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Groundwater Transport of Wastewater Nutrients at a coastal barrier bar, Marsh Complex, Point Pelee, Ontario, Canada

By:
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MANAGEMENT PERSPECTIVE

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EC Priority/Issue: This work was conducted as part of a larger study on the hydrogeology of the Point Pelee coastal barrier bar/wetland complex funded by Parks Canada, and by the GL2000 program. The work supports the ESD issue "Conserving Canada's Ecosystems" (nutrients and wetlands). It supports the business plan deliverable Thrust #1 under Conserving Canada's Ecosystems (nutrient loading, great Lakes coastal wetlands). Under EC Action Plan, the work supports the action item "Conserving Canada's Ecosystems" with the focus "Understand the impacts of human activities on ecosystems; develop and implement strategies to conserve ecosystems".

Current Status: This paper provides an overview of hydrogeological and geochemical studies conducted to determine the fate of wastewater derived nutrients in the shallow sand aquifer at Point Pelee. Point Pelee National Park relies on tile beds for wastewater treatment for over 500,000 park visitors annually. The groundwater chemistry was monitored in the vicinity of two active tile beds. Large plumes of nutrient-rich groundwater were observed downgradient of the tile beds. The transport of nitrate, phosphate and ammonia was observed to be closely related to redox zones developed within the plumes. The study began in late 1993 and will be completed in 1997. A final report will be provided to Parks Canada in 1997.

Next Steps: Seasonal monitoring of groundwater seepage and release of nutrients into an eutrophic open-water marsh pond will continue. Groundwater monitoring at an abandoned tile bed will be conducted to provide information on temporal changes in groundwater chemistry after tile-bed abandonment. The results will assist in evaluating the persistence of nutrient plumes in the groundwater zone after tile bed abandonment. The results will also assist in understanding the role of groundwater in influencing nutrient cycling in wetlands.

Abstract

A series of hydrogeological and geochemical studies was conducted to determine the transport of septic system effluent in the shallow sand aquifer at Point Pelee National Park. The shallow sand aquifer overlies a low permeability clay-till unit. Large changes in water table elevation occur in response to changes in precipitation, evaporation, and the elevation of Lake Erie. The groundwater flow direction changes seasonally in response to the relative elevations of Lake Erie and the Point Pelee marsh. Plumes of contaminated groundwater, containing elevated concentrations of nutrients, including NO_3, NH_3, and PQ , and other dissolved constituents were observed below two high capacity tile beds installed directly in the native barrier bar sands. At the Blue Heron tile bed site, located where strong seasonal reversals in groundwater flow direction occur, a bimodal plume has developed in both east and west directions of the tile bed. At the Camp Henry site, located where reversals in groundwater flow are less pronounced, a unimodal plume has developed in one direction away from the tile bed. Near the Blue Heron site, nutrient-rich groundwater was observed to be discharging from the barrier bar into an open-water marsh pond. The discharge of this water is likely contributing to elevated nutrient concentrations observed in the adjacent pond. One implication of the strong reversals in groundwater flow direction is that discharge of effluent to the marsh is expected to be less than if the groundwater flow was directed toward the marsh year-round. A second implication is that septic-system effluent is expected to persist in the barrier bar longer than if groundwater flow was in one principal direction year-round.

Keywords: wastewater, groundwater, nutrients, tile bed, wetland

Groundwater Transport of Wastewater Nutrients at a Coastal Barrier Bar, Marsh Complex, Point Pelee, Ontario, Canada

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Abstract

A series of hydrogeological and geochemical studies was conducted to determine the transport of septic system effluent in the shallow sand aquifer at Point Pelee National Park. The shallow sand aquifer overlies a low permeability clay-till unit. Large changes in water table occur in response to changes in precipitation, evaporation, and the elevation of Lake Erie. The groundwater flow direction changes seasonally in response to the relative elevations of Lake Erie and the Point Pelee marsh. Plumes of contaminated groundwater, containing elevated concentrations of nutrients, including NO_3, NH_3, and PO_4, and other dissolved constituents were observed below two high capacity tile beds installed directly in the native barrier bar sands. At the Blue Heron tile bed site, located where strong seasonal reversals in groundwater flow direction occur, a bimodal plume has developed in both east and west directions of the tile bed. At the Camp Henry site, located where reversals in groundwater flow are less pronounced, a unimodal plume has developed in one direction away from the tile bed. Near the Blue Heron site, nutrient-rich groundwater was observed to be discharging from the barrier bar into an open-water marsh pond. The discharge of this water is likely contributing to elevated nutrient concentrations observed in the adjacent pond. One implication of the strong reversals in groundwater flow direction is that discharge of effluent to the marsh is expected to be less than if the groundwater flow was directed toward the marsh year-round. A second implication is that septic-system effluent is expected to persist in the barrier bar longer than if groundwater flow was in one principal direction year-round.

Introduction

Elevated concentrations of nutrients are commonly observed in groundwater as a result of on-site wastewater disposal (LeBlanc, 1985; Robertson et al., 1991; Robertson and Cherry, 1992; Wilhelm et al., 1994; Walter et al., 1995). Coastal areas are usually highly developed with single family and seasonal recreational dwellings and often rely on on-site wastewater disposal systems. There is a large potential, therefore, for widespread contamination of groundwater in these coastal areas.

