



# The Impact of Peatland Restoration on the Site Hydrology of an Abandoned Block-Cut Bog

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**Abstract** Artificial drainage networks established throughout peatlands during the peat extraction process often remain active following abandonment, maintaining a water table relatively far from the surface of the peat, and hindering the survival and reestablishment of *Sphagnum* mosses. As an initial restoration effort, the primary drainage network of an abandoned cutover peatland was blocked with a series of peat dams, consequently reducing the runoff efficiency and causing the site-average water table to rise by 32 cm. Higher water tables and a blocked drainage network resulted in increased runoff variability, dependent upon antecedent conditions (capacity to retain additional water on-site), and event-based precipitation dynamics. Evapotranspiration (ET) rates were 25% higher following rewetting ( $3.6 \text{ mm day}^{-1}$ ) compared to pre-restoration ET rates of  $2.7 \text{ mm day}^{-1}$ . Total storage changes were restricted following rewetting, as a factor of the reduced runoff losses limiting water table drawdown, thereby constraining peat compression and preventing undue drying of the unsaturated zone. An average surface level rebound of 3 cm was observed, increasing the mean hydraulic conductivity by an order of magnitude. Changes to the system hydrology following restoration efforts produced hydrological conditions more favourable for the recolonization of *Sphagnum* mosses.

**Keywords** Hydraulic conductivity · Peat · Rewetting · *Sphagnum* moss · Water balance

## Introduction

Peatlands cover over 12% of Canada's total land area (Tarnocai 2006). Exploitation of peatlands for horticultural peat (Keys 1992; Bergeron 1994) and, more recently, the potential of peat as a fuel source (Gleeson et al. 2006) is an important industry in Canada. Peat mining activities primarily focus on extracting *Sphagnum* peat from bogs due to its desirable water-holding properties and resistance to decay (Read et al. 2004). Prior to extraction, peatlands are subject to drainage that lowers the water table, resulting in subsidence due to shrinkage and oxidation in the unsaturated zone and compression below the water table (Kennedy and Price 2005). Consequently, cutover sites are characterized by a more decomposed and compacted peat substrate (Price and Whitehead 2001) with a high water retention capacity and low specific yield (Schlotzhauer and Price 1999), resulting in harsh physical and hydrological conditions that limit the successful recolonization of *Sphagnum* mosses, the most dominant peat-forming plant genus (Kuhry and Vitt 1996). Inadequate spontaneous reestablishment of *Sphagnum* in cutover sites inhibits the restoration of natural peatland functions. In undisturbed peatland ecosystems, the uppermost layers of living, dead, and poorly decomposed plant material exist as the acrotelm (Ingram 1978). The hydrologic characteristics of this layer are such that surface runoff and evaporation losses are regulated and water table fluctuations are constrained to a narrow limit near the surface of the peat (Van Seters and Price 2001). Cutover peatland systems, however, lack these self-regulating characteristics, as the former acrotelm is removed during the peat extraction process. The remnant catotelmic peat differs from the acrotelm in hydrologic character, as it has a drastically reduced capacity to regulate WT variability, water storage, surface water runoff, and

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evapotranspiration rates, producing a water regime atypical of natural systems and harsh hydrological conditions for recolonizing plants, especially non-vascular mosses, following abandonment.

Seasonal peat volume changes have a direct effect on the hydraulic parameters (e.g., saturated hydraulic conductivity;  $K_{sat}$ ) and water storage capacity of the peat deposit (Kennedy and Price 2004), which influences the availability of water for non-vascular *Sphagnum* mosses. Shrinkage and compression are the dominant volume change mechanisms for peat soils that occur as a consequence of water table lowering for harvest (Eggelsmann 1976; Schothorst 1977), accounting for 96–97% of seasonal volume change in some cutover peatland systems (Kennedy and Price 2005). Below a material's critical stress level, shrinkage and compression are reversible, though in extremely dry conditions the peat can undergo a permanent structural change, preventing a peat layer from recovering 100% of its prior volume, even if completely rewetted to saturation (Kennedy and Price 2005). Site-scale rewetting experiments documenting the extent of this soil volume recovery in cutover peat deposits are required to quantify the reversibility of these processes. More importantly are the implications of these structural changes on the movement of water and nutrients through the saturated zone and the availability of water at the top of the unsaturated zone, where *Sphagnum* mosses rely upon capillary rise to supply water to their photosynthesizing capitula (Price et al. 2009). However, the effect of site rewetting on the physical properties of the remnant peat deposit is not known.

Successful *Sphagnum* recolonization is dependent upon restoration efforts of abandoned sites (Lavoie et al. 2003; Price et al. 2003; Rochefort et al. 2003). This is an essential step towards re-establishing the critical self-regulating processes of the acrotelm layer, allowing for the recovery of the peatland hydrological and ecological (peat-forming) function. Natural recolonization of abandoned sites may take decades or may not occur at all (Price et al. 2003), necessitating the implementation of proper site management techniques to reduce the impact of peat harvesting. Water management approaches, such as site rewetting by blocking drainage ditches, can accelerate the restoration of cutover sites by improving the hydrological conditions within the peat substrate (LaRose et al. 1997; Price et al. 2003; Shantz and Price 2006b); however, the response of the hydraulic parameters of the substrate (e.g.,  $K_{sat}$ ) following water table reestablishment is poorly understood (Holden 2005). Furthermore, altered water dynamics and distribution within a bog following rewetting has direct implications for the components of the water balance, inevitably changing the distribution and magnitude of water losses from the site. The water balance provides a good indication of the relative importance of hydrological processes and

their spatial variation throughout the site (Van Seters and Price 2001); however, full water balance studies of managed (rewet) cutover bogs are rare.

To improve peatland restoration strategies, there is a need to understand the impact of site rewetting on the system hydrology. Therefore, the specific objectives of this study are to (i) compare the full water balance of an abandoned block-cut bog prior to and following rewetting; (ii) characterize the impact of peatland restoration (rewetting) on the hydrological conditions of the remnant peat; and (iii) address the implications for *Sphagnum* moss recolonization.

