The hydrological and geochemical isolation of a freshwater bog within a saline fen in north-eastern Alberta

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SUMMARY

In the oil sands development region near Fort McMurray, Alberta, wetlands cover ~62 % of the landscape, and ~95 % of these wetlands are peatlands. A saline fen was studied as a reference site for peatland reclamation. Despite highly saline conditions, a freshwater bog was observed in the path of local saline groundwater flow. The purpose of this study was to identify the hydrological controls that have allowed the development and persistence of a bog in this setting. The presence of bog vegetation and its dilute water chemistry suggest that saline groundwater from the fen rarely enters the bog, which functions predominantly as a groundwater recharge system. Chloride (Cl^-) and sodium (Na^+) were the dominant ions in fen water, with concentrations averaging 5394 and 2307 mg L^{-1}, respectively, while the concentrations in bog water were 5 and 4 mg L^{-1}, respectively. These concentrations were reflected by salinity and electrical conductivity measurements, which in the fen averaged 9.3 ppt, and 15.8 mS cm^{-1}, respectively, and in the bog averaged 0.1 ppt and 0.3 mS cm^{-1}, respectively. A small ridge in the mineral substratum was found at the fen–bog margin, which created a persistent groundwater mound. Under the dry conditions experienced in early summer, groundwater flow was directed away from the bog at a rate of 14.6 mm day^{-1}. The convex water table at the fen-bog margin impeded flow of saline water into the bog and instead directed it around the bog margin. However, the groundwater mound was eliminated during flooding in autumn, when the horizontal hydraulic gradient across the margin became negligible, suggesting the possibility of saline water ingress into the bog under these conditions.

KEY WORDS: groundwater flow; peatland hydrology; saline wetlands; substrate topography; Western Boreal Plain

INTRODUCTION

Wetlands cover up to 50 % of the Western Boreal Plains (WBP) in Alberta, Canada (Vitt *et al.* 1996). In the Athabasca oil sands development region, wetland cover can be up to ~62 %, and ~95 % of this is peatland (Suncor Energy Ltd. 2005). The regulatory requirement to reconstruct peatlands as part of the reclamation of post-mined areas demands a better understanding of how landscape design and substrate morphology influences the hydrology and geochemistry of constructed systems (*cf.* Price *et al.* 2010), and this can be derived by studying natural analogues. The distribution and character of regional peatlands has resulted from the physiographic legacy of the most recent glaciation during the Late Wisconsinan period and the effects of climate change throughout the Holocene (Zoltai & Vitt 1990, Halsey *et al.* 1998). Similar climatic and physiographic factors continue to control present-day peatland development in north-eastern Alberta (Halsey *et al.* 1998), where the complex regional hydrogeology strongly influences peatland distribution and function. The abundance of peatlands in the WBP region can be largely attributed to the gently sloping topography in combination with substratum properties (Kuhry *et al.* 1993, Almquist-Jacobson & Foster 1995). Although the climate is sub-humid (i.e. relatively dry), the short, warm summers and long, cold winters result in persistent ground frost which can help maintain conditions that are sufficiently wet to sustain peatland processes (Petrone *et al.* 2008). The typical peatland succession begins with the accumulation of fen peat, and the transition to bog peat formation (Nicholson & Vitt 1989) is typically associated with the hydrological isolation that occurs as the water table rises (Siegel 1983). Nicholson & Vitt (1989) observed that the presence of traditional convex raised bogs was minimal in the WBP region and, instead, bogs developed where drainage divides had formed within peatland complexes. However, the degree to which substrate morphology affects the local distribution of bogs *versus* fens has not been well studied.

Within the WBP, there is a great diversity of peatland forms and types, but they are predominantly fens. This includes relatively rare saline fens which may be important analogues for oil sands reclamation, as post-mined landscapes contain oil sands process waters (OSPW) with varying levels of salinity which can affect the ecology and microbial function of reclaimed systems (Pouliot *et al*. 2012). Understanding why saline fens exist, how they function and how they interact with adjacent peatland systems can provide insights into landscape design.

In the Athabasca region, the presence of salt can be attributed to the hydrogeology of the Western Sedimentary Basin (Hamilton 1971, Meijer Drees 1994, Jasechko *et al.* 2012). The salinity originates from the dissolution of halite (Hamilton 1971) from a formation that extends in a north-westward direction across Alberta, approaching the surface along its north-eastern edge near Fort McMurray, where overburden is thinnest (Jasechko *et al.* 2012). The upwelling of saline formation water, probably through faulting in the Fort McMurray area, can generate temporally sporadic groundwater discharge regions in the landscape, termed quasi-springs by Ozoray (1974), which can support saline wetlands. These wetlands are characterised by abnormally high pH levels, sodium concentrations and electrical conductivities (EC), and atypical salt-tolerant vegetation (Trites & Bayley 2009).

The subsurface hydrological connectivity and consequent geochemical trends between these saline fens and adjacent landforms is highly dependent on substrate properties (C. Wells 2013, unpublished data). Since peatland development is often dependent on the presence of low-permeability substrate retaining sufficient water at the land surface (Labadz *et al.* 2010), vertical groundwater exchange between peatlands, especially bogs, and the substrate is typically small. Groundwater flow within mineral uplands and their connectivity with lowland wetlands has been well documented in the WBP, and is generally described as sporadic and sensitive to infrequent wet periods (e.g. Devito *et al.* 2005, Redding & Devito 2008, Redding & Devito 2010). However, hydrological interactions between lowland freshwater systems (e.g. bogs) and saline wetlands remain uncertain. To date, research on saline systems of the WBP has focused predominantly on ecological aspects (e.g. Vitt *et al.* 1996, Trites & Bayley 2009, Lilles *et al.* 2012). Given that bog waters have low solute concentrations resulting in low EC and pH (e.g. Zoltai & Vitt 1995), it is clear that water ingress from regional groundwater systems or adjacent fen peatlands is very limited.