Around the Great Lakes, there are a number of large coastal wetlands, and numerous smaller wetlands. These wetlands consist of protected lagoons that form behind natural barrier features, estuarine lagoons, and managed marshes behind earthen dykes (Herdendorf, 1992). Coastal wetlands are subject to large changes in water levels as a result of changing lake levels. These changes occur on both a short-term daily to monthly basis, and on a longer 7 to 10 year cyclic basis. The groundwater flow systems in coastal aquifers have also been observed to correlate to changes in lake levels. In the shallow sand aquifer at Point Pelee, large changes in water table elevations and changes in rates and direction of contaminant migration have been observed (Crowe and Ptacek, 1995; 1997). These changes have the potential to influence the rate of groundwater discharge to, or recharge from, nearby wetlands, and, therefore, have the potential to influence the rate of contaminant release (Ptacek and Crowe, 1997).

Previous studies conducted at Point Pelee noted elevated concentrations of nutrients in open water ponds in the inland marsh (McCrea, 1993). The highest concentrations of nutrients were observed in ponds adjacent to the locations where historical releases of wastewater were known to occur, and it was suspected that groundwater transport of nutrients from septic system tile beds was leading to these elevated concentrations.

This paper provides a summary of hydrological and geochemical studies conducted at Point Pelee, Ontario, to determine the transport of septic-system effluent in the shallow barrier bar sand aquifer, and to determine the potential for groundwater discharge of septic system effluent into the Point Pelee marsh.

Site Description and Methodology

Point Pelee is a triangular cuspate, approximately 8 km long, that extends southward into Lake Erie. The southern half of the point is occupied by Point Pelee National Park. The Park consists of two narrow barrier sand bars, on the eastern and western sides, and an inner protected wetland (Figure 1). The Park receives over 500,000 visitors annually. There are over 30 tile beds currently in use to service Park visitors and staff. These tile beds are installed directly into the upper native sands unit. The sand consists mainly of coarse-grained quartz fragments, with approximately 25% limestone fragments. Int the past, there were a large number of tile beds and vault style toilets, that have now been abandoned or removed (Thompson et al., 1997).

Groundwater monitoring networks were installed in the vicinity of two active tile beds located on the eastern (marsh) side of the western barrier bar (Figure 1). The tile beds were approximately 15 years old at the time of sampling. The networks consist of multilevel bundle piezometers, single-point stand-pipe piezometers, and hand-driven minipiezometers. Groundwater samples were collected from over 400 sampling points, and hydraulic head measurements were made at over 50 locations.

Additional minipiezometers were also installed at the groundwater/marsh interface to collect samples of groundwater and marsh sediment water. These minipiezometers were installed along the marsh edge and up to 10 m off-shore. Seepage meters were installed on the marsh bottom to measure rates of seepage into and out of the groundwater zone.

Samples of groundwater were collected to determine concentrations of nutrients (NO_3,

NH_3, PO_4, dissolved organic carbon (DOC)), major ions, trace metals and dissolved oxygen (DO), and pH, Eh, alkalinity, electrical conductivity (EC), and temperature. Samples were filtered, acidified for cation analyses, and left unacidified for anion and DOC analyses. Determinations of pH, Eh, and DO were made in the field in a sealed flow-through cell. Alkalinity was analysed in the field with standardized acid and an automatic titrator. Laboratory analyses were conducted by the National Laboratory for Environmental Testing, Burlington, Ontario, and MDS Environmental Services Limited, Mississauga, Ontario.

Summary of Groundwater Flow System

The thickness of the upper barrier bar sand deposit ranges between 3 and 20 m, increasing in thickness toward the west. Underlying the sand unit is a low permeability clay-till unit. Monitoring of the groundwater flow in the upper sand unit along three east-west transects on a monthly basis between 1994 and 1997 indicates that changes in the elevation of the water table in the sand unit are closely correlated to changes in the elevation of Lake Erie and to infiltration events (Crowe and Ptacek, 1995, 1997). During part of the year, the elevation of Lake Erie is lower than the marsh leading to groundwater flow to be directed toward the lake. During other parts of the year, the elevation of Lake Erie is higher than the marsh resulting in flow toward the marsh. The elevation of the marsh was observed to change by < 10 cm over the monitoring period, whereas changes > 0.5 m were observed in the elevation of Lake Erie.

The most pronounced changes in the groundwater flow system were observed in an east-west transect where the barrier bar is < 100 m wide (Crowe and Ptacek, 1997). At the Blue Heron site, where the barrier bar is intermediate in width (approximately 320 m), the groundwater flow is toward the marsh during the summer and early fall. During late fall, winter and early spring, groundwater flow is toward Lake Erie. At Camp Henry, where the barrier bar is wider (approximately 425 m), the reversals in groundwater flow direction are less pronounced. Here groundwater flow is primarily toward the marsh during the spring, summer and fall, and toward the lake during the winter. Net groundwater movement appears to be dominated by recharge processes (Crowe and Ptacek, 1997).

