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Towards a conceptual model of hydrological change on an abandoned cutover bog, Quebec

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Abstract:

Cutover bogs do not return to functional peatland ecosystems after abandonment because re-establishment of peat-forming mosses is poor. This paper presents a conceptual model of bog disturbance caused by peat harvesting (1942–1972), and the hydrological evolution that occurred after abandonment (1973–1998). Two adjacent bogs of similar size and origin, one harvested and the other essentially undisturbed, provide the basis for understanding what changes occurred. The model is based on historical trends evident from previous surveys of land-use, bog ecology and resource mapping; and from recent hydrological and ecological data that characterize the current condition. Water balance data and historical information suggest that runoff increased and evapotranspiration decreased following drainage, but tended towards pre-disturbance levels following abandonment, as vegetation recolonized the surface and drainage became less efficient over time. Dewatering of soil pores after drainage caused shrinkage and oxidation of the peat and surface subsidence of approximately 80 cm over 57 years. Comparisons with a nearby natural bog suggest that bulk density in the upper 50 cm of cutover peat increased from 0·07 to 0·13 g cm^{-3}, specific yield declined from 0·14 to 0·07, water table fluctuations were 67% greater, and mean saturated hydraulic conductivity declined from $4{\cdot}1 \times 10^{-5}$ to $1{\cdot}3 \times 10^{-5}$ cm s^{-1}. More than 25 years after abandonment, *Sphagnum* mosses were distributed over broad areas but covered less than 15% of the surface. Areas with 'good' *Sphagnum* regeneration (>10% cover) were strongly correlated with high water tables (mean −22 cm), especially in zones of seasonal groundwater discharge, artefacts of the extraction history. Forest cover expanded from 5 to 20% of the study area following abandonment. The effect of forest growth (transpiration and interception) and drainage on lowering water levels eventually will be countered by slower water movement through the increasingly dense soil, and by natural ditch deterioration. However, without management intervention, full re-establishment of natural hydrological functions will take a very long time. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS peatland restoration; hydrology; cutover bog; hydrological change; drainage; subsidence

INTRODUCTION

Approximately 700 000 to 800 000 t of peat are harvested from Canadian peatlands every year, representing about two-thirds of North American production (Bergeron, 1994). In the major peat-producing regions of Quebec and New Brunswick, undisturbed peatlands have become increasingly rare, with losses greater than 70% in the Lower St Lawrence area (Lavoie and Rochefort, 1996). After abandonment, cutover sites do not regain natural functions because re-establishment of *Sphagnum* moss, the primary peat forming plant, generally is very poor, although other bog species do recur (Lavoie and Rochefort, 1996). Poor regeneration of *Sphagnum* is both a cause and consequence of post-harvest alterations to the bog water balance and physical properties of the soil (Price and Waddington, 2000).

The harvested peat surface is characterized by higher bulk density, lower specific yield, and consequently, higher soil-water tensions (Price, 1996, 1997). Under these conditions, the natural supply of moisture to non-vascular mosses is inhibited, causing loss of the bog's peat-forming function (Waddington and Price,

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2001). Deforestation and drainage of surrounding lands for agriculture can produce similar consequences by modifying the hydrological controls governing bog morphology and its relationship to the adjacent environment (Ingram, 1982; Bragg, 1995). This includes increased runoff following peat cutting at the margins (Bragg and Steiner, 1995), and evapotranspiration losses created by advected dry air above cultivated soils (Linacre *et al*., 1970).

In drained peatlands, low water tables and high overburden pressures induce shrinkage (Price and Schlotzhauer, 1999; Schlotzhauer and Price, 1999), compression and oxidation (Schothorst, 1977) of the peat. Although shrinkage is largely reversible, oxidation and compression decrease the average pore size and permanently exclude water from the peat matrix (Hobbs, 1986). Initial consolidation (or primary compression) of the pore structure typically occurs within one year of drainage and is much more rapid than the gradual process of secondary compression that continues for many years thereafter (Hobbs, 1986). Consolidation reduces both the availability of moisture to plants (Price, 1997) and the rate of groundwater movement (Chow *et al*., 1992; Heathwaite, 1994).

Revegetation of cutover sites, mainly by trees, shrubs and/or grasses begins soon after abandonment (Money, 1995; Lavoie and Rochefort, 1996). The proliferation of trees alters hydrological conditions by intercepting rainfall and withdrawing soil water for transpiration, forcing the water table on drained bogs to fall further (Ledger and Harper, 1987; Burt *et al*., 1990). Interception can account for a significant portion of evaporation losses. For example, Verry (1986) reported interception for a black spruce forest in Minnesota at 30% of rainfall. Thus, whereas drainage increases runoff, revegetation should have the opposite effect. A conceptual model is needed to illustrate how water balance components evolve following harvesting and abandonment, as well as to clarify the linkages these components have with concurrent changes to hydrophysical soil properties.

The objectives of this paper are, therefore, to (i) understand the hydrological consequences of disturbance caused by peat harvesting, (ii) understand the hydrological evolution that followed abandonment, and (iii) present a conceptual model characterizing these changes. Two adjacent bogs of similar size and origin, one cutover the other essentially undisturbed, provide the basis for understanding what changes have occurred. The model is based on historical trends evident from previous surveys of land-use, bog ecology and resource mapping; and from detailed hydrological and ecological data collected in 1997 and 1998. Charting the course of past changes will provide a better basis upon which to predict future impacts, and offer insights into ways these may be managed to restore peat-forming functions to disturbed peatlands.

STUDY SITES

The main study sites were (i) an abandoned cutover bog (Cacouna bog) near Rivière-du-Loup, Québec (47 °53′ N, 69 °27′ W), and (ii) an undisturbed bog (St Arsène bog), 2 km north of the Cacouna bog. Both sites are raised bogs underlain by thick deposits of marine clay from the former Goldthwait Sea (Dionne, 1977). Extensive auger sampling at both bogs indicated that clay layers were continuous. Before disturbance, the cutover and natural sites were similar in size, originally covering areas of approximately 210 and 242 ha, respectively. Mean annual precipitation (1963–1990) recorded at a meteorological station in St Arsène, Quebec (<2 km from both sites) is 924 mm, 27% of which falls as snow. The mean annual temperature is 3 °C, ranging from −12 °C in January to 18 °C in July (Environment Canada, 1993). Construction of a railway approximately across a natural groundwater divide at the Cacouna bog created a highly compressed peat and flow barrier, separating the bog into two hydrologically distinct halves. This study focused on the larger 80 ha southern half and a small clearing and forested area within the undrained 'lagg' (Figure 1).

