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Characterization of surface storage and runoff patterns following peatland restoration, Quebec, Canada

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Abstract:

Blocking drainage ditches and creating bunds to limit surface water losses are important for restoring abandoned peat-extraction sites in North America. However, these runoff control techniques have not been well characterized, particularly during the snowmelt period. Therefore, patterns of runoff timing and magnitude were evaluated in a peatland (Bois-des-Bel, Quebec, Canada) undergoing restoration (restored site), in comparison with an unrestored section of the same peatland (unrestored site). Snowmelt dominated runoff, representing over 79% of the April to August runoff for both sites in 2001. Low (25–35 cm) bunds constructed on the restored site detained water for much of the melt period, but some water loss occurred where bunds were breached. Overland flow and surface ponding were prevalent at the restored site, but were not evident at the unrestored site. At the restored site, the presence of bunds and frozen, saturated (thus impermeable) ground contributed to differences in snowmelt runoff patterns relative to the unrestored site. In the post-snowmelt period (May–August 2001 and 2002), restored site runoff was reduced to 25% of that lost at the unrestored site. Both hydrometric and chemical hydrograph separation analysis using electrical conductivity indicated that blocked ditches restricted water losses from much of the restored site during the summer months, when the bunds had little effect on runoff. However, discharge peaks were greater at the restored site relative to the unrestored site and generally occurred more quickly following rainfall, because of the wetter antecedent conditions. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS peatland; restoration; runoff; snowmelt

INTRODUCTION

The water storage characteristics of undisturbed bog peatlands control water fluxes within and from the system (Ingram, 1983). Runoff varies both within and between seasons (Bay, 1969), being greatest during snowmelt (Fraser *et al*., 2001) and during periods of high water table (Evans *et al*., 1999), whereas baseflow contributions are limited (Burt, 1995; Kellner and Halldin, 2002). Flow occurs predominantly in the permeable surface layers (e.g. Hoag and Price, 1995; Fraser *et al*., 2001) or where macropores have developed (Baird, 1997; Evans *et al*., 1999; Holden *et al*., 2001). In highly disturbed sites, e.g. drained and mined peatlands, restoration management aims to return some or all of these water exchange characteristics (Money and Wheeler, 1999).

Site preparation for peat extraction usually requires installation of drainage ditches followed by removal of the permeable upper layer of living, dead and partly decayed plant material (the acrotelm). This profoundly affects water storage and alters flow characteristics of the peat and peatland (Price, 1996). Peatland drainage networks lower the water table (Boelter, 1972) and affect the timing and magnitude of site runoff (Mikalski and Lesniak, 1975; Robinson, 1985). Following ditching, summer baseflow can initially be higher (e.g. Prevost *et al*., 1999), and event water can dominate storm response (David and Ledger, 1988). The drainage impact is reduced over time as the ditch walls collapse and ditches are filled with vegetation (Van Seters and Price, 2001), but ditches continue to affect flow pathways (Klöve, 2000) and the chemical characteristics of the runoff (Prevost *et al*., 1999; Astrom *et al*., 2001; Joensuu *et al*., 2001). Drainage causes subsidence (Schothorst, 1977;

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Hillman, 1992; Prevost *et al*., 1997), leading to collapse of the peat structure (Silins and Rothwell, 1998), increased bulk density and lower specific yield (Price and Schlotzhauer, 1999), and a decrease in hydraulic conductivity (Chow *et al*., 1992; Price, 2003).

Hydrological conditions at abandoned sites are generally incompatible with the re-establishment of *Sphagnum* mosses (Price *et al*., 2003). Therefore, hydrological restoration is necessary for enhancing recovery of degraded sites (see Rochefort *et al*. (2003)). Decreasing runoff losses encourages rewetting of the system, manifest notably by swelling of the peat matrix, a change that is considered critical for effective hydrological restoration (Price and Schlotzhauer, 1999; Price, 2003). Decreasing site runoff can be achieved by blocking drainage ditches and adding surface bunds (e.g. Price, 1998), but there has been little effort to quantify this, particularly during snowmelt, which represents up to 30% of annual precipitation in parts of eastern Canada. There is also limited understanding of how water flow pathways change following restoration. This study, therefore, evaluated the role and importance of runoff controls for peatland restoration by comparing the runoff and surface water storage patterns at a site undergoing restoration and at an adjacent unrestored cutover site. In particular, the objective was to identify how the restoration design has altered the source, timing, and magnitude of snowmelt and storm runoff.

STUDY SITE AND RESTORATION APPROACH

The Bois-des-Bel peatland is located approximately 10 km north of Riviere du Loup, Quebec (47°53′N, 69°27′W) at an elevation of 20 m a.s.l. Climate data (1971–2000) (Environment Canada, 2003) recorded 5 km south at St Arsene indicates mean annual precipitation is 962·9 mm (29% falling as snow). Mean annual temperature is 3·2 °C, with mean August and February temperature of 16·5 °C and −10·9 °C respectively. The entire ombrotrophic peatland covers an area of approximately 200 ha, with a smaller section of approximately 11·5 ha drained in 1972 for peat extraction. Field surveys of the undrained peatland found mainly black spruce (*Picea mariana*) forest cover with *Sphagnum rubellum, Sphagnum russowii*, and *Sphagnum magellanicum* being the primary moss species (Lavoie *et al*., 2001). Peat is up to 3 m thick (though only around 1·5 m in the harvested area) and the site is underlain by a layer of marine clay that restricts vertical flow through the base of the peat deposit. Carbon dating of the nearby St Arsene peatland suggests that local peat formation was initiated approximately 9400 years ago (Van Seters and Price, 2002).

Following 8 years of peat extraction (1972 to 1980), work ceased at the site due to the overabundance of woody debris in the peat that caused problems for the machinery. The site was left in an abandoned state for 19 years and recovery of natural peatland vegetation and hydrological patterns was severely limited (Rochefort *et al*., 2004). Restoration was initiated in the fall of 1999 on 8·1 ha of the abandoned peatland (restored site) with the remaining 1·9 ha left for comparison purposes (unrestored site) (Rochefort *et al*., 2004). The restored site was cleared of all vegetation that had grown since abandonment. The old drainage ditches were blocked with well-decomposed peat and a new ditch was dug outside the bunded area along the southeast edge of the restored site perpendicular to the blocked ditches (see Figure 1) to monitor site runoff. Bunds (25–35 cm high) were created across the general slope of the peat surface to block and store surface runoff. The areas bounded by the bunds were named zones 1–5 (see Figure 1) with zone 1 being the most elevated and a gradual downward slope towards zones 4 and 5. Additional details on restoration methods are provided in Rochefort *et al*. (2003).

