


Fig. 1 Location and Pleistocene geology of study area in Southern Ontario, Canada. Frenchman's Bay watershed is *highlighted*

longest settled areas in Canada (since about 1795) but it was not until the 1940s that serious efforts were made to reverse the effects of a century of 'unplanned individualistic exploitation' of natural resources involving massive deforestation (Richardson 1974). In Southern Ontario, the effects of European forest clearances were most keenly felt across the Oak Ridges Moraine (ORM), a broad upland belt of sand and gravel some 40 km wide and 160 km in length along the northern shore of Lake Ontario (Fig. 1). The moraine's forests had earlier been protected out of military necessity to preserve straight white pines for masts for the Royal Navy under the famous 'White Pine Clause.' The ending of this agreement in 1854 left the ORM vulnerable to clear cutting (e.g., Moodie 1852). Stripped of trees, newly cleared areas became a moonscape of windblown sand and devastated creeks. Soil erosion was a widespread problem reflected in large volumes of sediment moving down valley and increased flooding (Fig. 2) recorded by a mud layer across the floor of Lake Ontario rich in weed pollen (Weninger and McAndrews 1989; McFadden et al. 2004). By the 1930s thousands of km^2 of formerly agricultural land was deemed submarginal and 'worn-out farms' were commonplace among blowouts and dunes. It was the Canadian equivalent of the 'dirty thirties' in the United States. Reduced infiltration and enhanced overland flow resulted in depleted groundwater levels especially during a severe drought in 1936 (Richardson 1944). The Guelph Conference of 1941 led to the Conservation

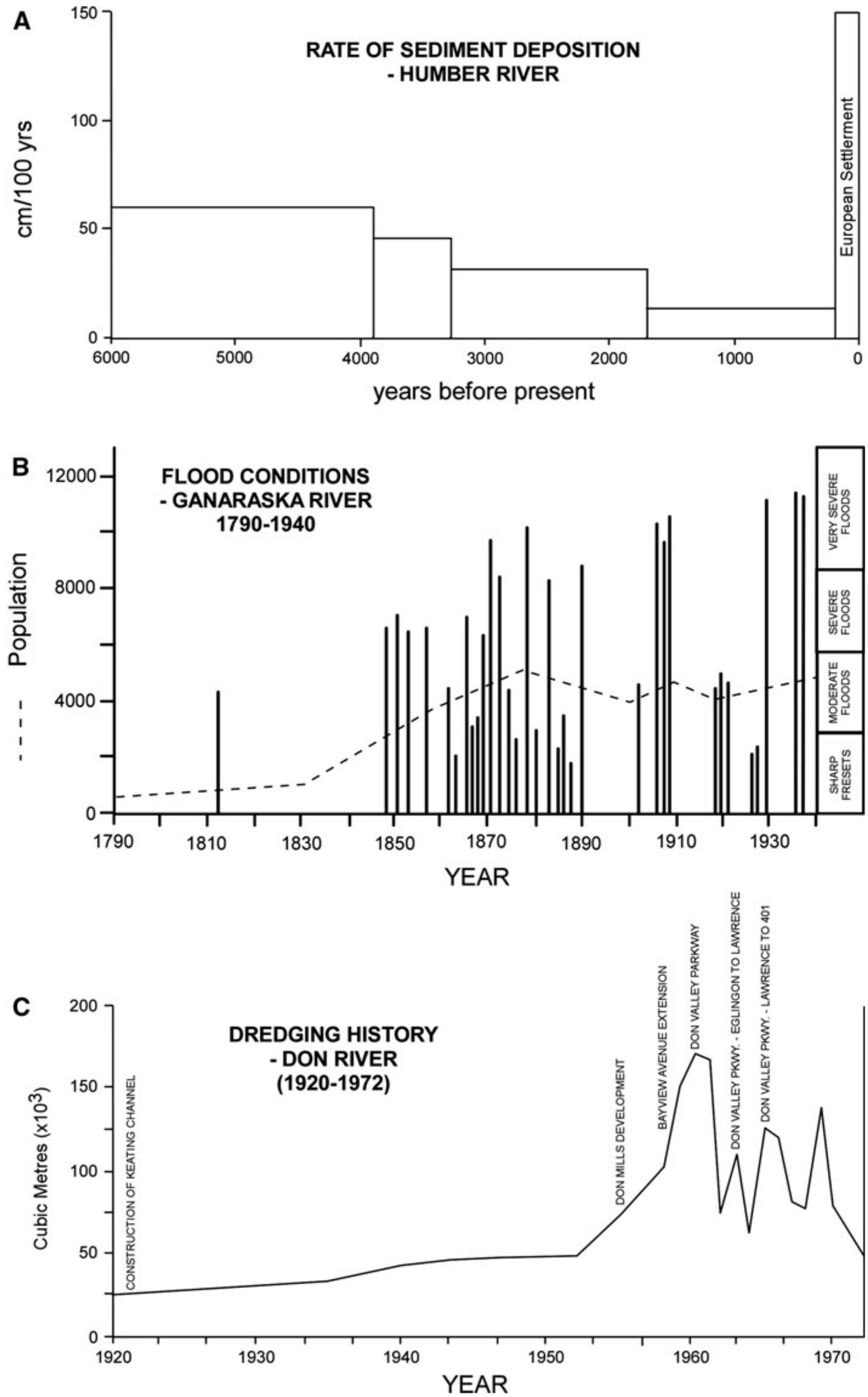


Fig. 2 Impact of European settlement and urbanization on rivers in Southern Ontario. **a** Long-term sedimentation rates along Humber River near Toronto reflecting rising levels of Lake Ontario and decreased hydraulic gradients. Note abrupt increase with European settlement (after Weninger and McAndrews 1989). **b** Impact of European settlement and forest clearance on flood frequency between 1790 and 1940 along the Ganaraska River (data from Richardson 1944). All area rivers have experienced a similar history as river floodplains have become choked with sediment and channel capacity has diminished. **c** Volume of sediment dredged from lower reaches of Don River 1920–1972 in response to soil loss by episodes of urbanization in the watershed (data courtesy of Toronto Harbour Commission and Eyles 1997)

Authorities Act of 1946 and for the first time in Canada a watershed approach was used for land-use management (Richardson 1944, 1974). While the effects of forest clearance and farming have now been reined in across Southern Ontario, watersheds face a new and much more dangerous threat from rapid urban development.

A virtual tidal wave of poorly planned urban sprawl has spread across Southern Ontario after World War II (Eyles 1997). Hardening of watersheds by roads and buildings reduces infiltration, introduces contaminants to surface and ground waters and enhances runoff of thermally and chemically contaminated waters to waterbodies. Despite this threat, there is little study or understanding of the complex interactions between geology, hydrology, hydrogeology and biology across urban watersheds. Small-scale ‘at-a-site’ studies are common but seldom published and

Fig. 3 Frenchman's Bay lagoon. Highway 401 transportation corridor crosses inflowing creeks from surrounding urban area (see Figs. 4, 5). Note fragmentation of wetland within the lagoon compared to earlier conditions (Fig. 4)

not integrated into multidisciplinary watershed-level analyses. In this regard, this paper provides the most detailed case study yet from a southern Canadian watershed with the aim of strengthening long-term management programs in the face of rapid environmental change.

Purpose of this paper

In this paper the changing pattern of environmental change over the past 170 years is traced in a small (27 km^2) watershed (Frenchman's Bay: Figs. 1, 3) located some 50 km east of downtown Toronto in the City of Pickering. The watershed was chosen for detailed study because it is one of the most densely urbanized areas in Canada with a population of more than 100,000 people. Some 76 % of the basin's area is urbanized as a consequence of rapid population growth accompanying construction of the nearby Pickering Nuclear Generating Station in the late 1960s (Fig. 4). The southern part of the watershed is crossed by a major transportation corridor up to 600 m wide that contains the nation's busiest highway (Highway 401) with accompanying road and rail lines (Fig. 3). The resulting environmental impacts in this watershed are numerous and typical of many urban watersheds but major data gaps remained in understanding the geology, hydrogeology, hydrology and aquatic biology of the watershed.