This study aims to identify the hydrological controls that isolate a freshwater bog which sits within a saline landscape despite having formed on mineral ground that lies below the limit of saline influence. The transition between saline fen and the adjacent bog was studied to (1) characterise groundwater flow patterns at the fen–bog margin, (2) determine the controls on local groundwater flow, and (3) assess whether groundwater geochemistry is consistent with the observed hydrological patterns. It was initially hypothesised (before topographic survey) that the bog was raised and, thus, hydrologically isolated from the local flow system, flushing freshwater towards the fen; while saline groundwater, having a higher density, flowed beneath it.

METHODS

Study site

The climate of the WBP region is sub-humid, i.e. relatively dry with warm summers and cold winters. Average (1971–2000) temperatures range from 16.8 °C (July) to -18.8 °C (January), with average annual precipitation ~456 mm (Environment Canada 2013). A regional water deficit exists during most summers, i.e. potential evapotranspiration (*ET*) exceeds precipitation (*P)*, and wet years occur on a 10–15 year cycle (Ferone & Devito 2004). Devito *et al.* (2005) conclude that, within the WBP, 50–60 % of the annual precipitation occurs between June and August, and autumn is typically dry.

The saline fen (111° 09′ W, 56° 20′ N) is a 37 ha fen located in the WBP near Fort McMurray (Figure 1). Large irregularly shaped ponds characterise its southern part (not shown), while in the north it is covered by a series of ridges and depressions. Dominant fen species include foxtail barley (*Hordeum jubatum*), wire rush (*Juncus balticus*), narrow reed grass (*Calamagrostis stricta*) and sea arrowgrass (*Triglochin maritima*) (A. Borkenhagen 2013, unpublished data). Nomenclature follows Moss (1983), Crum & Anderson (1981), Brodo *et al.* (2001), Packer & Gould (2012) and FNA (1993). A 5.5 ha area on a freshwater (i.e. non-saline) wooded bog located directly north-west of the fen was studied (extends beyond the border of the map in Figure 1). The dominant non-vascular species include *Sphagnum fuscum, S. capillifolium* and green reindeer lichen (*Cladonia mitis*), with dominant shrubs Labrador tea (*Ledum rhododendrum*) and cloudberry (*Rubus chamaemorus*), and about 40 % cover of black spruce (*Picea mariana*) (A. Borkenhagen 2013, unpublished data).

The site is underlain by ~20 m of Quaternary drift over Cretaceous age shale and sandstone of the Clearwater and McMurray formations, which sits

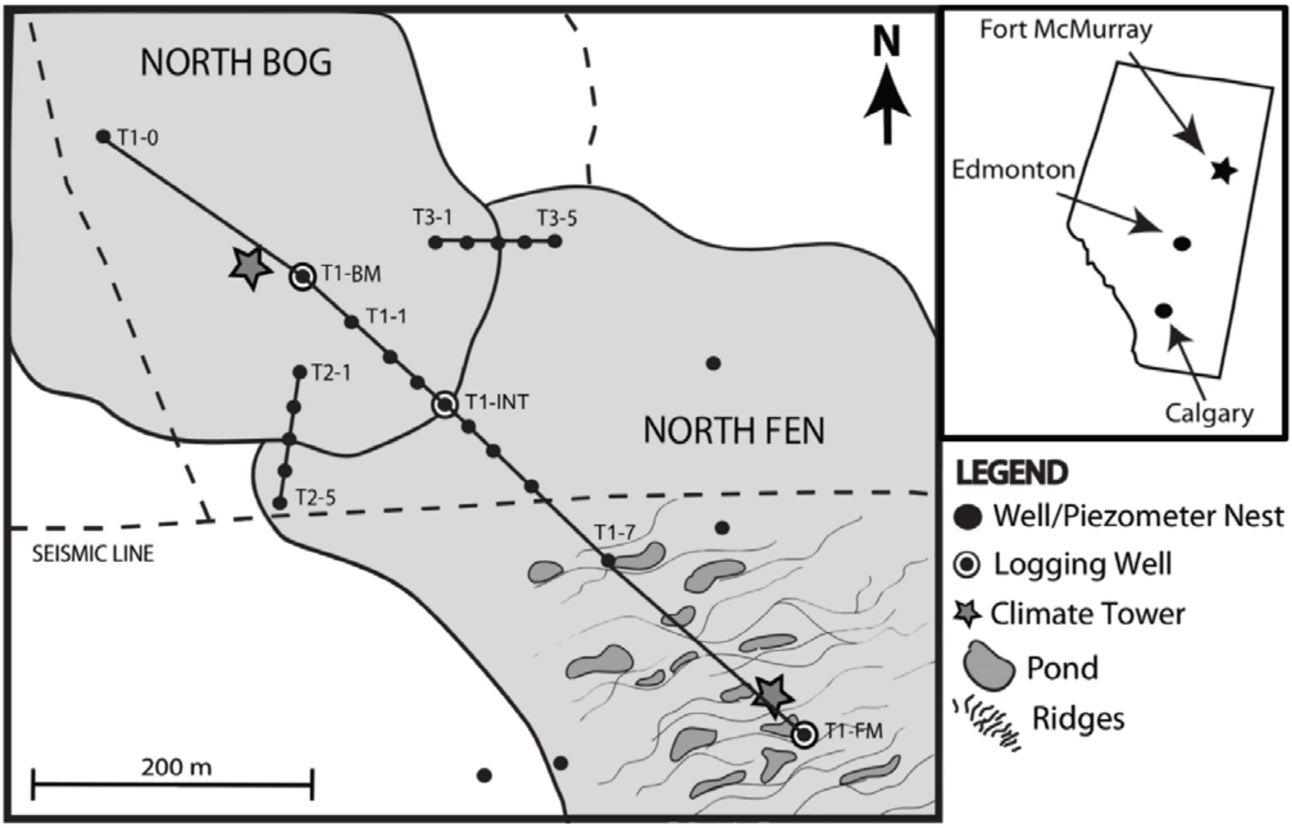

Figure 1. Map of the saline fen / bog study area located within the WBP of north-eastern Alberta (inset) ~18 km south of Fort McMurray (modified from C. Wells 2013, unpublished data).

above 180 m of Devonian age limestone of the Beaverhill Lake Group (Value Creations Inc. 2012). A continuous layer of dense marine clay underlies the fen, whereas coarser silty clay deposits are found beneath the bog. The ground slopes downwards towards the bog, creating a difference in altitude of ~1.5 m between T1-0 and T1-FM (Figures 1 and 2).

