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SEAWATER CONTAMINATION OF A HARVESTED BOG: HYDROLOGICAL ASPECTS

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Abstract: A low-lying coastal harvested bog in New Brunswick was inundated by a storm surge in January 2000 and commercially abandoned due to saltwater contamination. This study examines the hydrological processes controlling the seasonal and annual variability of salinity, and its long-term persistence. In the summer period there were two distinct hydrological zones characterized by differences in salinity, elevation, compressibility, soil moisture content, and water-table position. Low-lying sites had higher and more stable surface salinity concentrations (mean 5.7‰, coefficient of variation 0.57) than slightly elevated sites (mean 2.9‰, coefficient of variation 1.13) that experienced more evaporative enrichment. Salts permeated the peat column to a depth of at least 95 cm, with peak salinity occurring 35–75 cm below the surface. A persistent downward hydraulic gradient also indicated downward advective transport of salts, suggesting that over the long term salts will be leached out of the system.

Key Words: peat, salinity, salt, solute transport, wetland hydrology, wetland restoration

INTRODUCTION

Peatlands harvested for horticultural peat present a challenge for restoration because the residual peat substrate has a profoundly altered hydrology (Price 1997) that is typically unsuitable to the spontaneous re-establishment of the original plant community (Lavoie and Rochefort 1996, Rochefort 2000, Lavoie et al. 2003). Although appropriate water management techniques can overcome certain hydrological challenges to restoration (Price et al. 2002, Price 2003, Price et al. 2003) such that plant re-establishment can occur (e.g., Rochefort et al. 2003, Campeau et al. 2004), harvested bogs with altered water quality regimes (Wind-Mulder et al. 1996) require special consideration. Seawater contamination of coastal freshwater bogs in northeastern North America can affect peat development (Buynevich et al. 2004) and result in the premature closure of commercially harvested sites (Thibault, pers. comm.). Harvested bogs in coastal locations are particularly vulnerable to seawater contamination because of a lowered surface elevation and a ditch network that connects them directly to the ocean. Reintroduction of typical bog species adapted to freshwater conditions may fail because these plants are not salt-tolerant (Wilcox 1984, Wilcox 1986a, Wilcox and Andrus 1987). As a result, there needs to be a thorough understanding of the seasonal dynamics and long-term persistence of the salt before restoration initiatives are designed and implemented.

The dynamics of solute transport have been studied in natural peatlands, including solute-poor bogs, solute-rich fens, and tidally inundated peat-based salt marshes (Wilcox 1986b, Price and Woo 1988, Hoag and Price 1995, Puranen et al. 1999, Baird and Gaffney 2000, Reeve et al. 2001, Blodau and Moore 2002, McKenzie et al. 2002). The basic principles of solute transport are related to both the physical transport of water and the process of diffusion. Since solutes are dissolved in the water, they are predominantly transported in the same direction as the hydraulic gradient by advection (Wilcox 1986b, Hoag and Price 1995). Diffusion of solutes towards zones of lower concentration results in a slower transport of solutes through the peat pore structure. Peat contains both active (connected) pores and dead-end (disconnected, closed) pores (Loxham 1980). Water and solutes are primarily transported through the active pores, although the dead-end pores act as solute sinks due to diffusive processes (Loxham 1980, Hoag and Price 1997, Ours et al. 1997, Baird and Gaffney 2000). The concentration gradient between the active and dead-end pores results in an initial net diffusion of solutes into the dead-end pores. Once the concentration of solutes in the active pores falls below that of the dead-end pores, the direction of diffusion will reverse and the solutes will be re-released into the active pores. This process results in the overall retardation of a solute plume during its passage through the peat (Hoag and Price 1995, Baird and Gaffney 2000).

Although the processes of advection and diffusion can result in the transport of solutes through a peat soil, the concentration of solutes can be altered without any physical solute transport due to evaporative enrichment (Wilcox 1986b, Price and Woo 1988, Price 1991, Price 1994, Hoag and Price 1995). In addition, the annual freezing process can cause the downward migration of solutes in the peat profile due to the selective exclusion of solutes from frozen peat (Kadlec 1984, Kadlec and Li 1990, Chague-Goff and Fyfe 1997, Stahli and Stadler 1997). A greater amount of solutes will be excluded from the ice phase during a slow freeze, whereas a fast freeze tends to lock solutes in their pre-frozen location (Kadlec 1984). The concentration of solutes in unfrozen water and peat immediately below the frozen layer can be 10–20 times higher than the concentration within the frozen peat (Kadlec 1984, Kadlec and Li 1990, Chague-Goff and Fyfe 1997, Stahli and Stadler 1997).

Where widespread contamination has occurred, short- to medium-term changes in concentration due to horizontal flow processes are likely to be less important than those caused by vertical flow processes since contamination is already laterally extensive. It is the goal of this research to identify the main processes that control the annual and seasonal solute transport in a seawater-contaminated, harvested bog. The specific objectives of this study were: 1) to determine the spatial and vertical extent of saltwater contamination at the study site, 2) to identify the hydrological processes that contribute to the seasonal and annual variability of solute concentration, and 3) to assess the potential long-term persistence of saltwater contamination.