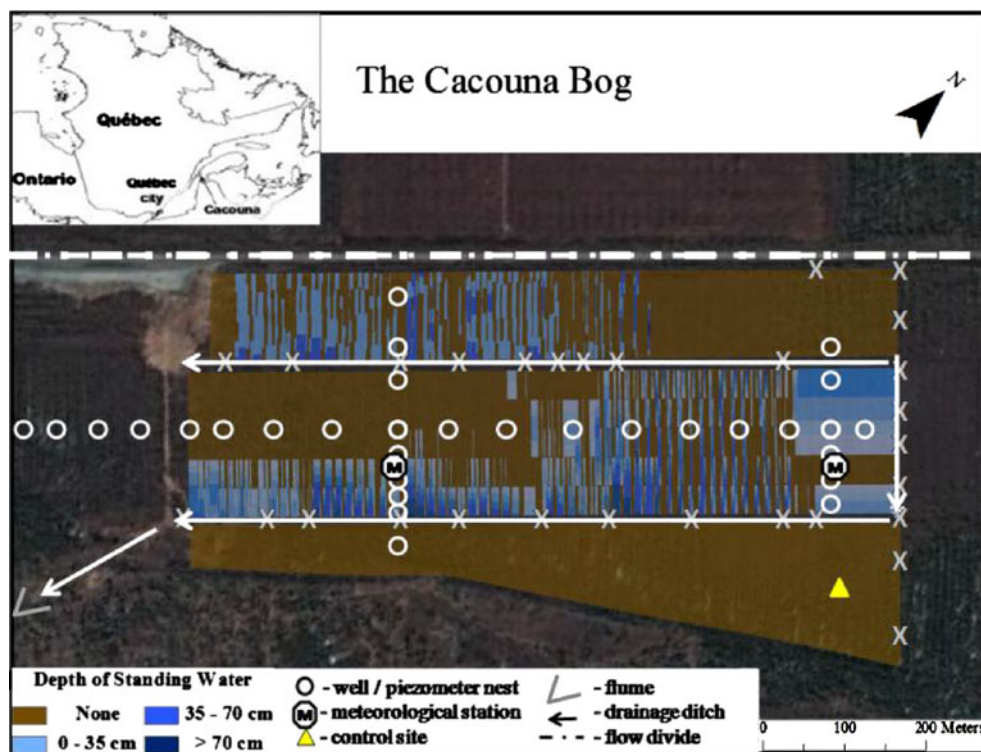
## Study Area

The study site is an abandoned block-cut bog near Cacouna (47°53' N, 69°27' W), approximately 10 km north-east of Rivière-du-Loup, Québec, Canada. Mean annual precipitation (1971–2000) recorded at a meteorological station in St. Arsène (< 2 km from study site) is 963 mm, 29% of which falls as snow (Environment Canada 2003). The mean annual temperature is 3.2°C, ranging from –10.9°C in February to 16.5°C in August (Environment Canada 2003).

Located within the St. Lawrence Lowlands, the Cacouna peatland is a domed bog of the Low Boreal Wetland Region (NWWG 1997), an area underlain by thick deposits of marine clay from the former Goldthwait Sea (Dionne 1977). Extensive auger sampling by Van Seters and Price (2002) indicate that the clay layers are continuous. At an altitude of 83 m a.s.l., the Cacouna bog originally covered an area of 210 ha, but has since been reduced in size to 148 ha as a result of agricultural encroachment and the development of roads through the bog margins (Girard et al. 2002). In the mid-1880s, a railway was constructed approximately along a natural groundwater divide, creating a flow barrier that separates the bog into two hydrologically distinct halves (Van Seters and Price 2001). This study focused on a 55 ha section within the 80 ha southern half (Fig. 1).

Peat harvesting began in 1945 and continued until 1975, using the traditional block-cut extraction technique, resulting in a cutover landscape of alternating baulks 2–4 m wide and raised approximately 0.5–1.0 m above adjacent, lower-lying trenches of 10–12 m width. These baulk-trench combinations occur in parallel, with typical lengths of 180 m, and are situated in an approximately north-south direction. The remaining cutover peat is up to 4 m thick (Van Seters and Price 2001) with average bulk density and specific yield values of 0.12 g cm<sup>-3</sup> and 0.08, respectively, for residual peat within the trenches (Price and Whitehead 2001). Following final abandonment, an attempt was made to block some drainage ditches with

**Fig. 1** Map of the Cacouna Bog. Standing water depth is indicated by areas shaded proportional to the depth of water observed following rewetting. Baulks and trenches are situated in an approximately north-south direction, producing the striped pattern of narrow (dry) baulks between mostly flooded trenches. Note the deepest water is located just upstream of the location of a peat dam, with no standing water (hence drier peat) further from the peat dam. A more gradual slope in the northeast end of the site resulted in a transition towards more uniform standing water depths



peat in the southwest portion of the bog; however, about half of the ditches still remained operational, resulting in runoff losses amounting to a significant proportion of precipitation (two-year average of 18%, snowmelt excluded) (Van Seters and Price 2001).

Since final abandonment, the site has been naturally recolonized by vegetation typical of raised bogs in the Rivière-du-Loup region (Lavoie and Rochefort 1996). The relatively dry conditions of the cutover peat favoured the growth of vascular vegetation, especially Ericaceous shrub species such as Labrador tea (*Ledum groenlandicum*), leatherleaf (*Chamaedaphne calyculata*), sheep laurel (*Kalmia angustifolia*), and blueberry (*Vaccinium angustifolium*) (Lavoie and Rochefort 1996). Additionally, prolific tree species included tamarack (*Larix laricina*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), and grey birch (*Betula populifolia*); tree cover was denser in areas abandoned longest as well as along the margins of the bog. A total of 90–100% of the harvested area has been recolonized by vascular vegetation (Girard et al. 2002). Conversely, only 10% of the harvested area has been recolonized by *Sphagnum* species (most commonly *S. capillifolium*, *S. magellanicum*, *S. rubellum*, and *S. fallax*), which are largely limited to the lowest, moist portions of the trenches (Girard et al. 2002). A more detailed description of plant species can be found in Lavoie and Rochefort (1996).

In October of 2006, peat dams were constructed within the southern portion of the Cacouna bog (Fig. 1), thereby blocking the remaining active ditches within the site

drainage network and consequently flooding the lower portions of some of the trenches. Our study includes data from two years prior to (2005, 2006) and one year following (2007) the site rewetting. A small section in the south-east corner of the site remained unaffected by the rewetting, providing a suitable control site.

## Methods

### Site Rewetting and Hydrology

The primary drainage network within the Cacouna bog (previously moderately functional) was blocked in October of 2006 through the construction of 29 peat dams, which were located predominantly along the length of the two primary drainage ditches that run approximately east-west (perpendicular to trenches—see Fig. 1). No other restoration measures were undertaken. Average spacing between peat dams was approximately 75 m, which corresponded to an approximate change in elevation of 25 cm between dams. The terminal end of raised balk structures that run perpendicular to primary drainage ditches and along the periphery of trenches provided a suitable location for peat dam construction as the baulks act as efficient flow barriers. As part of the dam construction technique, the upper vegetation mat (including rooting layer) was removed from both the surface of the drainage ditch and the borrow area and put aside. Deeper, well-decomposed peat was dug from

the borrow area and tamped into place in the centre of the drainage ditch until the top of the peat dam protruded slightly above the surrounding peat surface. Finally, the uppermost vegetation and root layer (previously removed) was placed atop the dam to stabilize the surface through revegetation. Piezometers were installed in seven of the constructed peat dams, and cores were extracted from three dams for estimates of  $K_{\text{sat}}$  and bulk density.