Correspondingly, the specific objectives of the present study being reported were: (1) to develop a geological framework for the watershed including Frenchman's Bay lagoon and areas of man-made fill; (2) to create a regional groundwater flow and hydrologic model that could simulate the hydrostratigraphic function of the watershed and its regional hydrologic balance; (3) identify the effects of urban development on water and sediment and (4) to identify the biological effects of contaminated runoff on fish and other organisms in Frenchman's Bay. By necessity, specific aspects of the broader study such as field and laboratory analytical procedures have been presented in considerable detail in several publications elsewhere (Seilheimer et al. 2007; Meriano et al. 2009; Eyles and Meriano 2010). The intent here is to draw together some broader findings and implications arising from the watershed study as a whole that can be applied to other basins facing rapid urbanization.

Physical setting and postglacial history of Frenchman's Bay watershed

The study area is located in the South Slope and Lake Iroquois Plain physiographic regions between Lake Ontario and the Oak Ridges Moraine (ORM) along the northern coast of Lake Ontario (Fig. 1). The ORM is a prominent high-standing glacial landform built 13,300 years ago during the recession of the Laurentide Ice Sheet towards the close of the last (Wisconsin) glaciation. The South Slope drains toward Lake Ontario and consists of a

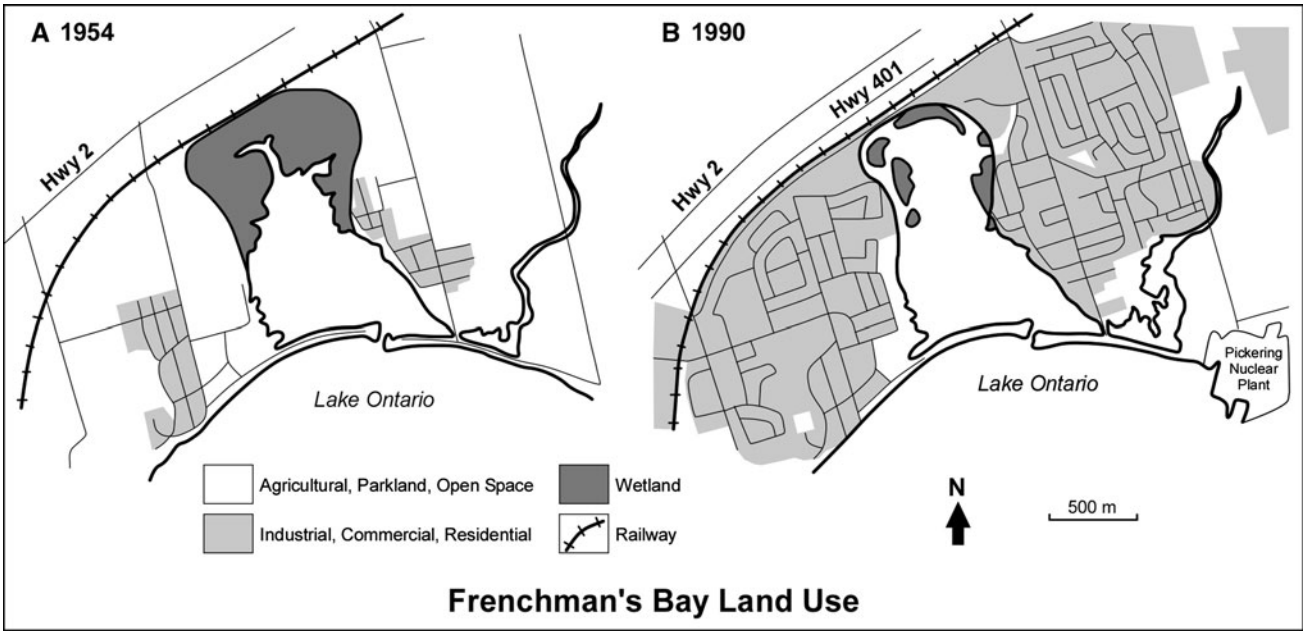


Fig. 4 Land use changes around Frenchman's Bay lagoon 1954 and 1990 and attendant reduction in wetland area within Frenchman's Bay lagoon. There has been a 60 % reduction in area since 1939 (see text)

drumlinized Halton Till plain underlain by glacial sediments as much as 100 m thick. The ice sheet had left the area by some 12,200 years ago when water levels in the Ontario basin were some 40 m higher than at present (glacial Lake Iroquois) as a consequence of ice damming along the St. Lawrence River Valley. The prominent shoreline bluff of glacial Lake Iroquois defines the northern inland limit of the Frenchman's Bay watershed and is marked by a series of springs that feed creeks that drain to Lake Ontario.

Water levels in the Ontario basin dropped abruptly with the sudden drainage of glacial Lake Iroquois about 12,000 years ago and were much lower than at present some 8,000 years ago reflecting lingering glacioisostatic depression of the lake's outlet to the east and a drier climate. Crustal rebound of the outlet has since raised lake level drowning the mouths of creeks around the shore. Frenchman's Bay lagoon (and other enclosed water bodies around the lake shoreline) appears to have been in existence for at least 3,000 years following an accelerated rise in lake level either as a consequence of upper Great Lake water being routed through the Niagara River or as a result of Neoglacial cooling (see also McCarthy and McAndrews 1988; McFadden et al. 2004; Finkelstein and Davis 2006). South of the Iroquois bluff the glacial sediment cover on bedrock is thin (<20 m) and dominated by till and fine-grained 'varved' glaciolacustrine silty clays left by glacial Lake Iroquois (Figs. 1, 5). Extensive areas are underlain by urban fill (Fig. 6a). Groundwater in the Frenchman's Bay watershed is composed both of regional waters moving south from the Oak Ridges Moraine together with local recharge waters generated within the urban area. The groundwater table is shallow (0.01–2 m) and underlying aquifers are unconfined and highly susceptible to contamination.

Climate in the study area is greatly influenced by Lake Ontario which acts as a temperature regulator minimizing extreme temperature ranges. Mean annual temperature at the Oshawa Water Pollution Control Plant 20 km east of the FBW is 7.8 °C with 34-year (1969–2003) mean daily temperatures ranging from −9.2 °C in January to 25.0 °C in July (Meriano 2007). The area receives frequent winter snowfalls requiring extensive use of road deicing chemicals (road salt). During the winter months, Frenchman's Bay lagoon freezes over entirely.

History of settlement and urban development

European settlement commenced in the Frenchman's Bay watershed in the later years of the eighteenth century after the American War of Independence when displaced Empire Loyalists, together with American Quakers, settled along the shore of Lake Ontario. Population increased dramatically during the so-called 'Pine Land Grab' of the mid-nineteenth century when valuable timber rights along the Oak Ridges Moraine reverted to private ownership. Frenchman's Bay lagoon became a port for the export of barley, corn and squared timber (and ice) and the importation of coal which is commonly found in the lagoon's

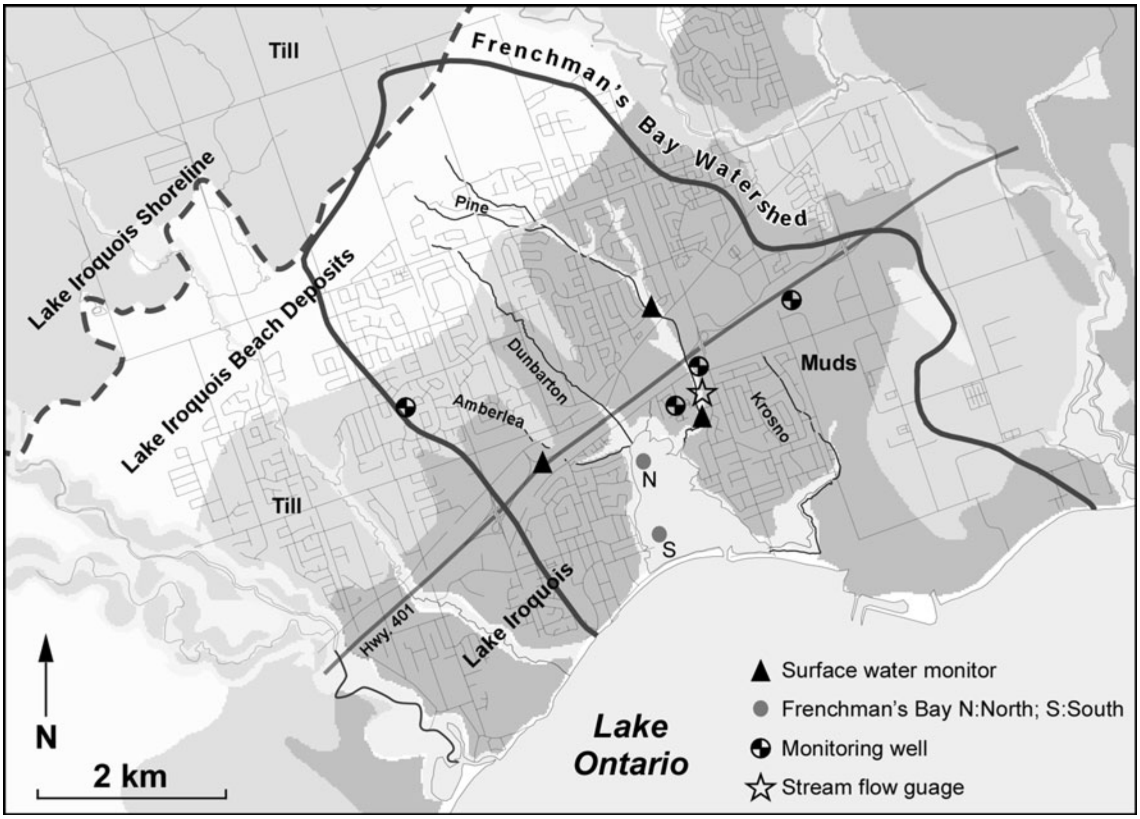


Fig. 5 Location and surficial geology of the Frenchman's Bay watershed (*outlined by heavy line*) and location of monitoring sites for characterizing groundwater and surface water quality