STUDY SITE

The study site was located on a 140-ha abandoned harvested bog on Pokesudie Island, New Brunswick, Canada (47°48′N, 64°46′W), which lies at the northern tip of the Acadian Peninsula (Figure 1). On average, this region receives 1,058 mm of precipitation annually, 30% of which falls as snow (Bathurst NB station, Environment Canada 2007). Mean temperatures in January and July are −11.1°C and 19.3°C, respectively (Bathurst NB station, Environment Canada 2007). The peatland is surrounded by ocean on three sides, including areas of open shoreline, mineral islands, and salt marsh. Its elevation varies from approximately 1–4 m.a.s.l., and the harvested peatland generally has a flat topography. Its low elevation with respect to sea level required ditches to be pumped to accomplish drainage. Harvesting of peat ceased after a 1.2- to 2.0-m storm surge caused extensive seawater contamination in January 2000 (OCIPEP 2005, Chiasson and Saulnier, n.d.). The lowest elevation areas in this harvested bog became inundated with both drift ice and up to 0.7 m of saltwater slush (Chiasson and Saulnier, n.d.). Ditches were pumped in February 2000 in an attempt to flush the saltwater out of the site, but pumping was stopped after two weeks when tests showed increasing saltwater contamination in the frozen peat (Chiasson and Saulnier, n.d.).

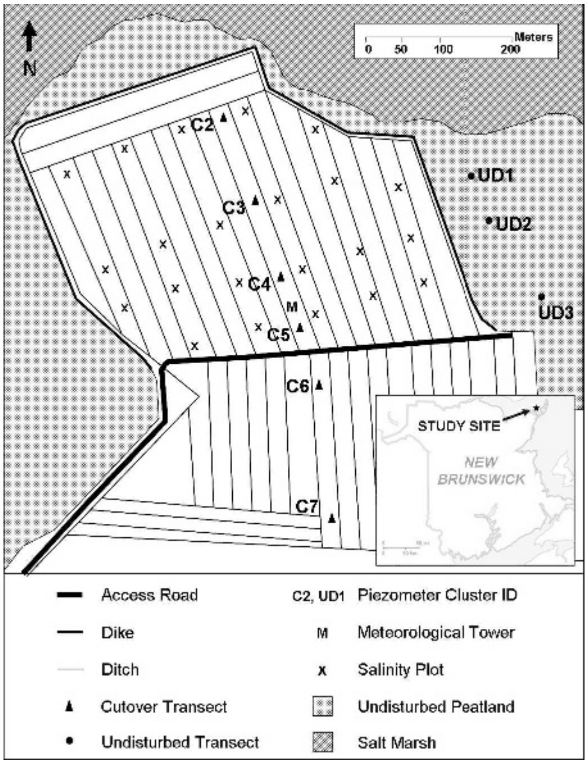

Figure 1. Experimental setup at Pokesudie Island harvested bog showing location of undisturbed and cutover piezometer transects, salinity plots, and meteorological tower.

This study focused on the northern field of the harvested bog, which was the most heavily affected by saltwater contamination due to its low elevation of 1–2 m.a.s.l. (LQG 2000, 2001, 2002; unpublished internal reports). This field is bordered by undisturbed peatland (which was also inundated during the storm surge), salt marsh, and an access road (Figure 1). After the storm surge abated, a peat dike was installed along the border of the study field to prevent future storm surges from affecting the harvested peatland. The thickness of the peat in this cutover (harvested) area ranges from approximately 1–3 m and is underlain by a sandy loam (72% sand, 19% silt, and 9% clay). Drainage ditches border crowned (upwardly convex) peat fields that are 25-

to 30-m wide. Since abandonment, the ditches have become partially or totally in-filled by peat sediment redistributed by floodwater during snowmelt and early spring precipitation.

METHODS

To identify the spatial and vertical extent of saltwater contamination at the study site, salinity levels in pore waters were monitored in three ways. The vertical distribution of saltwater contamination was determined by monitoring the salinity in water collected from piezometers and in pore water extracted from peat cores. The horizontal distribution of saltwater contamination was monitored in pore water extracted from 28 surficial sampling plots. Details of these three methods are discussed in detail following. In addition, the salinity and electrical conductivity of rain water was monitored for every rain event more than 5 mm.

Two parallel transects of well and piezometer clusters were established in the cutover portion of the peatland (Cutover, C2 to C7) and in the undisturbed peatland (Undisturbed, UD1 to UD3) (Figure 1). Cluster C1 (excluded from this discussion) was originally intended as an undisturbed comparison for the cutover transect and was established in line with the cutover transect in the natural peatland immediately beyond the peat dike. However, data show that C1 was hydrologically affected by the dike and the cutover area, and hence it could not be used as an adequate undisturbed comparison to the cutover transect.

The cutover transect was established immediately adjacent to the crown of the long-axis of a peat field. This transect included four well/piezometer clusters located in the field north of the access road (C2 to C5) with two additional clusters (C6 and C7) located in the field south of the access road (Figure 1). Each cluster comprised a well (100-cm depth) and five piezometers at depths of 50, 75, 100, 125, and 150 cm below the surface. The two clusters south of the access road (C6 and C7) were located in an area of shallow peat (<100 cm); as a result, the 125-cm and 150-cm piezometers were not required. The undisturbed transect contained three clusters (UD1 to UD3), starting with UD1 at an approximate distance of 50 m from the salt marsh. Each cluster in the undisturbed transect included a well (100-cm depth) and four piezometers at depths of 25, 50, 75, and 100 cm below the surface.

All piezometers had a 15-cm slotted intake except for those at the 150-cm depth (25-cm intake). All piezometers and wells were made of PVC pipe (2.5 cm i.d.), and the slotted intakes were covered with a Nitex geotextile screen to prevent clogging. In addition to the PVC piezometers, two stainless steel drive-point piezometers (18-cm intake) were installed in the mineral substrate at C2 and C7 (380-cm and 117-cm depth, respectively). The 125-cm and 150-cm PVC piezometers at C3 were also located in the mineral substrate. Piezometer response times are indicated in the following description of hydraulic conductivity methods.

