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Journal of Hydrology 161 (1994) 181–195

Journal of Hydrology

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Water exchanges in a shoreline *Typha* marsh on Lake Ontario

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Received 21 September 1993; revision accepted 21 February 1994

Abstract

A *Typha*-dominated marsh bordering Lake Ontario had a strong hydraulic connection with the lake during spring 1991, when the water level was more than 10–20 cm above the marsh surface. During this period, water-level changes were dominated by the general decline of Lake Ontario, by short-term fluctuations caused by seiche activity (1.7 h periodicity) and by setup (diurnal). These were transmitted into the marsh at 65–135 m h^{-1}. The water surface profile was generally flat over the marsh during this period but water depth was uneven owing to peat surface adjustment. High buoyancy of the surface in the 30 m margin adjacent to the lake minimized water depth there. By 21 June, water depth at the margin was essentially zero, but elsewhere was 0.07–0.1 m; all water exchanges between the marsh and lake were thereafter constrained to relatively slow subsurface flow (approximately 10^{-3}–10^{-4} m h^{-1}). Short-term fluctuations caused by lake-level variability were then restricted to the margin. The Lake Ontario water level then dropped faster than that on the marsh, as did the water table on the adjacent mineral terrain, resulting in an upwardly convex water surface profile on the marsh, where water flow was away from the marsh. Between 14 June and 6 August, 116 mm of rain and 264 mm of evapotranspiration resulted in 30 mm of lateral water loss from the marsh centre; only 1 mm was lost at the marsh margin, reflecting the frequent reversals of hydraulic gradient there.

1. Introduction

Hydrological processes in lakeshore wetlands control many ecological and geochemical functions, yet their internal hydrological regime and linkage with lake systems has not been well documented. The location of wetlands within the northern temperate climatic zone, and on the Great Lakes shorelines, ensures that water exchanges are pulse-fed, owing to seasonal inputs governed by snowmelt runoff (King, 1984), and shorter-term processes such as storm- and seiche-induced

SSDI 0022-1694(94)02481-P

water-level fluctuations (Sager et al., 1984). These processes are important as they affect the exchange of nutrients and contaminants between the lake and wetland system, as well as the sediment loading (Wetzel, 1992). Major storm surges and the resulting seiches are most common between October and November, whereas the summer months have relatively minor activity (Bedford, 1992).

Lateral water flows in non-tidal systems may result from gradients produced by the internal water balance (Price and Woo, 1988), and the exogenically controlled lake level. Small hydraulic gradients typical of coastal marshes (Nuttle, 1988), and frictional resistance from above-ground vegetation and microtopography (Kadlec et al., 1981), limit the rate of lateral water flow. Surface water flow in wetlands measured by Hammer and Kadlec (1986) was 10–100 m day^{-1}, whereas subsurface flows are typically many orders of magnitude lower. Mitsch and Reeder (1992) found that water inflow to a Lake Erie coastal marsh was dominated by surface inflow from the catchment, whereas lake water represented only 18% of the total water inputs. The vertical water fluxes in the form of rain accounted for only 5% of total inflow, whereas evaporation was 10% of total outflow. Snow entrapment by lakeshore wetlands may enhance the water flux to the marsh in the spring (Geiss, 1984). During summer, evapotranspiration from the *Typha* marsh bordering Lake Ontario was at the potential rate, and enhanced the water loss relative to the lake (Price, 1994). The water-level changes produced by these processes create subtle gradients which drive water and nutrient exchanges. However, water flow in wetlands is seldom uniform because of surface microtopography (Kadlec et al., 1981). Furthermore, peat surface adjustment occurs in some wetlands in response to changes in pore water pressure within the peat matrix (Nuttle et al., 1990; Roulet, 1991), affecting both lateral surface and subsurface water flows. The surface adjustment is caused when fluid pressure supporting the porous matrix changes, such as when the water table is raised or lowered (Freeze and Cherry, 1979).

This study examines the spatial and temporal water level variations in an extensive *Typha*-dominated marsh bordering Lake Ontario, to improve understanding of water exchanges between the marsh and adjacent upland and lake systems. Specifically, the objectives are to determine (1) the role of Lake Ontario on the marsh water level, (2) the effect of peat surface adjustment on water exchange, and (3) the effect of the water balance on lateral water flows.

2. Study area

The study area on the southeast shore of Wolfe Island (44°12′N, 76°22′W) (Fig. 1) is part of a 160 ha wetland complex, located at the head of semi-enclosed Bayfield Bay. The area is underlain by Ordovician limestone, covered with approximately 2 m of laminated clay originating from glacial lake Iroquois (Dalrymple and Carey, 1990). Poorly decomposed peat overlies the mineral sediments. The peat thickness ranges from 0 m at the interface with the mineral shore to 5 m at the lake margin. Peat in the upper 1 m is poorly to moderately decomposed, except at the marsh margin, where decomposition is moderate to good. This is an ‘open’ wetland (Mitsch, 1992), as there