Most of the shrub and tree species present at the cutover site are similar to the nearby natural bog, including various species of ericaceous shrubs (e.g. *Chamaedaphne calyculata, Ledum groenlandicum*), black spruce (*Picea mariana*), tamarack (*Larix laricina)* and jack pine (*Pinus banksiana*). Birch (*Betula papyrifera, Betula populifolia*) is more abundant at the cutover site, a phenomenon commonly observed after harvesting. The

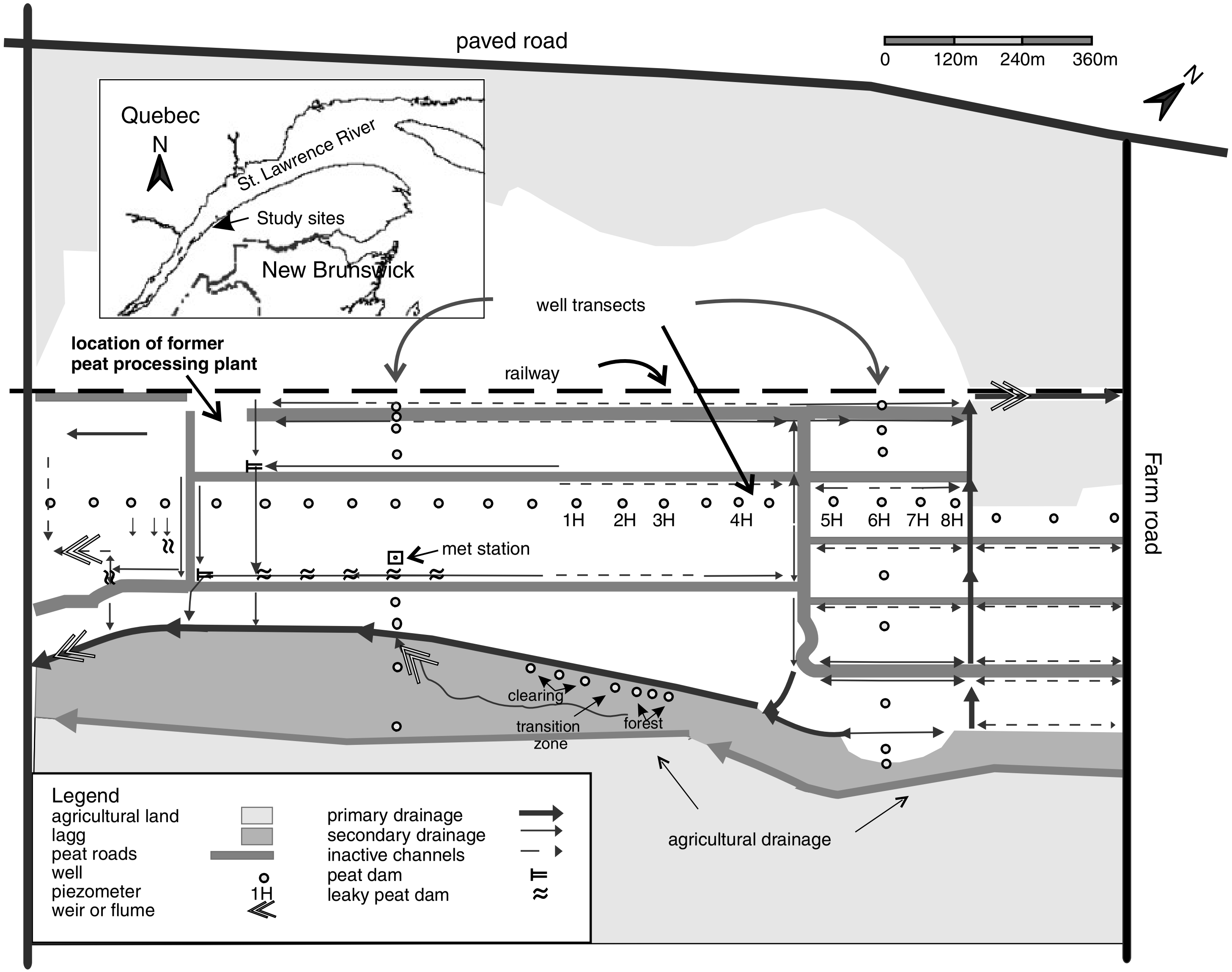

Figure 1. Experimental set-up at the Cacouna bog showing the drainage network, location of weirs, meteorological station, and well and piezometer transects

re-establishment of mosses (*Sphagnum* spp.) is sparse and irregular, occurring mostly in wet trenches and topographic depressions, and covers less than 15% of the total harvested area (Girard, 2000).

METHODS

This study is based on a comparison of a cutover bog and 'undisturbed' bog. Although the direct hydrological data are limited to the 1997 and 1998 field seasons, a wealth of historical data, including peat inventories and palaeoecological surveys (see below), allows a much broader interpretation of the changes that have occurred since exploitation began at Cacouna bog in 1942. This paper uses these data in combination with our understanding from the literature, to develop a conceptual model of hydrological change resulting from peat harvesting and spontaneous regeneration following abandonment.

Historical data

The historical information included: (i) basal peat radiocarbon dating (see below); (ii) tree pollen analysis of peat cores from the Cacouna and St Arsene bogs (Auer, 1930); (iii) 14 aerial photographs (1930–1995) of the Cacouna and St Arsene bogs; (iv) oral accounts of the harvesting process at Cacouna (Girard, 2000); (v) the original drainage plan (Girard, 1947); (vi) local history of settlement and regional developments; and (vii) topographic and peat depth surveys conducted in 1926 (Auer, 1930) before the bog was harvested, and again in 1946 (Girard, 1947) after the bog was drained, but only a relatively small quantity of peat had been removed. The latter surveys are compared with similar sets of measurements in 1997 to provide an estimate of morphological change at the Cacouna bog (as described below).