Distribution of Nutrients Below Tile Beds

Camp Henry

Analysis of wastewater collected from the holding tank at Camp Henry indicates the wastewater contains high concentrations of NH_3 and PO_4 (Table 1). There is a distinct plume of contaminated groundwater that has formed in a north-northeast direction of the tile bed (Figures 2 and 3; Ptacek, 1997). The plume is > 60 m long, 40 m wide and between 5 and 6 m thick. It extends through the complete thickness of the upper sand aquifer, and to the marsh edge, and likely beyond. There is some widening of the plume toward the east, in a direction consistent with observed changes in hydraulic gradient for part of the year.

The plume contains elevated concentrations of NO_3, NH_3, PO_4, DOC, Fe, Mn and other dissolved constituents (Figure 4). There is a reducing zone at the base of the aquifer, in which the lower portion of the plume is present. This reducing zone is characterized by elevated concentrations of Fe (1-10 mg/L) and low redox potentials. In the inner core of the plume, there is a subreducing to reducing zone, characterized by elevated concentrations of Mn (1-3 mg/L) and pockets containing elevated concentrations of Fe. Values of pH are also lower in the inner core of the plume, with values generally 0.5 pH units lower than in the background groundwater.

Concentrations of NO_3-N ranged between 1 and 80 mg/L in the upper 4 m of the plume, with the highest concentrations observed between 20 and 30 m downgradient of the tile bed. Very low concentrations of NO_3-N were observed at locations where elevated concentrations of Fe and low redox potentials were encountered. For example, at bundle location CH6 (Figure 4), elevated concentrations of Fe present at the base of the aquifer coincide with very low concentrations of NO_3. These low concentrations in the reducing zone are likely a result of microbial denitrification reactions.

Concentrations of NH_3-N were lower than NO_3-N yet substantially elevated above background values throughout the plume. Values of NH_3-N ranged between 0.1 and 15 mg/L, and were highest in a pocket of groundwater located about 20 m downgradient of the tile bed.

Groundwater concentrations of PO_4-P ranged between 0.1 and 3.0 mg/L in a zone extending approximately 20 m away from the tile bed. In a reducing zone present at the base of the aquifer, concentrations of PO_4-P were also elevated, ranging between 0.1 and 0.8 mg/L > 60 m from the tile bed. This relationship is illustrated in Figure 4 for bundle location CH6, where elevated concentrations of PO_4 are present in the reducing zone more than 30 m downgradient from the tile bed. Concentrations of DOC were elevated, ranging between 6 and 12 mg/L in a zone extending approximately 10 m downgradient of the tile bed, and between 6 and 8 mg/L elsewhere in the plume.

The presence of NH_3 and elevated concentrations of DOC in the groundwater indicate the effluent was incompletely oxidized prior to its recharge to the groundwater zone. This incomplete oxidation likely results from short effluent residence times in the unsaturated zone due to the shallow water table at the site (<1.5 m below ground surface).

The elevated concentrations of Mn and Fe near the tile bed suggest that reductive dissolution of Mn(IV) and Fe(III) (oxy)hydroxide solids is occurring and releasing dissolved Mn(II) and Fe(II). The relatively high concentrations of DOC and NH_3 entering the groundwater zone below the tile bed likely have lead to the consumption of available oxygen. In the absence of oxygen, bacterial degradation of organic matter relies on alternative terminal electron acceptors, including NO_3, Mn(IV) and Fe(III).

Blue Heron

At Blue Heron, a bimodal plume of septic-system effluent has developed east and west of the tile bed as a result of the seasonal reversals in groundwater flow direction (Figures 5 and 6; Crowe and Ptacek, 1995; Ptacek and Crowe, 1997). The plume is more than 100 m long, more than 60 m wide, and between 5 and 6 m thick. A reducing zone is also present at the base of the sand aquifer, and extends over the complete sampling network. In the plume core, elevated concentrations of Mn are present, again suggesting Mn(IV) (oxy)hydroxide solids are being utilized as alternative electron acceptors for organic matter degradation.

Concentrations of NO_3-N are elevated in the plume core and approach 30 mg/L. At the base of the plume and near the marsh edge, concentrations of NO_3-N are < 0.1 mg/L, and correspond to locations where high concentrations of dissolved Fe and low redox potentials were encountered (Figure 7, bundle location BH7). The absence of NO_3-N in the reducing zone at Blue Heron is also attributed to the occurrence of bacterial denitrification reactions.

Concentrations of NH_3-N are much lower than at Camp Henry, generally ranging between 0.1 and 1.5 mg/L. The highest values are observed close to the tile bed. Elevated values elsewhere correspond closely to elevated concentrations of Fe, suggesting greater stability of NH_3 in the reducing zone.

In the plume core, concentrations of PO_4-P are elevated approaching 1.3 mg/L. At the base of the aquifer, concentrations of PO_4-P are also elevated, ranging between 0.1 and 0.4 mg/L. These elevated concentrations of PO_4-P at the base of the plume were observed at all locations sampled and also correspond closely to the elevated concentrations of Fe (Figure 7).

The oxidation of NH_3 and DOC appears to be more complete at Blue Heron than at Camp Henry. This better treatment is likely the result of the greater depth to the water table at Blue Heron (generally 2.5 m below the tile bed), the use of a dosing pump to more evenly distribute the wastewater through the tile lines, and the lower initial concentrations of nutrients in the untreated wastewater (Table 1).