bottom sediments (see also Lewis et al. 2000). A narrow cut was made through the barrier beach between 1843 and 1845 to facilitate the entry of steam ships from Lake Ontario. After 1845, the lagoon became a center for the 'stonehooking' industry which collected rock slabs and large glacial erratic boulders from the nearshore waters of Lake Ontario. Wharves were built at the northern (inner) part of the lagoon but by 1853 had to be abandoned because of the excessive costs of dredging silt eroded from newly deforested watersheds. The Grand Trunk Railroad was constructed across the northern perimeter of the lagoon in 1856.

The watershed remained predominantly agricultural until the early 1970s when Pickering Nuclear Generating Station was built on the southeast corner of Frenchman's Bay lagoon. Since then the watershed has been transformed. The areal extent of impervious urban cover across the watershed (76 %) is one of the highest in Canada. Of this total, road surfaces cover 20 % of the watershed with paved parking extending across an additional 19 %. Residential subdivisions occupy 29 % and commercial premises another 7 %. The remainder consists of rail lines, open space and the floodplains of four small creeks Amberlea (380 hectares), Dunbarton (210 ha), Pine (810 ha), and Krosno (670 ha; Fig. 5). Pine Creek is the largest in the watershed with flows ranging from a summer baseflow of 0.002 m^3/s to high flows of 4.2 m^3/s in summer involving 'flashy' storm runoff events from the hardened urban basin. Many tributaries have been infilled (Fig. 7a) or extensively engineered by pipes and gabion boxes (Fig. 7b, c). The near surface geology has also been greatly altered by deep excavations (for sewers and municipal piped water) and by the emplacement of coarse-grained 'fill' material that is as much as 8 m thick in areas of low topography (Fig. 6a).

Frenchman's Bay lagoon now functions essentially as an 'end of pipe' retention pond for contaminated sediment and water from the urban watershed. The lagoon consists of some 50 ha of open water separated from Lake Ontario by a narrow opening cut through a 900-m-long barrier beach. The lagoon is shallow with a maximum depth of 3.5 m and across much of its area is less than 1.5 m deep. Water levels track seasonal variation in Lake Ontario elevations with maxima occurring in May and minima in December with a range of about 30–50 cm (Wells and Sealock 2009). The geology below the lake floor consists of 'pre-settlement' marl derived from secretion of $CaCO_3$ from submergent aquatic vegetation (e.g., *Myriophyllum*) resting on

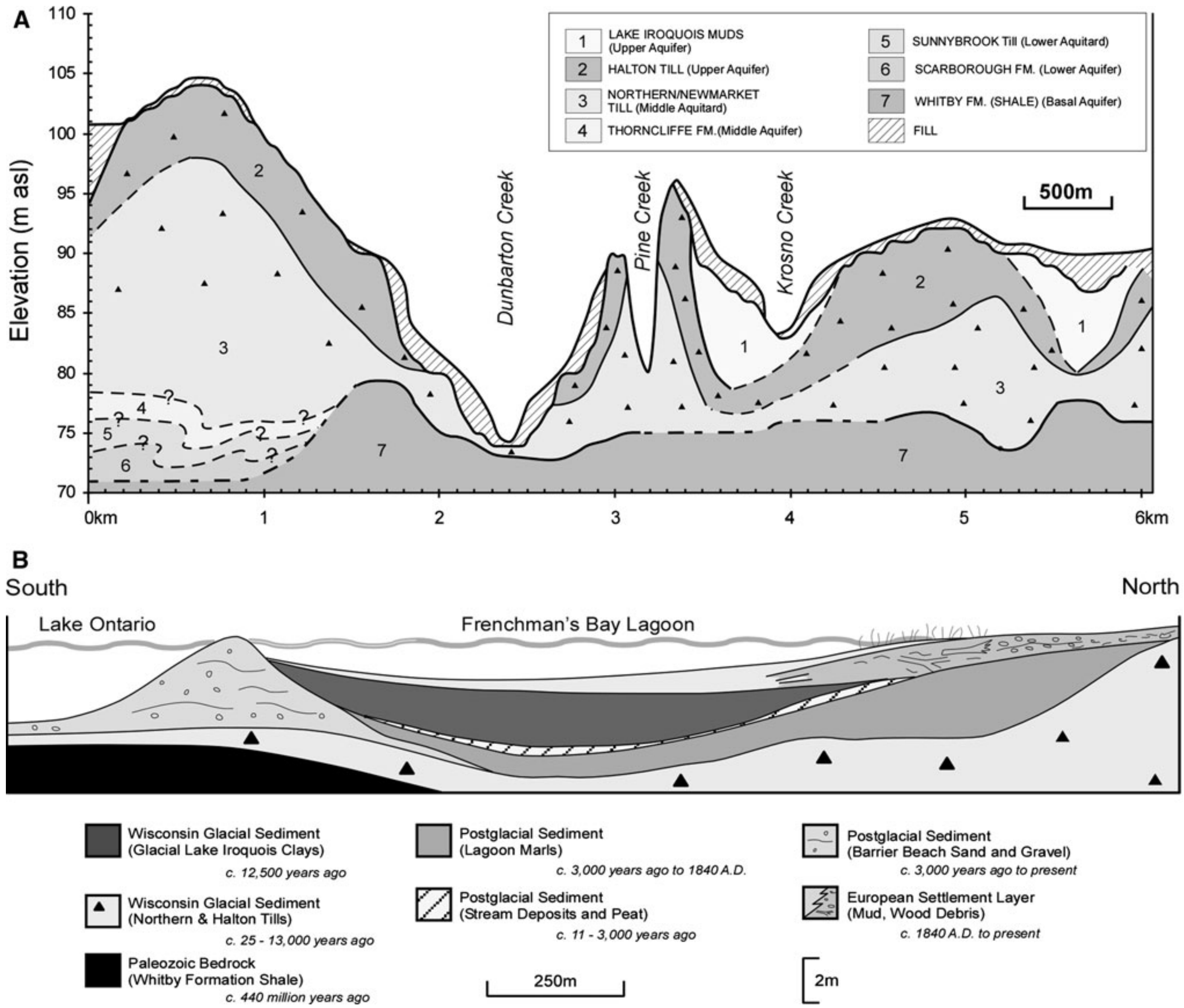
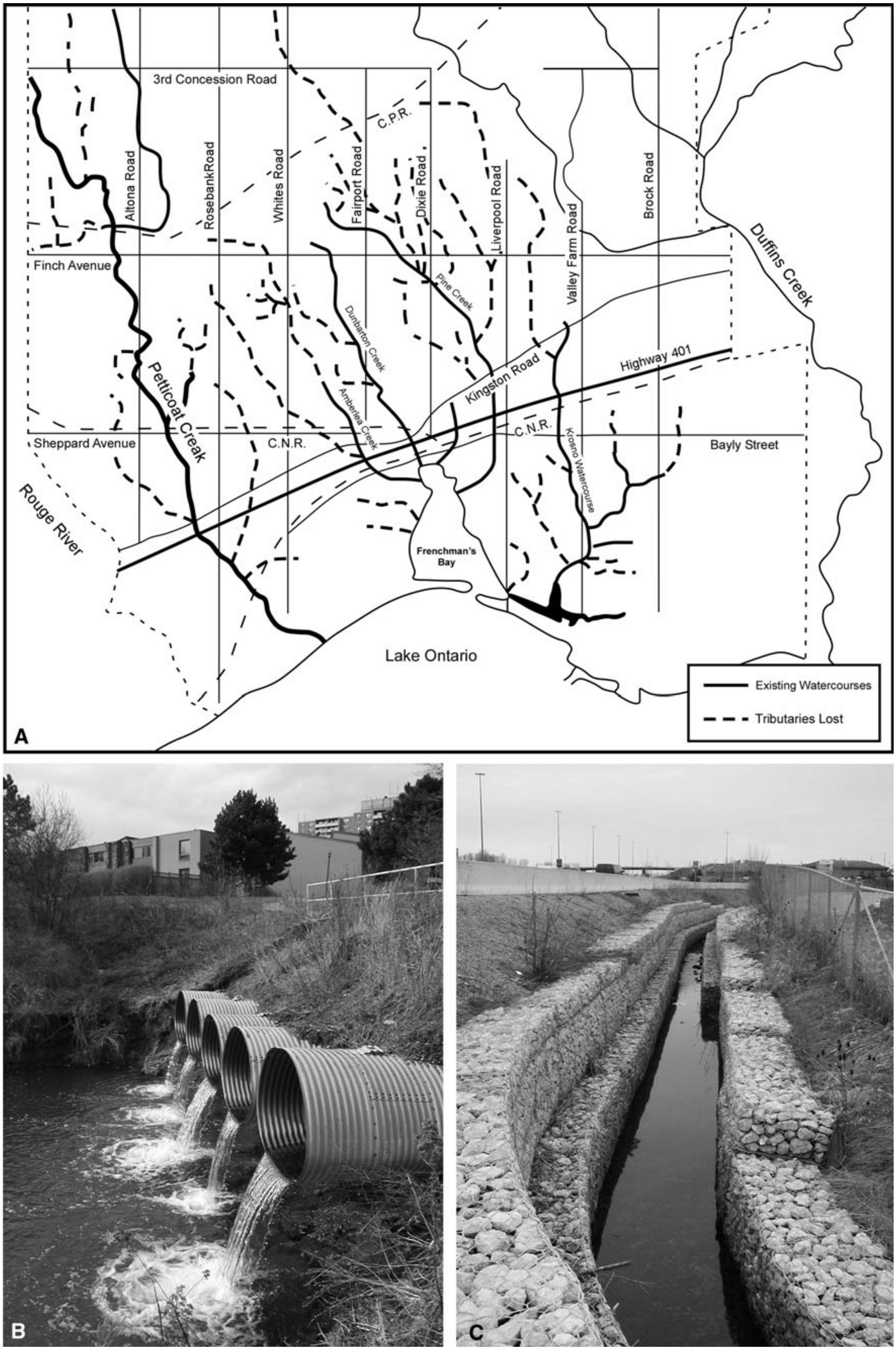