This study took place during the summer of 2012. Field observations were carried out from May 04 (Day 125) to August 12 (Day 225). All dates in this report are given as the day of year from the start of the calendar year.

Hydrology

Transect 1 (T1) was instrumented with fen and bog meteorological stations, T1-FM and T1-BM, respectively (Figure 1). Values of precipitation (*P*) and evapotranspiration (*ET*) reported in this article were measured at T1-BM. A tipping bucket rain gauge was used to continuously estimate site-scale *P*, which was compared with data from a bulk rain gauge. Missing rainfall data (Days 187–198) were substituted with data from the Fort McMurray Airport manual rain gauge, ~8 km to the north. Meteorological variables necessary to calculate *ET* were substituted from the fen meteorological station. Measurements of net radiation (Q^*), ground heat flux (Q_G) and air temperature (T_a) were used to calculate equilibrium evapotranspiration (ET_{eq}) using the Priestley-Taylor method (Priestley & Taylor 1972)

$$ET = \alpha\left(\frac{s}{s+q}\right)\left(\frac{Q^* - Q_G}{L\rho}\right) \qquad [1]$$

where s is the slope of the saturation vapour pressure-temperature curve (kPa °C^{-1}), q is the psychrometric constant (0.0662 kPa °C^{-1} at 20 °C), L is the latent heat of vaporisation (J kg^{-1}), ρ is the density of water (kg m^{-3}), Q^* is the net radiation flux (W m^{-2}), Q_G is the ground heat flux (W m^{-2}) and the Priestley-Taylor coefficient of evaporability α = 1. Actual evapotranspiration (ET_a) was determined for the fen and bog using weighing lysimeters, where monoliths of peat were weighed over time to quantify mass changes due to water loss. Lysimeter data were plotted against ET_{eq} values to empirically obtain the coefficient of evaporability α (=ET_a/ET_{eq}), which is the slope of the line. When Q^*, Q_G and T_a are available, an

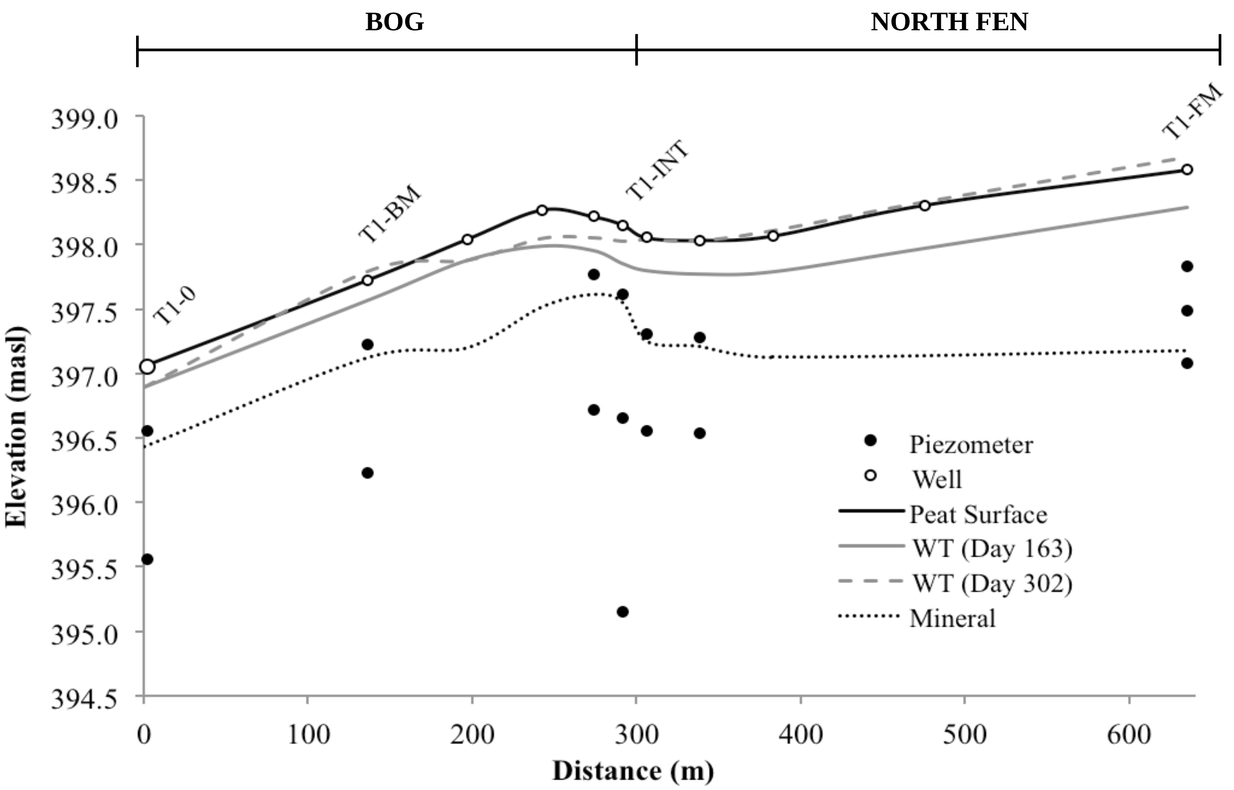

Figure 2. Stratigraphy and water table position along T1, measured from T1-0 (0 m) to T1-FM (635 m), showing water table position during a dry period (Day 163) and a wet period (Day 302).

empirical α value can be substituted in Equation 1 to calculate representative daily ET_a (e.g. Price & Maloney 1994). A literature derived value from Angstmann *et al*. (2012) was used to estimate black spruce evapotranspiration ET_{bs}. An ET_{bs} value of ~0.6 mm day^{-1} was estimated from a representative black spruce stand and summed with daily ET_a values to yield an integrated site *ET*.