Hydrometric monitoring

Data were collected from 18 June to 15 August in 1997 and from 9 May to 13 August in 1998. Location of weirs and the meteorological station used in estimating the water balance at the Cacouna bog are shown in Figure 1. The methods used in estimating water balance components at both sites are described in detail by Van Seters and Price (2001). Briefly, for the watershed south-east of the railway and north-west of the primary drainage ditch (lower left in Figure 1), precipitation was measured with tipping bucket and manual rain gauges, and inflow and runoff were measured with three weirs and one flume. Evapotranspiration was estimated using the Priestley and Taylor (1972) combination model, calibrated with soil lysimeters (each $0{\cdot}12\ \mathrm{m}^2 \times 0{\cdot}2$ m deep). Instrumentation included two net radiometers, two soil heat flux plates and a shielded thermistor for air temperature. Change in storage within the zone of groundwater fluctuations was measured in groundwater wells (Figure 1) and volumetric soil moisture changes in the unsaturated zone were estimated by time domain reflectometry (TDR) and gravimetrically in 1997 and 1998, respectively. A block of peat ($20 \times 10 \times 12$ cm) extracted from the cutover bog was used to calibrate the TDR. Instrumentation at the St Arsène bog included, a continuous well recorder, a manual rain gauge and four manual wells installed along a 520 m transect from the centre of the bog to the forested margin. Runoff at this site was negligible and evapotranspiration was calculated from energy flux data over a partially *Sphagnum* covered surface at the Cacouna bog.

Water-level changes over the entire study area were measured at 3 to 10 day intervals with 44 PVC wells (1·9 cm i.d.) slotted along their entire length and arranged in transects parallel and perpendicular to the railway track (Figure 1). Staff gauges were used to record water levels in selected ditches. The drainage network was mapped and ditches were classed as active or inactive depending on whether they transmitted drainage water during and after heavy storms.

Water levels in two transects of nested piezometers and wells were measured every 3 to 14 days in each of the Cacouna and St Arsène bogs. Piezometers with 20 cm intakes were made of PVC pipe (1·25 cm i.d.) and wrapped with geotextile screen to prevent clogging. Nests consisting of three to six piezometers and a well were set to depths from 0·9 to 5 m. All piezometers were surveyed relative to a fixed benchmark during wet and dry measurement periods to eliminate the possible distorting effects of seasonal subsidence.

The hydrological influence of an undrained forested section on the south-eastern margin of the bog (Figure 1) was investigated from 4 June to 10 August 1998. A transect across a recently cleared and forested section consisted of eight wells to assess the difference in water tables and hydraulic conductivity (by the method described above). Throughfall in the forest was determined with three plastic gutters (200 × 18 cm) placed beneath the forest canopy, that emptied into a bucket. Interception by logging debris and short vegetation in the cleared area was assessed with three rain gauges sunk level to the surface beneath the litter. The difference in soil moisture in the upper 20 cm between the forest and cleared area was evaluated by TDR every 2 weeks during the summer. The forested area consisted primarily of black spruce (*Picea mariana*), white birch (*Betula papyrifera*) and balsam fir (*Abies balsamea)* with a sparse undergrowth of herbaceous plants.

Hydrophysical properties

The specific yield was determined in the laboratory using eight cores (80 × 10 × 12 cm) extracted from a representative sample of surface types at the Cacouna and St Arsène bogs. Cores cut into 5–10 cm sections were saturated in standing water and weighed (W_s), drained for 24 h, then weighed again (W_d). The specific yield (Sy) was calculated as

$$Sy = [(W_s - W_d)/\rho]/(W_s/\rho) \tag{1}$$

where ρ is the density of water. Results were averaged to provide a final measure of Sy for substitution into Equation (1). The oven-dry weights (24 h at 105 °C) of the same samples were divided by the drained volumes to determine soil bulk density as described by Boelter (1975).

Hydraulic conductivity of the peat was measured in the groundwater wells and piezometers described above using the Hvorslev (1951) water recovery method.

Morphology

The surface and substrate elevation along three well transects (Figure 1) were surveyed in 1997 using a level, probing rod and compass. Seasonal fluctuations in surface elevation (Price and Schlotzhauer, 1999) were monitored at eight locations of differing peat depths, by measuring the distance between a 0·15 × 0·15 m perforated board resting on the ground surface and the top of an iron rod (1·5 cm diameter) firmly set into the clay substrate, protruding through the board.

Pre-disturbance elevations (PD) along the transect shown in Figure 1 were determined as

$$PD = M + T + S + C \tag{2}$$

where M is the elevation of the mineral layer, T is the 1998 peat thickness, S is the estimated amount of subsidence and C is the approximate depth of peat removed. Subsidence values for all points along the transect were determined from the slope of the best-fit line ($R^2 = 0{\cdot}94$) relating subsidence estimates provided in this study (see below for method of estimation and results) to pre-harvest peat depths. The depth of peat removed was estimated from the length of time a given section was harvested (Girard, 2000), the general shape of a transect surveyed by Auer (1930) in 1926, and where applicable, the peat depth difference between trenches and adjacent uncut areas.

Surface subsidence

Two methods were used to estimate the magnitude of long-term surface subsidence caused by drainage and oxidation at Cacouna. The first method involved a simple comparison of peat depths surveyed in 1946 (Quebec Ministry of Mines) with current peat-depth measurements at approximately the same locations on uncut remnants of the bog. The difference between the measurements made in 1946 and 1998 represents the magnitude of peat subsidence at each measurement point over the intervening period.

The second method was based on the assumption that the Cacouna and St Arsène bogs accumulated organic matter at similar rates. This probably is valid given the relative proximity of the two bogs, and similarities in their size, geological origin and age (see Table I). Two cores extending to the base of the peat deposits were extracted from the centre of the natural bog and an uncut portion near the centre of the cutover bog. The cores were wrapped in plastic and transported to the laboratory for analysis. Two pairs of ^{14}C dates (one pair from each bog) were taken at 0·01 and 2 m above the mineral layer, and analysed by the University of Waterloo Radiocarbon Dating Laboratory using standard techniques. Radiocarbon dates were calibrated against a 20-year tree ring data set using version 3·0 of the CALIB program (Stuiver and Reimer, 1993) and shifted to years before AD 1998. The rest of the core was cut into 10 cm sections for measurement of bulk density. Using the surfaces at the cutover and natural bogs as third points (i.e. time = 0), the age–depth profiles were plotted (see Figure 3 in 'Hydrophysical data' section), and the total depth of drainage-induced subsidence and oxidation was calculated from their difference at the point of maximum departure. To corroborate this result, depths were also measured as cumulative mass from the bulk density measurements at the natural bog, and fitted to a peat growth model (Clymo, 1984)

$$X = p/\alpha(1 - e^{-\alpha T}) \tag{3}$$

where X and T are the mass and age of the peat below an arbitrary datum in the catotelm (assumed to correspond with the surface), and p and α are rates of input and decay in the catotelm, respectively. Plausible values of p and α were chosen and adjusted within a narrow range until a 'best' fit of the data was achieved. The fitted values for p and α, and the three calibrated ages (T) (two radiocarbon + surface) from the cutover bog, were then substituted into Equation (3) to predict the pre-drainage values of X at Cacouna and their corresponding depths below the surface. As before, the difference between the current and predicted age–depth profiles represented the total depth of drainage-induced subsidence and oxidation.