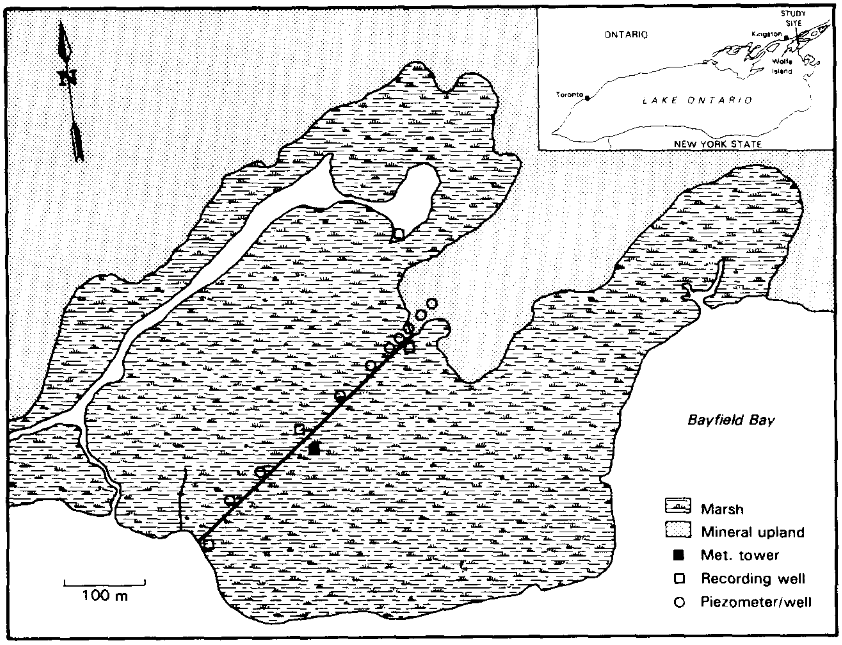

Fig. 1. The study area, and instrument location.

is relatively little mineral sedimentation, and no barrier or impoundment. The upper 0.2–0.3 m contains abundant *Typha* roots and rhizomes. The marsh is dominated by *Typha latifolia* L., *T. angustifolia* L., and hybrid *T. glauca* Godr.

The climate can be described as cool temperate, with 30 year mean January and July temperatures at Kingston of −7.7°C and 20.1°C, respectively, and 30 year mean annual precipitation of 867 mm, 22% of which falls as snow (Environment Canada, 1982). The study site (Fig. 1) is an approximately 400 m × 400 m section of the wetland complex which has developed around a peninsula of mineral terrain. The wetland is surrounded on three sides by water, half of which is open water of Bayfield Bay, and half of which is channel and shore lagoon.

3. Methods

The study was conducted between 23 May and 9 August 1991. A transect was established from 20 m upslope (−20 m) of the mineral terrain–wetland interface (0 m) to within 3 m of the Lake Ontario shoreline (375 m). Recording wells placed 10, 175 and 375 m along the transect, were constructed of stovepipe of 0.2 m diameter, slotted along their entire 1 m length, and anchored to the mineral substrate. A similarly constructed recording well was placed in the pond just north of the transect (Fig. 1). Wells on the mineral upland (−20 and −10 m) were constructed of slotted 16.5 mm (i.d.) PVC, set into a 0.1 m borehole, and backfilled with sand. Piezometers were placed along the transect at −20, −10, 0, 10, 20, 50, 100, 250 and 300 m (Fig. 1).

Piezometers on the marsh were constructed from 16.5 mm (i.d.) PVC, with 0.3 m slotted intakes. These were lowered into 25 mm boreholes, so that their intakes were below the peat–clay interface. Water table measurements were made at these locations by measuring to the water table along the outside of the tube. Piezometers on the mineral terrain (−20 and −10 m) were of similar design, but were installed into a borehole of 0.1 m diameter with sand intake of 0.4 m length, and backfilled with hydraulic cement.

At 175 and 375 m transect locations the peat surface elevation was monitored continuously with an aluminium foot resting on the peat surface. The water table and peat surface were monitored with a potentiometer–pulley device connected to a data logger. Precipitation and evapotranspiration were measured at the 175 m location along the transect (Fig. 1). Rain was measured with a tipping bucket gauge, and evapotranspiration was estimated with a three-level Bowen ratio–energy balance system. A complete description of this instrumental setup and theoretical background has been given elsewhere (Price, 1994).

Specific yield (S_Y) is the volume of water released or stored per unit area of soil, for a unit change in water table. S_Y was measured from 0.05 m sections of peat monoliths 175 and 375 m along the transect, which were extracted when frozen. The sections were thawed, saturated, then drained for 24 h. Specific yield was calculated as

$$S_Y = \frac{(M_{\text{saturated}} - M_{\text{drained}})/\rho_w}{M_{\text{saturated}}/\rho_w} \tag{1}$$

where M is mass, and ρ_w is density of water, assumed to be 1000 kg m^{-3}. Two samples of the mineral substrate at depths of 0–0.1 and 0.1–0.2 m below the peat/mineral-sediment interface were collected 10 m along the transect (unfrozen), and S_Y was calculated in the same manner (Eq. (1)).