Hydraulic head measurements were taken biweekly from nests of wells and piezometers installed along three transects (T1, T2 and T3), and labelled sequentially away from the bog meteorological station (Figure 1). Wells and piezometers were constructed from 2.5 cm diameter PVC pipe and covered with glass fibre filter sleeves. Wells at the T1-BM, T1-INT and T1-FM nests were instrumented with continuous water level loggers. Most of the piezometers had 17 cm slotted intakes, which were centred at depths ranging from 0.50–0.75 m in the peat and 1.0–1.50 m in the underlying mineral stratum. Where the peat layer was only 0.4 m thick along T2, piezometers with 12 cm slotted intakes were installed just above the peat–mineral interface. Nests consisted of a well and two piezometers, one in the peat and the other in mineral. At each nest within the fen–bog transition zone, a 3.0 m piezometer was also installed for water sampling purposes. Substrate stratigraphy, based on visual and textural analysis of soil type and peat composition, was recorded from the peat surface to mineral along each transect. Site topography was surveyed using a Topcon differential GPS unit.

Horizontal hydraulic conductivity (K_h) was determined using the bail test method (Hvorslev 1951), outlined in Freeze & Cherry (1979), at all peat and mineral piezometers. Specific discharge was calculated using in-field K_h values from the peat and mineral deposits.

Laboratory measurements of vertical hydraulic conductivity (K_v) and K_h, along with bulk density, particle density, porosity and specific yield, were measured at regular 10 cm intervals from two peat cores taken from the bog and fen. Hydraulic conductivities were measured using cores encased in paraffin wax using a method modified from Hoag & Price (1997). A trendline was applied to the peat K_h values to standardise K_h with depth for all transects. Transmissivity was calculated on the basis of saturated thickness of the aquifer.

Geochemistry

Groundwater sampling and *in-situ* measurements of EC and pH using a YSI 63 conductivity probe were carried out twice during the study period, on June 19 (Day 171) and August 12 (Day 225). Groundwater was sampled from peat and mineral piezometers, as well as from pits dug to the water table (near-surface samples). Water samples were analysed for calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), chloride (Cl^{-}) and sulphate (SO_4^{2-}) at the University of Waterloo Ecohydrology Laboratory, using Inductively Coupled Plasma-Optical Emission Spectrometry for cations and an ICS-5000 Capillary Chromatography System for anions.

RESULTS

Substrate characteristics

The thickness of the peat layer along the northern margin of the fen ranged from 0.8 m to 1.4 m, averaging ~0.9 m; in the bog it ranged from 0.4 m to 0.8 m and averaged ~0.6 m. The surface of the mineral substrate was elevated at the fen–bog margin on T1 (Figure 2), resulting in a locally thinner peat layer (~0.55 m). This elevated mineral mound was replicated by the ground surface, creating a local topographic high at the fen-bog margin and an adjacent shallow depression along the fen margin. This pattern was not evident on T2 and T3, where the substrate and surface sloped away from the bog and depth to mineral substrate increased towards the fen.

The fen was composed of fairly uniform dense sedge peat, while the bog peat was predominantly composed of *Sphagnum* peat and showed greater variability with depth, including a thin charcoal layer overlying the mineral horizon (Table 1). Over a 0.6 m profile, bulk density of the fen peat ranged from 0.03 to 0.11 g cm^{-3}, whereas that of the bog peat ranged from 0.07 to 0.38 g cm^{-3}. In the bog, bulk density increased and porosity decreased below 0.4 m, especially in the charcoal layer at the base. Figure 3 shows saturated K_h in various substrate strata across the site. K_h decreased by three and two orders of magnitude between the surface and 50 cm depth in bog and fen, respectively, being typically an order of magnitude higher in the bog.

Site-scale hydrology

From June 01 to August 12 (Days 153–225), 229 mm of rainfall was measured at the bog meteorological station. The largest rainfall event delivered 30 mm on Day 186 (Figure 4). In early July, from Day 183 to Day 188, the site received 94 mm of rainfall, or 41 % of the total seasonal *P*. Seasonal *ET* totalled 165±0.8 mm (average 2.3 mm day^{-1}) from the bog and 210±1.5 mm (average 2.9 mm day^{-1}) from the fen (Figure 4). Cumulative *ET* typically exceeded cumulative *P* until Day 183, after which *P* consistently exceeded *ET*.

Table 1. Comparison of peat properties between a soil core from T1-BM (bog) and T1-FM (fen).

	Bog				North Fen[a]			
depth (cm)	bulk density (g cm^{-3})	specific yield	porosity	K_h[b] (cm s^{-1})	bulk density (g cm^{-3})	specific yield	porosity	K_h (cm s^{-1})
0–10[c]	0.10	0.06	0.91	6.6×10^{-2}	0.13	0.07	0.78	6.0×10^{-3}
10–20	0.07	0.08	0.93	3.0×10^{-2}	0.11	0.05	0.85	9.7×10^{-3}
20–30	0.10	0.06	0.90	1.1×10^{-2}	0.11	0.03	0.79	6.0×10^{-3}
30–40	0.11	0.06	0.91	5.6×10^{-3}	0.13	0.05	0.83	4.7×10^{-3}
40–50	0.18	0.06	0.86	1.8×10^{-3}	0.13	0.04	0.81	2.8×10^{-3}
50–60[d]	0.38	0.19	0.77	1.4×10^{-4} [e]	0.17	0.11	0.85	3.7×10^{-3}

[a] C. Wells (2013, unpublished data).
[b] K_h values measured in the laboratory.
[c] 5–10 cm in bog peat core.
[d] 50–55 cm in bog peat core (charcoal layer).
[e] Value taken from field bail test in the charcoal layer at the base of the peat profile.