Fig. 6 A West–east geologic cross-section through Frenchman's Bay watershed along Highway 401 (Fig. 5) showing extensive coverage of fill. **b** North–south cross-section through Frenchman's Bay lagoon

fluvial and glacial sediments (Fig. 6b). The abrupt termination of marl deposition around 1840 is recorded by the so-called 'European Settlement Layer' (ESL: Eyles and Chow-Fraser 2003; Fig. 6b) which is a black silty-clay (mud) that is foul smelling and rich in woody debris and weed pollen resulting from widespread soil erosion accompanying deforestation across the watershed (e.g. Weninger and McAndrews 1989). This layer forms a distinct marker horizon across the floor of Lake Ontario reflecting enhanced flooding of creeks and rivers around the lake basin in response to massive 'post-settlement' soil loss in the upper reaches of watersheds (Eyles 1997; Eyles et al. 2003; Finkelstein et al. 2005, 2006). Frenchman's Bay lagoon is a spawning and nursery habitat for fishes (Brazner and Beals 1997; Jude and Pappas 1992) but is now badly impacted by influxes of mud, road salt, and nutrients, and a marked loss of wetland and submergent plant species (Chow-Fraser et al. 1998; Forman and Deblinger 2000; Freeman et al. 2001; Clinton and Vose 2006; Meriano and Eyles 2009; see below).

Hydrogeology and hydrology of the watershed

As part of the study of the impact of urbanization on waters across the entire FBW watershed a regional ground and surface water flow model was developed using a finite element numerical code (FEFLOW; Diersch 2002). Full details of the model and its calibration can be found in Meriano (2007). The model incorporates much geological data available from several investigations for land fill sites and deep sewers (e.g., Meriano and Eyles 2003) together


3rd Concession Road
C.P.R.
Altona Road
RosebankRoad
Whites Road
Fairport Road
Dixie Road
Liverpool Road
Valley Farm Road
Brock Road
Duffins Creek
Finch Avenue
Pine Creek
Dunbarton Creek
Kingston Road
Highway 401
Petticoat Creek
Amberlea Creek
Sheppard Avenue
C.N.R.
C.N.R.
Krosno Watercourse
Bayly Street
Rouge River
Frenchman's Bay
Lake Ontario
Existing Watercourses
Tributaries Lost
A
B
C

◀ **Fig. 7** **a** Frenchman's Bay watershed has been fundamentally altered by urban development as a consequence of the widespread employment of culverts (**b**) and gabion boxes (**c**) within channels and the ongoing use of coarse fill to infill tributary valleys (Fig. 6a)

with a large digital water well dataset (3,400 records). The hydrostratigraphic framework of aquifers and aquitards was identified by overlaying well screen depth and static water level information on the geologic stratigraphy of the watershed and for the surrounding area as far north as the Oak Ridges Moraine including adjacent watersheds. Groundwater flow directions were then delineated and areas of groundwater recharge and discharge identified along with vertical and horizontal hydraulic gradients across the area. A field monitoring system of groundwater and surface water was implemented (Fig. 5) to calibrate the model and to determine the nature of groundwater recharge and the chemical impact of urbanization on those waters draining to Lake Ontario and Frenchman's Bay.

Model results and field data show that the overall direction of groundwater flow within the watershed is southward from the glacial Lake Iroquois shoreline to Lake Ontario and Frenchman's Bay lagoon. The model indicates that total surface recharge in the watershed is some 7,500 m^3/day and most of this is rapidly discharged as baseflow to the four creeks that flow to the lagoon. Other waters ($\sim$237 m^3/day) discharge as seeps around the shoreline of Lake Ontario with an additional 60 m^3/day discharging across the floor of the lagoon. Analysis of well screen data and static water levels indicates three aquifer systems are present in the FBW (upper, middle and lower aquifers) separated by aquitard layers though the entire flow system has been greatly impacted by deep excavations and the extensive use of fill (the 'fill layer' of Fig. 6a). Knowledge of the geology and lateral geometry of this fill layer is at present rudimentary and awaits detailed geophysical studies using ground penetrating radar. A further complication is that the stratigraphy and hydrostratigraphy (and thus the hydrogeological model) is always evolving as new construction activity, excavation and landfilling occurs.

The uppermost aquifer occurs in till (Halton Till; Fig. 6a) and the associated fill layer of the built landscape and has a very high hydraulic conductivity (values up to 8×10^{-5} m/s). This aquifer is developed in otherwise impermeable glacial till as a result of weathering, fracturing and the presence of more permeable zones or 'windows' of glaciofluvial sediment with average hydraulic conductivities ranging from 10^{-9} to 10^{-5} m/s. Groundwater flow is horizontal to Lake Ontario at a velocity of 30 m/year with local deflections towards creeks. A middle aquifer is developed in deeper glaciolacustrine sediments (Thorncliffe Formation; Fig. 6a) with a wide range of hydraulic conductivity values (1×10^{-8}–3×10^{-4} m/s) and groundwater flow is horizontal towards the south at a reduced average flow velocity estimated at <10 m/year. A lower aquifer is developed in deltaic sands (principally Scarborough Formation; Fig. 6a) and the fractured and weathered upper surface of shale bedrock (Late Ordovician Whitby Formation) where southerly flow is at an average horizontal flow velocity of 1 m/year.