Discharge of Nutrient-Rich Water into Marsh

Minipiezometers were installed along the cattail marsh edge east of the Blue Heron tile bed and further south along an open water pond containing elevated nutrient concentrations (Figure 8). Groundwater collected from these minipiezometers contained elevated concentrations of nutrients along the entire section of shoreline monitored. Concentrations of NH_3-N generally ranged between 2 and 10 mg/L, and concentrations of PO_4-P ranged between 0.1 and 1.0 mg/L. Under anaerobic conditions, the decay of organic matter results in the release of NH_3 and PO_4. The elevated concentrations of NH_3 and PO_4 observed along the marsh edge are generally consistent with concentrations expected for decaying organic matter co-deposited with marsh sediments. While installing the minipiezometers and seepage meters, organic-rich sediments were observed at the marsh interface. There are, however, local pockets of groundwater containing concentrations of NH_3 and PO_4 that were much higher than elsewhere along the shoreline. Concentrations of NH_3 of up to 80 mg/L and concentrations of PO_4 of up to 8 mg/L were observed in an isolated zone close to the marsh edge. These extremely high concentrations correspond closely to locations where historical releases of wastewater were known to have occurred (Thompson et al., 1997).

Discharge of groundwater to the open water pond was monitored in the location where extremely high concentrations of NH_3 and PO_4 were observed in the groundwater zone (Figure 8, cross-section B-B', and Figure 9). In May 1996 groundwater was observed to be discharging into the marsh. The rate of discharge was observed to be variable, ranging between 0.02 and 0.13 litres/m^2/day. Consistent with the measurements of outward discharge, measurements of hydraulic head made in piezometers along the shoreline indicated an upward gradient at the groundwater/marsh interface, indicating groundwater discharge to the marsh. Samples of water were collected from the sediments below the marsh in December 1995 and May 1996. Concentrations of nutrients in the samples ranged between <0.01 to 80 mg/L NH_3-N and between < 0.01 to 8 mg/L PO_4-P, with the lowest values observed at the shallowest locations sampled (Figure 9). Concentrations of Cl, a conservative tracer, and NH_3 and PO_4 generally decreased with increasing distance from the shoreline. Elevated concentrations of nutrients were also observed in the marsh waters. Elevated concentrations of dissolved Fe^- were observed at all locations sampled, indicating a reducing environment throughout this zone. The combination of outward seepage and elevated nutrient concentrations in the groundwater suggest that the seepage of nutrient-rich groundwater is a likely cause of the elevated nutrient concentrations observed in the marsh pond.

Implications

Coastal wetlands along Lake Erie do not appear to exhibit the normal aging process associated with inland freshwater wetlands because of regular flushing by changing water levels in the Great Lakes (Herdendorf, 1992). This flushing leads to constant rejuvenation of the wetland communities, prolonging the life of coastal wetlands in comparison to wetlands receiving less water flow. At Point Pelee, elevated nutrient concentrations and eutrophic conditions occur in open water ponds adjacent to the developed western barrier bar. These elevated concentrations can be attributed to either less efficient flushing of the ponds closest to the barrier bar, or higher nutrient inputs as a result of wastewater release over decades of development. This release likely occurred directly, as well as through the subsurface, during the early part of the century. More recently, release of nutrient-rich water is probably dominated by groundwater discharge. A combination of less effective flushing at the western edge of the marsh and decades of wastewater nutrient release has likely lead to the eutrophic conditions observed in the ponds along the barrier bar.

Continued release of nutrient-rich groundwater will likely lead to even greater eutrophication of these ponds. Because of the reversing nature of the groundwater flow system, the discharge of nutrient-rich groundwater is less than if the groundwater flow was directed toward the marsh year-round. When nutrients, in particular phosphorous, are released to open water ponds, they are usually consumed rapidly in the growth of algae. At the end of the growing season, much of the biomass settles to the marsh bottom and decays. There are carp in the Point Pelee ponds, which cause continued resuspension of these nutrients and make them available for renewed growth.

The reversing groundwater flow system near the Blue Heron tile bed suggests that the residence time for wastewater in the groundwater zone will be longer than if unidirectional flow conditions were present year-round. These longer residence times and the potential for the development of bimodal plumes, requires additional consideration when using groundwater for potable purposes.

Conclusions

Elevated concentrations of nutrients and other dissolved constituents are present in the groundwater zone as a result of wastewater discharge. While the reversing nature of the groundwater flow system reduces the amount of groundwater discharge to the nearby marsh, there are periods during the year when groundwater discharge of nutrients occurs, increasing the nutrient concentrations in the marsh. The plumes emanating from the tile beds are subreducing to reducing as a result of continued oxidation of organic matter below the water table and consumption of available oxygen. While low redox potentials are beneficial for the removal of nitrate, the transport of phosphate, ammonia, and DOC appear to be greater under reducing conditions. The redox status of an aquifer, in addition to other parameters, requires consideration when making predictions of groundwater transport of wastewater nutrients.

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References

Crowe, A.S. and Ptacek, C.J., 1995. Groundwater flow at a large freshwater coastal wetland: The Point Pelee Marsh, Ontario, Canada. In: Solutions '95 - Proceedings of the XXVI International Congress of the International Association of Hydrogeologists, June 4 - 10, 1995, Edmonton, Alberta, 6 pp (published electronically on CD).