Water table levels were monitored on a weekly basis throughout the three study periods with a network of over 70 PVC wells slotted along their entire length and arranged in transects running approximately north-south and east-west throughout the site (Fig. 1). Since trenches dominated spatially over baulks in the Cacouna bog, and to be consistent, all wells were installed in trenches. Surface level changes were monitored concurrently by measuring the distance between the top of a stationary steel rod (firmly set in the underlying clay layer) and a 25 cm diameter plastic disc resting on the surface of the peat. Nine nests of piezometers were installed throughout the site (Fig. 1) and consisted of PVC pipes slotted along only the bottom 20 cm; pipe intakes were situated at varying heights above the peat-mineral interface. The altitude of all well and piezometer pipe tops were referenced to a common datum using a total station and standard surveying techniques. Field estimates of  $K_{\text{sat}}$  were conducted in each study period using bail tests following Hvorslev's (1951) hydrostatic time-lag method. Piezometers remained in the ground throughout the three-year study period to allow for a direct comparison of  $K_{\text{sat}}$  between seasons.

#### Micrometeorological Conditions

Meteorological data were monitored continuously from 19 May to 16 August in three consecutive years (2005–2007) using a Campbell Scientific Inc.™ data logger at a meteorological station established within the central portion of the site (see Fig. 1). Precipitation was automatically measured with two tipping bucket rain gauges, and data checks were made using a manual rain gauge adjacent to each of the tipping bucket rain gauges. Values were within  $\pm 10\%$ . Measurements were compared to climate averages for the region (1971–2000) as recorded at the nearby (< 2 km) St. Arsène meteorological station. Air temperature and relative humidity (RH) were measured using shielded copper-constantan thermocouples (air temperature) and a self-logging Hobo™ Temperature and RH logger.

#### Evapotranspiration

A net radiometer was installed 1.5 m above the cutover peat surface and centred in an 11 m wide trench that exhibited typical shape and vegetation cover, which provided a

representative measurement of the net radiation flux ( $Q^*$ ). Additionally, two soil heat flux plates were installed (in the trench) at the meteorological station to provide measurements of ground heat flux ( $Q_G$ ). These measurements of  $Q^*$  and  $Q_G$  were used for estimation of daily equilibrium evapotranspiration ( $ET_{eq}$ ) using the Priestley and Taylor (1972) combination method where

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

and where  $L$  is the latent heat of vaporization ( $\text{J kg}^{-1}$ ),  $\rho$  is the density of water ( $\text{kg m}^{-3}$ ),  $s$  is the slope of the saturation vapour pressure-temperature curve ( $\text{Pa } ^\circ\text{C}^{-1}$ ),  $q$  is the psychrometric constant (assumed to be  $0.0662 \text{ kPa } ^\circ\text{C}^{-1}$  at  $20^\circ\text{C}$ ),  $Q^*$  is the net radiation flux ( $\text{J day}^{-1}$ ),  $Q_G$  is the ground heat flux ( $\text{J day}^{-1}$ ), and  $Q_W$  is the pool heat storage ( $\text{J day}^{-1}$ ). Where standing water was present (2007 only),  $Q_W$  was determined based on changes in water temperature and the depth of the standing water (Price and Maloney 1994). The  $\alpha$  coefficient is the Priestley-Taylor coefficient of evaporability, which represents the slope of the regression line relating actual ( $ET_a$ ) to equilibrium ( $ET_{eq}$ ) evapotranspiration. This empirical estimate of  $\alpha$  can be substituted into Eq. 1 to determine evapotranspiration when only energy balance data are available (Price and Maloney 1994). It is equal to unity when evaporation is occurring at the equilibrium rate, when the near-surface atmospheric vapour pressure deficit is zero.

$ET_a$  was determined using an evaporation pan (representing standing water only) and nine weighing lysimeters filled with peat monoliths and supporting vegetation representative of four of the major surface types and dominant vegetation covers (three repetitions each) for use in deriving the  $\alpha$  coefficient. The  $\alpha$  parameter for evapotranspiration from forested sections of the bog (less than 20% of the study area) was derived from the literature. In a previous study, Van Seters and Price (2001) used an  $\alpha$  value of 1.07 for evapotranspiration calculations from forested sections within the Cacouna bog. Raising or lowering the forest  $\alpha$  value by 0.1 (i.e., 1.17 and 0.97) would change the aerielly weighted evapotranspiration value from the site by  $\pm 1\%$ . The study area was approximately divided into five surface classes (open water, wet, moist, dry and forest), based on field observations of vegetation cover, the topographical position of each lysimeter (thus moisture conditions), and previous studies in the Cacouna bog involving detailed vegetation surveys and aerial photograph interpretation (Van Seters and Price 2001; Girard et al. 2002). The 'wet' trench lysimeters maintained an approximate water table within the upper 5–15 cm with a surface cover dominated by *Sphagnum* moss and bare peat. The 'moist' lysimeters exhibited water table



depths between 20–30 cm below the surface and contained a combination of *Sphagnum* moss, bare peat and Ericaceous shrub cover, while the ‘dry’ lysimeters (approx. water table >–50 cm) were limited to Ericaceous shrubs and bare peat. The extent and depth of standing water (2007 only) was quantified through manual staff gauge measurements along 10 transects (25–30 m spacing between transects) spanning the entire length of the site.

Individual  $\alpha$  values were derived for each surface type, and an aerially weighted  $\alpha$  value was derived for the Cacouna bog where

$$\text{Site } \alpha = \sum_{i=1,5} (\alpha_i A_i) \quad (2)$$

and  $A_i$  is the fractional aerial coverage of  $i$  surface class (1–5 representing dry, moist, wet, open water, and forest) with an  $\alpha_i$  coefficient of evaporability. Each study period was temporally divided into four separate time periods (approximately 20–30 days each, with the exception of 2005, which was divided into only two periods) with separate *Site*  $\alpha$  values determined for each period. This provided an estimation of total evapotranspiration from the Cacouna bog. Following site rewetting (i.e., 2007 study period), the relative aerial coverage of the different surface types of the previous two years was altered as a consequence of a rise in the average site water table level (~30 cm) and the flooding of low-lying portions of the site. The magnitude of this water table rise and consequent alteration of the surface type distribution varied according to the site topography in addition to the proximity to a peat dam. Based on water table levels and field observations of moisture content, the proportion of wet sites in the 2007 study period was increased by 25% as compared to 2005/2006, with dry sites being reduced by 25% accordingly. A sensitivity analysis determined that raising or lowering this percent change by 10% (i.e., 15% and 35% change in surface type proportions) would change the aerially weighted evapotranspiration rate by only  $\pm 1\%$ .