METHODS

Monitoring of hydrological characteristics at the Bois-des-Bel site occurred during the snowmelt period of 2001 (days 87 to 125) and summers of 2001 and 2002 (days 125 to 243). Equipment set-up varied slightly between the snowmelt monitoring period and the summer periods. Differences in techniques will be noted where necessary.

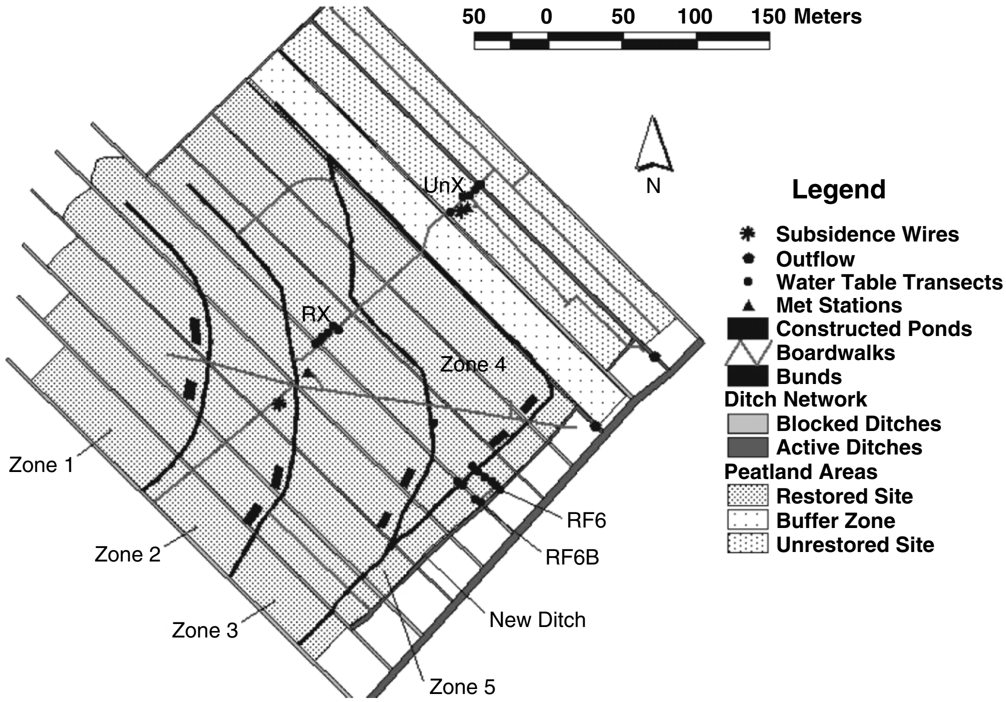

Figure 1. Map of the Bois-des-Bel peatland

Table I. Summary statistics for snowpack depth, density, and SWE measured on day 87, 2001, at the Bois-des-Bel peatland[a]

	Snow depth (cm)			Snow density (g cm^{-3})			SWE		
	R	UR	F	R	UR	F	R	UR	F
Mean	58·4	66·8	93·8	0·25	0·24	0·23	13·7	15·0	23·5
SD	11·2	20·4	21·1	0·03	0·04	0·02	3·02	6·02	4·12
Sample size	46	97	99	20	15	13	20	15	13

[a] R: restored area; UR: unrestored area; F: forested area.

Snow distribution and ablation characteristics

An initial snow survey was conducted in the spring of 2001 on day 87 (28 March) with the peatland stratified into three sites (the undrained forested area, the restored zone, and the unrestored zone) based on visual observation of snow and vegetation distribution (Adams and Roulet, 1982). Spatially random snow depth and density measurements were made at the three sites (sample size provided in Table I) using a Canadian Meteorological Service of Canada snow tube (1·2 m in length with 6·5 cm internal diameter). Snow water equivalent (SWE) was calculated for each of the three sites based on snow depth and density measurements using methods described by Adams and Roulet (1982).

Snowpack ablation was measured daily in all three snow sampling zones until snowmelt was completed (between days 87 and 125, 2001). Ablation was determined by measuring the distance to the snow surface at 10 increments across a taut horizontal wire strung between metal rods anchored into the peat. Snow temperature was measured manually at the base of the snowpack.

During the main snowmelt period, generalized maps indicating the extent of surface snow cover and surface water flooding were created daily. Grid markers located on the site were used as reference points to improve map accuracy. For a given measurement day, a grid area (30 m $\times$ 40 m) was considered flooded if greater than 50% of its surface area was submerged.

Micrometeorological conditions

Micrometeorological data were collected at the restored and unrestored sites (see Figure 1 for location of meteorological stations). During the snowmelt period, air temperature (at 1·5 m) and peat temperature profiles (at depths of 2, 5, 10, and 25 cm) were logged half-hourly at both sites with a Campbell Scientific™ 21X data logger. A tipping-bucket rain gauge, ground heat flux plate, and a REBS (Q^*8) net radiometer were located at the restored site, the radiometer being 0·8 m above the snow surface from days 87 to 116 and at 1·5 m thereafter.

Evaporative fluxes were determined at both sites during the summer monitoring periods. At the unrestored site, a Priestley–Taylor (P–T) approach similar to Van Seters and Price (2001) was used. Restored site evaporation was monitored using a more detailed eddy covariance system required by other site researchers (see Petrone *et al*. (2001) for further details). Rainfall was measured at the restored tower using a manual rain gauge with readings taken following rainfall events, and with a tipping-bucket rain gauge (Texas Electronics model TE525) logged every half-hour.

Runoff characteristics

During the snowmelt period, discharge was measured manually (one to three times daily) at culverts located at the restored and unrestored site outflow locations (Figure 1). During lower flows (less than 5 l s^{-1}), discharge was determined using the average of three measurements with a calibrated bucket and stopwatch. For flows over 5 l s^{-1}, the bucket could not be used and discharge was determined by measuring the time required for an NaCl solution to travel the length of the outflow pipe (10 m at both sites) as indicated by a spike in electrical conductivity (EC). The average velocity (based on three trials) was then multiplied by the cross-sectional area of water measured at the end of the culvert to determine discharge.

During the summer periods, manual discharge measurements were taken at the restored and unrestored site pipe outlets (Figure 1) using methods similar to those used during the snowmelt monitoring. Rating curves were developed with stage readings taken at V-notch weirs installed at the pipe outflow using manually calibrated RDS stilling wells (Remote Data Systems™) that recorded every half-hour.

Site runoff was calculated using the discharge measurements and the known site area for both the snowmelt and summer monitoring periods. The restored site area was 8·1 ha and the unrestored site was 1·9 ha. However, the contributing area of the unrestored site was larger during the snowmelt event. During this period (days 87 to 125), water from a forested (unharvested) but originally ditched section of peatland entered the ditch system at the north corner of the unrestored site. Field observation and analysis of aerial photographs of the site indicate that the maximum probable extent of the unrestored site drainage area during the snowmelt period was 3·2 ha. This area was used in the calculation of runoff at the unrestored site during the snowmelt period.