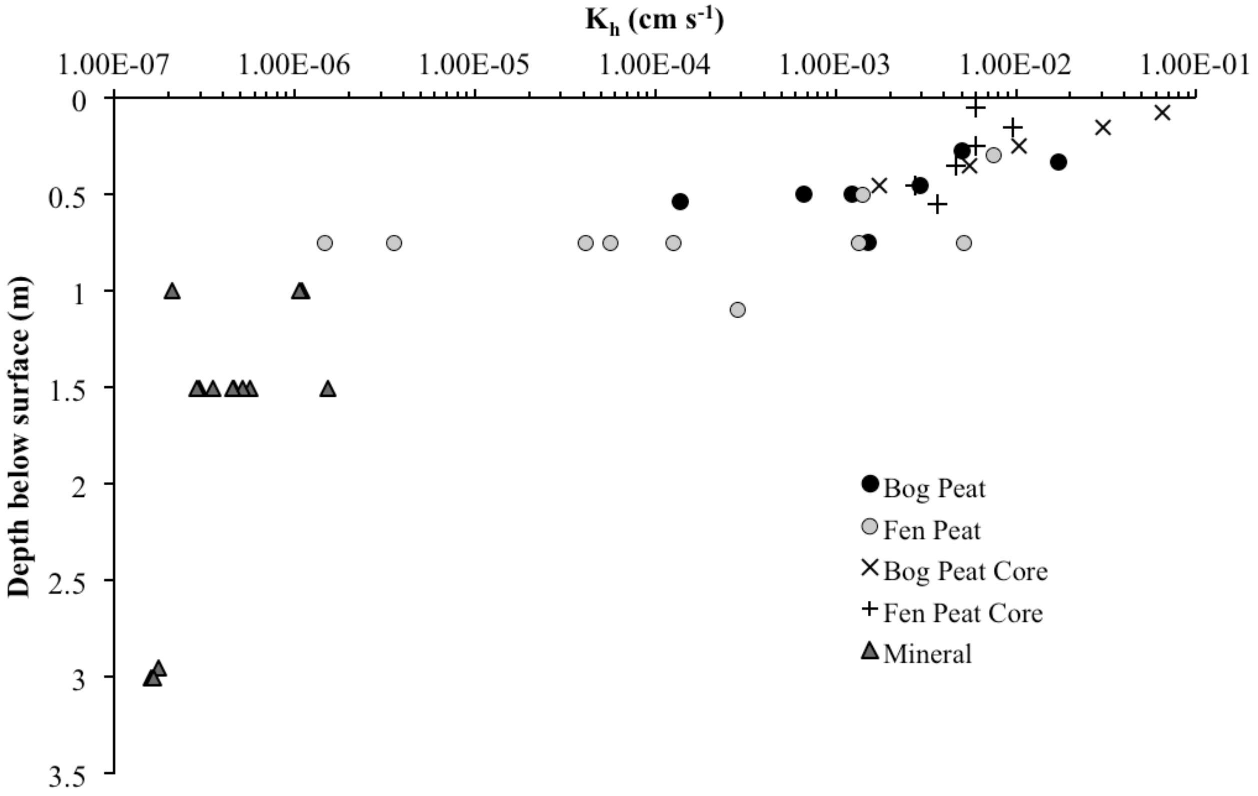

Figure 3. Saturated horizontal hydraulic conductivities (K_h) along T1, T2 and T3, calculated using the bail test method. K_h values, measured in the laboratory on the bog (T1-BM) and fen (T1-FM) peat cores, are also shown.

The water table was approximately 1 m lower at T1-BM than at T1-FM. Following spring thaw (Days 125–150), the water table fell across the whole site (Figure 4). Later in the season there was a general rise in water table level in the fen and margin, whereas bog water levels remained fairly constant (±17 cm), responding only temporarily to precipitation events (Figure 4). During a dry period between Day 171 and Day 182 the water table in the fen fell by 30 cm, compared to 14 cm and 10 cm at the margin and in the bog, respectively. However, the fen water table was relatively insensitive to rainfall and drying events later in the summer (after Day 185), when the water table rose above the ground surface. Prior to this, water table fluctuations were greatest within the fen and noticeably damped at the margin and within the bog. From June to August, the water table position changed by +36, +7 and -4 cm in the North Fen, margin and bog, respectively. The intense rainfall received from Day 183 to Day 188 shifted the hydrological regime of the North Fen to a persistently flooded state for the remainder of the study. Flooding did not occur within the bog during this period. However, higher than normal autumn precipitation, in addition to antecedent saturated conditions, caused the water table to rise above the ground surface in parts of the bog in October (Figure 2).

Groundwater flow

The water table followed the topographical gradient, decreasing in altitude from the fen to the bog (Figure 2). Horizontal gradients showed consistent groundwater flow towards the bog at an average rate, calculated using Darcy's law, of 1.0 mm day^{-1}. This rate increased by less than 0.1 mm day^{-1} when the water table was highest in October (Day 302).

The elevated mineral layer at the T1 fen-bog margin created a localised groundwater mound, higher than the water table in the fen margin. This groundwater mound persisted throughout the summer, but was most distinct under dry conditions (Figure 2). Horizontal gradients indicated flow from the crest of the mound to the fen margin at a rate of 14.6 mm day^{-1} under dry conditions (Days 153–183). This rate was reduced to 11.9 mm day^{-1} when the groundwater mound became less distinct after increased rainfall in July (after Day 183). The groundwater mound was eliminated under highly flooded conditions in October (Day 302), when the horizontal hydraulic gradient across the T1 fen–bog margin became negligible (Figure 2).