To monitor the vertical distribution of the saltwater contamination, the salinity and electrical conductivity (EC) of water extracted from defrosted piezometers was tested once per week. Water within the piezometers was purged 24 hours prior to testing. All samples were tested immediately following extraction from the piezometers.

To establish a detailed vertical saltwater contamination profile, four peat cores were extracted between July 22 and July 23, 2003, using a Wardenaar peat corer to depths ranging from 60–100 cm (either to the base of the peat layer or to the top of the frost layer). Three cores were taken in different topographic locations near a relatively wet piezometer cluster (C3): the first was located immediately adjacent to the collapsed ditch, the second was located approximately ten meters from the ditch, and the third was located in the center (crown) of the peat field (approximately 15 m from the ditch). The fourth core was extracted near a relatively dry piezometer cluster (C5) near the access road. All four cores were sliced into 5- or 10-cm layers and the pore water extracted and filtered by vacuum flask for electrical conductivity, salinity, and chloride testing (see following).

To assess the horizontal distribution of the saltwater contamination, the salinity of extracted pore water was tested in three surficial layers of peat. Blocks of peat $7 \times 7 \times 24$ cm deep were extracted from the surface at six plots in the cutover transect once per week and at 22 plots throughout the study area once every other week (Figure 1). All plots were located immediately adjacent to the crown of the field; no plots were located near or in ditches. The 24-cm deep peat blocks were divided into three layers (0–7, 7–15, 15–22 cm deep) for testing. The sampling depths were consistent with sampling conducted at the site by the Lameque Quality Group Limited peat company between 2000 and 2002 (LQG 2000, 2001, 2002; unpublished internal reports). Pore water was extracted from the peat samples and filtered using a vacuum flask.

In the laboratory, pore water extracted from the block and core peat samples was tested for electrical conductivity (EC) and salinity using the WTW Conductivity Handheld Meter (LF 330). Chloride testing was conducted to ensure that changes in salinity were indeed related to changes in chloride concentrations, since chloride is a conservative tracer and an indicator of seawater inputs (Atkinson et al. 1986, Shotyk 1997). A VWR Scientific Combination Chloride Electrode was used to determine chloride concentration in 445 of the pore-water samples. Water samples were tested in groups of twenty, in random order; standard solutions were re-tested after the 20th sample (approximately once every hour). Results indicated a strong correlation between salinity (sal) and chloride concentrations ($r^2 = 0.989$, $p < 0.001$, Cl = 624.01*sal) and between salinity and electrical conductivity ($r^2 = 0.995$, $p < 0.001$, EC = 1.73*sal). For the remainder of this article, only salinity values are used, while electrical conductivity values are used when salinity levels were below detection (<0.1‰).

To identify hydrological processes contributing to the seasonal and annual variability in solute concentration, we monitored vertical and horizontal hydraulic gradients, water table location, evapotranspiration, depth to the frost table, and peat surface subsidence. These monitoring data were complemented by an evaluation of the peat's hydraulic characteristics, i.e., hydraulic conductivity, specific yield, and bulk density.

The water table was monitored in 20-minute intervals using a Campbell Scientific datalogger at a 60-cm deep, 15-cm diameter well located at a site between C4 and C5. Water level and hydraulic head were monitored in all defrosted piezometers and wells in the Cutover and Undisturbed transects. In addition, pore water pressures were monitored in three arrays of tensiometers (at 2-, 5-, 10-, 20-, and 30-cm depths) established at C2, C4, and C7. Clusters C2 and C4 represent a relatively dry and wet site, respectively, while cluster C7 was an extremely dry site.

Daily evapotranspiration (mm day^{-1}) was estimated for a site located between C4 and C5, using the Priestley and Taylor (1972) combination method:

$$E = \alpha(s/(s + q))(Q^{*} - Q_G)/L\rho) * 10^3$$

where α is the ratio of actual to equilibrium evapotranspiration, s is the slope of the saturation vapor pressure – temperature curve (kPa °C^{-1}), q is the psychrometric constant (0.0662 kPa °C^{-1} at 20°C), Q^* is the net radiation flux (J day^{-1}), Q_G is the net ground heat flux (J day^{-1}), L is the latent heat of evaporation (J kg^{-1}), and ρ is the density of water (assumed to be 1,000 kg m^{-3}). An α value of 1.25 was used to represent the cutover peat surface (Price 1997). Temperature, Q_G, Q^*, and precipitation were measured in 20-minute intervals using a Campbell Scientific datalogger at a meteorological station located between C4 and C5: temperature was measured using a shielded thermocouple (1 m above peat surface); Q_G was measured with two Radiation Energy Balance Systems soil heat flux plates (1 cm below peat surface); Q^* was measured with a Radiation Energy Balance Systems net radiometer (1 m above peat surface); and rainfall was monitored using a tipping bucket rain gauge and a manual rain gauge for verification.

Depth to the frost table was measured three to five times a week near the meteorological station between C4 and C5. Frost table depth was monitored by inserting a 1-cm diameter rebar into the peat until the solid frost table was reached. Three randomly located measurements were taken in an untrampled area adjacent to the crown (center) of the peat field, and the average of these three measurements represented the frost table for that particular measurement date.

Peat surface subsidence was measured using two concrete reinforcing rods installed at C2 and C4. The concrete reinforcing rods were driven into the mineral substrate to provide a stable reference elevation.