### Runoff

Runoff was measured with a current meter in a box flume located in the southwest corner of the site at the outlet of the primary drainage network (Fig. 1). Water stage was continuously measured with a Remote Data Systems Inc.™ water level monitoring device secured to a staff gage for manual verification. A stage-discharge relationship was developed and applied to allow for the empirical derivation of hourly discharge rates for each of the study periods. Although snowmelt represents a predominant component of seasonal runoff, few studies evaluate runoff control techniques (i.e., blocking drainage ditches) during the snowmelt

period (Shantz and Price 2006a); the snowmelt period is not included in this study.

### Storage Changes

According to Van Seters and Price (2001), seasonal changes in storage within peatlands can be determined by

$$\Delta S = dh(S_y + bS_s) \pm d\theta \quad (3)$$

where  $dh$  is the change in the water table,  $S_y$  is the specific yield,  $b$  is the aquifer thickness,  $S_s$  is the specific storage, and  $d\theta$  is the change in moisture content of the unsaturated zone. The  $S_s$  parameter characterizes the volume of water released from storage by compression of the peat matrix where

$$S_s = (db/dh)/b \quad (4)$$

and  $db/dh$  represents the slope of the surface subsidence versus water table level relation (Price and Schlotzhauer 1999). This component is often omitted from storage change estimates due to the relatively large specific yield from unconfined aquifers (Van Seters and Price 2001); however, the high compressibility of peat soils results in a significant contribution of the specific storage term in estimates of storativity (Price and Schlotzhauer 1999). As such, Eq. 3 includes the effects of water table changes on aquifer compression and moisture content changes in the unsaturated zone in seasonal estimates of storage change. Water table levels ( $dh$ ) and relative changes in surface elevation ( $db$ ) were monitored on a weekly basis along the transect of wells and surface level monitors running approximately east-west through the centre portion of the site (Fig. 1). In the unsaturated zone,  $d\theta$  was estimated by *in situ* volumetric moisture content surveys conducted within a representative trench using a HydroSense® soil water content measurement system that was calibrated in the lab using peat extracted from the same area. Seasonal  $d\theta$  was calculated as the difference in average  $\theta$  at the end of the study period compared to that at the start. During each study period, five cores were extracted from the surface to depths of 50–80 cm from representative surface types within the Cacouna bog. The cores were carefully transported back to the laboratory where they were sliced into 5 cm sections and analysed for bulk density and  $S_y$  using standard methods (Price 1996).

## Results

### Water Distribution Following Rewetting

Water ponding was evident behind peat dams and between baulks, producing a series of water reservoirs across the site (Fig. 1). The  $K_{\text{sat}}$  of the constructed peat dams was

comparable to that of the borrow peat deposit, with geometric mean values of  $2 \times 10^{-4}$  and  $6 \times 10^{-4}$   $\text{cm s}^{-1}$  (at 75 and 100 cm below the surface of the peat dam, respectively) and  $2 \times 10^{-4}$  and  $5 \times 10^{-4}$   $\text{cm s}^{-1}$  (at 75 and 100 cm within the remnant peat deposit, respectively). However, the  $K_{\text{sat}}$  at 150 cm depth was an order of magnitude higher within the peat dam ( $3 \times 10^{-2}$   $\text{cm s}^{-1}$ ) than the borrow peat deposit ( $1 \times 10^{-3}$   $\text{cm s}^{-1}$ ). Average bulk density values within the upper 80 cm of the peat dam structures ranged from 0.08 to 0.20  $\text{g cm}^{-3}$ , which were more dense (with one exception) than the borrow peat deposit. The hydraulic parameters of the constructed peat dams were sufficient for detention of spring snowmelt and summer precipitation waters on-site up to the site water-holding capacity. Consequently, the average site depth to water table increased from approximately  $-44$  and  $-39$  cm (with reference to the cutover peat surface) during the 2005 and 2006 study periods, respectively, to  $-10$  cm in the 2007 study period (Fig. 2). Topographical variability within the study site, in combination with the location of the constructed peat dams, had a profound influence on the magnitude of the water table rise at any given location within the site. A typical trench exhibited an elevation change of over 2 m along an approximate 180 m length, resulting in a slope of 0.013. The low elevation ends of the trenches were disproportionately wet given their proximal location to the main drainage ditch and the peat dams compared to the upper reaches of the trenches that were farthest from the peat dams. For example, the water table level rose by 112 cm at a well situated in the lower end of a trench, 7 m upslope from a peat dam, while a well situated 153 m upslope in the same trench exhibited a rise in water

table level of only 26 cm (Fig. 2). Similarly, topographical changes between peat dams in an east-west direction (i.e., perpendicular to trenches) complicated the variable influence of site rewetting. Prior to rewetting, standing water occupied a small (<5%) proportion of the site; however, in the 2007 study period, standing water covered 37% of the study site (average depth=24 cm) and occupied some trenches along their entire length and others not at all (Fig. 1).

#### Water Inputs and Outputs

Cacouna bog is underlain by a low permeability continuous clay base ( $5 \times 10^{-8}$   $\text{cm s}^{-1}$ ) that restricts water exchanges with the regional aquifer (Van Seters and Price 2001). As such, the only water input to the Cacouna bog was precipitation; evapotranspiration and runoff accounted for the only water losses from the site.