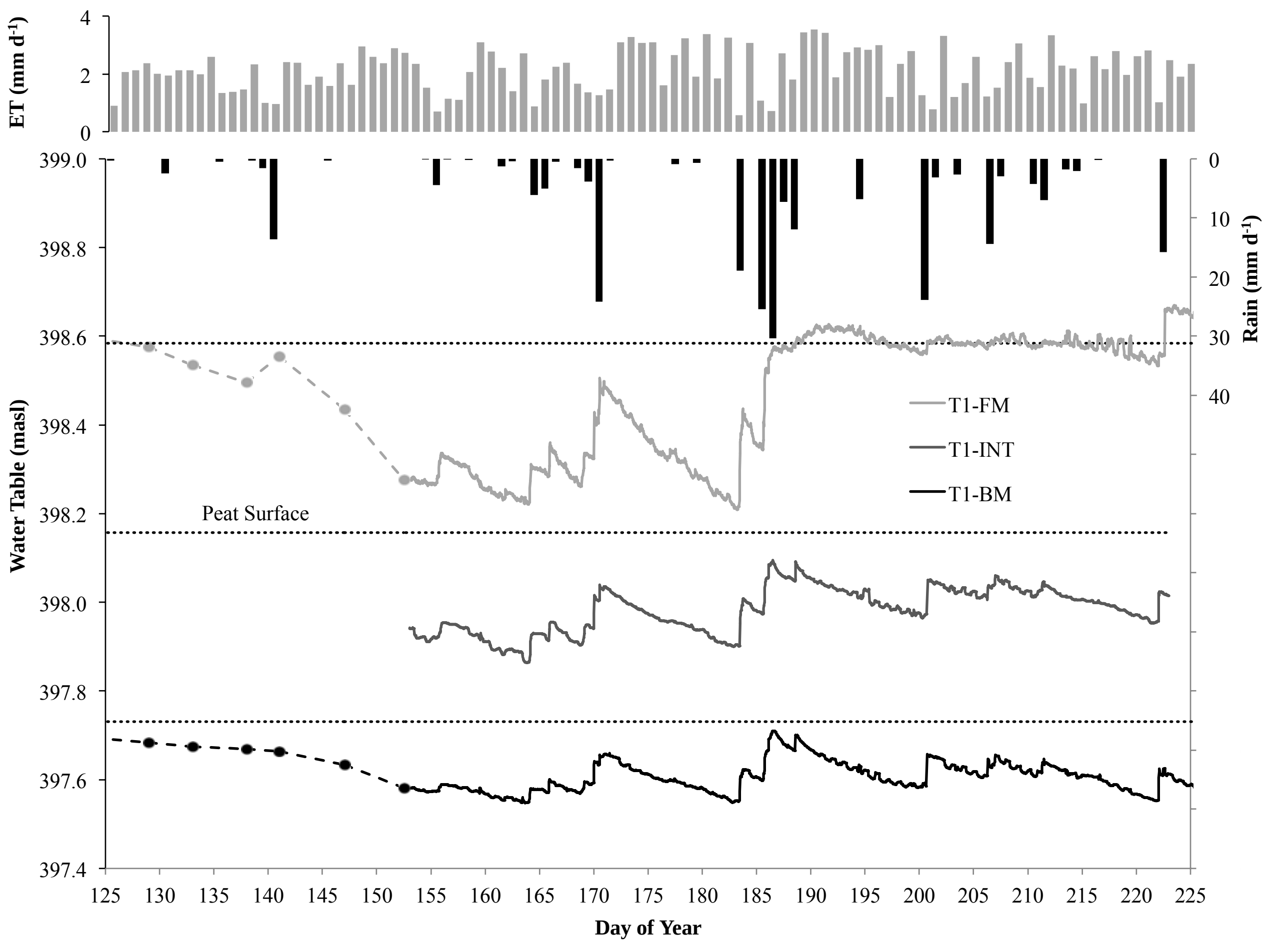

Figure 4. Water table position along T1, with the respective ground surface altitudes associated with each (dotted lines), from May 4 (Day 125) to August 12 (Day 225). Solid lines indicate continuous water level measurements and dashed lines indicate manual measurements. There were no manual measurements prior to June 01 (Day 153) for T1-INT. Daily P and ET, calculated from the bog meteorological station data, are plotted for the same time period.

Groundwater mounds were not found at the fen–bog margin on T2 and T3, where groundwater flow generally followed the local topography, which slopes away from the bog. Horizontal gradients were greatest during periods of low water table. Average discharge rates from T2 and T3 were 29.5 mm day^{-1} and 2.3 mm day^{-1}, respectively. The greater discharge rate along T2 occurred in a thinner (~0.48 m) peat layer with higher average hydraulic conductivity. Although K_h along T2 (1.3×10^{-2} cm s^{-1}) was an order of magnitude higher than along T3 (1.2×10^{-3} cm s^{-1}), the differences in saturated thickness between T2 and T3 reduced the difference in transmissivity (to 0.43 cm^2 s^{-1} and 0.13 cm^2 s^{-1}, respectively). Flow into the bog along T2 was observed on one occasion, at a rate of 8.0 mm day^{-1}, when the water table rose in August (Day 216). Hydraulic head measurements at the fen margin showed horizontal gradients from T1 to T2 and T3, indicating groundwater flow parallel to the bog margin at average rates of 1.2–7.9 mm day^{-1}.

The vertical hydraulic gradients indicated that the site functioned predominantly as a groundwater recharge system early in the season, and that the fen tended towards hydrostatic equilibrium later in the summer. The average seasonal vertical gradients within the peat layer were 0.06 in the bog and 0.02 in the fen, both promoting deep groundwater recharge. However, later in the summer, a slight upward gradient (average value -0.02) developed at depth within the peat profile at T1-0. Groundwater recharge to the mineral sediment (1.0–1.5 m) was greatest in the bog (at T1-0) and along its margins (at T1-3, T2-3 and T3-3), with average gradients of 0.22 and 0.35, respectively. The largest values (0.74–0.89) occurred in spring when there was still substantial frost in the peat. Discharge from depth within the mineral substratum occurred primarily in the fen (T1-FM) and at its margins (T1-5), with average gradients of -0.12 and -0.10, respectively. However, the gradients were small and coupled with low hydraulic conductivity (Figure 3), so the maximum rates of groundwater discharge from the mineral layer (Day 163) were negligible (<0.04 mm day^{-1}). The vertical gradients in both the peat and the mineral substratum were largest and most variable at the fen margin and at T1-FM.

Geochemistry

Because the peat layer in the bog was thin, water samples were drawn from the saturated layer just above its interface with mineral material, where the concentrations of dissolved ions were higher than in water collected near the surface. In the bog, pH increased from 4.1 near the surface to 6.5 at the base of the peat profile (Table 2). On average, the highest ion concentrations, salinity and EC were observed in the North Fen, where the dominant ions were Cl^-, Na^+, Ca^{2+}, Mg^{2+} and SO_4^{2-}, with average concentrations of 5394, 2307, 493, 183 and 80 mg L^{-1}, respectively. In the bog, Ca^{2+} and Mg^{2+} were the dominant ions (30 and 11 mg L^{-1}, respectively), followed by Cl^-, Na^+ and SO_4^{2-} (5, 4 and 1 mg L^{-1}, respectively) (Table 2). This was reflected in the salinity and EC measurements, whose ranges were 2.0–22.0 ppt and 3.7–35.0 mS cm^{-1}, respectively, in the North Fen, and 0.0–0.7 ppt and 0.1–1.4 mS cm^{-1} in the bog (Table 2). Values in the margin were intermediate between those in the North Fen and the bog. In both the fen and the bog, the highest ion concentrations and EC values were generally found in the mineral substratum, but the concentrations of Mg^{2+} and Ca^{2+} were greatest in the fen peat and in the bog peat, respectively (Table 2).