Hydraulic conductivity was measured using the bail test procedure described by Hvorslev (1951), in the wells and piezometers described above. Additional tests were made in further 0.2 m wells which were slotted from depths −0.02 to −0.5 m.

4. Results

For the period May to August 1991, temperature and rainfall measured at the Kingston, Ontario, weather station 10 km to the northwest was 18.6°C and 233 mm, compared with 30 year mean values of 16.9°C and 264 mm, respectively (Environment Canada, 1982, 1991). The Lake Ontario water level during the same period averaged 74.91 m above sea-level (Fisheries and Oceans, 1992, 1992a), compared with the 30 year mean of 74.85 m above sea-level (Environment Canada, 1992).

Between 23 May and 6 August, total rainfall measured at the site was 155 mm (Fig. 2). Rain was not evenly distributed over the study period. It was relatively dry during June, with most events being less than 5 mm. During July and early August, most of the rain fell in convective storms producing over 15 mm of water (Fig. 2). The energy balance measurements indicate that evapotranspiration ranged from 0.6 to 7 mm day^{-1}, and averaged 4.8 mm day^{-1}. Some periods lack evapotranspiration data

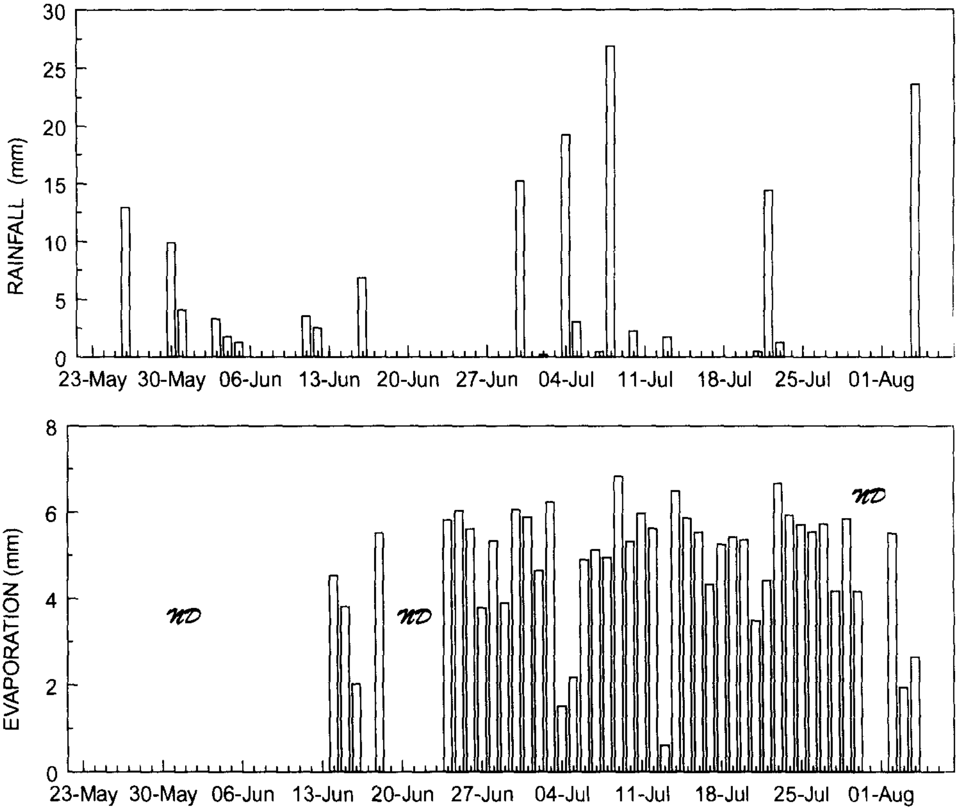

Fig. 2. Rain and evapotranspiration. 'ND' indicates periods of two or more days with no data.

but, based on the daily average, the total for the measurement period was 365 mm, indicating that a 210 mm moisture deficit accumulated between 23 May and 6 August.

There was a general lowering of the water table over the study period at all measurement locations (Fig. 3). On 27 May, the water surface profile was flat across the marsh and continuous with the lake. The water table in the adjacent mineral soil was elevated following local snowmelt recharge and there was a groundwater ridge immediately adjacent to the marsh, which developed in response to 13 mm of rainfall on the previous day. By 10 June, the water table in the mineral soil had receded, but the general water level was still above the surface of the marsh. The rapid recession of the water level in the mineral soil resulted from the low specific yield there (0.05), compared with the marsh peat (0.15–0.5) (Fig. 4). By late June, the lower water levels near the mineral terrain induced drainage away from the marsh, albeit relatively slowly because of the low hydraulic conductivity of the mineral sediments (Table 1). The water table at the nearby 10 m marsh site receded into the mineral substrate and thereafter exhibited relatively large fluctuations in response to rain and evapotranspiration (Fig. 5). At the 175 m site, the water table remained within the upper 0.1 m of the peat, where the specific yield was higher; likewise at the 375 m site,