Field estimates of saturated hydraulic conductivity were obtained with bail tests, using the hydrostatic time-lag method of Hvorslev (1951). Bail tests were conducted on one occasion at all defrosted piezometers in the Cutover transect and at three mineral substrate piezometers (at C2, C3, and C7) between July 21 and August 4. Hydraulic conductivity was monitored either until greater than 95% recovery was achieved or for up to five hours; recovery rates ranged from 50% to greater than 95%. Recovery rates were log-linear for all monitored piezometers.

Specific yield and bulk density were measured for 5-cm layers sliced from a 75-cm peat core that was extracted from C3 on July 22, 2003, with a Wardenaar peat corer. The peat core was frozen and returned to the laboratory for analysis. Two tests were conducted using brass rings of known volume (Test #1: 84.8 cm^3, Test #2: 68.7 cm^3). Samples were cut from the frozen peat core to fit the ring volume of interest. In the first test the sample was defrosted in the ring prior to testing, while in the second test the sample was defrosted in the ring while immersed in water. All samples were trimmed to fit the ring volume once defrosted. The second test was conducted to determine if there was swelling of the peat upon immersion in water, which would cause a change in sample volume. Trimming the sample after saturation was assumed to minimize the

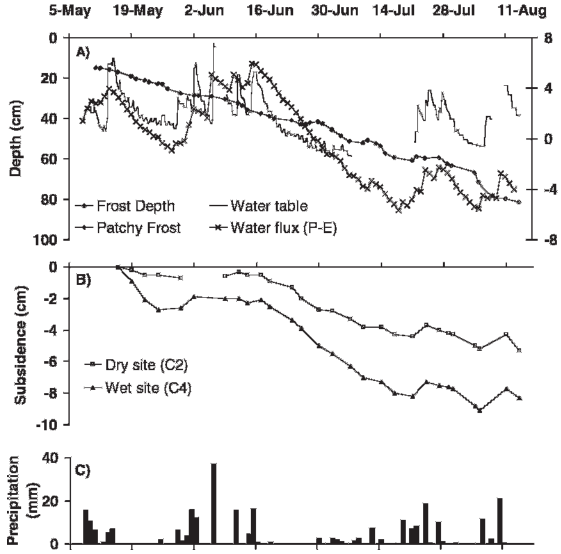

Figure 2. A) Mean daily water table, frost table, and water deficit (P-E). All three variables were measured between C4 and C5. B) total subsidence of the peat surface. C) daily precipitation.

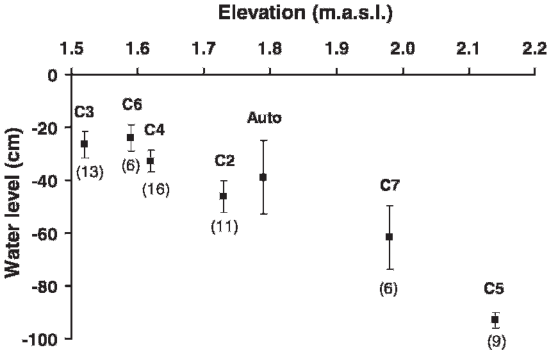

Figure 3. Relationship between surface elevation and water level ($r^2 = 0.92$, $p < 0.001$) for C2 through C7 and the automatic well (located between C4 and C5). Mean piezometer water level is used as a surrogate for water table (with the exception of the automatic recording well), with each mean representing all unfrozen piezometers for four measurement dates (July 14, July 29, August 4, and August 11, 2003). Error bars indicate standard deviations, while the numbers in brackets indicate the number of piezometers included in the mean. The mean for the automatic well (Auto) represents the mean of all automatic water level readings taken on the above-listed days. This four-day mean is within ± 0.5 cm of the seasonal mean water level at the automatic well.

measurement impact of this volume change; results showed that there was less than 2% and less than 9% difference between trials for bulk density and specific yield, respectively.

To assess the long-term persistence of saltwater contamination at the study site, data collected to meet the first and second objectives were compiled. In particular, analyses focused on any changes over time in salinity levels.

RESULTS

Mean air temperatures for the months of May through August were 8.3, 15.8, 19.5, and 18.6°C, respectively, which deviated from the 30-year mean by −16%, 0%, +1%, and +2%. The frost table within the cutover peat receded at an average rate of 0.8 cm day^{-1} and persisted until July 17, 2003, after which the frost was patchy (Figure 2a). The rate of frost recession varied from a mean of 0.6 cm day^{-1} during May and June, to a mean of 1.1 cm day^{-1} during July. The frost layer was not continuous across the study area; a faster thaw was observed in wetter areas. In addition, areas that were saturated during freezing conditions tended to have impermeable frost, whereas areas that were partially unsaturated tended to have permeable frost. Since the frost was permeable in many areas (including the area around the continuous water table well), the water table could fluctuate freely above and below the frost layer. From May 9 to August 14, 2003, 280 mm of precipitation (P) was recorded, with 106 mm falling during June (Figure 2c). For this same measurement period, evapotranspiration (E) was estimated to be 320 mm. The net P-E deficit was 40 mm, with the majority of this deficit (36 mm) occurring during July (Figure 2a).

Hydrologic Characteristics

Due to the presence of ground frost, the water table could not be monitored in the 2.5 cm i.d. PVC wells in the cutover transect until July 29, 2003, after which a total of six water-table values were obtained at each of C2, C4, and C6. Mean piezometer water levels for the same clusters and dates were within ±2 cm of the water table, and thus mean water levels in unfrozen piezometers in C2 to C7 were used to approximate water table for four measurement dates (July 14, July 29, August 4, and August 11, 2003). The water table was closer to the surface at lower elevation sites such as C3, C4, and C6 (Figure 3, $r^2 = 0.92$, $p < 0.001$). Areas near the access road (such as C5) had deeper water tables and higher elevations as a result of peat harvesting techniques. During harvesting, peat is temporarily stored in piles close to the access roads until the peat can be transported to a processing plant. Over time, the residual piles add elevation to these sites so that they become higher than the surrounding harvested peatland. The relatively flat water table across the study area (horizontal gradient = 0.001) results in a deeper water table in these sites due to higher surface elevations.