Crowe, A.S. and Ptacek, C.J., 1997. Groundwater-surface water interaction at Point Pelee, Ontario, Canada: Conceptual model of the groundwater flow regime. For submission to J. Hydrol.

Harman, J., Robertson, W.D., Cherry, J.A. and Zanini, L., 1996. Impacts on a sand aquifer from an old septic system; nitrate and phosphate. Ground Water, 34: 1105-1114.

Herdendorf, C.E., 1992. Lake Erie coastal wetlands: An overview. J. Great Lakes Res., 18(4): 553-551.

LeBlanc, D.R., 1985. Sewage plume in a sand and gravel aquifer, Cape Cod, Massachusetts. U.S. Geological Survey Water-Supply Paper 2218, 28 pp.

McCrea, R., 1993. An Assessment of the Trophic Status of the Point Pelee Marsh, Environmental Quality Branch Inland Waters Directorate, Ontario Region, 16 pp.

Ptacek, C.J. and Crowe, A.S. , 1997. Groundwater-surface water interaction at Point Pelee, Ontario, Canada: Transport of septic-system derived nutrients. For submission to J. Hydrol.

Robertson, W.D. and Cherry, J.A., 1992. Hydrogeology of an unconfined sand aquifer and its effect on the behaviour of nitrogen from a large-flux septic system. Appl. Hydrogeol., 1: 32-43.

Robertson, W.D., Cherry, J.A. and Sudicky, E.A., 1991. Ground-water contamination from two small septic systems on sand aquifers. Ground Water, 29: 82-92.

Thompson, D.L., Mouland, G., Ptacek, C.J. and Crowe, A.S., 1997. The effect of past land use on groundwater nutrient concentrations, Point Pelee National Park, Ontario, Canada. This issue.

Walter, D.A., Rea, B.A., Stollenwerk, K.G., and Savoie, J., 1995. Geochemical and hydrogeological controls on phosphorous transport in a sewage-contaminated sand and gravel aquifer near Ashumet Pond, Cape Cod, Massachusetts. U.S. Geol. Surv. Open-File Report 95-381.

Wilhelm, S.R., Schiff, S.L. and Robertson, W.D., 1994. Chemical fate and transport in a domestic septic system: unsaturated and saturated zone geochemistry. Environ. Toxicol. Chem., 13: 193-203.

Table 1. Composition of septic-system effluent collected from Camp Henry and Blue Heron holding tanks, May, 1996.

Parameter	Concentration (mg/L)	
	Camp Henry	Blue Heron
NO_2+NO_3 (as N)	0.05*	<0.05
NH_3 (as N)	97.9	36.4
P, total	11.8	4.12
DOC	31.8	34.7

* Concentration equal to analytical detection limit

Figure 1. Map of Point Pelee, Ontario, showing locations of western barrier bar, interior marsh, and Blue Heron and Camp Henry study sites.

Figure 2. Aerial map showing locations of Camp Henry tile bed, bundle piezometers (circles), approximate location of marsh, and contours of equal values of electrical conductivity.

Figure 3. Cross-sectional view along Camp Henry plume centerline (section A-A', Figure 2) showing locations of sampling points (circles), and contours of equal values of electrical conductivity.

Figure 4. Values of pH, Eh, and concentrations of Mn and Fe, NO_3, NH_3, and PO_4 in groundwater *versus* depth at Camp Henry bundle location CH6 (see Figure 3).