An upper aquitard comprises thin (<5 m) Lake Iroquois glaciolacustrine silty clays that form the surface deposits over much of the basin but which show surprisingly high hydraulic conductivity values (10^{-9}–10^{-5} m/s). The bulk permeability of these otherwise fine-grained and relatively impermeable sediments is substantially increased by pipes and trenches backfilled with gravel. The low permeability of the fine-grained till deposits outside the trench contrasts sharply with fill material which is two to five orders of magnitude more permeable. The high contrast between porous fill and native till deposits creates a 'leaky aquitard' with many secondary pathways for water allowing very rapid infiltration and lateral movement of water (Meriano 2007). A middle aquitard consists of a dense till (Northern Till; Fig. 6a) that separates the upper and middle aquifer systems but which also acts as a 'leaky aquitard' with an estimated bulk hydraulic conductivity from 4×10^{-10} to 5×10^{-9} m/s because of thin sand and gravel beds, boulder concentrations and fractures Gerber and Howard (2000); Gerber et al. 2001; Meriano and Eyles 2009). A lower aquitard consists of low permeability (1×10^{-9}–4×10^{-7} m/s) fine-grained sediments (Sunnybrook Till) and associated glaciolacustrine silty clays.

Oxygen-18 (^{18}O) and tritium (T) content in shallow groundwaters were used to identify and trace water pathways through the shallow aquifer in the upper (less urbanized) and lower (highly urbanized) parts of the watershed. In this way the effects of construction, trenching and the use of coarse fill could be assessed. Changes in ^{18}O and T content with changes in elevation are shown in Fig. 8. In general, shallow groundwater samples from the upper basin are more enriched in δ^{18}O than those to the south. The more depleted δ^{18}O concentrations in the southern portion of the watershed indicate shorter residence times in the unsaturated zone and active groundwater flushing as a consequence of recharge and discharge occurring over very short distances. It is noted that tritium levels in general show strong positive correlations with chloride concentrations ($r^2 = 0.80$) (Meriano 2007) supporting the inference of rapid shallow groundwater recharge of contaminated waters in the highly urbanized parts of the catchment. Data indicate a highly dynamic urban groundwater flow system much impacted by fill materials which allow rapid lateral and vertical movement of waters in the shallow subsurface.

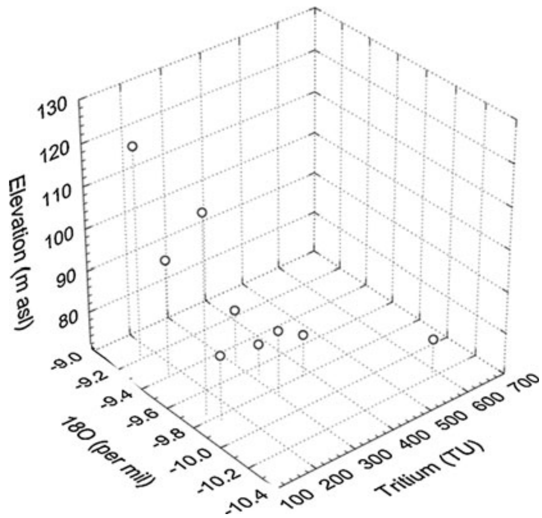


Fig. 8 Variation in oxygen isotope and tritium with elevation within the upper aquifer of Frenchman's Bay watershed, November 2002. See text for details

Urban impacts on surface and groundwater quality

The network of groundwater wells and surface water monitoring stations (Fig. 5) was logged continuously from May 2002 until March 2003. These captured a series of seasonal precipitation events (snow and rain) allowing the effects of these on water quality to be determined above and below Highway 401 (Fig. 9a). Hourly measurements of temperature, conductance (converted to chloride), dissolved oxygen (DO), total suspended solids (TSS) and nutrients such as total phosphorus (TP) and sulphate (SO_4^{2-}) were made at two surface water monitoring stations one above Highway 401 (Pine Creek; Fig. 5) and one below (Amberlea Creek; Fig. 5). Total Kjeldahl nitrogen (TKN), total nitrate nitrogen (TNN), total-ammonia nitrogen (TAN) and total nitrogen (TN) were also determined. Additional sites were monitored in the lagoon in the summer of 2002. Full details of sampling methods, monitoring and analytical equipment are presented in detail by Eyles and Chow-Fraser (2003), Meriano (2007) and Seilheimer et al. (2007) and are only briefly summarized here.

Data reveal large seasonal differences in surface water quality as a consequence of winter snowfalls and the need for road salting. This is seen by the close association of snowfalls with sharp spikes in surface water conductivity values in creeks (Fig. 9a). In general, conductivity shows extreme values from <1 to >30 mS/cm in agreement with other studies of waters impacted by road salt runoff (e.g., Granato et al. 1995; Marsalek et al. 2003; Gray 2004; Chang and Carlson 2005). These data are significant because they allow identification of the specific impact of the Highway 401 corridor on water quality in creeks that flow under the transportation corridor and receive runoff directly from the road surface above (Fig. 9a). The highway accounts for only 1.3 % of the total area of the Frenchman's Bay watershed but receives 26 % of all salt applied to the entire watershed. Peaks in conductance values in surface waters of Amberlea Creek (below the 401) approached or exceeded 20 mS/cm reflecting saline road runoff whereas they seldom exceeded 15 mS/cm in waters of Pine Creek located above the highway (Fig. 9a). Road salt-impacted drainage leaves the highway through culverts that drain directly into creeks and drainage swales along the edge of the highway where salt can enter groundwater.

At the time of this study a total of 7,600 tonnes of NaCl road deicing chemicals were applied annually to the Frenchman's Bay watershed. Based on monitoring of Pine Creek sub-basin, between 50 and 57 % of the 1,021 t of chloride applied to roads within the sub-basin enters the upper aquifer, representing between 510 and 580 t per annum. This compares with an estimated 340–400 t that leaves this aquifer as baseflow (Meriano et al. 2009). This suggests that chloride is still accumulating in the aquifer and that a chemical steady state has not yet been reached. This situation is very common across Southern Ontario (see Howard and Haynes 1997). When a steady state is eventually attained, the mass out flux of chloride will balance the influx; the mean annual chloride concentrations in baseflow will correspondingly rise to eventually equal the annual mass loading of chloride divided by the annual volume of recharge. For the Pine Creek sub-basin, the future steady-state chloride concentration in baseflow is calculated to be between 390 and 440 mg/l. Extrapolating the Pine Creek results to the entire Frenchman's Bay watershed suggests some 3,700 tonnes of chloride enter Frenchman's Bay lagoon each year. Depending on the separation method used, it is concluded that baseflow accounts for between 40 and 48 % of the total mass of chloride entering the bay.

Surface waters in the watershed are impacted by many other urban contaminants. For example, regardless of monitoring location or season, surface waters exceed Provincial Water Quality Objectives for *E. coli* and total coliform indicating persistent bacterial source(s) in the watershed (Table 1). This may include leaking sewer mains, illegal connections or most probable the presence of combined sewers where sanitary sewers handle storm runoff. These overflow during major storm runoff events. Very high values of total nitrate and total phosphate during flood events are typical of sewage-impacted urban waters. Creek waters also contain elevated levels of metals, such as cobalt, copper, chromium, iron, zinc, phosphorus, aluminum and vanadium typical of automobile-related contaminants found in urban surface waters draining roadways and parking lots. These occur at concentrations that greatly