HISTORICAL DEVELOPMENT

Pre-disturbance conditions

The formation of the Cacouna and St Arsène bogs began with the accumulation of non-*Sphagnum* organic deposits (esp. *Carex* spp.) in shallow clay-bottom depressions (Auer, 1929, 1930). Radiocarbon C^{14} dating of basal peat indicated that initiation occurred 9801 ± 90 and 9361 ± 90 years ago on the Cacouna and St Arsène bogs, respectively, at roughly the same time as emergence from the post-glacial sea (Elson, 1988). The later initiation date on the St Arsène bog is explained by its lower elevation (53 m a.s.l.) relative to the Cacouna bog (83 m a.s.l.). Peat accumulation subsequently elevated the bog surfaces to the pre-disturbance condition. Auer's (1930) pollen analysis of peat profiles at Cacouna and St Arsène indicated that bogs in the region supported a broadly similar mix of peatland tree species during the course of development, and according to early aerial photographs (1930 to 1942), trees were small and sparsely distributed.

Although a small natural stream is visible in a 1930 aerial photograph of the Cacouna bog, evapotranspiration must have been the dominant water output, as it is today in the St Arsène bog, consuming most precipitation inputs, and withdrawing additional moisture from storage (as discussed below). Vertical moisture loss through evaporation on undisturbed bogs is regulated by the low matric potential of non-vascular *Sphagnum* cushions, and the capacity of *Sphagnum* capitula to 'whiten' and reflect incoming radiation back into the atmosphere (Ingram, 1983). Mechanisms regulating runoff and evaporation, combined with high storage coefficients in the acrotelm, limited water table fluctuations at the St Arsène bog to within 45 cm of the peat surface in 1998.

Agriculture and transportation development

Settlers started to arrive in the Cacouna region as early as 1750, but it was not until the 1830s that lands surrounding the Cacouna bog were cleared and drained for agriculture on a large scale. The road cutting through the south-western portion of the bog was constructed in 1839, followed by completion of the railway in 1876 (Girard, 2000). Between 1890 and 1901, some local residents cut peat for fuel from a small area on the northern edge of the bog (Girard, 2000). A shallow drainage ditch shown in a 1930 aerial photograph, located roughly where the main drainage ditch now lies (Figure 1), may have been installed to promote tree growth in the adjacent wood lot (and former lagg). The two roads through the north-east and south-west margins (Figure 1) reduced the central bog area from 210 to 148 h.

Drainage, peat extraction and post-abandonment conditions

Harvesting activities by *Belle Peat Moss Co. Inc.* began in 1942 with the installation of a network of primary and secondary ditches. By 1947, approximately 69% (103 ha) of the bog area (148 ha) was drained and cleared of vegetation (Girard, 1947; Girard, 2000). The traditional 'block cut' method used in extracting the peat involved removing peat blocks by hand from trenches approximately 10 m wide and up to 200 m long. The peat blocks were stacked on 2 to 4 m uncut swaths or 'baulks' separating adjacent trenches, and the unwanted vegetation, or 'skag', was piled in the centre of the trench. Over time, the skag settled and decomposed to form a convex shape, unintentionally providing a seedbank for future plant regeneration (Rochefort *et al*., 1995). If another round of cutting was planned the baulk was removed and the harvesting process started anew. At Cacouna, approximately 15% of trenches on the south side had their baulks removed before final abandonment.

Changes in morphology resulting from peat extraction, drainage and subsidence are represented in Figure 2 as the difference between 1998 and pre-disturbance elevations. Cutting was most intense in the south-west near the former peat processing plant, resulting in steeper surface gradients towards the south corner (from 0 to 600 m along the transect, Figure 1). Localized pooling of water there after snowmelt has caused the emergence of vegetation well adapted to widely fluctuating water tables (e.g. *Carex* spp.). Although the upper portion of the peat mound was removed, the water table maintained its characteristic dome shape (Figure 2), but with local drawdown on either side of ditches (not shown).

Main, and secondary ditches (Figure 1) were on average 2·4 and 1·2 m deep (Girard, 1947), whereas tertiary ditches hand-dug as part of the peat extraction process were usually less than 0·15 m in depth. Drainage density increased from less than 0·002 m m^{-2} before disturbance (estimated from aerial photographs) to approximately 0·012 m m^{-2} (not including tertiary ditches) during the peak harvest period in the 1950s and 1960s.

After final abandonment in 1972 (south side) some ditches in the south-west portion of the bog were intentionally blocked, probably to facilitate transportation (Girard, 2000), and many more became