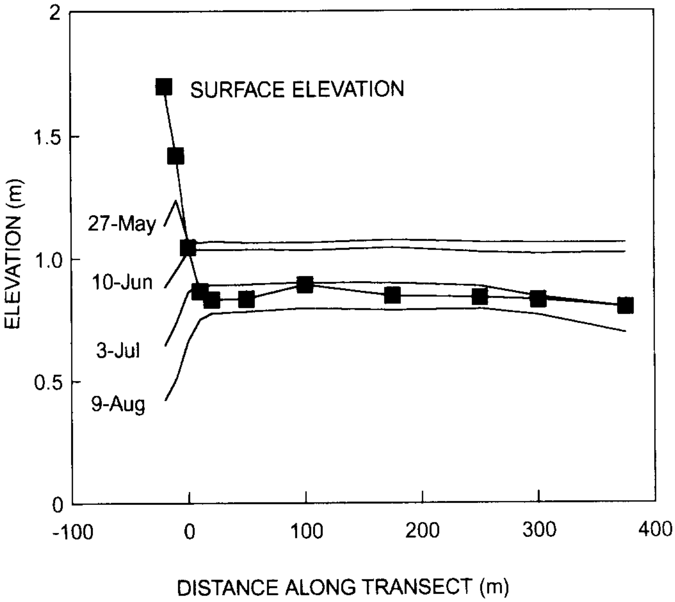

Fig. 3. Water surface profiles on date shown. Surface elevation is that recorded on 3 July.

the average elevation of the water table did not drop more than 0.03 m below the peat surface. On 3 July and 9 August (Fig. 3), the water table data indicate that the Lake Ontario level had receded more quickly than that in the marsh, leaving an upwardly convex profile during the latter half of the study period.

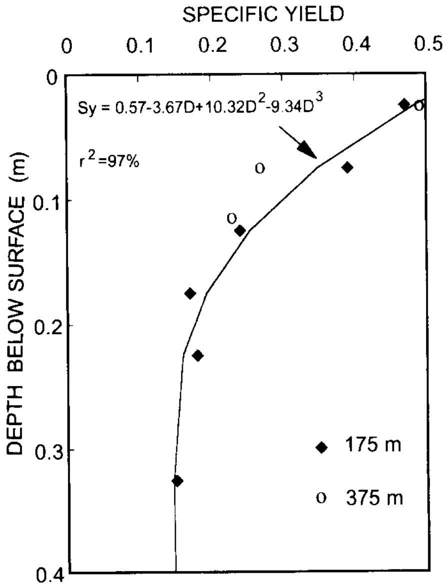

Fig. 4. Specific yield at 175 m and 375 m along the transect.

Table 1
Hydraulic conductivity of peat and mineral sediments ($m\,s^{-1}$)

	Distance along transect (m)					
	0	50	100	250	300	375
Peat 0–0.5 m	–	8.4×10^{-4}	–	9.6×10^{-4}	–	7.4×10^{-4}
Peat 0.5–1.5 m	–	2.3×10^{-6}	–	–	3.0×10^{-6}	2.8×10^{-6}
Basal peat	–	–	–	–	1.0×10^{-7}	4.2×10^{-6}
Mineral substrate	1.1×10^{-5}	4.6×10^{-8}	5.0×10^{-8}	–	5.0×10^{-8}	–

Water levels measured continuously at 10 m, 175 m, 375 m, and at the pond show the general decline in water levels (Fig. 5) and a corresponding decline in the peat surface elevation at 175 m, especially at the 375 m location. The marked decline in peat surface elevation at the 375 m site was representative of the outer 30 m of the marsh, which was characterized by 5 m of notably buoyant peat. In the marsh interior (i.e. at 175 m), the 2.7 m of peat was firmer, and there was less subsidence (Fig. 5). No measurable surface adjustment was found at the 10 m site, where the peat thickness was only 0.6 m. At the 375 m location, spot measurements between 23 May and 15 June indicated that the water level ranged between 0.05 and 0.10 m above the peat surface; by 21 June it had declined to the elevation of the surface (continuous recording of the surface elevation at this site did not commence until 4 July). In the marsh interior, the water level on 21 June was still approximately 0.7 m above the marsh surface (at 175 m). The water level in the pond responded similarly to the lake, but with reduced amplitude, as the channel connecting the lagoon and pond (Fig. 1) was constricted (i.e. not navigable by canoe). Surface adjustment was not important at the margin of the lagoon, as the peat thickness was only about 1 m.

Superimposed on the general decline of the water table were periodic peaks related to rainfall events and frequent variations not associated with rain or local precipitation. Rapid water-level fluctuations not associated with rain were most evident in the record 375 m along the transect, which was about 3 m from the actual lakeshore, and essentially recorded the local lake-level fluctuations.