Water table, hydraulic head, and hydraulic conductivity

Water table was monitored manually every 1 to 3 days at the restored and unrestored tower locations during the snowmelt period and the two summer monitoring periods. In addition, half-hourly logged readings were recorded using an RDS well during the summer monitoring periods. Logged values were fit to observed measurements based on relationships established between manual and automatic readings. Manual wells (spatially distributed throughout the restored and unrestored sites) were monitored every 2–3 days in 2002. The well network included wells installed up- and down slope of the four main bunds, to evaluate water table gradients. Well transects perpendicular to blocked and active ditches were used to record water table profiles.

The transects were across old peat fields in the restored (RX) and unrestored (UnX) sites. In the restored site, two additional transects were located perpendicular to the new drainage ditch in the middle of an old peat field (Field 6) and in the adjacent blocked ditch (RF6 and RF6B respectively). Transect locations are shown in Figure 1. Water levels in the wells in each transect were measured manually every 1 to 5 days during the two sampling summers.

During the summer, hydraulic head was measured in piezometers located within the well transects (RX, UnX, RF6, RF6B; locations provided in Figure 1). Piezometer depths were 50, 75, 100, 125, and 150 cm where the peat was deep enough. The RX, UnX, and RF6 transects were installed in 2001 using 2·5 cm PVC with intake lengths of 15 cm. The RF6B transect was installed in 2002 with similar standards, except that 2 cm internal diameter PVC was used. All piezometers were covered with Nitex screening (250 μm) to prevent smearing and clogging. Pilot holes were drilled to allow for clean insertion and all piezometers were pumped two or three times immediately following installation to allow fine material near the screen to be removed. Piezometers were surveyed relative to the site benchmark following restoration, using a Kern level. Weekly manual water level measurements were taken and corrected for pipe offset above the peat surface.

Horizontal saturated hydraulic conductivity was measured in the field using bail tests (Hvorslev, 1951). To limit the effects of peat storage changes on recovery results, the piezometers were kept empty for a few minutes before refilling could take place. Piezometers were emptied using a syringe and plastic tubing and measured to a minimum recovery of 60%, but more generally in the range of 85 to 90%. Sampling occurred during high and low water table periods in 2001 and at weekly intervals in 2002.

EC measurements

During the snowmelt period of 2001, groundwater, snowmelt water, and outflow water temperature and EC were measured in the field using an Orion™ SCT meter. All EC values were later corrected to 25 °C standard conductivity values. Restored and unrestored outflow EC was taken one to three times daily. Restored site outflow EC measurements were supplemented using water samples from an ISCO™ autosampler collecting water every 4–6 h. Snow samples were collected using a snow tube, and melted at room temperature before measuring EC. Groundwater EC measurements were taken at piezometers located at the restored (intake range 10 cm) and unrestored micrometeorological tower locations (intake range 20 cm) (Figure 1) with mid-slots approximately 45 cm above the peat clay interface.

During the summer monitoring periods of 2001 and 2002, bulk rainfall samples were collected for EC measurements using a large funnel and plastic container located near the middle of the restoration site. Sample EC and temperature were measured directly in the field using the Orion™ SCT meter and WTW™ (model LF 330) EC meters in 2001 and 2002 respectively.

Outflow water temperature and EC were also determined for both sites in the summer monitoring periods 2001 and 2002. In 2001, manual temperature and EC measurements of outflow water were taken with an Orion™ SCT meter during various flow periods. Similar measurements were taken in 2002 with a WTW™ (model LF 330) EC meter. From day 163 to 245 in 2001 and from day 127 to 245 in 2002, outflow EC was also logged every half-hour using Campbell Scientific™ CS547A conductivity probes. The probes were located just upstream from the outflow pipes at each site. A regression was developed between manual and logged readings to produce comparable results.

Groundwater EC and temperature were measured during the 2001 and 2002 summer monitoring periods. In 2001, groundwater EC was measured two or three times a week using an Orion™ SCT meter. The probe was inserted directly in the piezometers that were pumped on a weekly basis. In 2002, a WTW™ (model LF 330) EC meter was used directly in the piezometers. Measurements were taken weekly with piezometers pumped the day prior to sampling. Sampling locations included the RF6, RX, and UnX transects in 2001. The same transects, along with the RF6B transect, were sampled in 2002.

Hydrograph separation

The distinct EC characteristics of precipitation (snowmelt or rain water; low EC), groundwater (high EC), and runoff (variable EC in relation to discharge magnitude) at the site allowed the application of a simple hydrograph separation (e.g. Kobayashi, 1986; Matsubayashi *et al.*, 1993):

$$Q_o = Q_t \frac{C_t - C_n}{C_o - C_n} \tag{1}$$

where Q represents discharge, C (μS cm^{-1}) is the EC reading, and subscripts 'o', 'n', and 't' indicate old, new, and total contributing water respectively. The possibility of EC not being a conservative tracer is recognized, since flow components may not have fixed EC values throughout the event (Pilgrim *et al.*, 1979; Buttle, 1994). In the context of this study, the EC hydrograph separations were primarily a means of furthering interpretation of the hydrometric data measured at the restored and unrestored sites.

RESULTS

Snow distribution and melt patterns

Initial characterization of snow depth at the forested, restored and unrestored areas of the peatland (day 87) indicated mean values of 93·8 cm, 58·4 cm and 66·8 cm respectively (Table I). Analysis of variance (ANOVA) testing indicated significant differences between mean snow depth for the three sites (significance level for testing of 0·05). In contrast, the three sites did not have significantly different mean snow density values (0·23, 0·25, and 0·24 for the forested, restored, and unrestored sites respectively). Mean SWE values of 235 mm, 137 mm, and 150 mm for the forested, restored and unrestored sites respectively were significantly different at the 0·05 level (ANOVA). As indicated by t-tests, SWE at the unrestored site was not significantly greater than at the restored site. However, SWE at each of the two peat-extraction sites was significantly lower than that in the forested area ($p < 0{\cdot}001$). SWE standard deviation was greatest at the unrestored site (60·2 mm) and substantially lower at the forested (41·2 mm) and restored sites (30·2 mm).

Snowmelt caused the snow surface to decline between days 87 and 125 (Figure 2a). Initial mean snow depths at the forested, restored, and unrestored site ablation wires were 91·8 cm, 57·7 cm, and 71·9 cm respectively. Lowering of the snowpack was gradual at all sites until day 102, after which the snowpack depth at the restored and unrestored sites decreased rapidly relative to the forested site. Snow at the restored site ablation wire was completely melted by day 111 and at the unrestored site a day later. The snow beneath the forest ablation wires lasted approximately 9 days longer (day 120).