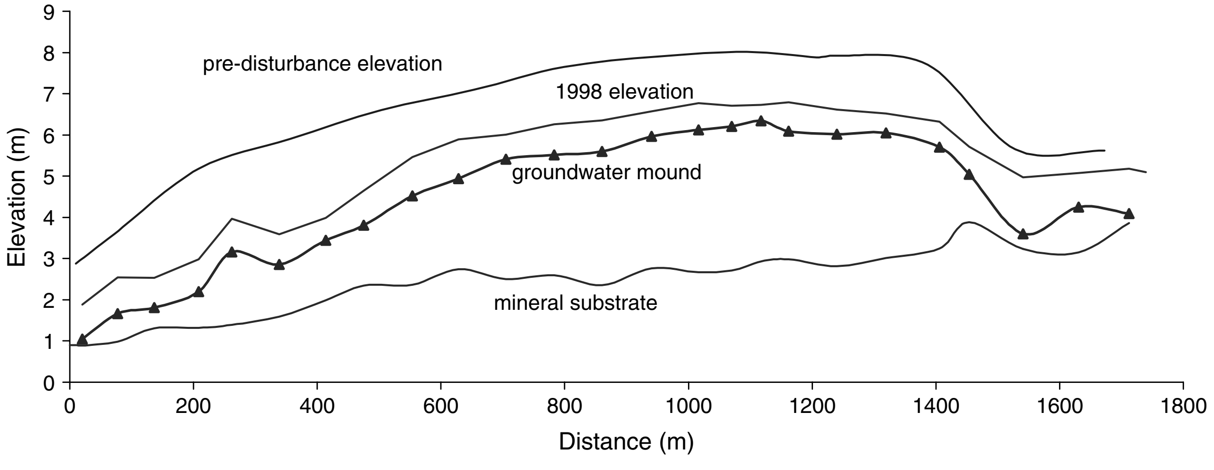

Figure 2. Current and pre-disturbance topographic profiles for the long transect, as shown in plan view in Figure 1. The water table is for a dry (13 August) day during the 1998 study season. Ditches and baulks are not shown

filled with vegetation and sediment. These naturally filled secondary (50–80 cm) and tertiary (5–15 cm) ditches had relatively gentle gradients and were observed during a detailed survey of the drainage network to conduct very little storm runoff, even during large rain events. In 1998, the active drainage density was only approximately 58% (0·007 m m^{-2}) of that during the peak harvest period (Van Seters, 1999).

HYDROPHYSICAL DATA (1997–1998)

Peat subsidence

Drainage induced subsidence and oxidation estimated by subtraction of 1998 from 1946 peat elevations at three uncut remnants in the Cacouna bog, indicate a surface lowering of 62, 60 and 10 cm from the 1946 peat depths of 3·9, 3·0, and 1·0 m (or 0·30, 0·38, and 0·19 cm year^{-1} m^{-1}), respectively. The peat depths are relevant, because for a given load, thicker peat deposits undergo greater consolidation (Heathwaite *et al.*, 1993).

Table I shows ^{14}C dates of cores extracted near the centre of the St Arsène and Cacouna bogs. The cutover site core was from a drained but uncut remnant. Taking the surface date as 0·0, the calibrated ages are plotted against depth in Figure 3. This figure shows that peat in the uncut remnant of the Cacouna bog, of equivalent age to that in the St Arsène bog, is closer to the surface because of subsidence and oxidation. Extrapolation of the natural bog age–depth curve by 440 years (the difference between the Cacouna and natural bog ages) to 9801 (the Cacouna age) reveals total subsidence from 1942 to 1998 of 80 cm (0·27 cm year^{-1} m^{-1}). By comparison, pre-disturbance Cacouna peat depths estimated based on cumulative mass from a bulk density profile at the natural site, and fitted using Clymo's (1984) peat growth model (Equation 3), indicated subsidence of 77 cm (0·26 cm year^{-1} m^{-1}).

These long-term values compare with direct measurements (on 18 June and 13 August 1998) of maximum seasonal subsidence averaged over all subsidence meters of 1·6 and 1·5 cm at the cutover and natural bogs, respectively.

Water balance

Water balances at the cutover and natural study sites for the period 9 May to 13 August, 1998 are compared in Table II, and are discussed in detail by Van Seters and Price (2001). Precipitation was similar at the two sites, and close to the 28-year average (1963–1990) from the St Arsène meteorological station. Evapotranspiration (2·9 mm day^{-1}) also was similar at both sites, despite denser tree cover and a mean summer water table approximately 30 cm lower at the abandoned site. The cutover site evapotranspiration rate varied significantly among forests (3·6 mm day^{-1}), *Sphagnum* dominated areas (3·6 mm day^{-1}), trenches

Table I. Radiocarbon (± standard deviation) and corresponding calibrated dates of peat extracted from the Cacouna and St Arsène bogs in 1998.

Location	Depth above mineral substrate (m)	^{14}C age (years before AD 1950)	Calibrated age[a] (years before 1998 AD)
Natural bog	0·01	8320 ± 90	9361
Natural bog	2·00	4270 ± 100	4888
Cutover bog	0·01	8730 ± 90	9801
Cutover bog	2·00	4230 ± 70	4878

[a] Calibrated ages were determined from a 20 year tree-ring data set in the CALIB v.3.0 program (Stuiver and Reimer, 1993), then shifted to years before AD 1998. The basal dates (0·01 m) represent the average of three estimates provided by the CALIB program. These were 9418, 9338 and 9328 at the natural bog and 9898, 9758 and 9748 at the cutover bog.