From May 9 to August 14, 2003, the mean water-table depth ± standard deviation in the continuous recording well was 38.5 ± 11.7 cm below the peat surface (Figure 2a). The maximum water-table depth in the cutover area occurred between July 8 and July 20, when the 60-cm deep continuously recording well was dry and when the P-E water deficit was at its greatest. Daily changes in water-table depth vary weakly in response to the daily water flux (P-E) ($r^2 = 0.37$, $p < 0.001$). The mean water-table depth ± standard deviation in the undisturbed transect was 14.2 ± 6.9, 8.0 ± 6.6, and 12.9 ± 7.3 cm for UD1, UD2, and UD3, respectively.

Surface subsidence was weakly related to changes in water table (C2: $r^2 = 0.37$, $p < 0.01$; C4: $r^2 = 0.32$, $p < 0.01$) (Figure 2b). There was greater total subsidence at the wet site (C4, 8 cm) than at the dry site (C2, 5 cm). Subsidence was converted to strain rate between the surface and the frost table, where strain is the relative change in thickness of the defrosted peat layer. C2 and C4 experienced strain ranging from +0.4% to −0.8% and +0.6% to −2.1%, respectively. C4 had up to four times the rate of strain of C2 during comparable compression events, although both C2 and C4 had comparable rates of strain during swelling events. Strain at both C2 and C4 was moderately related to changes in the daily water flux (P-E) ($r^2 = 0.45$, $p < 0.001$).

The mean ± standard deviation of specific yield and bulk density was 0.23 ± 0.02 and 0.09 ± 0.02 g cm^{-3}, respectively. Neither specific yield nor bulk density changed significantly with depth. Saturated hydraulic conductivity at C2 to C5 decreased with depth, ranging from 10^{-5}–10^{-8} m s^{-1} (Figure 4). Saturated hydraulic conductivity of the mineral substrate ranged from 10^{-5}–10^{-6} m s^{-1}, with a mean of 10^{-6} m s^{-1} ($n = 3$). Hydraulic conductivity could not be obtained for all piezometers due to either lack of water (C5: 50 cm, 75 cm), the presence of ice (C2: 50 cm, 75 cm) or insufficient head recovery (C3: 125 cm, 19% recovery).

A minimum soil water pressure of −50 to −60 cm occurred during a mid-summer dry period at C2 and C4, and −110 cm at C7. Soil water pressure decreased during the summer as drying occurred due to evaporation (Figure 2a). The tensiometer data from 2 to 30 cm indicate that there was a vertical hydraulic gradient whose direction and magnitude varied throughout the summer, although this variation was not linked to the P-E induced water flux ($r^2 = 0.015$, $p < 0.5$) or to water-table depth ($r^2 < 0.01$, $p < 0.8$). Deeper vertical hydraulic gradients (at depths of 50 to 75 cm, and 100 to 150 cm) indicate a predominant downward gradient in C2, C3, C6, and C7, a predominant upward gradient at C5, and a predominantly upward but variable gradient at C4 (Table 1). The consistent direction of these gradients results in a poor relationship with the P-E induced water flux ($r^2 = 0.02$, $p < 0.5$). The horizontal hydraulic gradient was less than 0.001, or less than 1/10th of the smallest vertical gradient, thus horizontal transport was relatively unimportant.

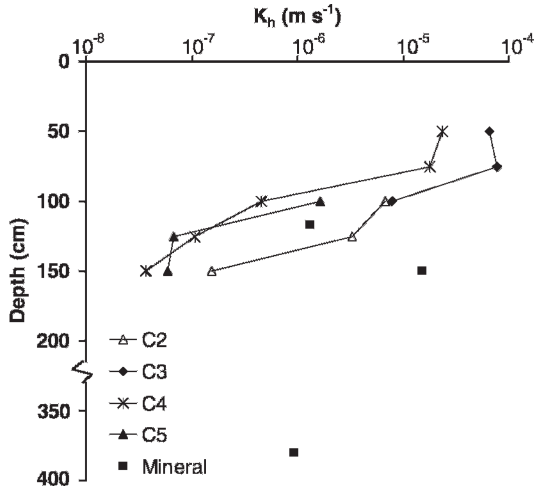

Figure 4. Field-measured saturated hydraulic conductivity at C2, C3, C4, and C5, and at three piezometers situated in the mineral substrate.

Spatial and Temporal Solute Distribution

The salinity of rainwater was consistently below detection, but its electrical conductivity ranged from 10 to 50 μS cm^{-1}. Vertical profiles of salinity in the upper 100 cm of cutover peat near C3 (22 July 2003) show that peak salinity levels occurred between 30 and 75 cm from the surface (Figure 5), with the shallower peak occurring in the crown of the peat field (site A). The depth of peak concentration was greater at lower elevation areas, increasing in depth from A to C. Salinity at a site not inundated by seawater (C5) was negligible (less than 0.1‰) at all measured depths (0–55 cm). The water table at C3 was approximately 20 to 25 cm below the surface on July 22, 2003.

In the cutover area (C2, C3, and C4), salinity generally decreased with depth and the mineral layer underlying the peat was slightly saline (less than 2‰) (Figure 6). However, in the undisturbed area (UD1, UD2, and UD3), salinity generally increased with depth to a peak near the 75-cm layer. UD1 had

Table 1. Hydraulic gradients for C2 to C7 on available measurement dates from June 19 to August 11, 2003.