[Cl^-], [Na^+] and [Ca^{2+}] increased abruptly from the bog to the fen, with peak concentrations occurring at the bog–fen margin (Figure 5). [Mg^{2+}] and [SO_4^{2-}] (not shown) continued to rise with distance from the bog margin, whereas [Ca^{2+}], [Na^+] and [Cl^-] decreased slightly.

DISCUSSION

Site-scale hydrology

Continuous *P* measurements within the bog were highly comparable to measurements taken from the bulk rain gauge, with an average difference of 1.2 mm over the sampling intervals for bulk rainfall collection. Total *P* was 229 mm. Although previous parallel studies of fens and bogs have shown that fen water tables are typically less variable (c.f. Bay 1967, Price & Maloney 1994), the water table fluctuations observed in this study were greatest in the fen before Day 184. In the dry period from Day 171 to Day 183, the drop in water table was 33 cm in the fen, compared to 11 cm in the bog, at locations where the specific yield of the 0–40 cm layer in fen and bog averaged 0.07 and 0.05 (Table 1). The larger water table recession in the fen

Table 2. Average site-wide water chemistry from the June and August sampling periods. Water samples were taken from peat and mineral piezometers in the North Fen (n=7), fen–bog margin (n=8) and bog (n=6). Surface water chemistry ~10 cm below the water table in the bog was also examined.

		pH	Salinity *ppt*	EC *mS cm⁻¹*	Cl^- *mg L⁻¹*	SO_4^{2-} *mg L⁻¹*	Na^+ *mg L⁻¹*	Ca^{2+} *mg L⁻¹*	Mg^{2+} *mg L⁻¹*
Bog	Peat (surface)	4.1	0.0	0.1	-	-	-	-	-
	Peat (above mineral)	6.5	0.1	0.3	5.2	1.1	3.9	28.9	11.0
	Mineral	6.8	0.4	0.8	12.0	5.2	10.0	21.0	112.7
Margin	Peat	5.0	1.6	3.0	1611.8	13.1	592.5	102.2	36.9
	Mineral	6.5	2.1	4.0	974.1	23.7	288.4	155.0	44.4
North Fen[a]	Peat	6.2	9.3	15.8	5393.7	80.3	2307.4	182.9	492.7
	Mineral	6.4	12.4	20.6	6943.0	96.1	3491.6	243.3	146.6

[a] C. Wells (2013, unpublished data)

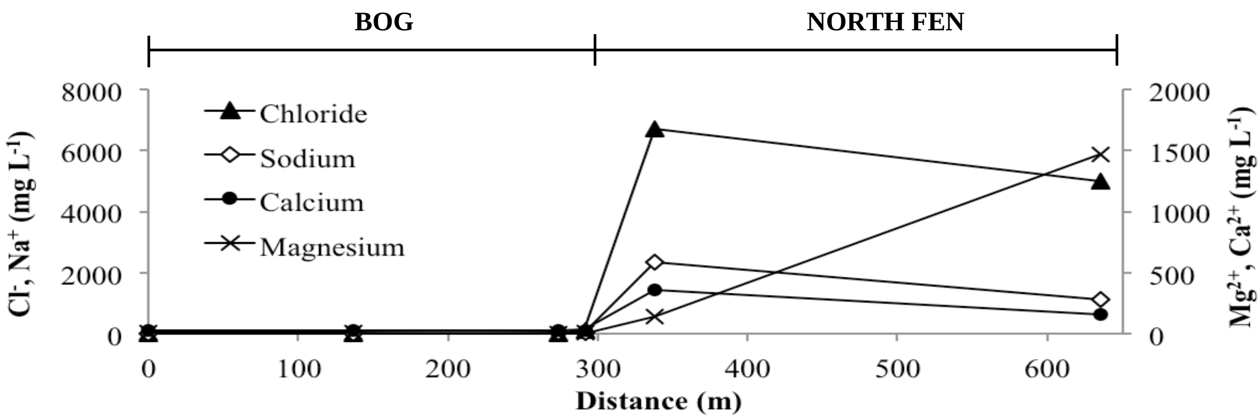

Figure 5. Groundwater chemistry along T1, measured from T1-0 to T1-FM. The values are averages of measurements from the June and August sampling periods where available.

can be attributed partly to its lower specific yield (but note the small sample size), and partly to *ET*, which was ~27 % higher from the fen over the whole measurement period. *ET* from fen peatlands is typically higher than from bogs and poor fens because of the prevalence of vascular vegetation (Lafleur & Roulet 1992, Price & Maloney 1994). From Day 184 onward, heavy rainfall caused flooding of the fen; thereafter, the responses of the water table to *P* and *ET* were very small in the fen because the effective specific yield was unity. Interestingly, the water table at T1-FM continued to rise for four days after the rain on Day 189, whereas it declined elsewhere. This could be attributed to surface inflow from the extensive upper reaches of Saline Fen, which has implications for the transport of saline water in the North Fen. The water table remained below the surface at the fen–bog margin because incoming water drained around both sides of the bog rather than accumulating there. Within the bog there is no substantial upslope contributing area to cause a delayed rise.

Controls on groundwater flow

Groundwater flow at the fen–bog transition was controlled by local substrate topography and hydraulic conductivity, subject to variations in hydraulic gradients caused by wetting and drying periods. Due to the low hydraulic conductivity of the extensive clay-rich mineral deposits underlying the site (Figure 3), the peatland complex has limited connectivity with the regional groundwater system. Ferone & Devito (2004) report similar observations from a study of a boreal peatland in the region, where seasonal groundwater flow was restricted to near-surface local exchanges due to the low-permeability clay-rich till base. However, it may not be valid to assume that the hydraulic conductivity of the substratum is uniformly low. In a concurrent study of the saline fen, zones of very high EC (108 mS cm^{-1}) were found in the southern part of the system ~600 m south of T1-FM (C. Wells 2013, unpublished data), suggesting localised strong connections with deep saline groundwater. No such patterns were evident in the bog.