Rainfall was only 7 mm during the snowmelt period. Air temperature at both the restored and unrestored sites averaged 5 °C between days 91 and 125 (see Figure 2b). Net radiation remained below 250 W m^{-2} at the restored tower up to day 111, after which values increased due to the patchy snow cover (Figure 2b). No measurable ground heat flux occurred before the snowpack was gone from the monitoring area. Based on an energy balance method similar to Carey and Woo (1998), solar radiation Q^* was estimated to be the dominant component of the melt energy (>85% between day 95, when the snowpack was estimated to have become isothermal, and day 110) with turbulent fluxes of minimal importance.

Discharge at both the restored and the unrestored sites was <0·02 l s^{-1} prior to day 106, beginning to rise on day 107. Rapid decline of the snowpack (Figure 2a) led to high discharge rates of 24·7 l s^{-1} at the unrestored site (day 111) and 30·7 l s^{-1} at the restored site (day 110). Discharge at the unrestored site declined following day 111 to negligible levels by day 125. Discharge at the restored site also declined following day 110, but unexpected spikes coincided with broken bunds observed on days 112 and 114 with flows of 44·4 l s^{-1} and 53·3 l s^{-1} respectively. Bunds appeared to fail due to overtopping at low or weak points, which ultimately led to rapid erosion and large breaks. Discharge at the restored site dropped below 0·5 l s^{-1} by day 125.

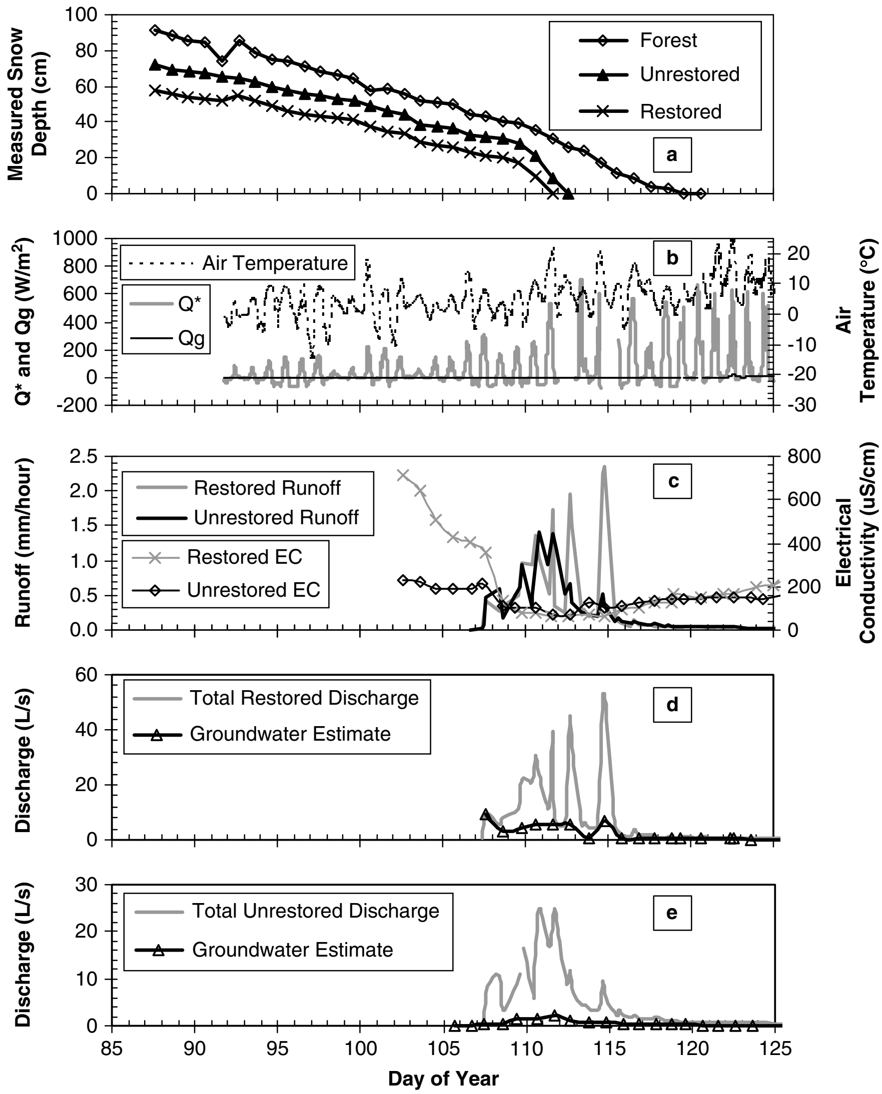

Figure 2. Snowmelt characteristics from the Bois-des-Bel site during spring 2001: (a) snowpack lowering; (b) air temperature, net radiation Q^* and ground heat flux Q_g; (c) discharge and EC. Hydrograph separations are also provided for the restored (d) and unrestored sites (e)

Cumulative runoff between days 87 and 125 for the restored and unrestored sites represented a water depth of 156 mm and 258 mm respectively.

Surface water flooding at the restored site between days 107 and 125 is indicated in Figure 3. There was no observable flooding at the unrestored site throughout the snowmelt period. Most flooding at the restored site occurred where old ditches had been blocked and generally upslope of the bunds, particularly in zones 3 and 4. However, some water flooding did occur on areas downslope of these bunds. Ponded water in zone 4 drained quickly following a break in the bund on day 115.

Snowmelt EC characteristics

Daily snow water EC values averaged 12·3 μS cm^{-1} between days 87 and 125 and had a small range (3·4 to 33·3 μS cm^{-1}). Spatial patterns in snow water EC were not determined. Ponded surface water at the