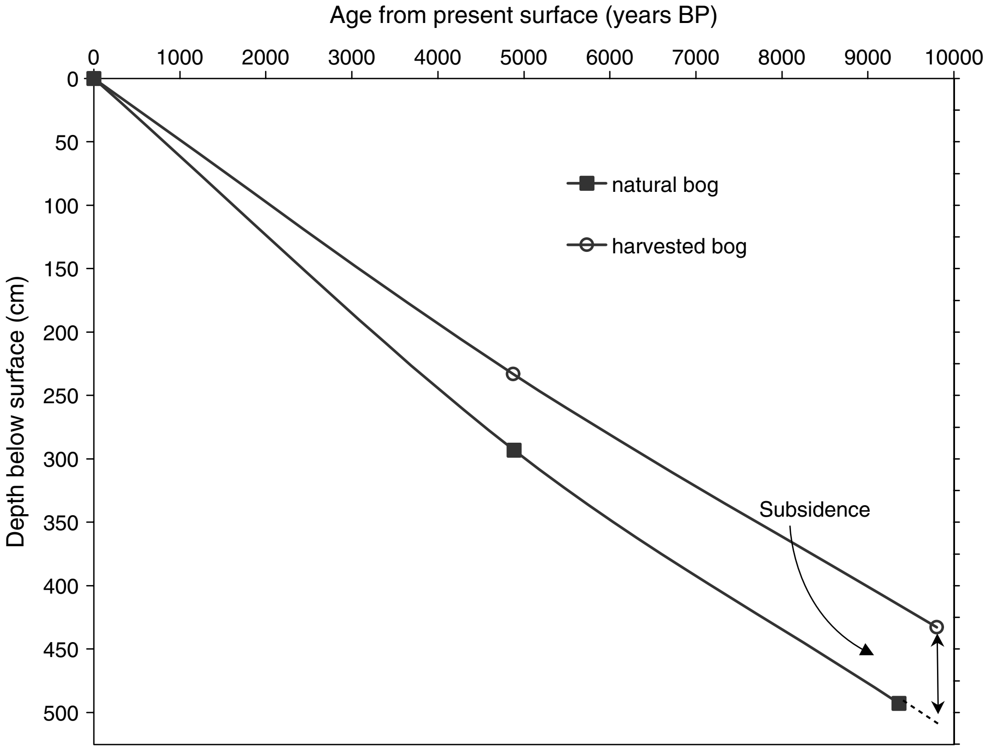

Figure 3. Calibrated ages versus depth at the cutover and natural bogs. The assumption of similar development history allows for subsidence to be represented on the graph as the difference between the curves at their maximum point of departure

without *Sphagnum* (2·9 mm day^{-1}), and dry raised peat surfaces (1·9 mm day^{-1}) such as baulks and peat roads. Runoff constituted the major difference in water fluxes between sites, consuming 54 mm more moisture (24% of precipitation) from the abandoned bog. Although there was significant variation among surface types, the mean water table was −60 cm at Cacouna, compared with an average of approximately −31 cm at the natural bog.

Since abandonment in 1972, forest cover increased from approximately 5 to 20% of the study area at Cacouna (mostly near the margins) and tree cover on the open bog also increased. Over the same period, tree cover on the natural bog increased only slightly. Interception in a forested area of the Cacouna bog was 32% of precipitation, compared with 23% by logging debris in an adjacent open area. The mean water table beneath the forest (−103 cm) was 29 cm lower than that of the clearing (−74 cm), and the mean water table fell by 10 and 27 cm, respectively, over the measurement period (Table III). Mean volumetric moisture

Table II. The relative magnitude of water balance fluxes in millimeters at the cutover and natural bogs from 9 May to 13 August 1998. The water balance was calculated as $P = Et + R + \Delta S + \varepsilon$, where P is precipitation, Et is evapotranspiration, R is runoff, ΔS is change in storage and ε is the residual term (Van Seters and Price, 2001)

	P	Et	R	ΔS	ε
Cutover bog	220	285	54	−100	−19
Natural bog	212	281	0	−58	−11

Table III. The mean water table below the peat surface, change in water table, moisture content in the upper 20 cm of peat and interception from 4 June to 10 August 1998. Numbers in parentheses represent standard deviations.

	Mean water table (cm)	Water table change (cm)	Mean moisture content (%)	Interception (%)
Number of observations (n)	20	—	6[a]	23
Forest	−103·1(±8·1)	−9·9	45·7(±9·6)	32
Clearing	−73·9(±5·1)	−26·6	49·7(±10·6)	23

[a] Individual observations represent the average of three repeat measurements.

contents ($n = 6$) in the upper 20 cm of peat in forested and cleared areas were 46 and 50% respectively. Although these values are similar, moisture content over the measurement period fell 29% (from 57 to 28%) in the forest, compared with only 21% (from 62·5 to 40·7%) over the same period in the clearing.

Groundwater flow dynamics

The groundwater flow pattern (Figure 4a) at St Arsène exhibited groundwater recharge during a wet period (18 June, 1998), and discharge when conditions became dry (13 August, 1998). At the Cacouna bog (Figure 4b) groundwater flow was redirected by drainage ditches, and created local zones of vertical discharge to the surface during dry periods. Maximum specific discharge from the middle of the peat mass for wet and dry periods were approximately −2·9 and 4·1 mm day^{-1} (site 4H) at the abandoned site, compared with −6·1 and 2·5 mm day^{-1} (site 1N) at the natural bog. Between drainage canals, upward flow was strongest at or near the point of highest elevation (especially site 4H), where water tables were closest to the peat surface. Conversely, along the natural bog transect specific discharge was strongest (8·5 mm day^{-1}) at low elevations near the margins, where the water table was furthest from the peat surface. Owing in part to differences in hydraulic conductivity between sites (see below), lateral flow towards the periphery was just over half (0·12 mm day^{-1}) that of the natural site (0·23 mm day^{-1}).

Hydrophysical properties and Sphagnum regeneration

Less than 15% of the south side of the Cacouna bog was covered by mosses in 1998 (Girard, 2000). The distribution of regenerated *Sphagnum* mosses (sections >10% by area) was not random, but relegated to distinct regions of the bog (Girard, 2000) where the water table was higher (Table IV). Approximately one-quarter of these regions were located in seasonal groundwater discharge zones at the base of sloped surfaces (gradients from 1 to 2·5%). These areas were very wet after spring snowmelt but dried out considerably during the summer, producing mean water table fluctuations 1·3 times greater than other non-forested areas. In some discharge areas near the bog margins, *Sphagnum* grew well even near drainage ditches and where several trees were present. Price and Whitehead (2001) noted that *Sphagnum* recolonization in the Cacouna bog generally was restricted to areas where volumetric soil moisture and pore-water pressure in the surface peat were greater than 50% and −100 mbar, respectively.

Figure 5 compares depth profiles of specific yield and bulk density beneath bare peat and naturally regenerated *Sphagnum* from the Cacouna bog with an undisturbed hollow from the St Arsene bog. Within the upper 50 cm of peat, the mean bulk density was 0·13 g cm^{-3} under bare and naturally regenerated surface types, compared with 0·7 g cm^{-3} beneath the undisturbed *Sphagnum* hollow. Specific yield within the same depth range was 0·06, 0·09 and 0·14 beneath bare, regenerated and undisturbed surfaces. Regenerated *Sphagnum* cushions at Cacouna were up to 30 cm in height, compared with 50 cm in the natural bog.