The generally weak vertical connection between the deeper groundwater and that in the peat is illustrated by the limited discharge from the low-permeability mineral substrate (<0.04 mm day^{-1}). The site exhibited a general tendency towards recharge over the season. This is expected in bogs (Siegel & Glaser 1987), and is not uncommon in fens of the Western Boreal Plain (Devito *et al.* 2005). From Day 184 onwards the whole system, and especially the fen, became much wetter, shifting towards a state of hydrostatic equilibrium. Vertical gradients within the peat profile were generally small (<0.04 on average), so must be interpreted with caution given the potential measurement error. Large downward gradients early in the season can be attributed to ground frost, on which water can become perched (Petrone *et al.* 2008), but which does not necessarily facilitate recharge.

Horizontal hydraulic gradients across the fen–bog boundary were fairly consistent throughout the season, shifting only after the fen became flooded (Day 185) and peaking in late October (Figure 2). At this stage they could potentially direct groundwater flow from the fen into the bog. For most of the time this was precluded by the groundwater mound at the fen-bog margin which created a barrier to groundwater flow. The presence of the groundwater mound can be attributed to the local topography of the mineral substratum, whose hydraulic conductivity is several orders of magnitude lower than that of peat (Figure 3). The blocking action of the mound resulted in a higher water table at the bog margin than would otherwise occur there. This enhanced transmissivity by exploiting the high hydraulic conductivity of the surface peat layer (Figure 2), creating relatively efficient flow pathways directing water around the bog along the fen margin. This also varied seasonally, with transmissivity under wet conditions being more than double that in dry periods.

Patterns in groundwater geochemistry

The ion concentrations measured reflected the groundwater flow patterns found within the fen-bog complex. The abrupt drop in ion concentrations, most predominantly Na^+ and $Cl^–$, and in EC values (Figure 5) in the bog confirmed that the flow of saline groundwater into the bog was impeded. The higher concentrations of Na^+, $Cl^–$ and Ca^{2+} at the fen margin (T1-5) compared to T1-FM could be caused by an accumulation of ions at that location. This could be attributed to localised groundwater upwelling from the mineral layer which, over extended periods, could contribute to higher dissolved ion concentrations.

Despite its low relative altitude within the landscape, the chemistry (Table 2) of near-surface water within the bog (which is accessible to mosses) is comparable to that revealed by geochemical studies of other WBP bog systems (e.g. Zoltai & Vitt 1995). The bog peat layer was fairly thin (~0.60 m) and the near-surface pH and EC were 4.1 and 0.1 mS cm^{-1}, respectively, increasing to 6.5 and 0.3 mS cm^{-1} at 0.50 m depth. Thus, while the pore water at the base of the peat is minerotrophic, the net water flux (*P-ET*) must be positive, inferring long-term net recharge of the mineral aquifer below the bog, as evidenced by comparing the (much lower) EC values obtained for mineral groundwater beneath the bog with the equivalent data for North Fen (Table 2). Therefore, the bog remains a groundwater recharge system despite the localised discharge observed at T1-0 late in the summer which, over extended periods, could alter the near-surface water chemistry and, consequently, the vegetation (Siegel & Glaser 1987).

Implications for peatland development

It has been shown that regional hydrogeology can affect the distribution of bogs and fens in a flat landscape such as the James Bay lowlands, for example, with bogs developing on interfluves (Glaser *et al*. 2004). In this study, the irregularity in substratum topography was only a small ridge ~50 cm high, less than 100 m wide (Figure 2) and less than 200 m long (it did not extend along the fen–bog margin from T1 to either T2 or T3). Nevertheless, the bog “downstream” is extensive, and extends well beyond T1-0, where it is about 300 m wide (Figure 1). There was no detectable difference in hydraulic conductivity of the underlying sediments between bog and fen (Figure 3), and the vertical hydraulic gradients in both were small so that important differences in recharge/discharge function cannot be implicated. Yet, the water chemistry was substantially different. Salinity decreases steadily from the headwaters of the fen (33 mS cm^{-1}) to T1-5 in the North Fen (17 mS cm^{-1}) (C. Wells 2013, unpublished data), but it drops sharply at the fen-bog margin and is low in the bog (Figure 5). The interruption of flow caused by the substratum ridge (and the resulting groundwater mound) has protected a relatively large area from salt water intrusion, and this has allowed bog formation. This section is now predominantly ombrogenous (rain-fed), and there is apparently a surplus of precipitation over evapotranspiration that suppresses near-surface ion concentrations (Table 2) and causes water egress northwards along T1. The presence of this distinct ecosystem is largely due to a minor irregularity in substrate topography, whose influence is at least an order of magnitude greater in size than the feature that caused it to develop.

CONCLUSIONS

Groundwater flow within the peatland complex is controlled primarily by subtle irregularities in the substratum, which greatly influence subsurface hydrology, water chemistry and ecological development. It is probable that variations in substrate topography are common in the WBP, and it is evident that these can strongly influence the course of peatland development and, significantly for regional ecology, the spatial extent and distribution of bogs and fens. However, the integrity of these systems may be threatened by very wet conditions such as those experienced during the summer and autumn of 2012, which can result in saline water ingress to the bog. The dilute water chemistry of the bog indicates that these transient incursions have had little influence to date. However, since increased rainfall and potentially wetter conditions are expected under some climate change scenarios (IPCC 2007), an influx of water (and salt) to the bog from the fen that is sufficiently sustained to alter its geochemical and ecological composition could occur in the future. The influence of subtle features of the substratum on peatland development also has implications for the design of peatland systems for reclamation of post-mined oil sands landscapes (Price *et al.* 2010), where manipulation of substratum topography could be used to encourage diversity in the hydrological, geochemical and, hence, ecological character of the restored landscape.

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