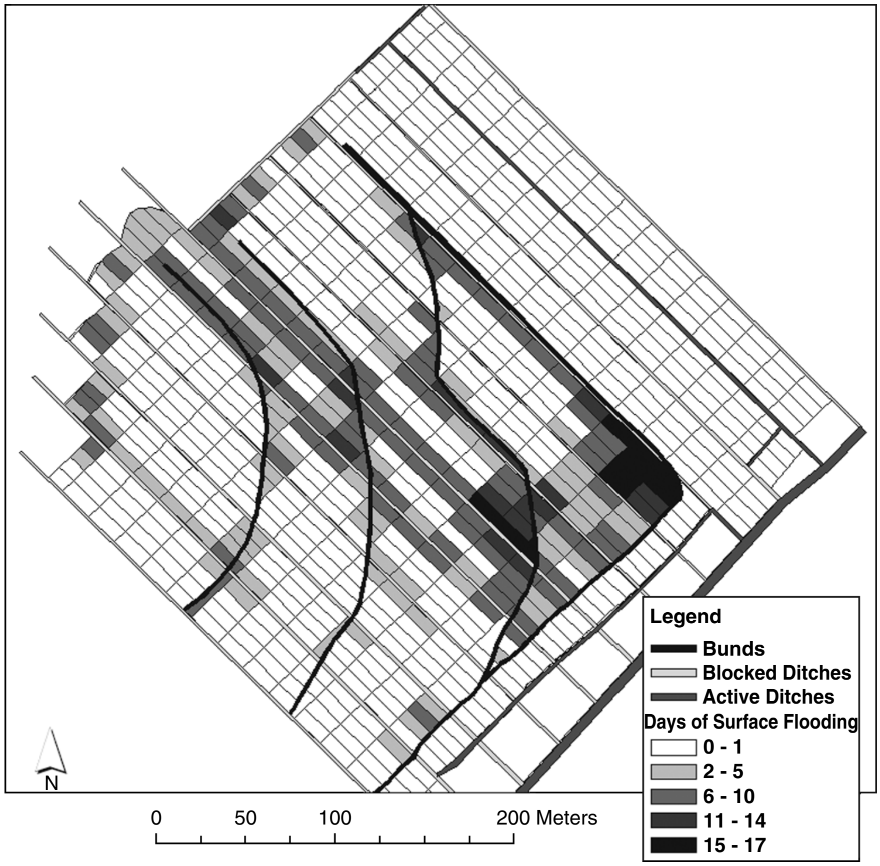

Figure 3. Surface water ponding frequency during the spring 2001 snowmelt period

restored site (zone 3 near the boardwalk) rose from 24·4 μS cm^{-1} on day 110 to 241 μS cm^{-1} on day 125 (mean of 155 μS cm^{-1}). Groundwater EC measured in the restored and unrestored piezometers 45 cm above the peat–clay interface averaged 2259 μS cm^{-1} and 2981 μS cm^{-1} respectively. Groundwater contribution to baseflow, as determined by pre-melt stream discharge, had lower EC values, with the unrestored site averaging 584 μS cm^{-1} (Figure 2c) and the restored site EC was 345 μS cm^{-1} (not shown in Figure 2c). During peak discharge periods, restored and unrestored site discharge EC dropped, reaching lows of 61 μS cm^{-1} and 72 μS cm^{-1} respectively (Figure 2).

Hydrograph separations were attempted using observed EC characteristics (Figure 2d and e). Outflow EC and discharge (l s^{-1}) were based on direct measurements. Snowmelt EC values of 20 μS cm^{-1} represented new water. Baseflow observations were used for the groundwater contribution: 345 μS cm^{-1} at the restored site and 584 μS cm^{-1} at the unrestored site (pre-discharge values). The results indicate that groundwater was a small component of the discharge contributions at the unrestored site, representing between 15 and 20% during peak runoff periods. At the restored site, EC separations also indicate minimal groundwater contributions to the measured outflow (15%). Estimates based on the higher EC piezometer data (approximately 200 m from the outflows) would result in even lower estimates of groundwater contribution.

Summer runoff timing and magnitude

Precipitation totalled 286 mm and 253 mm for days 125 to 243 in 2001 and 2002 respectively. At the restored site, evaporation was 377 mm and 267 mm in 2001 and 2002 respectively, and at the unrestored

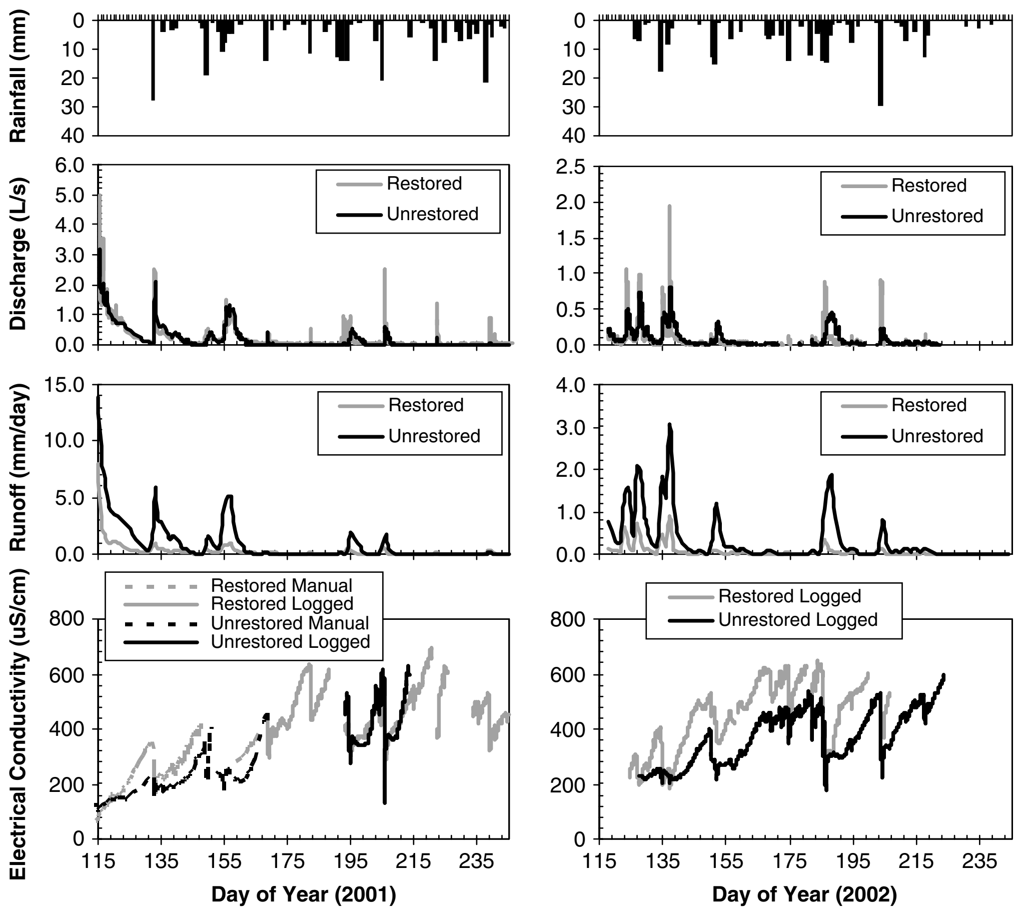

Figure 4. Summer precipitation, discharge, and discharge EC patterns from the 2001 and 2002 field seasons

Table II. Restored and unrestored site runoff totals and percentages from the 2001 and 2002 monitoring seasons

		Total (mm)	Snowmelt		Summer		Summer, % of total	
			(mm)	% of total	(mm)	% of total	Prior to day 160	After day 160
2001	Restored	172	156	90·7	16	9·3	61·6	38·4
	Unrestored	325	258	79·4	62	19·1	80·6	19·4
2002	Restored	NA	NA	NA	7	NA	79·4	20·6
	Unrestored	NA	NA	NA	37	NA	71·8	28·2

site it was 467 mm and 281 mm in 2001 and 2002 respectively. Discharge responded quickly to rainfall inputs (Figure 4), and with similar flow volumes despite the large differences in the size of the restored and unrestored sites' contributing areas. However, peak discharge at the restored site was slightly higher.