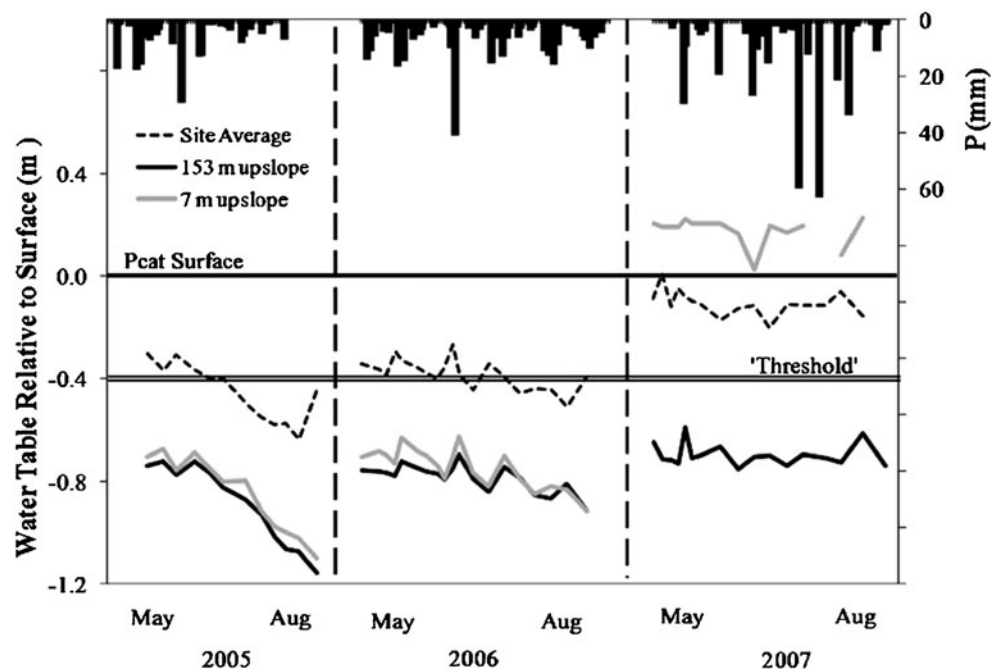
#### Precipitation

Precipitation (P) recorded during the 2005, 2006, and 2007 study periods totalled 200, 222, and 327 mm, respectively. The 30-year average (1971–2000) precipitation for the months of June and July total 179 mm as recorded at the St. Arsene meteorological station (Environment Canada). Precipitation for the same two months of 2005, 2006, and 2007 totalled 137, 158, and 216 mm, respectively.

#### Evapotranspiration

Owing to the highly variable surface microtopography within the Cacouna bog (baulks and trenches) and a

**Fig. 2** Water table levels at the Cacouna bog (dashed line represents the average site water table). The ‘threshold’ level ( $> -0.4$  m) identifies water table levels which are generally suitable for moss survival at the Cacouna bog (Price and Whitehead 2001). Water table levels near to (7 m upslope; grey) and far from (153 m upslope, black) a peat dam illustrate the non-uniform rise of water table levels following rewetting. Black bars represent precipitation (P)



relatively flat water table beneath this microtopography, substantial differences in the water table, and thus ET rate, exist on a small scale (metres). During  $\alpha$  derivation, the best relationships (highest  $R^2$  values) were typically achieved from wet surfaces;  $\alpha$  values, and hence ET rates, trended open water>forest>wet>moist>dry for each of the study periods (Table 1). As such, ET losses from open water and wet surfaces were the largest (the forest makes up only a small portion of the site) since these were the areas within the site where moisture was generally the most available. Aerially weighted  $\alpha$  values ranged between 0.72 and 1.11 over the three study periods (Table 2). The highest estimated average  $\alpha$  value was from open water ( $\alpha=1.37$ ). ET rates were 25% higher following rewetting in 2007 (3.6 mm day<sup>-1</sup>) as compared to pre-restoration ET rates of 2.7 mm day<sup>-1</sup> during both the 2005 and 2006 study periods (Table 2).

### Storage Changes

The greatest storage change was due to the deepening water table during the course of each study period. The water table declined by 258, 215 and 113 mm during the 2005–2007 study periods, respectively. The specific yield value for the substrate was estimated at 0.18 (three year average), which generated water losses due to the drainage of soil pores of approximately 47, 39, and 20 mm over each study period, respectively. Storage changes associated with compression of the peat matrix, as estimated by Eq. 4, were 16, 10, and 5 mm. Good  $R^2$  values ( $> 0.75$ ) were obtained during calculation of the slope of the surface subsidence versus water table level relation. Changes in moisture content (drying) of the unsaturated zone throughout each study period resulted in storage losses of 12, 23, and 5 mm. Using Eq. 3, total storage change during the 2005, 2006, and 2007 study periods was estimated to be 75, 71, and 31 mm, respectively.

### Runoff

A network of primary and secondary drains transmitted runoff from the site. Runoff was 25 and 73 mm in the 2005 and 2006 study periods. After construction of the peat dams in the fall of 2006, runoff during the 2007 study period was 32 mm. Runoff losses were the largest in 2006, due mainly to the occurrence of one large (60 mm) precipitation event and an active primary drainage network. An average runoff efficiency (percent precipitation produced as stream discharge) of 10% was observed following drainage ditch blocking (2007), which was reduced from 23% during the 05/06 study periods (Price and Ketcheson 2009). Storm hydrograph lag-times were also generally shortest in 2007. Table 3 presents the runoff efficiency and lag-times for storms with similar antecedent water levels in each year. Antecedent water levels were measured a few days prior to the event at the same location each year, which remained unaffected by the site rewetting. The control site had not been established prior to the storm event in 2005 so it was unsuitable for this application; however, water levels at the control site were similar in 2006 (–52 cm) and 2007 (–50 cm) prior to the respective events. The hydrographs for each of the storms (Fig. 3) indicates that stream flow returned to pre-storm conditions rapidly following ditch blocking (2007). Moreover, the daily flow duration curve shifts to the left and exhibits a much steeper slope in 2007, which indicates a reduction in daily discharge rates in all but extreme conditions with a blocked drainage network (Fig. 4). The Cacouna bog exhibited an increased storage capacity in 2007, whereby a critical storage threshold had to be exceeded for the system to respond rapidly to precipitation inputs. For example, precipitation produced deepening pools within trenches during a 60 mm precipitation event in 2007 until the site storage capacity was reached, as indicated by an increasing discharge and decreasing rate of water rise in the trench (Fig. 5). Hysteresis was apparent, as similar discharge depths were

**Table 1** Percent cover and ET rates for the Cacouna bog for 19 May to 16 August, 2005–2007. Note: open water was only present during the 2007 study period

Surface type	Dominant surface cover	Percent cover 05/06 (07)	ET rate (mm day <sup>-1</sup> )			Average ET rate (mm day <sup>-1</sup> )
			2005	2006	2007	
Wet trenches	<i>Sphagnum</i> spp. and bare peat	21 (29)	3.0	3.0	3.2	3.1
Moist trenches	Ericaceae spp. and some <i>Sphagnum</i> spp.	24 (15)	2.4	2.8	2.8	2.7
Dry baulks and roads	Ericaceae spp. and bare peat	35 (7)	2.3	2.3	2.5	2.4
Forest	Various tree species	19 (12)	3.7	3.1	3.7	3.5
Open Water		(37)	–	–	4.6	4.6
Aerially Averaged Seasonal ET Rate (mm day <sup>-1</sup> )			2.7	2.7	3.6	

**Table 2** Alpha values and ET losses for the Cacouna bog for 19-May to 16-August, 2005–2007

Year	Total ET losses (mm)	Average ET rate (mm day <sup>-1</sup> )	Aerially weighted alpha for time period				
			Julian Day				
			139–156	157–182	183–211	212–228	
2005	246	2.7	0.78	0.78	0.72	0.72	
2006	227	2.7	0.96	0.89	0.94	0.91	
2007	328	3.6	0.72	0.73	1.07	1.11	
			Water $\alpha$ 1.36	Forest $\alpha$ 1.07			

observed at different standing water levels for the rising and receding limbs.