In Fig. 6(a) the measured water level at 375 m is shown along with the 2 h running mean. The periodicity appears to be a response to at least two different cycles not related to rainfall. The shorter-term fluctuations had a periodicity averaging 1.7 h, and their average amplitude was 14 mm. These were probably seiche related. There were also longer, diurnal cycles (visible from the 2 h running mean) which peaked at about 13:30 h, corresponding to the daily setup which occurred in response to wind stress (Fig. 6(b)). The average amplitude of the longer cycle was 43 mm. Together, these cycles produced a total (maximum minus minimum) daily water-level change averaging 62 mm. These exogenically controlled pulses were transmitted across the marsh at a rate which decreased as the water level dropped. Lake-level fluctuations forced water in and out of the marsh, causing subdued and lagged water-level changes in the marsh interior (i.e. at 10 m, 175 m, and at the pond) (Fig. 5). The velocity at which these pulses were transmitted from the lakeshore (approximately 375 m), to the

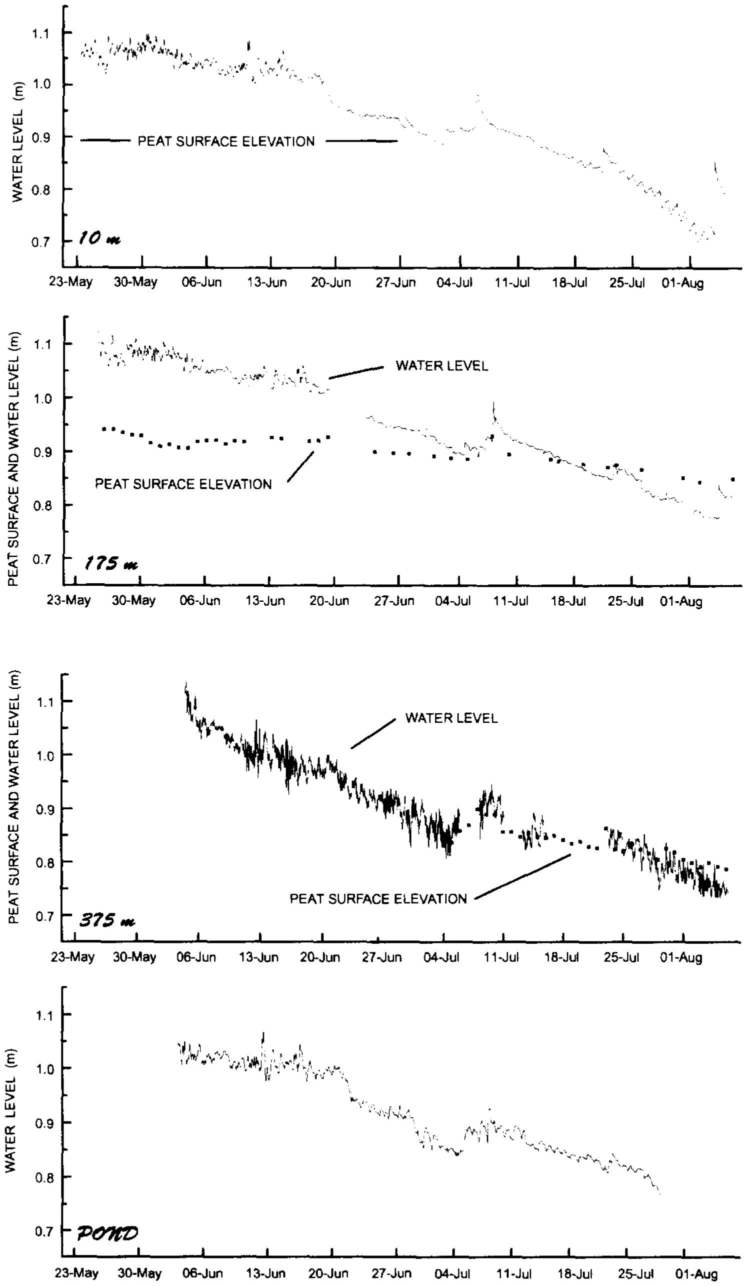

Fig. 5. Water and/or peat surface elevation 10, 175 and 375 m along the transect, and at the pond.