Cumulative runoff estimates indicate that the restored site losses were only 26·6% and 18·3% of unrestored site runoff during the summers of 2001 and 2002 respectively. Snowmelt dominated annual runoff in 2001 (Table II). During the summer period, most runoff occurred prior to day 160 (the first week of June). In the June–August period, very little water was lost to runoff at either site, with flow at the unrestored site periodically ceasing. The ratio of runoff (millimetres) for the restored site versus the unrestored site for individual storm events was 0·37 based on 31 events where flow occurred at both sites in 2001 and 2002. An event was defined as rainfall greater than 3 mm with more than 12 h since previous precipitation.

Summer EC characteristics

Restored site discharge EC ranged from 167 to 690 μS cm^{-1} in 2001 and 194 to 642 μS cm^{-1} in 2002, while the unrestored site saw ranges of 162 to 608 and 176 to 594 μS cm^{-1} for comparable sampling seasons (Figure 4). At both sites, EC was lowest during high discharge periods and elevated during baseflow. EC between rainfall events increased during periods of recession, and was highest during the driest periods. During event flow greater than 0·5 l s^{-1}, EC was consistently around 200 μS cm^{-1} at both sites.

Rainfall EC averaged 16·8 μS cm^{-1} (SD: 10·5 μS cm^{-1}) and 17·4 μS cm^{-1} (SD: 14·4 μS cm^{-1}) based on 8 and 14 measured events in 2001 and 2002 respectively. No seasonal patterns in rainfall EC values were evident, nor was there a distinct relationship between rainfall EC and total storm rainfall.

Cross-sectional profiles of EC at the UnX, RX, and RF6 transects (not shown) indicate no distinct spatial (horizontal) patterns. However, distinct vertical gradients were evident, as EC increased with depth below the water table (Figure 5). EC at the RX and UnX locations increased logarithmically with depth, whereas at the RF6 transect, which abuts an active drainage ditch, the EC increased linearly with depth.

In the hydrograph separation (Equation (1)), a rainfall EC value of 17 μS cm^{-1} was used at both sites. Outflow EC and discharge rates (l s^{-1}) were based on direct measurements. Because groundwater EC varied strongly with depth in the peat deposit (as indicated previously), values were estimated from observed baseflow measurements taken in the period prior to the storm: 600 μS cm^{-1} and 630 μS cm^{-1} at the restored site and 500 μS cm^{-1} and 700 μS cm^{-1} at the unrestored site for the early- and late-season storms respectively. Figure 6 shows that, for an early- and late-season storm at both sites in 2002 (days 134 and 184 respectively), old water had less than 50% contribution during peak flow periods. At the restored site, peak old water contributions were around 30% for the early-season storm and 42% during the late-season storm. At the unrestored site, the old water contribution during the peak runoff period was close to 40% for both the early and late season storms. However, runoff patterns clearly differed; the unrestored site had a damped response, particularly in the late season storm.

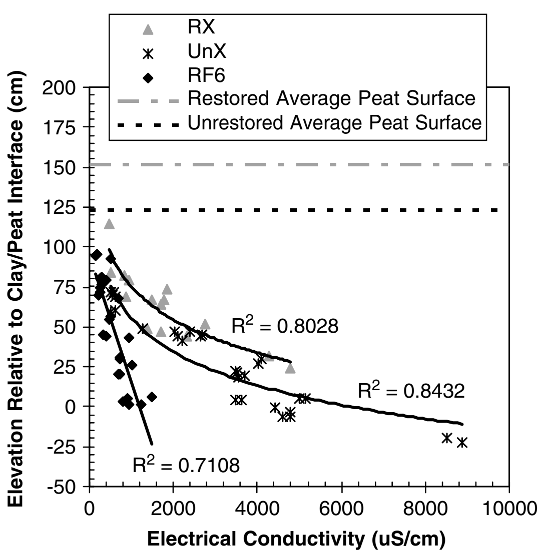

Figure 5. Vertical profiles of peat pore water EC characteristics for piezometers located in the RX, UnX, and RF6 transects relative to the peat–clay interface

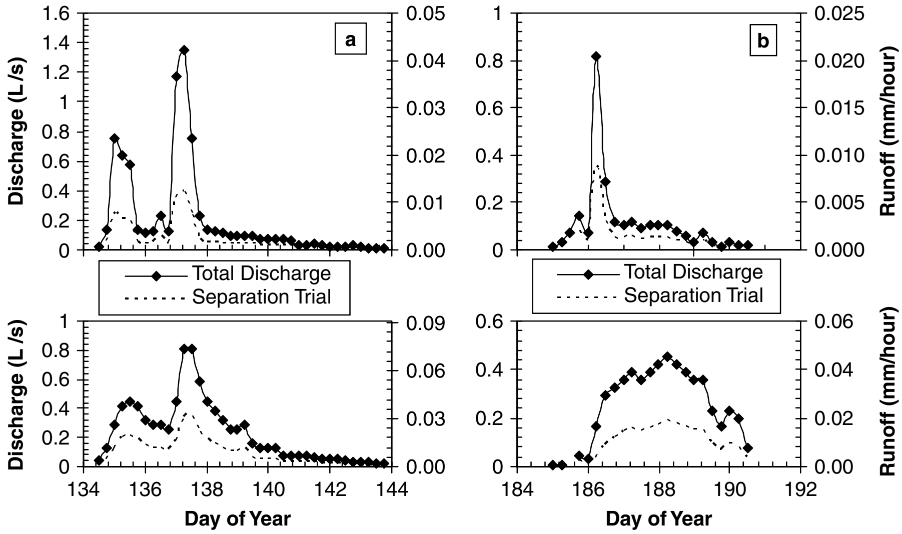

Figure 6. Hydrograph separation patterns for (a) early-season storm (day 134) and (b) late-season storm (day 184) at the restored (upper graph) and unrestored (lower graph) sites

Groundwater linkages to outflow

Mean spatially averaged water table at the restored site was −19·6 cm in 2001 and −27·7 cm in 2002. Unrestored site values for similar time periods were −47·9 cm and −50·0 cm, respectively. In both years the restored-site water table was significantly higher ($p < 0{\cdot}001$) than the unrestored-site water table. No distinguishable difference in water table depth was evident between restoration zones (1–4). Furthermore, there were no distinguishable water table gradients across the bunds when the water table was below the surface.