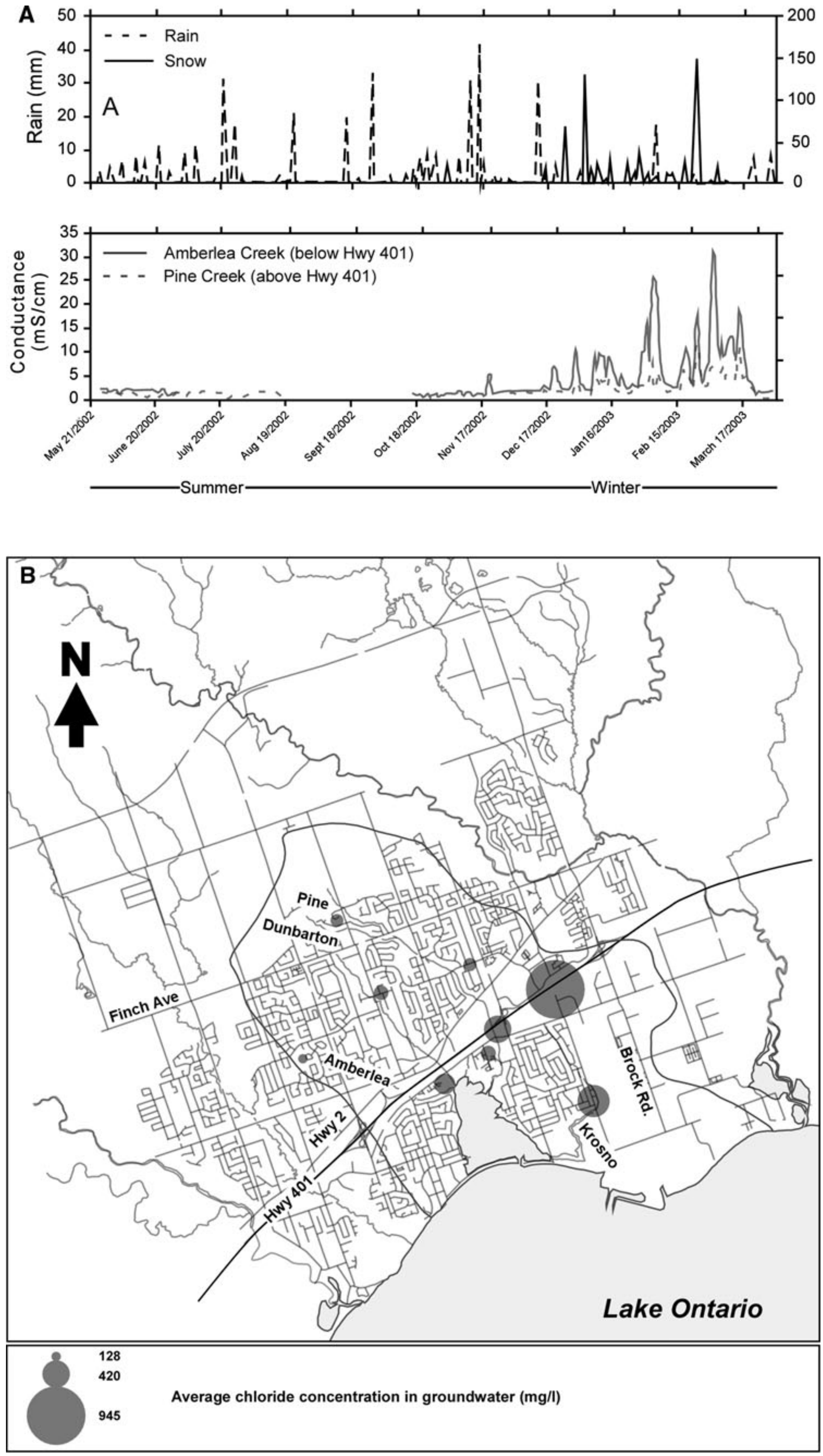


Fig. 9 **a** Conductance values for waters of Amberlea Creek below Highway 401 (see Fig. 5 for location of monitoring site) and on Pine Creek above the highway during precipitation events between May 2002 and March 2003. Winter snowfalls and application of road salt trigger spikes in surface water conductivity below Highway 401. Summer runoff shows the continuing effects of brackish water baseflow diluted by rainfall runoff. **b** Average chloride concentrations in groundwaters at monitoring wells shown in Fig. 5 identifying higher values below Highway 401

Table 1 Comparison of measured chemical parameters against drinking water standards (Provincial Water Quality Objectives) in waters of creeks flowing to Frenchman's Bay lagoon

Parameter	Type of value	Units	Sub-watershed		
			Krosno Creek	Pine Creek	Amberlea Creek
Area	–	(ha)	670	810	380
Period of record	–	Years	2002–2003	2002–2003	2002–2003
Conductance	Observed range	ms/cm	n/a	1–32	2–32
	PWQC		–	–	–
Total suspended soils	Observed range	mg/l	10–575	5–1,700	4–33
	PWQC		25	25	25
E coli	Observed range	#/100 ml	300–30,000	350–2,500	n/a
	PWQC		100	100	100
Aluminum	Observed range	μg/l	50–4,600	50–1,200	n/a
	PWQC		75	75	75
Iron	Observed range	μg/l	200–7,500	250–2,300	n/a
	PWQC		300	300	300
Zinc	Observed range	μg/l	20–370	10–100	n/a
	PWQC		20	20	20
Copper	Observed range	μg/l	2–33	1–9	n/a
	PWQC		5	5	5
Lead	Observed range	μg/l	2–35	–	–
	PWQC		5	5	5
Phosphorus	Observed range	μg/l	25–480	50–160	n/a
	PWQC		20	20	20
Chloride	Observed range	mg/l	100–1,900	400–800	n/a
	PWQC		230	230	230
Sulphate	Observed range	mg/l	30–80	40–70	n/a
	PWQC		–	–	–
Total phosphorus	Observed range	μg/l	25–440	10–140	15–180
	PWQC		30	30	30
Nitrate	Observed range	μg/l	400–1,300	1,400–3,800	1,200–4,400
	PWQC		–	–	–
Total Kjeldahl nitrogen	Observed range	μg/l	450–2,400	300–1,700	n/a
	PWQC		–	–	–

PWQC Provincial Water Quality Objective

exceed Provincial Water Quality Objectives (McNeely et al. 1979) by considerable margins regardless of season (Table 1). A concern is that surface waters below Highway 401 and the wide transportation corridor remain brackish year round and the role of chloride in increasing metal mobility has been emphasized by Warren and Zimmerman (1994), Shanley (1994), Gray (2004) and Granato et al. (1995). These data indicate that surface waters in the lower Frenchman's Bay watershed have been extensively degraded by urban development upstream.

Seasonal fluctuations in total suspended solids (TSS), total phosphorus (TP) and sulphate (SO_4^{2-}) were determined from weekly composite samples of surface runoff collected from Amberlea Creek. Both TSS and TP concentrations are high during spring runoff and then drop to relatively low levels by the beginning of summer. Thereafter, the peaks in TSS and TP levels coincide with individual rainfall events. Data from one storm on Krosno Creek (July 22nd, 2002) showed loadings of sulphate (SO_4^{2-}) nutrients to be as much as 594 kg/h. Instantaneous suspended sediment concentrations reach 1,600 g/m^3 during major storms when sediment is derived from erosion of stream banks cut into Lake Iroquois silty clays and from debris flushed from road surfaces and culverts such as sand for example, which is a common constituent of road salt.

Figure 9b shows variation in chloride concentration in groundwater north and south of Highway 401. Significantly, the mean groundwater chloride concentration in a well located about 10 m down-gradient of Highway 401 is as much as seven times higher than other groundwater samples.

Sites of exceptionally high chloride concentration (up to 1,600 ppm) are located along and to the south of the highway. These observations re-enforce the findings of Labadia and Buttle (1996) who studied salt dispersal along Highway 115 near Peterborough, Ontario, and showed that snow plowing and localized spray readily convey salt and traffic-related pollutants to roadside swales where it can recharge the aquifer. Mikkelsen et al. (1997) also found that infiltration of runoff from salted roads resulted in elevated concentration of chloride and heavy metals in roadside soils.

A major finding that arises from this study is that the effects of road salting on surface waters are felt year round as a consequence of brackish base flow from road salt-impacted groundwaters. This effect will increase in future as the aquifer reaches a steady state with regard to chloride loadings (see above). During the summer of 2002 for example, mean conductance values in Amberlea Creek (1.86 mS/cm) downstream of the highway always exceeded those in Pine Creek above the highway (mean value 1.27 mS/cm) reflecting year-round release of chloride stored in groundwater. Summer rainfall and increased creek discharges act to dilute conductance values.

Impact on water quality in Frenchman's Bay lagoon

Frenchman's Bay lagoon is the final sink for contaminated ground and surface waters draining from the urban watershed. As related above, the lagoon essentially acts as an 'end of pipe' retention pond. Reinhardt et al. (2005) determined that Arcellacean (thecamoebian) microfauna preserved in the upper part of the ESL on the floor of Frenchman's Bay lagoon record widespread eutrophication of the lagoon's waters accompanying the start of urbanization just after 1960. This 'urban mud' shows greatly elevated concentrations of metals from road runoff (e.g., Brezonik 2002; Buffleben et al. 2002; Charlesworth et al. 2003; Eyles and Chow-Fraser 2003; Pozza et al. 2004; Zhu et al. 2008). Many parameters such as total Kjeldahl nitrogen (TKN), phosphorus, cyanide, oil and grease and total organic carbon exceed Ontario Ministry of Environment Provincial Sediment Quality Guidelines. The construction of Pickering Nuclear Generating Station in the late 1960s resulted in hardening of 3 km of Lake Ontario shoreline and the loss of 15 ha of wetland in Frenchman's Bay; until 1997 warmed condenser cooling water was discharged directly into the lagoon through an aquaculture facility. SENES (1998) reported that copper, zinc, lead, arsenic and radionuclides were released with cooling water into the bay as a consequence of the corrosion of condenser tubes but the precise contribution of metals has not been assessed. As related above, the lagoon receives substantial volumes of fine-grained contaminated sediment and it is estimated that between 100 and 110 tonnes accumulates in the lagoon every year. Between 40 and 50 % of this load is composed of algae, protozoans and other organic detritus (Eyles and Chow-Fraser 2003). Bottom foraging and turbation of sediment by carp act to resuspend fine sediments and their contaminants into overlying lagoon waters.