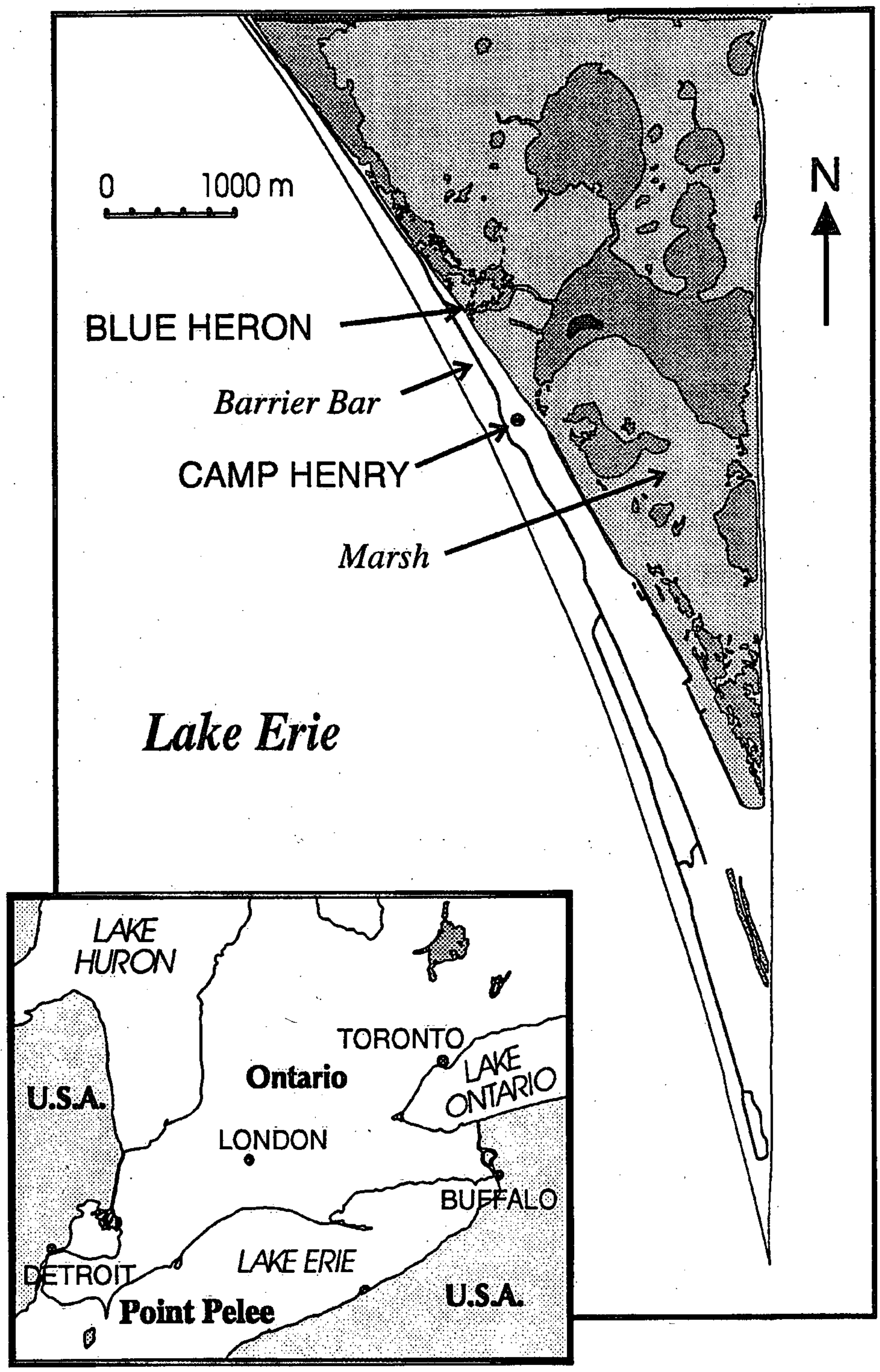
Figure 5. Aerial map showing locations of Blue Heron tile bed, bundle piezometers (circles), approximate location of marsh, and contours of equal values of electrical conductivity.

Figure 6. Cross-sectional view along Blue Heron plume centerline (section A-A', Figure 5) showing locations of sampling points (circles), and contours of equal values of electrical conductivity.

Figure 7. Values of pH, Eh, and concentrations of Mn and Fe, NO_3, NH_3, and PO_4 in groundwater *versus* depth at Blue Heron bundle location BH7 (see Figure 6).

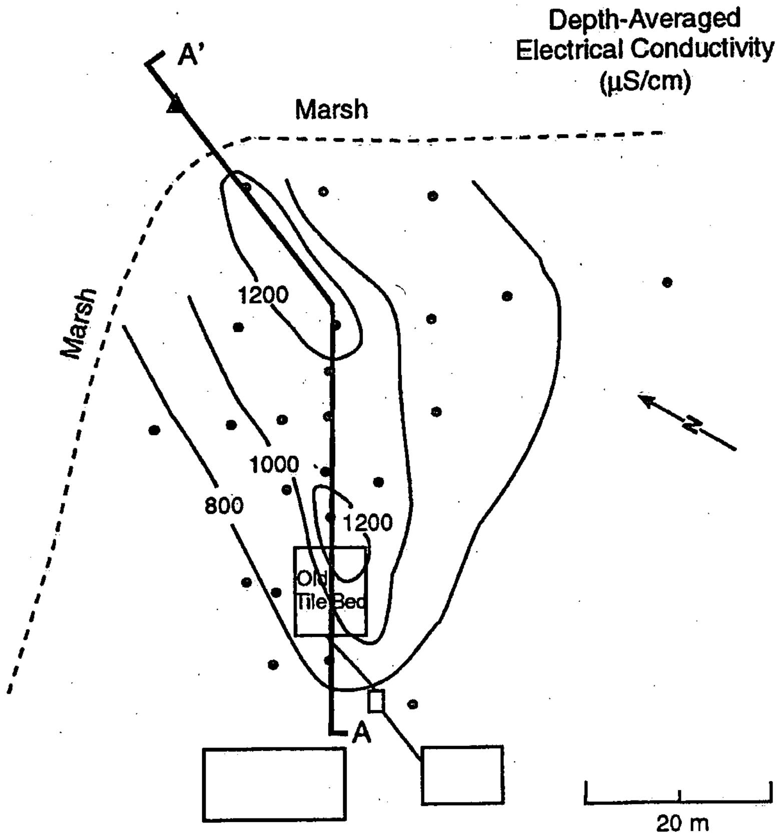
Figure 8. Map showing location of cross-section B-B' instrumented to determine composition of groundwater at marsh interface.

Figure 9. Cross-sectional view along marsh interface (section B-B', Figure 8) showing locations of minipiezometers (circles), and concentrations of Cl, NH_3 and PO_4 observed in groundwater above clay till in December 1995.