Cross-sectional profiles for the RX and UnX transects during the 2002 summer period did not indicate measurable water table gradients towards old ditches. In contrast, the RF6 transect had a distinct water table gradient towards the new ditch. Water table gradients in the RF6 transect were closely linked to restored site discharge for the 2002 summer season (Figure 7). Higher discharge was associated with increased gradients between the ditch water level and the water table at 2 and 14 m. There was little measurable water table gradient beyond 15 m from the ditch, indicating little potential for generating groundwater flow that would account for observed runoff patterns at the restored site.

Geometric mean hydraulic conductivities at the restored and unrestored sites were similar, with values of $3{\cdot}5 \times 10^{-5}$ cm s^{-1} and $1{\cdot}4 \times 10^{-5}$ cm s^{-1} respectively based on 2001 and 2002 data from both the 75 and 100 cm depths (restored site had 29 samples at 12 locations, and the unrestored site had 24 samples at six locations). A Mann–Whitney test indicated that differences between the two sites were not significant at the 0·05 level. Within-site variability was slightly greater at the restored site relative to the unrestored site. For example, at the −75 cm sampling depth, restored-site seasonal geometric mean values ranged from $3{\cdot}4 \times 10^{-5}$ cm s^{-1} at RF6_14m to $1{\cdot}5 \times 10^{-6}$ cm s^{-1} at RX_9m. In general, the readings taken as part of the RF6 transect were slightly higher than those found along the RX transect.

DISCUSSION ON STORAGE AND RUNOFF CONTROLS

Snow accumulation and melt characteristics

The restoration process has not returned the snow accumulation function of the forested peatland in the short term, potentially limiting restoration success through decreased water available for storage. The forested areas

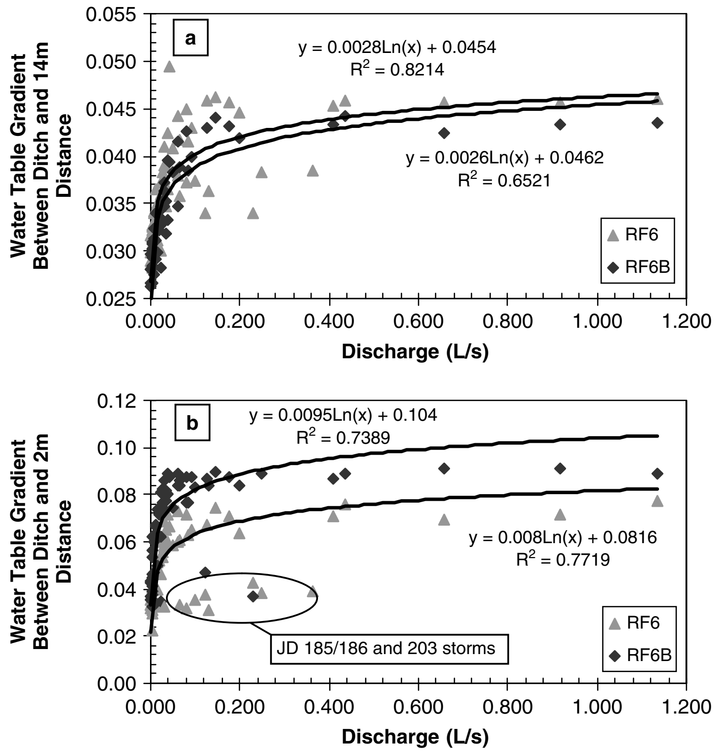

Figure 7. Relationship between restored site discharge and groundwater gradients adjacent to the active drainage ditch for distances of 2 and 14 m

had greater snow accumulation than both the restored and unrestored sites (Table I) because the vegetation community protected against wind scouring and associated ablation losses (Pomeroy *et al.*, 1998). Similar patterns of snow accumulation for forested and open mire were observed by Nisula and Kuittinen (1988). Both the restorated and unrestored sites had similar SWE accumulations, but there was higher variability in snow depth measurements at the unrestored site, because it had a sporadic and patchy cover of shrub and (birch) trees (Adams, 1976; Adams and Barr, 1979; Adams and Roulet, 1982), which were removed from the restored site as part of the restoration treatment.

Ablation trends were similar at the restored and unrestored sites, declining sharply following day 110 as the snowpack became patchy. Nisula and Kuittinen (1988) and Woo and Heron (1987) also observed more rapid snow ablation in open wetland relative to adjacent forest.

Discharge prior to the main snowmelt period was negligible (Figure 2c), indicating minimal groundwater contribution. The main snowmelt discharge began (day 107) when the sites had lost about 50% of their original snow depth (Figure 2) and the snowpack had ripened. The two sites showed similar timing and magnitude of instantaneous discharge, with the main peak occurring before the snow had completely melted (Figure 2c). Two significant spikes in restored-site discharge (days 112 and 115) were caused by the release of ponded water when surface bunds failed.

Despite similarities in discharge volume, cumulative runoff at the restored site (156 mm) was much lower than at the unrestored site (258 mm). Snowmelt runoff dominated the annual hydrograph, accounting for 90·7% and 79·4% of the total runoff at the restored and unrestored sites respectively (Table II). Total snowmelt runoff of 156 mm at the restored site was just above the measured SWE of 137 mm. However, the measured cumulative runoff at the unrestored site (258 mm) exceeded the estimated water available from local snowmelt by 73 mm based on the weighted-area SWE from the unrestored site and the forested area. Although the difference is large, it is reasonable based on the measured variability in SWE at the unrestored and forested sites (Table I). The uncertainty in accurately determining the catchment area of the unrestored site during the snowmelt period (3·2 ha was the estimate used) would likely account for the remaining difference.

Within the restored site, surface water ponding prior to fall freeze-up was not accounted for in the snow survey, providing additional water to that estimated from the snow survey. Although the bunds were clearly effective at retaining water for much of the melt period (Figure 3), breaks in the bunds near the end of the melt period occurred where large ponds developed. When the bunds broke, a portion of the stored water was quickly released via overland flow, causing sporadic peaks in discharge (Figure 2c). Nevertheless, considerably more water was retained on the restored site relative to the unrestored site, as reflected by the higher summer soil moisture conditions at the former location (Petrone *et al*., 2004).