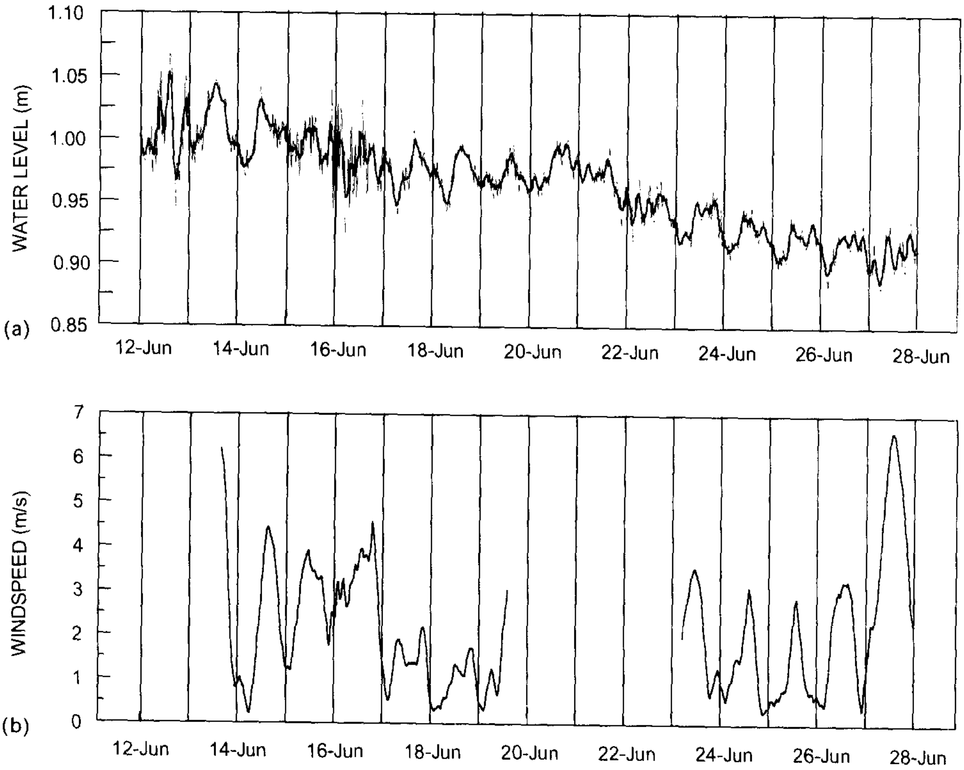

Fig. 6. Water table at 375 m along the transect, and 2 h running mean (above), and windspeed (below).

marsh centre (175 m), ranged from 65 to 135 m h^{-1} depending on the water depth above the surface (measured at 175 m) (Fig. 7). Seiche- and setup-induced flood waves were no longer apparent after 21 June, when water level dropped to 0.7 m above the surface of the marsh interior. Importantly, this water level corresponded to the surface elevation at the marsh margin, so that the water depth there was zero.

After 21 June, when the seiche- and setup-induced water-level changes became insignificant in the marsh interior, inflow and outflow forced by seiche and setup processes was constrained to the 30 m margin, which experienced surface adjustment. Based on the average daily water-level change at the margin (62 mm), and assuming the peat surface was relatively fixed 30 m beyond the marsh margin (30 m), the hydraulic gradient was 0.002. Given that the hydraulic conductivity near the surface was 7.4×10^{-4} m s^{-1} (Table 1), the subsurface flow rate was 5×10^{-3} m h^{-1}, or about four to five orders of magnitude less than water pulses transmitted across the surface by seiche and setup activity. Given the alternating direction of the hydraulic gradient, the net subsurface water flow was small. As the lake water-level dropped more quickly than that of the marsh (Fig. 3), the net flux was in the direction of the lake.

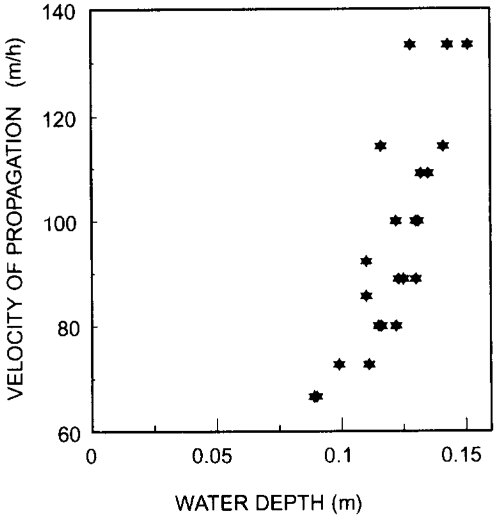

Fig. 7. Velocity of transmission of seiche-induced pulses of water from the lakeshore (375 m), to the marsh interior (175 m), plotted against water depth above the surface 175 m along the transect.

5. Water balance

A water balance was performed for the marsh interior (175 m), and the marginal zone (375 m). The water balance is

$$P + Q_i = E + Q_o + dS \tag{2}$$

where P is rain, Q_i and Q_o are lateral inflow and outflow, E is evapotranspiration, and dS is storage change. Rearranging Eq. (2),

$$(P - E) - dS = Q_o - Q_i \tag{3}$$

where the right-hand side ($Q_o - Q_i$) represents the net lateral flow, which was determined as a residual. The difference between the moisture deficit ($P - E$) and the measured storage change (dS) represents the amount of water that is required or released as surface and subsurface flow. Storage change was determined as

$$dS = \Delta h \tag{4}$$

or, if the water table was beneath the surface,

$$dS = S_Y \Delta h \tag{5}$$

where Δh is the change in water table elevation. S_Y at both sites was adjusted daily based on observed water table depth (Fig. 4). The results of the water balances calculated for the period 14 June–6 August are shown in Fig. 8. At both sites, the rain was 116 mm and evaporation was 264 mm, so that the moisture deficit ($P - E$) was 148 mm. At 175 m, the storage change was down 178 mm, resulting in an estimated net outflow of 30 mm. At 375 m, the storage change of 147 mm was close to the moisture deficit, so there was little net lateral outflow (1 mm). Net lateral