#### Surface Elevation Change and Hydraulic Conductivity

Site-averaged seasonal surface level adjustment (relative to the first measurement of each respective study period) was found to be  $-2.3$ ,  $-0.6$  and  $+0.2$  cm in 2005, 2006 and 2007, respectively, with a maximum subsidence of over 5 cm at one location in a single season (2005). The surface level rebounded by an average of 3.2 cm following rewetting (relative to the 2005/2006 average level) (Fig. 6). Contemporaneous with peat surface rebound following site rewetting, the mean  $K_{\text{sat}}$  increased by an order of magnitude (2007) both at the site scale (55.1 ha) and within an instrumented trench (the ‘study trench’  $\sim 0.2$  ha) (Fig. 7). Values of  $K_{\text{sat}}$  within the control section of the Cacouna bog (hence not affected by the rewetting) increased only slightly (32% higher than 05/06 average) as compared to the site average  $K_{\text{sat}}$ , which showed an increase of 269% (higher than 05/06 average) (Table 4).

#### Water Balance

The seasonal water balance of the Cacouna bog (devoid of surface and ground water inputs) is estimated as

$$P = ET + R \pm \Delta S + \varepsilon \quad (5)$$

where  $P$  is precipitation,  $ET$  is evapotranspiration,  $R$  is runoff,  $\Delta S$  is change in soil storage, and  $\varepsilon$  is the residual term. Each of the components used in the water balance

(with the exception of  $P$ ) were influenced by rewetting (Table 5).  $ET$  was the dominant water loss from the site each year and exceeded precipitation inputs in both years prior to rewetting, which resulted in a summer water deficit. The cumulative  $P$  minus  $ET$  during the 2005, 2006, and 2007 study periods was  $-46$ ,  $-21$ , and  $-1$  mm, respectively, indicating a shortage of water in each of the two study periods prior to rewetting and the absence of a summer water deficit in 2007 following rewetting. A water deficit did not occur in 2007 despite the substantial increase in  $ET$  losses due to above average precipitation. Runoff losses were the largest in 2006 due mainly to the occurrence of one large (60 mm) precipitation event and an active primary drainage network. Even though more precipitation occurred in 2007 (327 mm) as compared to 2005 (200 mm), runoff was similar due to the reduced runoff efficiency following blockage of the drainage network. Both the storage changes and the residual term were smallest in 2007. The residual terms in 2005, 2006, and 2007 represented 2, 10, and  $<1\%$  of water inputs, respectively.

## Discussion

#### Hydrological Consequences

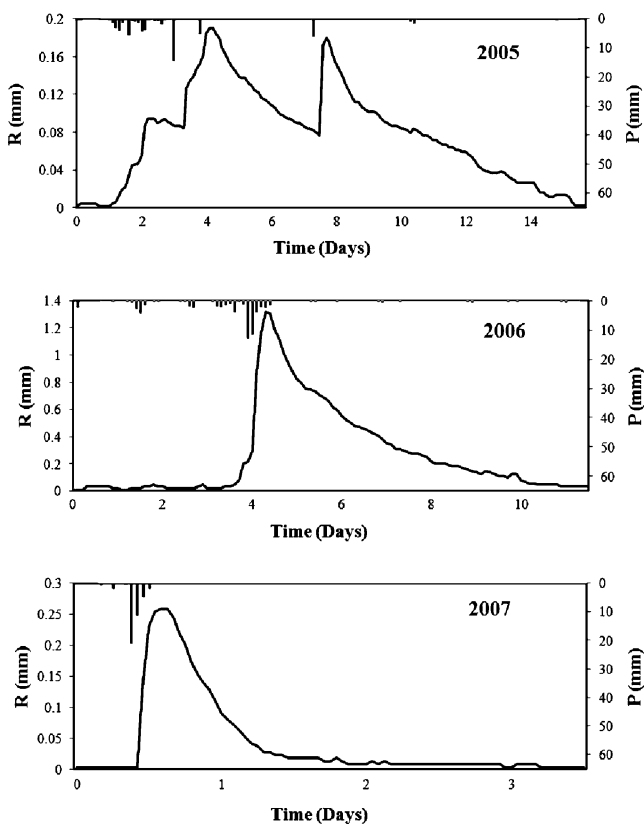
The rewetting of the Cacouna bog caused the water table to rise and flood lower-lying trenches. Topographical variability and the location of the peat dams strongly influenced the magnitude of the water table rise at any given location (Fig. 2), which is similar to a trend observed following

**Table 3** Runoff efficiency, lag-times and storm characteristics for events with similar antecedent water levels each year. Note: a small (9 mm) secondary precipitation event occurred in 2005, which increased the time from peak to baseflow

Year (Julian Day)	Antecedent water level (cm)	Event duration (hrs)	Average event intensity (mm/hour)	P (mm)	R (mm)	Runoff efficiency (%)	Lag-time (hrs)*	Time from peak to baseflow (hrs)
2005 (165)	-89.2	106	0.5	51	12	24	50	245
2006 (158)	-93.4	79	0.7	59	30	51	14	158
2007 (192)	-88.3	12	3.6	43	4	9	6	32

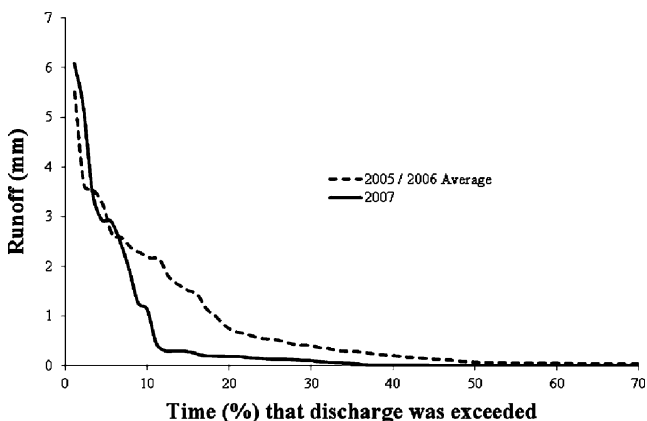
\* Time from centre mass of rain storm to peak