Nest	Depth Range (cm)	K_h (m s^{-1})**	Gradient ($\Delta h/\Delta z$)*								
			June 19	June 26	June 30	July 10	July 14	July 27	July 29	Aug. 4	Aug. 11
C2	50–75	no data									0.16
C2	100–150	3.4×10^{-6}								0.04	0.03
C2	150–380***	9.4×10^{-7}						0.24	0.3	0.32	0.28
C3	50–75	7.2×10^{-5}							0.04	−0.12	
C3	100–150***	7.6×10^{-6}							0.09	0.11	
C4	50–75	2.1×10^{-5}						−0.04	−0.08	−0.05	−0.03
C4	100–150	2.0×10^{-7}						0.02	−0.01	−0.04	0.12
C5	50–75	no data	frozen for all measured dates								
C5	100–150	5.9×10^{-7}	−0.16	−0.12	−0.08	−0.03	−0.05		−0.06	−0.01	
C6	50–75	2.5×10^{-6}			0.11	0.19	0.01		0.04	0.06	
C7	50–75	no data									0.09
C7	100–117***	7.7×10^{-7}	0.46	0.09	−0.16	0.28	−0.09		0.59	0.40	0.17
Auto Water Table Depth (cm)			**−38.1**	**−50.1**	**−55.5**	**< −60**	**< −60**	**−33.7**	**−38.3**	**−53.2**	**−25.3**

*Negative values indicate an upward flux; positive values indicate a downward flux.

** Geometric mean saturated hydraulic conductivity.

*** Across peat/mineral substrate boundary.

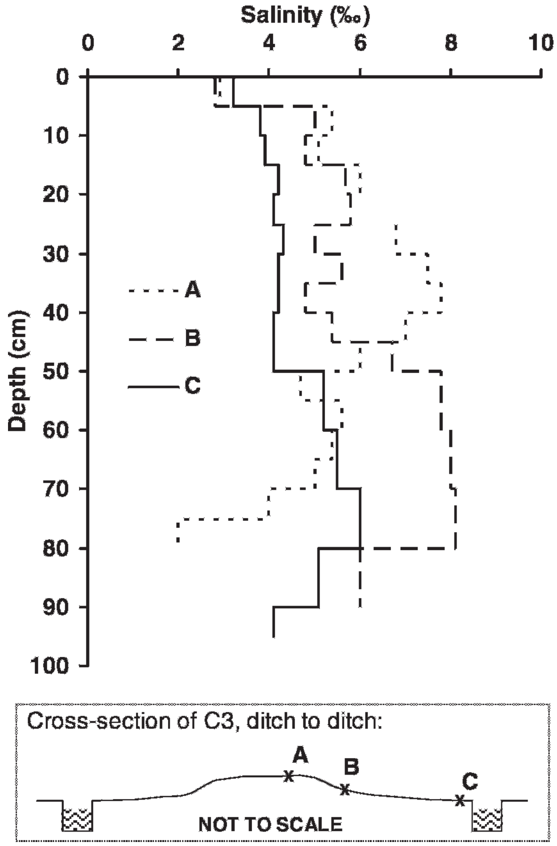

Figure 5. Salinity concentration in pore water extracted by vacuum on July 22, 2003. Salinity levels are plotted for each sampled layer. Cores A, B, and C were taken along a linear transect across the field, from the crown towards the ditch (see diagram below graph), in an area with known contamination at the surface (C3). A comparison core (0–60 cm deep) was taken in an area of higher elevation (C5) that was not inundated by seawater, and no saltwater contamination was detected within the core.

much higher salinity levels and a continued increase in salinity with depth likely due to its close proximity (<50 m) to a salt marsh.

Salinity in the surface peat layers (0–15 cm) at C2 and C4 increased during the dry period of the summer, with a 20-fold increase in salinity in the near-surface layer (0 to 7 cm) and up to a 4-fold increase in the 8- to 15-cm layer (Figure 7). Very little change was observed in the 16- to 22-cm layer (Figure 7). Similar trends were observed in sites that had relatively high salinity. Mean salinity levels at C2 and C4 ranged from 5‰ to 7‰ for all three measured depths, and the coefficient of variation decreased with depth. There is a moderate to weak relationship between changes in surface salinity (0–7 cm layer) and the water deficit (P-E). This relationship is moderate at C4 ($r^2 = 0.49$, $p < 0.05$), and weak at C2 ($r^2 = 0.16$, $p < 0.5$).

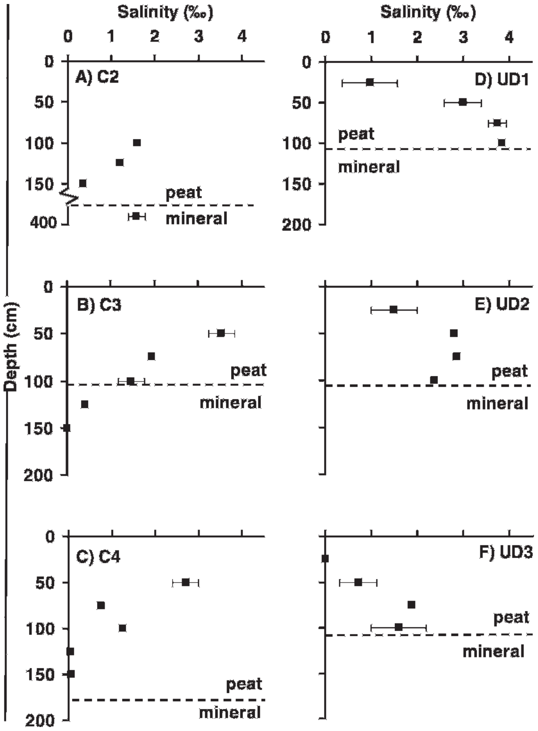

Figure 6. Mean pore-water salinity for the period of May 26 to August 5, measured in piezometers at C2, C3, and C4 in the cutover peat, and at UD1, UD2, and UD3 in the undisturbed peatland. Error bars indicate the standard deviation for the mean pore-water salinity. Error bars representing standard deviations ≤ 0.1‰ are obscured by the symbol.