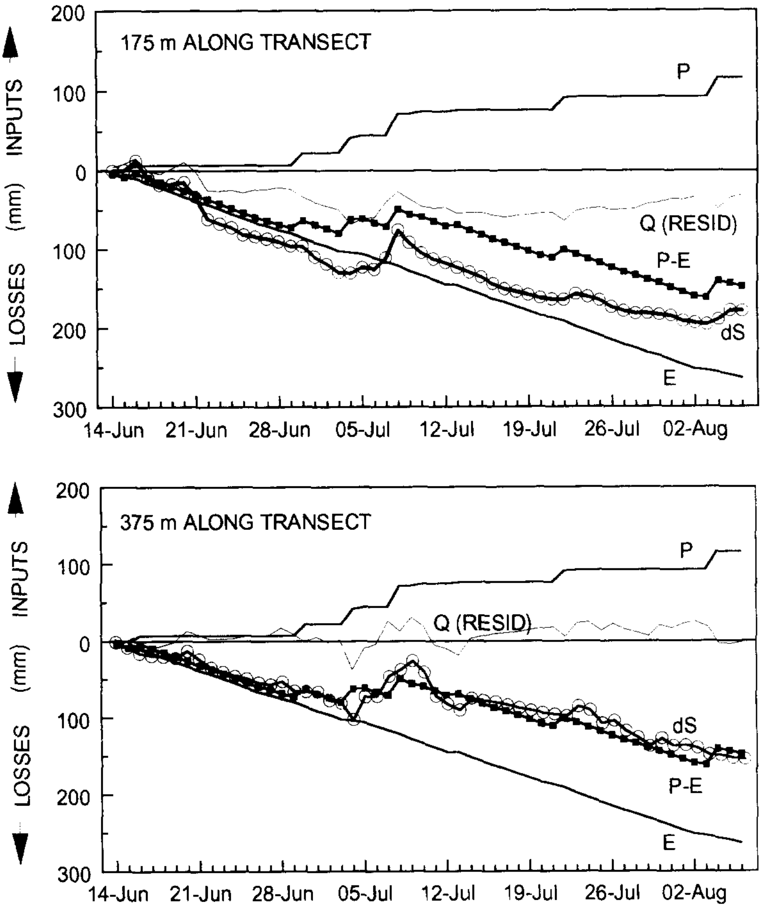

Fig. 8. Water balance 175 and 375 m along the transect. *P* is rain, *E* is evapotranspiration, d*S* is measured storage change, and *Q*(resid) is lateral flow calculated as a residual.

flow at 375 m experienced numerous periods of flow reversal, shown in Fig. 8 by the alternating positive and negative values of *Q*(resid). As vertical hydraulic gradients were typically less than 0.005, vertical seepage to or from the low-permeability mineral substrate was less than 1 mm.

6. Discussion

Water levels in the Great Lakes undergo cyclical changes (Burton, 1984), but the long-term trend through the Holocene has been a rise of approximately 3 m at the eastern end of Lake Ontario (Dalrymple and Carey, 1990). This has resulted in the formation of marsh peat in Bayfield Bay, which has undergone accretion and advanced up the mineral shoreline over time, causing progressive paludification there. The result is a thin, relatively dense fibrous peat at the mineral terrain interface; this experiences more frequent drying than do other outer parts of the wetland, and thicker peat of similar genesis toward the marsh centre. There has been a simultaneous outward growth toward the lake (terrestrialization), where amorphous sedimentary peat has accumulated beneath the outermost floating portion of the marsh. The peat at 375 m is continuous for 5 m beneath the surface, down to the mineral substrate. However, the peat there is of low density, and the fibrous mat above it is notably buoyant (e.g. Hogg and Wein, 1987). It is important to note that this marsh is distinct from many shoreline marshes of the lower Great Lakes, which are typically dominated by mineral sediments resulting from longshore transport processes (Mitsch, 1992). As the marsh has formed in an embayment on Wolfe Island, it has a limited source of sediment compared with the main shore of Lake Ontario. The highly compressible nature of organic deposits accentuates the surface adjustment described in this study. Changes in water level cause surface adjustment, as fluid pressure bears much of the effective stress in a compressible medium such as peat. The low-density sedimentary peat found at the marsh margin is therefore highly susceptible to surface adjustment. This has important implications for the hydrological processes that operate on the marsh, as changes in the peat surface affect the depth of standing or flowing water over the surface. This process will be discussed later, in conjunction with changing water levels caused by the seasonal regime of Lake Ontario.

During spring, Lake Ontario water levels were high, so there was a very strong hydraulic connection between the lake and marsh systems. Because of the strong linkage, and the extreme difference in the size of lake and wetland, water-level variability in the marsh was imposed by the lake. For example, even though evapotranspiration was 3.7–12.5 times higher from the marsh than from the lake (Price, 1994), water loss in the marsh was immediately replaced by lake inflow owing to the good hydraulic connection during that period.

Frequent short-term variations (periodicity 1.7 h) which were superimposed on the general trend of declining water levels are attributable to seiche activity. However, these do not compare well with the theoretical uninodal seiche in Lake Ontario calculated by Crystal's formula (Hutchinson, 1957), which has a periodicity of about 5 h. This disagreement is caused by the complex local bathymetry, whereby much of eastern Lake Ontario is effectively isolated in a rather small basin by the Duck–Galoo sill (Gilbert, 1990). Setup was not influenced by harmonic behaviour or local nodes; rather, it responded to the daily wind shear caused by prevailing winds, peaking in early afternoon.