Hydrograph separation (Figure 2d and e) confirms that surface flow dominated losses during the peak snowmelt period, whereas groundwater contributions were minimal. The potential for subsurface water movement existed at the unrestored site, since overland flow was not commonly observed during the snowmelt period. However, the outflow EC characteristics did not suggest the flushing of existing high-EC groundwater that was present deep within the peat profile. The frozen ground appeared to limit the infiltration capacity of the peat surface (e.g. Kane and Stein, 1983; Price and FitzGibbon, 1987) and affected flow pathways (Metcalfe and Buttle, 2001). This was particularly so at the restored site, where impenetrable ground ice formed due to high moisture contents at the time of freezing (Price and FitzGibbon, 1987), allowing surface water ponding and overland flow. At the unrestored site the water table was below the frost-line, so the porosity of the surface peat available for water storage remained high and no ponding resulted. Differences in ground ice characteristics have been shown to influence infiltration and runoff patterns of frozen soils (Haupt, 1967; Kane, 1980; Price and FitzGibbon, 1987; Carey and Woo, 1998), along with surface–groundwater interactions within wetland areas (Price and FitzGibbon, 1982). Therefore, large amounts of snowmelt water were lost from the restored site before infiltration could recharge the peat and enhance dilation storage (e.g. Nuttle *et al*., 1990). Low variability in groundwater EC during the melt period further indicated that there was little rewetting of the deeper peat during this period.

Summer runoff characteristics

During the summer period, runoff losses were a small percentage of precipitation inputs to the site. Discharge for both 2001 and 2002 (Figure 4) showed low baseflow and distinct rainfall-associated peaks common to natural peatlands (Evans *et al*., 1999). However, discharge peaks were greater at the restored site and the recession time was shorter, suggesting a more efficient drainage network (Robinson, 1985). In addition, there were events that caused discharge at the restored site but not at the unrestored site. The lower water table at the unrestored site and low hydraulic gradients damped the drainage response to discharge events. The partially infilled condition of older ditch networks (Van Seters and Price, 2001) also likely contributed to slowed drainage response at the unrestored site. At the restored site, the presence of a new ditch for monitoring purposes likely contributed to the apparent increased drainage efficiency.

Cumulative runoff was greater at the unrestored site relative to the restored site, with most occurring prior to day 160 (Table II). Despite the faster time to peak and greater peak discharge at the restored site, runoff (i.e. discharge per unit area) was less (Figure 4), confirming the general effectiveness of the restoration design, which included blocking ditches and creating bunds. There is geochemical evidence (dissolved organic carbon (DOC); see Toth (2002)) to suggest old ditch-lines at this site provide a preferential conduit for flow (see also Heathwaite (1994)). However, water table gradients were not evident across the old peat fields towards blocked ditches. Further work is required to link hydrometric and DOC data at the site.

The strongest water table gradient evident in the restored site was perpendicular to the new drainage ditch in the RF6 transect. In this area, the water table showed gradients of 0·09 and 0·02 during high and low water table periods respectively. For the early- and late-season storms of 2002, hydrometric measurements based on area estimates indicate rain falling directly on the restored site (new) ditch represented only 5% and 12%

of total storm runoff for the respective events. The majority of runoff appeared to originate within 15 m of the ditch in the zone where water table gradients were greatest and water table recession occurred quickly following rain events. Low hydraulic conductivity values at the site suggest slow groundwater flow; however, the quick movement of water through preferential pathways is possible at this peatland due to the high amount of woody debris. Such pathways are known to affect water flow estimates and have been observed in various peat deposits (Baird, 1997; Holden *et al.*, 2001). At the unrestored site, hydrometric data did not provide a clear indication of hydraulic linkages with the ditch network. Clear water table gradients between the middle of the peat field and the ditch were only evident after a few storm events.

Runoff, groundwater, and rainwater EC showed distinct patterns at both sites. Time trends at the restored and unrestored sites indicated distinct drops in runoff EC during rainfall events (Figure 4). Values were consistently around 200 μS cm^{-1} for instantaneous discharge values greater than 0·5 l s^{-1}, and increased sharply for lower discharge rates. Runoff EC values were lower during the early part of the field season. Baseflow EC increased during the dry (lower water table) periods, when deeper, higher EC groundwater (Figure 6) made a greater contribution. The distinct vertical patterns in EC were likely caused by the upward diffusion of ions present in the marine clay below (e.g. Price and Woo, 1988).

In the context of the flow separation, the low EC in discharge water during peak flow suggests a predominant contribution of event water in runoff. This differs from patterns in a drained Swedish fen by Klöve and Bengtsson (1999), where elevated EC occurred in higher discharge periods caused by flushing of nitrate from the unsaturated zone during events. Outside the snowmelt period, overland flow was rarely observed at either site, indicating below-ground pathways. Although the EC of the various components may not be strictly conservative (Pilgrim *et al.*, 1979), groundwater EC was temporally stable throughout the field season compared with discharge, so the general findings can be treated with confidence.

CONCLUSIONS AND RESTORATION IMPLICATIONS

The patterns of surface storage and runoff at the Bois-des-Bel site suggest that runoff controls are an important aspect of full site restoration strategies. During the summer months, restored site runoff was generally 25% of that lost at the unrestored site, even though restoration had raised the water table and increased soil moisture, which would likely reduce the storage capacity at the site. The older, blocked ditches at the restored site were not important contributors to measured runoff during the summer months, although they may have been a conduit for preferential overland flow early in the field season. At the unrestored site, the ditch network remained active, allowing direct water contribution from a large proportion of the catchment area.

Both hydrometric and EC separation evaluation indicated that most runoff water at the restored site originated within 15 m of the new drainage ditch. Linkages beyond this area were not evident. Although the new ditch has influenced the timing and source of restored site runoff, it has not negatively affected the restoration process, with the exception of the adjacent areas in zone 5. Direct precipitation onto the ditch was small, but not negligible. However, the high water in the restoration zone leaves this segment of the peatland primed to contribute to runoff. The findings regarding the overall decrease in runoff, despite the site-specific influence of the new monitoring ditch, confirm that blocking drainage ditches can be an important component of increased water storage as part of the restoration process.

The introduction of surface bunds also contributed to increased water storage at the restored site; particularly as evidenced through flooding at the site during the snowmelt period when surface runoff was the dominant water loss mechanism. The observations suggest that surface bunds can be an important technique for increasing surface water storage at harvested peatlands. However, the bunds at the Bois-des-Bel site were not sufficiently strong, and thus snowmelt water was inadvertently released. Decreasing the distance between bunds, and thus the head difference between them, may help alleviate this problem. Much of snowmelt water was lost via overland flow before the ground was thawed, reducing infiltration and dilation storage that would otherwise have occurred. During the summer months, the bunds did not play an important role in controlling water redistribution at the restored site, since water levels were rarely at the surface.

Overall, monitoring of the Bois-des-Bel site suggests that the runoff controls have restricted direct water flow losses from much of the restoration site. This effectiveness has been partly masked by the site-specific introduction of the new drainage ditch that has altered the timing of runoff patterns. The snowmelt period represented considerable water for storage within the peat, but observations indicated that this was not occurring as anticipated. High water table levels leading up to the freeze-up period in late fall, when evaporation demands were generally low, led to the development of an impermeable frozen surface layer. The late-fall period may be an important time for accumulating water behind bunds and causing dilation storage, but this has not been assessed and requires quantification.

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