The spatial distribution of salinity in the 0–7 cm layer was moderately related to elevation (Figure 8) ($r^2 = 0.62$, $p < 0.001$ for June 24; $r^2 = 0.51$, $p < 0.001$ for July 8, 2003), with higher salinity at lower elevation sites, which were flooded during the spring. In addition, there was a greater total increase in salinity at lower elevation sites during a drying period from June 24 to July 8 (Figure 8) when evapotranspiration exceeded precipitation by 58.7 mm. The salinity of lower elevation sites (<1.6 m.a.s.l.) increased by an average of 4.2‰ during this period, while the salinity of higher elevation sites (>1.6 m.a.s.l.) increased by 1.9‰ during this same period. During this period, salinity increased over the starting level by an average of 2.5 times in the higher elevation sites and 0.5 times in the lower elevation sites.

DISCUSSION

The storm surge of January 21, 2000, inundated the low-lying areas of Pokesudie Island, including a narrow band of undisturbed bog and perimeter fields of the harvested bog. At the study site, the extent of contamination of the harvested bog was related to surface elevation (Figure 8). Seawater flooding in the harvested bog was estimated to be between 0.3 m and 0.7 m deep (Chiasson and Saulnier, n.d.), and thus the elevated access road

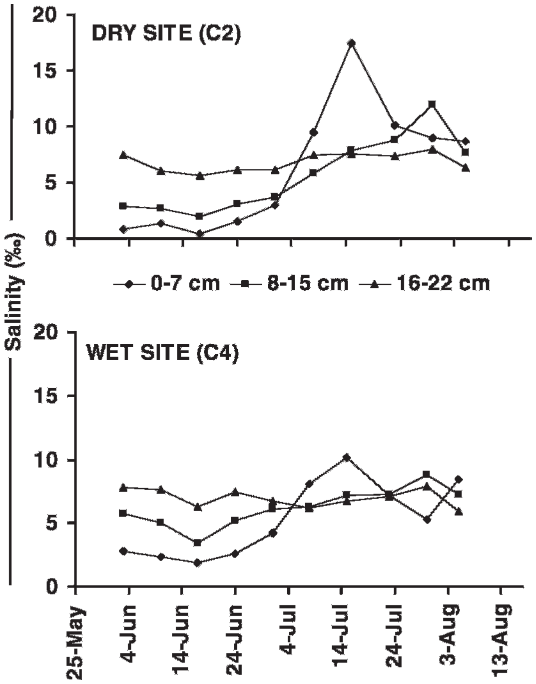

Figure 7. Temporal variability of salinity within the top 22 cm of peat at a relatively dry (C2) and a relatively wet site (C4), from June 3 to August 5, 2003.

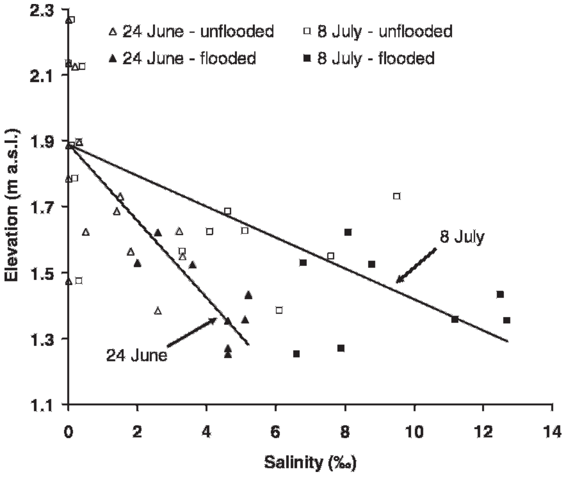

Figure 8. Relationship between elevation and salinity of the 0–7 cm layer at 24 salinity plots (two of the 26 plots were missed during the elevation surveying) on June 24, 2003 ($r^2 = 0.62$, $p < 0.001$) and July 8, 2003 ($r^2 = 0.51$, $p < 0.001$). Only 10.4 mm of precipitation occurred between these two measurement dates, and the P-E deficit was 58.7 mm. Solid symbols indicate salinity plots that undergo seasonal flooding during snowmelt.

(1 m above the mean elevation of the contaminated area) protected inland areas (such as C6 and C7) from the storm surge.

As the surge abated, the seawater receded into the lowest areas of the harvested bog and into the drainage network. At that time, little infiltration could have occurred into the frozen saturated peat in the lowest areas, where the frost would have been relatively impermeable (Price and Fitzgibbon 1987). Drainage was incomplete at the time of inundation because the drainage network at this site was a closed system that required pumping to remove water. In February 2000, the drainage system was reactivated in the hope that the seawater would be removed and harvesting operations could resume (Chiasson and Saulnier, n.d.). However, soil testing at that time and in spring 2000 continued to reveal residual seawater contamination that resulted in abandonment of peat mining operations; pumping of the drainage system was also discontinued (Chiasson and Saulnier, n.d.).