As water levels in spring were high, the hydraulic connection was strong. Both seiche- and setup-induced fluctuations were transmitted readily into the marsh at rates of 65–135 m h^{-1}. The relatively short lag which was experienced in the marsh interior was due to the frictional resistance from the dense *Typha* stems and marsh microtopography. Given this relatively rapid adjustment, however, the marsh and lake water levels quickly equilibrated, and the general water surface profile was flat (Fig. 3).

As the lake level declined further, the depth of the water on the marsh exhibited spatial variation such that at the marsh margin the relative depth approached zero, whereas in the marsh interior the water level remained above the surface. This was not due to a sloping water surface, but rather occurred because peat surface adjustment responded differently at different locations. At the marsh margin, the buoyant surface matched the lake level by 21 June. However, the more dense and rigid peat matrix of the marsh interior remained approximately 0.7 m below the water surface. Therefore, although lateral surface flows were theoretically possible within the marsh, water exchanges between the marsh and lake occurred only as subsurface flow through the peat matrix of the marsh margin, where the water table was not above the surface. Although the hydraulic conductivity of surficial peat was high (Table 1), comparable with values suggested by Boelter (1972) for slightly decomposed herbaceous peat, this still resulted in much lower seepage than surface water flows (Fig. 7). This severely restricted lateral water flow, and the marsh interior became effectively decoupled from the lake. Owing to relatively rapid drainage of the lake, the lake surface receded faster than that in the marsh, leaving an upwardly convex water surface in July and August (Fig. 3). During this period, water drained predominantly away from the marsh centre, and by mid-July the water table fell below the marsh surface everywhere. The water table drawdown in the peat was less than 70 mm, however, as the specific yield was large (Fig. 4). The specific yield in the poorly decomposed *Typha* mat is comparable with values for slightly decomposed (0.57) to moderately decomposed (0.13) herbaceous peat measured by Boelter (1972). Drainage was also occurring toward the mineral upland, as the low specific yield there (0.05) resulted in a large water table drop for a given abstraction of water. This drainage most notably affected the marsh at the nearby 10 m location, where the water table receded into the mineral substrate. Here again, variability caused by rain and evapotranspiration became more apparent, because of the low specific yield. A similar phenomenon was reported by Price (1991).

The upwardly convex shape of the water surface later in the summer (Fig. 3) resulting in lateral water loss from the marsh was confirmed by the water balance calculations. These indicate that the marsh interior lost approximately 30 mm in a continuous outward drainage, whereas the marsh margin experienced frequent flow reversals caused by alternating hydraulic gradients and had a net outflow of only 1 mm. The result of this water balance is very different from that described by Mitsch and Reeder (1992). Here, water fluxes were dominated by vertical flows, notably rain and evapotranspiration. Lateral flows would no doubt have been more important if the water balance period had included the spring season, when the water levels were higher.

As lake levels continue to decline into the autumn and winter, drainage toward the lake can be expected to predominate. However, as storm surges and seiches are typically larger and more frequent during the October to December period (Bedford, 1992), occasional water inputs from the lake may occur.

7. Conclusion

The *Typha*-dominated wetland bordering Lake Ontario experienced a hydrological regime which was intimately linked to the lake, but which was distinct from it. Lake Ontario water levels follow an annual cycle of high water in spring, and declining water levels thereafter. In spring, the marsh was inundated, transmitting seiche- and setup-induced water-level fluctuations (with 1.5 h and 24 h periodicity, respectively) from the lake at rates of 65–135 m h^{-1}. During this period, there was a strong two-way linkage between the lake and marsh, which may be important to the redistribution of solid and dissolved material within the marsh and across the marsh–lake boundary. The strong hydraulic connection was broken abruptly when the lake level declined to the level of the buoyant outer margin of the marsh. This precluded surface water exchanges, so flow was reduced to 10^{-3}–10^{-4} m h^{-1}, occurring as subsurface seepage.

The lake level fell at a faster rate than the water level in the marsh interior, resulting in an upwardly convex water surface profile by mid-June. This ensured that water flows from the marsh were predominantly outward. The exception was in the 30 m marginal zone of the marsh adjacent to Lake Ontario, where buoyant peat responded readily to changing gradients, and experienced alternating inflow and outflow. The water balance calculations support this, suggesting that there was a relatively strong export of water (30 mm) from the marsh centre, and a relatively small net export (1 mm) at the margin, because of the frequent flow reversals. The reversing hydraulic gradients in this zone amplified the amount of water moving through, which has important implications for the nutrient budget and for sequestering contaminants which may be in the lakewater. Except for a brief period during spring, it is only this buoyant margin which maintains good two-way hydraulic connection with the lake.

8. Acknowledgements

Financial assistance was received from the Natural Science and Engineering Research Council of Canada. Access to the private property was readily granted by Dale and Linda Sutherland.

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