Some 50 % of the total salt applied to the entire Frenchman's Bay watershed is conveyed directly to Frenchman's Bay Lagoon via overland flow (see above). The remainder eventually enters the bay via a slower, subsurface route through the upper aquifer, such that impacts on the bay are delayed. The upper aquifer in the Frenchman's Bay watershed is relatively thin, storage is low and mean groundwater travel times for conservative ions such as chloride are likely to be short, probably less than 40–50 years which is approximately the same time frame that salt has been applied in the area. As a result, the upper aquifer system is rapidly approaching a chemical steady state whereby the mass of chloride entering the aquifer in recharge will be balanced by the mass of chloride leaving in baseflow. Currently, the mass of chloride leaving the aquifer as baseflow is about 70 % of the salt entering as recharge. Assuming salt application rates remain essentially the same in future, the salinity of baseflow reaching the lagoon can be expected to increase further over the next several decades.

Electrical conductivities were recorded at two locations within Frenchman's Bay lagoon (North and South sites; Fig. 5) to determine the impact of road salting on water quality in 2002. Values ranged from 0.36 to 1.82 mS/cm in the north, and from 0.23 to 0.50 mS/cm in the south and also show the same abrupt increases in electrical conductivity during winter months as seen in inflowing creeks (Fig. 9a). In addition, the northern, innermost part of the lagoon shows high chlorophyll and turbidity, extensive areas of contaminated sediment, enhanced temperatures and lowered oxygen content (Fig. 10). Overall, water quality in the lagoon is better than the quality of feeder streams which is the result of mixing with Lake Ontario water via the narrow channel at the entrance to the lagoon. Higher salinity waters from feeder streams likely form a deeper wedge on the lagoon floor that underlies and slowly mixes with fresher, less dense water that seasonally enters the lagoon from Lake Ontario. The muddy bottom sediment in the lagoon is enriched with heavy metals; a concern is that metals buried in the near surface sediments could be released into solution through complexation with chloride (e.g., Mikkelsen et al. 1997; Koryak et al. 2001; Bradford and Gharabaghi 2004; Polkowska et al. 2005; Taniguchi 2005; Novotny et al. 2008).

Effects on biota in Frenchman's Bay lagoon

The most dramatic expression of the impact of urban runoff to the lagoon since 1970 is the marked reduction in the area

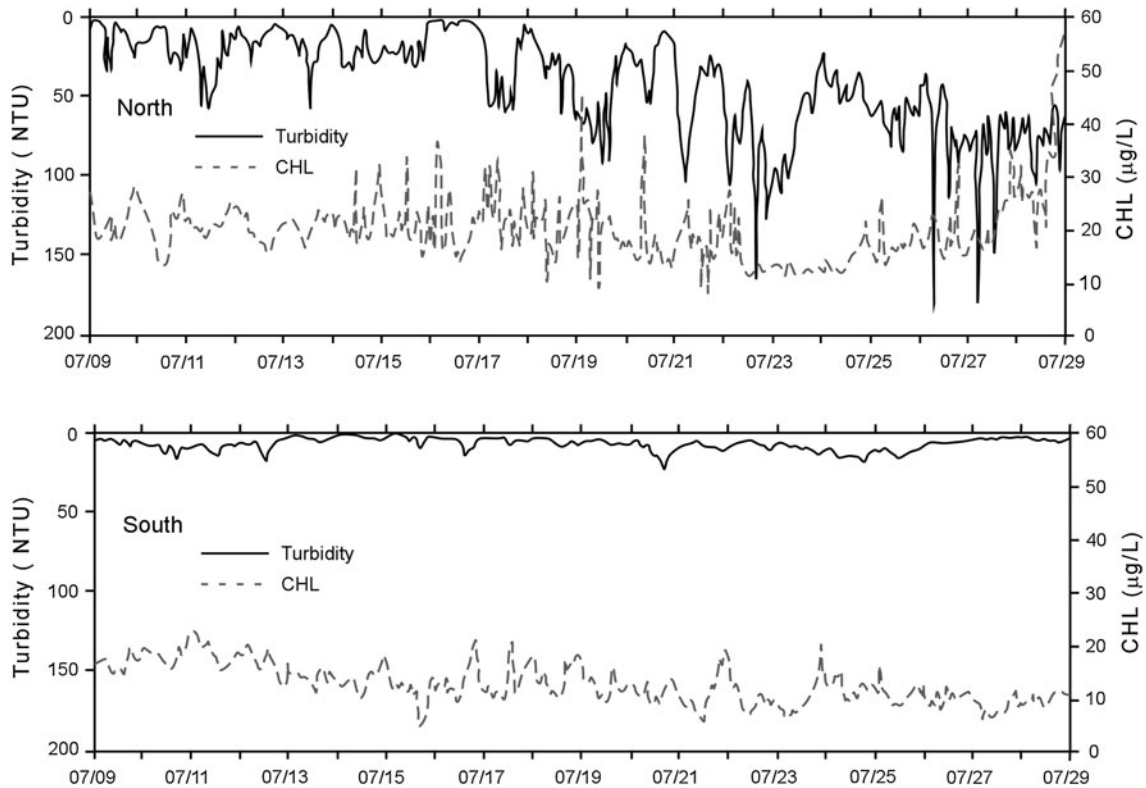


Fig. 10 Turbidity and chlorophyll in northern Frenchman's Bay (*top*) and southern part (*bottom*) determined at sites *N* and *S* (see Fig. 5 for location) following rainfall events and inflows of urban water in July 2002. Data clearly show effects of inflowing turbid urban creeks and dilution by inflowing waters from Lake Ontario

of fringing wetland around the northern part of the lagoon adjacent to creek mouths (Figs. 3, 4). There are currently 47 ha of emergent vegetation remaining representing a reduction in area by 30 % since 1970 and 60 % since 1939. The wetland has been classified as 'Provincially Significant' but this is an entirely notional status given the dramatic reduction in its area and thus ecological significance within the lagoon. The effects of excavations for boat moorings and elevated inflows of storm water runoff, burial by muddy urban sediment are primarily responsible (e.g., Ehrenfeld 2000). The remaining islands of wetland vegetation are at risk from ongoing erosion by storm flows into the lagoon and bioturbation associated with carp spawning and feeding (Lougheed and Chow-Fraser 2001). Degraded wetlands such as these are also more easily invaded by exotic species such as purple loosestrife (*Lythrum salicaria*) which now colonizes large areas of the marsh. Reduced diversity and coverage of submergent plant species is reflected in changing fish populations in the lagoon (see below). Five dominant emergent taxa can be recognized in wetlands surrounding Frenchman's Bay including three cattail species (narrow-leaved cattail *Typha angustifolia*, broad-leaved cattail *T. latifolia*, and hybrid cattail *Typha* × *glauca*),with two loosestrife species (swamp loosestrife *Decodon verticillatus* and the invasive exotic species, purple loosestrife).

Submergent vegetation has been greatly reduced as a consequence of mud deposition and frequent algal blooms created by enhanced nutrient loadings. This is unfortunate as submergent macrophytes provide critical spawning habitat for adults and refugia from predators, and habitat for prey of all life stages (Jude and Pappas 1992). In addition, plants provide shade for juveniles and ensure that the water does not become too warm for cool water species. Most of the phosphorus that discharges into Frenchman's Bay is in a form readily available for algal growth which in association with high suspended sediment results in much reduced diversity and coverage of submergent vegetation (Chow-Fraser et al. 1998; Seilheimer and Chow-Fraser 2006).