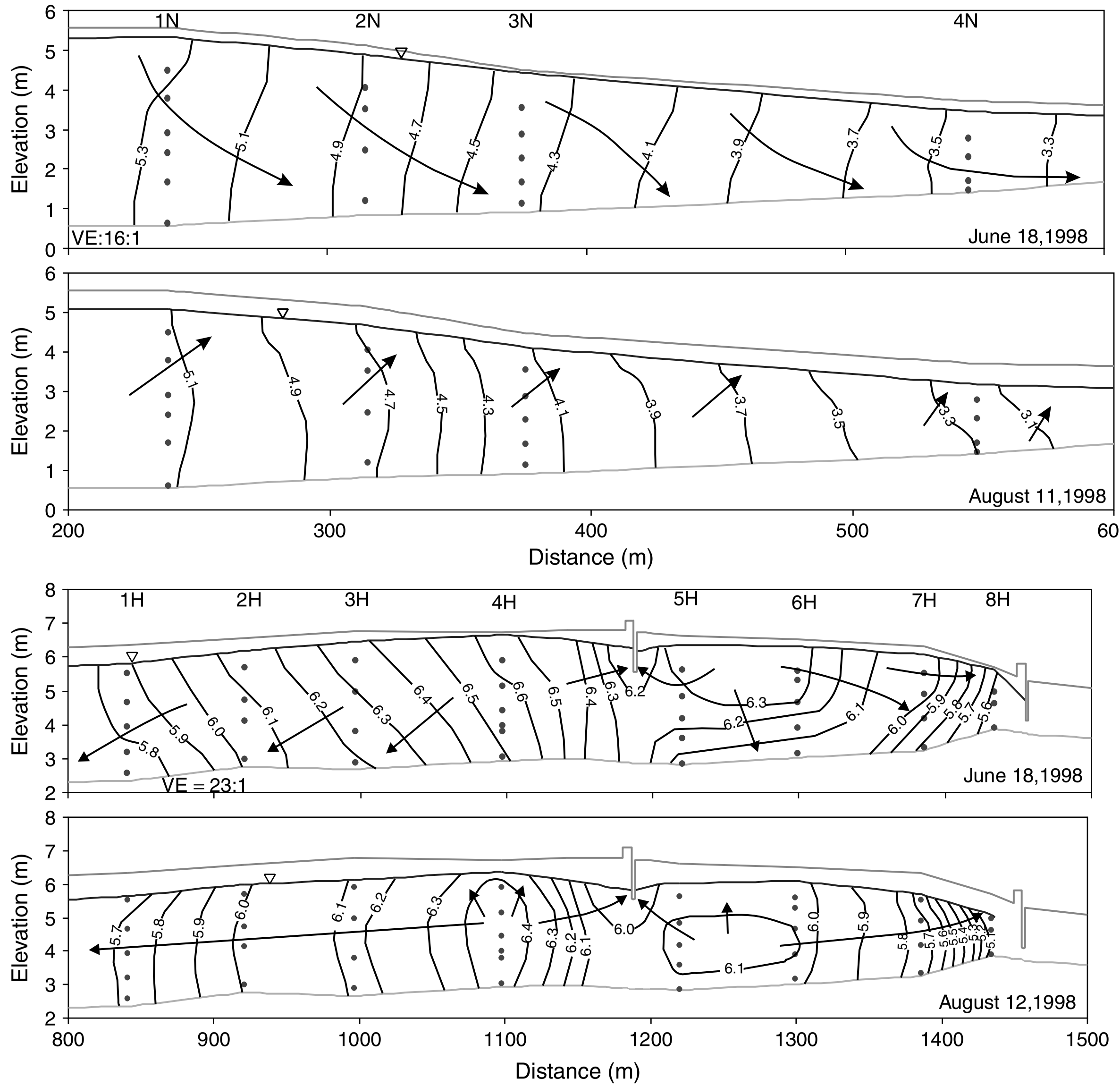

Figure 4. Flow nets on wet (18 June) and dry (12 August) days in 1998 for the (a) natural and (b) cutover bogs. Dots represent location of piezometer tips, contour lines represent points of equal hydraulic head and arrows indicate the direction of groundwater flow

Table IV. The mean (± standard deviation) of the water table and lower limit of water table fluctuations beneath the peat surface of areas with different vegetation covers from 9 May to 13 August, 1998

	Sphagnum cover >10% by area	Non-forested trench skags without Sphagnum	Forest
Number of wells (n)	20	18	6
Mean water table (cm)	−22·1(±10·0)	−54·2(±11·6)	−87·8(±19·2)
Mean lower limit (cm)	−45·4(±12·2)	−74·9(±12·9)	−113·8(±16·8)

Along with an increase in bulk density, reduced saturated hydraulic conductivity was observed. The geometric mean of hydraulic conductivity (Figure 6) was an average of $4{\cdot}1 \times 10^{-5}$ at the St Arsène bog, compared with $1{\cdot}3 \times 10^{-5}$ cm s^{-1} at the Cacouna bog. As a consequence of changes in hydrophysical properties, greater water table fluctuations characterized the cutover site (range of 375 mm at Cacouna compared with 225 mm at St Arsene in 1998).

DISCUSSION

Hydrology of the St Arsene and Cacouna bogs (1997–1998)

Hydrological differences between the natural and cutover bogs represent changes that occurred following exploitation and abandonment. Runoff was the most significant difference in water budgets between the sites. The 1998 data found runoff was 25% of the rainfall at Cacouna, but negligible at St Arsène (Table II). Higher runoff is not uncommon on drained bogs, especially in the first year after drainage, but sometimes losses return to pre-drainage levels within 20 years of abandonment (e.g. Heikurainen *et al.*, 1978; Ledger and

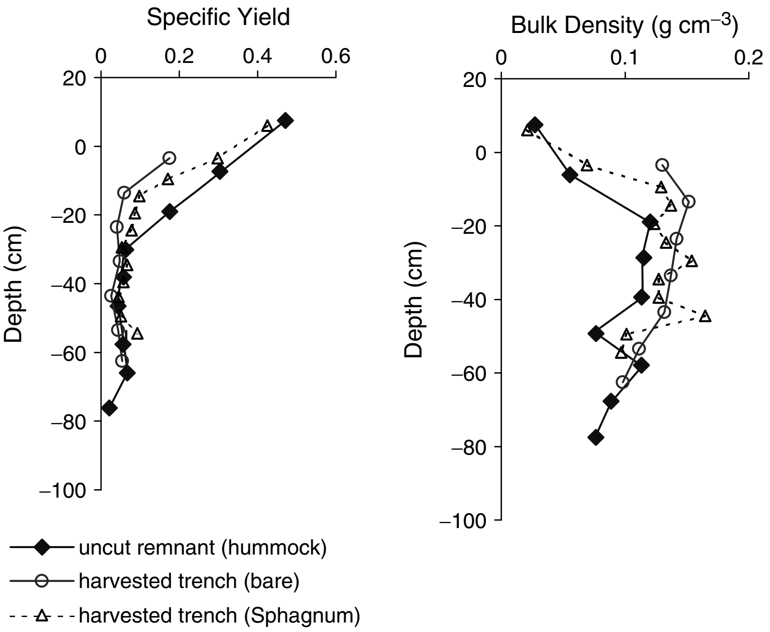

Figure 5. Depth profiles of specific yield and bulk density with respect to the cutover peat surface (cutover bog) and lawn surface (natural bog) Above surface values represent *Sphagnum* cushions