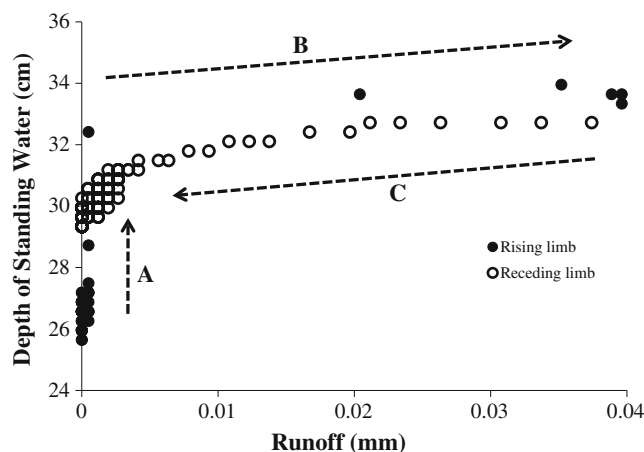


**Fig. 3** Hydrographs for storms during the 2005, 2006, and 2007 study periods (similar antecedent water levels)

ditch blocking in a nearby block-cut peatland (Roul 2004). Peat dams effectively detained P waters on-site; however, several peat dams failed via deep through-flow or undercut in 2009 (personal observation) where the  $K_{sat}$  was much higher. This portion of the dam near to its base is more likely to have macropore flow, as it is composed of peat from the upper portion of the borrow area. This peat has been above the water table consistently for decades and,

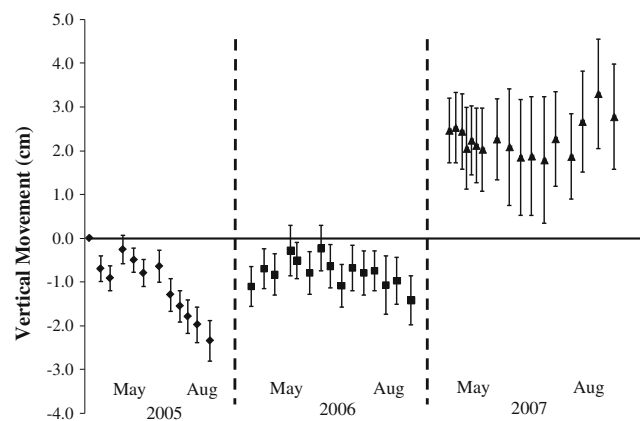


**Fig. 4** Daily flow duration curves for the Cacouna bog. The steeper curve following rewetting (2007) indicates a tendency towards low-flow conditions



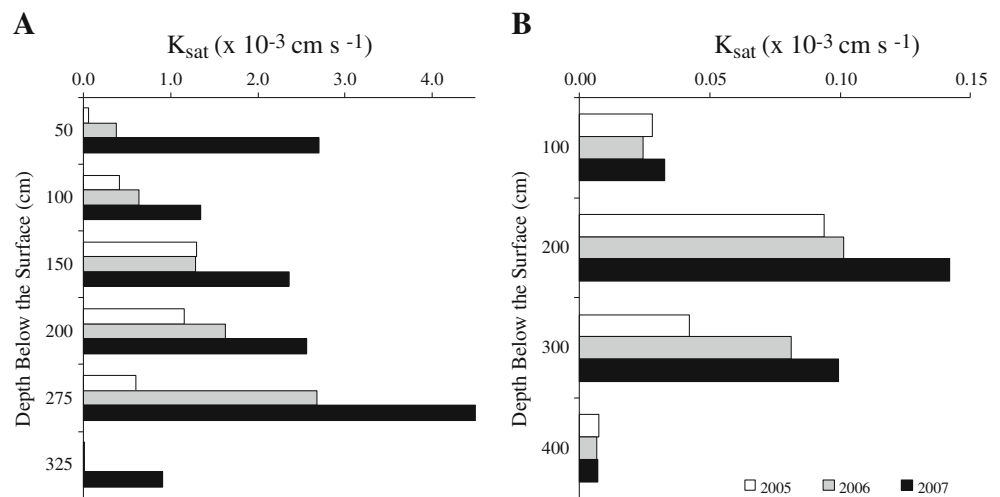
**Fig. 5** Standing water depth within a trench versus runoff during a 60 mm precipitation event in 2007. **a**—Depth of standing water within a flooded trench increases during the precipitation event, as water is detained on-site due to the blocked drainage network (closed symbols); **b**—the site water storage capacity is exceeded and precipitation inputs produce site runoff (closed symbols); **c**—runoff from the site recedes as precipitation inputs cease and the site returns to its maximum water holding capacity (open symbols)

through oxidation, compression and shrinkage, has become quite dense and structurally sound (i.e., less amorphous) and, hence, more resistant to being tamped into place. Further, differences in standing water levels across some peat dams consistently exceeded 0.5 m. This large pressure difference across the peat dam could result in hydraulic lifting and separation of the peat dam material at depth, which would allow water to flow through the dam more easily. Closer peat dam spacing would reduce these large pressure differences and thereby restrict the water flow through the dam as a consequence of hydraulic lifting. Use of peat from the uppermost borrow sites for dam construction is advised against, in favour of peat from deeper within the deposit.



**Fig. 6** Surface elevation changes (relative to the first measurement in 2005) over the three study periods. Error bars represent the standard error of the mean

**Fig. 7**  $K_{\text{sat}}$  with depth within a trench at the Cacouna Bog (a; left) and at the control site (b; right). Note the different scales (X and Y axes)



ET losses were the greatest following rewetting due to the increased abundance of water as well as the addition of pooled (open) water within flooded trenches. Despite the increased ET rates, drying of the unsaturated zone was reduced in 2007. Increased P amounts (in 2007) are partially responsible for this; however, the reduced runoff efficiency following ditch blocking is likely the most important factor. Storm hydrographs returned to pre-event conditions quickly following rewetting (Fig. 3) and, despite having the highest event intensity and shortest lag-time, the storm event in 2007 produced the smallest amount of runoff (Table 3). Holden (2005) documented dramatic changes to the runoff regime in disturbed peatlands that included high stream peak flows, rapid responses to rainfall, and a strong dependency upon antecedent moisture conditions. These characteristics become more prevalent at the Cacouna bog following rewetting where, following blockage, the discharge regime remains somewhat unresponsive to precipitation until the site storage capacity has been reached, after which the system becomes more responsive (see Fig. 5). Large discharge rates are produced and time lags are shortened, which are characteristics more typical of a surface-flow dominated regime (Spieksma 1999). Thus, despite the substantial reduction in the efficiency of the primary drainage network, the behaviour of the system depends upon a critical storage threshold. This emphasizes the influence of antecedent moisture conditions on the

runoff regime following site rewetting. Seasonal storage change was reduced by over 60% following rewetting as a result of increased water abundance within the site. Prior to restoration, higher R losses resulted in increased drying of the unsaturated zone and large water table drawdown during the summer season. The volume change associated with the surface rebound during the site rewetting (Fig. 6) caused the  $K_{\text{sat}}$  of the remnant peat deposit to increase by an order of magnitude (Fig. 7). The higher  $K_{\text{sat}}$  could increase subsurface site drainage; however, the blocked drainage network is sufficiently deep to intercept this subsurface flow.