Impairment of Frenchman's Bay waters is clearly reflected in fish population dynamics. Data from several sources were used in this study to assess changes in the fish community since data were first collected in the lagoon in 1985 (Stephenson 1990). Species captured in the course of the present study were classified as either juvenile or adult based on length (Scott and Crossman 1998). In a total of 26 species from 12 families, brown bullhead, emerald shiner, and yellow perch were most common. Rare taxa included mimic shiner, rock bass, white perch, white bass and rainbow smelt. Some fish tended to be caught only as adults when they migrated into the marsh to spawn during the spring or fall (alewife, white sucker, and northern pike). When all the fish were pooled, the South station nearest the outlet to Lake Ontario (Fig. 5) had significantly greater numbers, whereas the North station had significantly higher biomass. Fish data indicate that a greater number of small-sized individuals were present at the South station, with fewer at the North station. The analysis shows further that the fish community in the more highly contaminated North location is dominated by turbidity-tolerant, benthivorous species. By comparison, the fish community at the South site was dominated by percid and centrachid species that are less tolerant species. However, even though the South station has relatively good water quality as a result of its proximity to Lake Ontario (see above) the outer southern part of the lagoon does not provide suitable habitat for fish because it cannot any longer support emergent or submergent vegetation. The results presented here are consistent with other published data that indicate that urban waters have lower fish diversity, low ecological index score (e.g. index of biotic integrity) and fish deformities (Weaver and Garman 1994; Casselman and Lewis 1996; Helms et al. 2005; Wang et al. 2000).

Some overall indication of the general level of ecological impairment in Frenchman's Bay lagoon is afforded by the Wetland Quality Index (WQI) of McNair and Chow-Fraser (2003). This allows comparison of water- and sediment-quality in wetlands across all five North American Great Lakes (Chow-Fraser et al. 1996, 1998; Chow-Fraser 1999; Wei and Chow-Fraser 2005, 2006). In this scheme, Frenchman's Bay lagoon is ranked as 'moderately degraded', but it is important to emphasize that this designation disguises the fact that the northern inner reaches of the lagoon are severely impacted and that the survival of less impacted aquatic habitat in the outer parts of the lagoon is entirely reliant on dilution by inflowing waters from Lake Ontario.

Discussion and broader significance of study

This paper presents a summary of historical changes in the environment since 1840 and the current state of the environment from season to season, in an urbanized watershed and lagoon in southern Canada. As such it is one of the most detailed multidisciplinary studies of an urban watershed completed anywhere to date.

Frenchman's Bay watershed has undergone two massive and abrupt changes in environment over the past 170 years that far exceed anything of the preceding 10,000 years (Fig. 2a). The first event was rapid forest clearance associated with the arrival of Europeans in the early nineteenth century. By 1940, legislated conservation was in place to address the effects of a century of deforestation and soil erosion in rural areas and farming communities (Richardson 1974). By and large these have been successful. The second major shock is ongoing and results from post WWII urbanization which has seen not only physical changes in creeks as they become progressively more hardened but major changes in the chemistry of ground and surface waters and sediments with major impacts on fish habitat and associated wetlands. The events that have affected the Frenchman's Bay watershed over the past 170 years are common to most southern Canadian watersheds where the bulk (92 %) of the Canadian population resides and which have a similar history of settlement and urban development. Results from Frenchman's Bay watershed are widely applicable and paint a very disturbing picture of the current environmental quality of waters in urban watersheds.

Regional climate plays a major role in environmental degradation in Canadian urban areas. The single most important finding arising from this study is that the largest contemporary impactor on environmental quality in Frenchman's Bay watershed derives from the seasonal application of large volumes of road salt. This finding is consistent with results of studies elsewhere across large areas of mid-central and northern North America and northern Europe (e.g., Baltrenas and Kazlauskiene 2007, 2009; Novotny and Stefan 2009). The watershed is representative of many around the periphery of the Great Lakes where inflowing creeks are crossed by roads and highways salted during winter. Most, like the Frenchman's Bay watershed, discharge into semi-enclosed waterbodies or harbors only partly connected to the larger lakes. The use of stormwater retention ponds to trap saline surface runoff during winter thaws fails to address the issue of saline recharge to groundwaters and the *year-round* effects of saline groundwater flow to rivers and lagoons.

It also needs to be emphasized that environmental conditions in the study watershed are not static but deteriorating as the urban area evolves in response to 'infilling' and the move to higher density development and as the urban area expands further. It has already been identified that saline baseflow to creeks will increase as upper aquifers eventually reach a steady-state chemical balance over the next several decades. Other (poorly understood) changes in the groundwater system are occurring as a result of the leakage of newly installed municipal drinking water mains (as much as 40 mm/year—a leakage rate of 44 %) that can enhance base flow amounts in excess of predevelopment rates (Meriano 2007). At the same time, groundwater (as much as 24 mm/year) is removed by flow into deeper sewer mains excavated into otherwise low permeability sediments. Unfortunately, the stratigraphy and lateral variation of the man-made 'fill layer' together with the hydrogeological role of deep excavations are very poorly known (e.g., Ding et al. 2008). Additional urban expansion to the north of Pickering across the South Slope of the Oak Ridges Moraine (Fig. 1) represents new sources of contaminated urban water that will eventually move to Lake Ontario.

The findings identified in this paper are highly significant internationally with regard to the long-term management of water quality in Lake Ontario by Canada and the US. While earlier conservation efforts in Southern Ontario dramatically arrested the effects of deforestation and soil loss from watersheds, a completely new strategy is now needed to limit the effects of chemical loads being delivered to rivers and waterbodies from rapidly expanding urban areas. Unfortunately, the densely settled Frenchman's Bay watershed lacks space to accommodate modern stormwater management ponds. In 2003, the International Joint Commission (IJC) jointly administered by Canada and the US reported that the onset of annual seasonal stratification and depletion of oxygen in the Great Lakes is now occurring earlier in the year as a result of enhanced influxes of contaminated sediment and water from urban areas. The combined effect of future climate change and predicted land-use alteration in the Great Lakes basin are thought to increase surface runoff from 17 % at present (1994–2003) to 21 % in the near future (Barlage et al. 2002). IJC (2003) emphasized that Great Lakes Water Quality Agreement objectives will be more difficult to achieve in future but few watersheds have been studied in the detail presented here for Frenchman's Bay.

In general, understanding of the environmental geology of urban areas and watersheds suffers from a lack of data; published detailed investigations and monitoring systems are few in number (see Chilton 1997; Perry and Taylor 2007). Yet, urbanization proceeds world-wide at a gathering pace with only sporadic attempts to understand and limit its impacts. A lack of watershed-wide data is a major constraint on the design, implementation and rigorous testing of effective mitigation measures in the face of a changing climate and uncertainty over urban water resources. Without detailed watershed-wide field data such as collected in the course of this study, it is not possible to assess the impacts of ongoing climate change on urban water resources or to design urban areas that are chemically sustainable.

Conclusions

This paper synthesizes the results of a multi-year, multidisciplinary watershed-wide analysis of the effects of urban development across the Frenchman's Bay watershed (27 km^2) of southern Canada. This area is representative of many urban watersheds along the northern coast of Lake Ontario. First settled in the later years of the eighteenth century the area experienced widespread soil loss in response to deforestation that began in earnest in 1840, an event recorded by a distinct organic-rich mud deposit (European Settlement Layer) in Frenchman's Bay lagoon through which the watershed discharges to Lake Ontario. The watershed was stabilized by conservations measures beginning in the 1940s but has experienced rapid urbanization after 1970; today 76 % of its area is urbanized with large areas of urban fill within the built landscape which is still rapidly evolving. The major impactor on surface and ground waters arises from cold winters and the application of 7,600 t of road salt across the watershed each year; Frenchman's Bay lagoon receives 3,700 t of chloride annually n the form of direct runoff from Highway 401, Canada's busiest highway. The discharge of brackish groundwater results in the continuing impact on surface water quality even in summer; groundwater modeling suggests that chloride continues to be stored in underlying aquifers and that the system has yet to reach a steady-state discharge. Should salt application rates remain the same, the salinity of baseflow reaching the lagoon can be expected to increase by about 40 %.

The inner reaches of Frenchman's Bay lagoon are severely impacted by poor water quality and contaminated sediment reflected in a fish community dominated by turbidity-tolerant, benthivorous species. The lagoon essentially functions as an end-of-pipe retention pond. Closer to the lagoon's outlet with Lake Ontario the fish community is dominated by less tolerant percid and centrachid species but there has been significant habitat loss because the extent of emergent and submergent vegetation has been greatly reduced by urban runoff and sedimentation. The Frenchman's Bay watershed underscores the need for data to be collected at the appropriate watershed-level scale in order to assess the impact of urbanization on Great Lakes water quality. This information is key to meeting the challenge of continuing global change where long-term management of urban water resources is an emerging priority.

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