The inoperative drainage system caused partial rewetting of the site. Currently, snowmelt water causes extensive spring flooding of the studied peat fields. The drainage ditches between fields in these seasonally flooded areas have become in-filled with peat that has been dislodged from the surrounding fields and reworked by wave action. This reworked peat has formed broad, flat expanses of very wet peat. Thus, in the harvested bog two distinct hydrological conditions were found to exist: 1) low lying areas with a shallow water table (Figure 3), a sedimentary surface peat of high compressibility (c.f. Price 2003) (Figure 2b), and high levels of residual contamination (Figure 8); and 2) more elevated areas where there was a distinct unsaturated zone (C5 and C7 in Figure 3) and where residual contamination was minimal or non-existent (Figure 8).

As discussed prior, the spatial distribution of residual saltwater contamination was partly associated with the entry point of contamination, surface elevation, and containment by barriers (access road). Aside from the season following inundation when the drainage system was in operation, there was no significant water sink in the harvested bog other than evaporation and the potential vertical loss through the mineral substrate. Consequently, short-term changes in salinity at this site were driven primarily by changes in water volume during precipitation and evaporation events. Short-term evaporative enhancement of solute concentration (Wilcox 1986b, Casey and Lasaga 1987, Price and Woo 1988, Price 1991) was evident in the near-surface layer; changes were most pronounced in the 0–7 cm layer, and diminished with depth (Figure 7). In the long-term, changes in salinity were affected by the vertical redistribution of solute within the peat profile due to advection.

Changes in surface salinity were also related to the compressibility of the peat since compression of the soil matrix can affect the soil moisture content (Price 2003). During drying events, more compressible peat (C4, Figure 2b) can maintain a more stable moisture content than less compressible peat (C2, Figure 2b) due to corresponding changes in soil volume. Despite the loss of water during drying events, the stable moisture content of more compressible peat results in a relatively stable concentration of salts, while the reverse is true for less compressible peat. The effects of compression were evident during the dry period of the summer, when the salinity of the less compressible C2 peat increased up to 20-fold in the surface layer (0 to 7 cm), while the more compressible C4 peat increased in salinity up to 4-fold in the same layer (Figure 7).

Although the evaporative enhancement of solute concentrations in the surface peat is particularly important to restoration during the growing season (Figure 7), the long-term vertical redistribution of solutes in the peat profile will determine the persistence of this salt contamination. The downward hydraulic gradients at the majority of monitored piezometer clusters indicated an overall downward advective transport of solutes toward the mineral layer, although this downward transport will be retarded by the closed pore structure of the peat matrix (Loxham 1980, Hoag and Price 1997, Ours et al. 1997). By 2003, solute had migrated downwards to at least 95 cm below the surface in the cores extracted near C3, where there were consistent downward hydraulic gradients (Figure 5). Although there was evidence of low salinity levels (less than 2‰) in the mineral substrate (Figure 6), the dominant downward hydraulic gradient likely countered the upward diffusion of salts from areas with slightly saline mineral sediments (McKenzie et al. 2002). It is currently unknown whether the salt in these mineral sediments are of tidal origin or if they are the result of the net downward transport of salts from the January 2000 storm surge. The former is likely the case at C2 (380 cm depth), whereas the latter may explain the salinity at C3 (125-cm and 150-cm depths).

A downward hydraulic gradient is not the only mechanism that can explain the depth of solute distribution in the peat profile. The annual formation of ground frost can force a downward migration of solutes in line with the freezing front. The depth of ground frost at this site extended at least

80 cm below the peat surface (Figure 2a), and harvested peatlands have been shown to exhibit lower soil temperatures and deeper ground frost than natural peatlands (Price 1996). Solutes are selectively excluded from ground ice and the accumulation of solutes at the freezing front can result in a downward movement of solutes during the freezing process (Kadlec 1984, Kadlec and Li 1990, Chague-Goff and Fyfe 1997). Since the formation of ground frost and its influence on solute levels was not directly measured in this study, it was difficult to assess its overall contribution to the vertical redistribution of solutes, particularly since the magnitude of solute exclusion from ground ice depends upon the rate of freezing (Kadlec 1984).

CONCLUSION

The long-term fate of solutes at this site depends on the ability of solutes to migrate to and through the sediments underlying the peat deposit, since there were no significant lateral outflows. The flux of solutes toward the lower boundary depended on vertical transport processes. Diffusion is a very slow process (Wilcox 1986b, Puranen et al. 1999) that will not significantly alter the salinity in the next decade. In the near-surface layer, changes in soil moisture result in the dilution of solutes during precipitation events and the concentration of solutes during drier periods. Moreover, evaporative drying can increase the salinity in the rooting zone by up to 20-fold over the summer season (Figure 7). In the 50-cm to 150-cm deep layer, hydraulic gradients were more stable in direction with a predominant downward flow at most piezometer clusters (Table 1). In the lower elevation areas (Figure 8), it is likely that the total peat thickness has been contaminated by seawater, as has occurred at C3 (Figure 5). The net downward transport that has occurred has been significantly retarded by the closed pore structure of the peat (Loxham 1980), which delays solute flux (Hoag and Price 1997, Ours et al. 1997).

The predominant downward vertical hydraulic gradients suggest that salts will eventually be leached out of the peat profile over a long time span; however, the rate of this leaching could not be estimated by this study. Despite this downward movement of solutes in the peat profile, salt in the surface layer (0 to 22 cm) still remains above the threshold limit for native bog species (Wilcox 1984, Wilcox 1986a, Wilcox and Andrus 1987) and will likely remain so for many years due to the seasonal cycle of salt dilution during the spring snow melt and salt concentration during summer evaporation.

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