#### Implications for *Sphagnum* Moss Recolonization

Initially, restoration efforts aim to create hydrological conditions more favourable for the recolonization of non-vascular *Sphagnum* mosses to ultimately facilitate the reestablishment of an upper acrotelm layer and a self-sustaining (peat accumulating) ecosystem. At the Cacouna bog, the drying of the unsaturated zone and concurrent water table decline throughout the summers of 2005 and 2006 (Fig. 2) are an excellent illustration of why the natural recolonization of the peatland following abandonment favoured vascular vegetation (90–100% coverage) over *Sphagnum* moss recolonization (<10% coverage; Girard et al. 2002). Price and Whitehead (2001) deter-

**Table 4** The geometric mean  $K_{\text{sat}}$  values (in  $\text{cm s}^{-1}$ , all depths included in calculation) for the entire Cacouna Bog ('site average'), for within the study trench, and at the control site (standard error of the mean in brackets)

Year	Site Average		Study Trench		Control Site	
	$K_{\text{sat}}$	n	$K_{\text{sat}}$	n	$K_{\text{sat}}$	n
2005	$2.7 (\pm 3.4) \times 10^{-4}$	136	$3.1 (\pm 4.6) \times 10^{-4}$	98	$3.0 (\pm 1.8) \times 10^{-5}$	20
2006	$3.8 (\pm 4.4) \times 10^{-4}$	130	$4.5 (\pm 5.1) \times 10^{-4}$	100	$3.4 (\pm 2.3) \times 10^{-5}$	14
2007	$12 (\pm 17) \times 10^{-4}$	134	$15 (\pm 15) \times 10^{-4}$	101	$4.2 (\pm 3.1) \times 10^{-5}$	10
Change (%)	+ 269		+ 284		+ 32	

**Table 5** The components of the water balance for the Cacouna bog (all values in mm). Percent error was calculated by dividing the residual term by the precipitation amount for each year

Year	P	ET	R	Delta S	Residual	% Error
2005	200	246	25	-75	-4	2
2006	222	243	73	-71	23	10
2007	327	328	32	-31	1	<1

mined hydrologic thresholds for *Sphagnum* recolonization at the Cacouna bog and identified that *Sphagnum* recolonized areas where soil water pressures were greater than -100 cm and water tables remained high ( $-24.9 \pm 14.3$  cm). Water tables deeper than -40 cm were found to be imperfectly related to soil water pressures; however, this appears to be the lower limit of water table levels within which *Sphagnum* mosses are able to survive. It is therefore reasonable to use a water table depth of -40 cm as a general indicator of site suitability for *Sphagnum* moss recolonization at the Cacouna bog. The average site water table level in both 2005 and 2006 was drawn below the -40 cm threshold level (labelled 'threshold' in Fig. 2). This signifies that, in general, the site was not suitable for *Sphagnum* recolonization and survival in the years prior to rewetting. However, in 2007 the average site water table remained above -25 cm for the entire season, which indicates that the site is suitable for the survival of *Sphagnum* moss following rewetting.

Prior to rewetting, the *Sphagnum* mosses that were able to recolonize naturally on the surface of the remnant peat deposit were mostly limited to the lowest lying moist portions of the trenches (Girard et al. 2002). Following rewetting, the lowest areas became inundated with water, which resulted in the death of much of the naturally recolonized mosses. Despite the flooding of the sites that were previously the most suitable for *Sphagnum* recolonization, the water table rise increased the proportion of the site that is suitable for moss survival by raising and maintaining high water table levels throughout most of the site. The inevitable ecological succession as a consequence of the new moisture regime following rewetting should favour *Sphagnum* mosses over vascular vegetation. Signs of vascular vegetation stress (dying leaves and needles on shrubs and trees growing in newly waterlogged areas) were apparent during the summer of 2007; however, other drier areas (i.e., locations farther from dams; baulks) will continue to favour an ericaceous shrub cover. Aquatic *Sphagnum* spp. growth was observed within flooded portions of many trenches by late August 2007. By 2009, >50% of the flooded areas appeared (visual observation) to be colonized by *S. fallax*.

Baulk-trench topography distinguishes block-cut peatlands (such as the Cacouna bog) from those harvested using

the vacuum technique, which are relatively flat and exhibit fairly uniform conditions that are generally worse for *Sphagnum* moss recolonization (i.e., less moisture and lower soil-water pressure) (Price et al. 2003). Ideally, for the successful recolonization of *Sphagnum* mosses, site rewetting (i.e., water table rise) would occur uniformly throughout the entire site and surface topographical features would be minimized. This can be accomplished by reducing the spacing between water retention structures (e.g., peat dams). Typically, post-extraction restoration efforts on vacuumed sites rely on ditch-blocking (Price et al. 2003), constructed open water reservoirs (Spieksma 1999), and bunds (Shantz and Price 2006b) to increase the site water storage capacity. Our study demonstrates the practicality of achieving this by means of moderately flooding the relatively wide trenches that remain as a legacy of the peat extraction process. In spite of the differences between vacuum and block-cut peatlands, the importance of maintaining water availability on restored sites is paramount.

## Conclusions

Rewetting transformed the system hydrology and altered water relations within the Cacouna bog. Although it is beneficial to limit the ET losses from a restored site, since it is the dominant water loss each year, the most important impact of site rewetting on the system hydrology was the reduction in runoff efficiency following blockage of the drainage network. The restricted water losses via the site drainage network resulted in an increased water abundance following site management. The new runoff regime was more dependent upon antecedent water table levels following rewetting; as the system responded rapidly once the site water holding capacity was exceeded and low-flow conditions dominated otherwise. The site is generally well-suited for *Sphagnum* moss survival due to the higher water table levels following rewetting; however, the site topography and location of peat dams caused the impact of rewetting to be highly spatially variable. Flooded portions of the site are rapidly recolonizing with aquatic *Sphagnum* species, while more time will be required for *Sphagnum* to colonize the cutover peat surface where moisture is more limited.

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