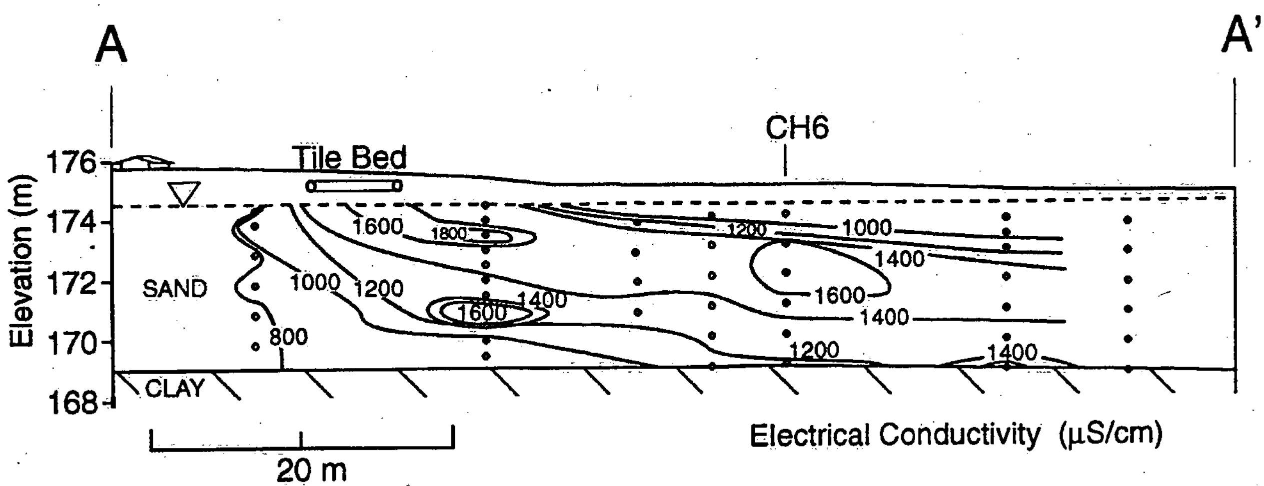
0
1000 m
N
BLUE HERON
Barrier Bar
CAMP HENRY
Marsh
Lake Erie
LAKE HURON
U.S.A.
Ontario
TORONTO
LAKE ONTARIO
LONDON
BUFFALO
DETROIT
LAKE ERIE
Point Pelee
U.S.A.

Fig. 1



Depth-Averaged
Electrical Conductivity
(µS/cm)
A'
Marsh
Marsh
1200
1000
800
1200
Old
Tile Bed
A
N
20 m

Fig. 2



A
A'
CH6
Tile Bed
176
174
172
170
168
Elevation (m)
SAND
CLAY
1600
1800
1000
1200
1400
800
20 m
Electrical Conductivity (µS/cm)

Fig. 3

Camp Henry Tile Bed - Bundle CH6

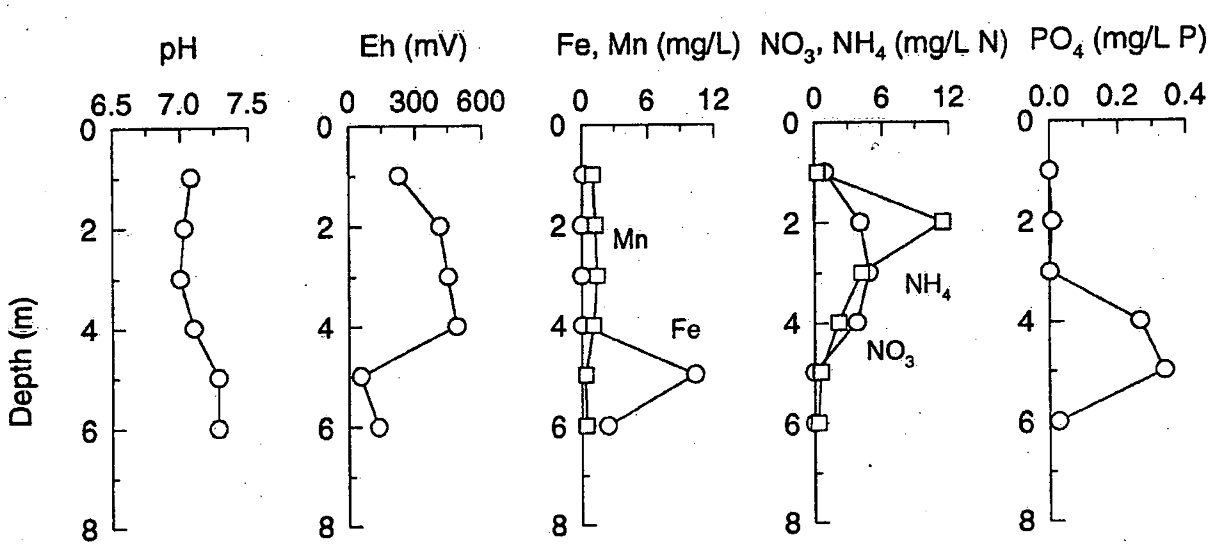


Fig 4

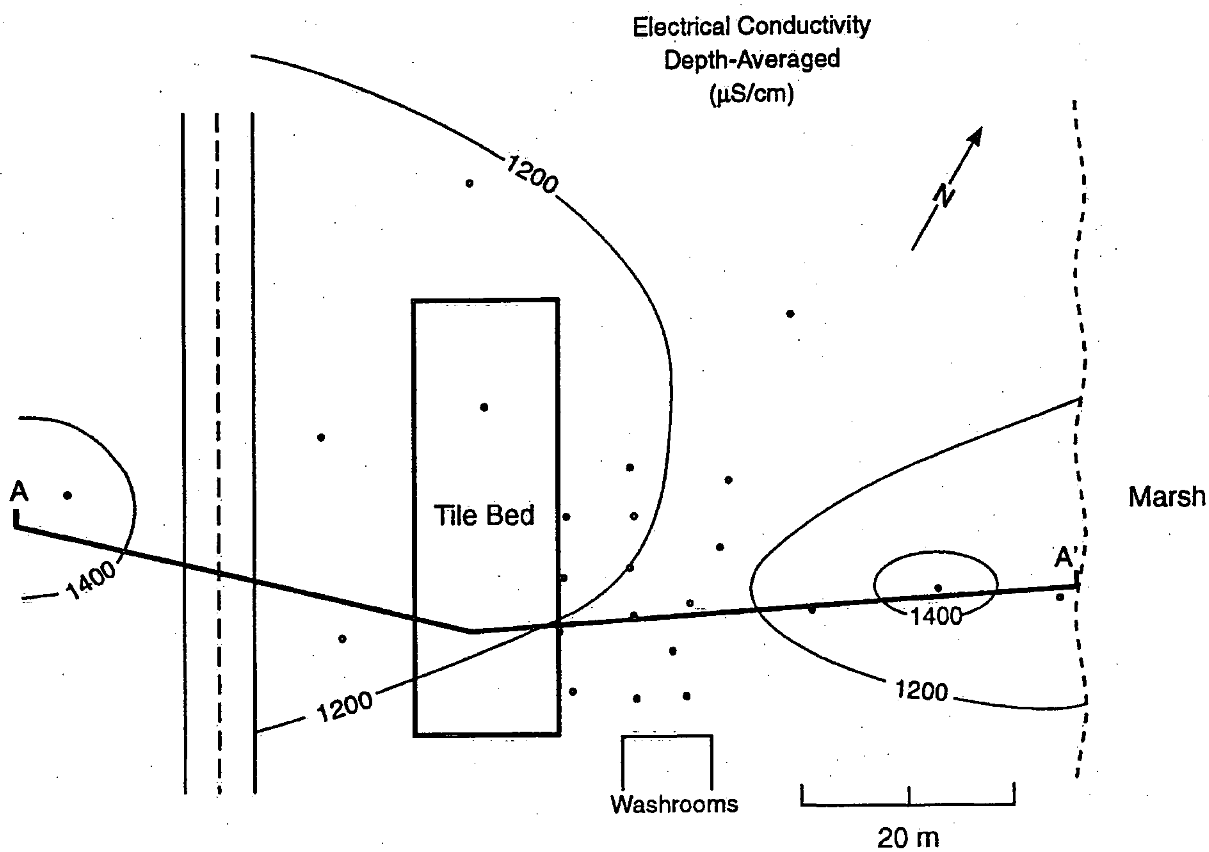

Electrical Conductivity
Depth-Averaged
(µS/cm)
1200
N
Tile Bed
A
1400
1200
A'
1400
1200
Marsh
Washrooms
20 m

Fig 5

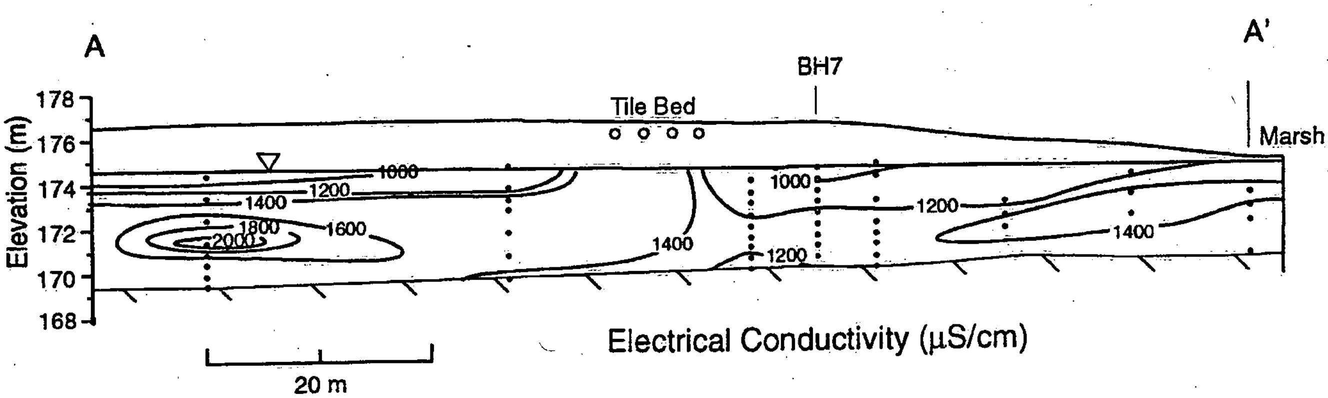

A
A'
BH7
Tile Bed
Marsh
Elevation (m)
178
176
174
172
170
168
1000
1200
1400
1800
2000
1600
1400
1000
1200
1200
1400
20 m
Electrical Conductivity (µS/cm)

Fig 6

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Canada

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