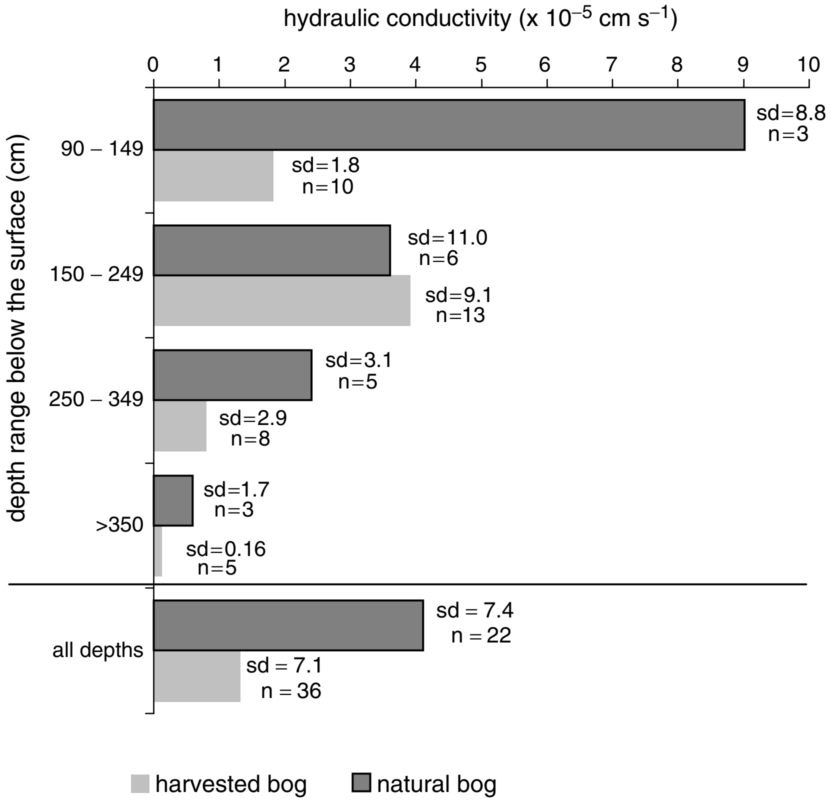

Figure 6. Geometric mean of hydraulic conductivity at the cutover and natural bogs. Numbers to the right of the bars represent standard deviations ($\times 10^{-5}$ cm s^{-1}); *n* is the number of observations.

Harper, 1987). Deep primary drainage canals (up to 250 cm deep) and sparse forest cover (20% by area) are responsible for the high post-abandonment runoff losses relative to other studies.

Despite lower mean water levels at Cacouna, losses to evapotranspiration were similar, owing to differences in vegetation and surface moisture availability. At the Cacouna bog, low evaporation from raised surfaces such as baulks and roads was countered by high evaporative losses from moist depressions in cut trenches and forested areas near primary drainage canals. The importance of forest in intercepting and transpiring water was reflected along the clearing-to-forest transect by the higher water table, volumetric soil moisture content and smaller soil moisture change in the cleared area.

The mean subsidence rates estimated by comparison with the 1946 peat depth survey (mean = 0·29 cm $year^{-1}$ m^{-1}) and radiocarbon dating (mean = 0·27 cm $year^{-1}$ m^{-1}) were very close. Both methods used in estimating subsidence are coarse, but the similarity of results is encouraging. The estimates are slightly higher than the 0·14 to 0·24 cm $year^{-1}$ m^{-1} range reported by Schothorst (1977) on low moor peat 7 m thick, over a period of 6 years in The Netherlands. On forested fen peat from 1·5 to 3 m deep in Alberta, Rothwell *et al.* (1996) found much higher rates of 7·7 and 11 cm (3·73 and 2·26 cm $year^{-1}$ m^{-1}) over a period of 11 and 26 months after drainage, respectively. Their estimates reflect the importance of primary compression, which can produce subsidence of up to 30 cm on raised bogs in the first 2 years after drainage (R.A. Robertson, as cited by Stewart and Lance, 1983). Subsidence at Cacouna has resulted in a lower mean saturated hydraulic conductivity. Hydraulic conductivity was particularly low in the 90 to 149 cm range (Figure 6), suggesting that compression caused by drainage and traffic during harvesting may disproportionately impact layers nearer to the surface.

Following disturbance there is loss of acrotelm function, peat consolidation and a decrease in hydraulic conductivity, which with the localized effects of drainage ditches alters the groundwater flow regime. Upward flow in discharge zones helps to sustain wet conditions near the surface during dry periods, and as such may be an important self-regulating mechanism during prolonged droughts (Siegel *et al.*, 1995; Devito *et al.*, 1997). Aquifer compression and expansion may play a role in producing flow reversals (Devito *et al.* 1997), but this is not evident from weekly measurements of subsidence meters and specific discharge measurements at piezometer nest sites.

Conceptual model of hydrological change

Although there are no hydrological data for the period immediately following harvesting and drainage, a conceptual model of hydrological change at Cacouna can be developed from historical information on the vegetation and drainage density during the harvesting period, relevant literature references and observed hydrological differences between the cutover and natural bogs in 1997 and 1998. The model for the pre-disturbance (1930–1941), harvesting (1942–1972) and natural regeneration (1973–1998) periods is shown schematically in Figure 7.

Before disturbance, the hydrodynamics of the Cacouna bog were governed by the two-layer (or diplotelmic) structure of the peat deposit in which a thin hydraulically conductive, seasonally aerobic upper layer (acrotelm) of living and poorly decomposed plant material is underlain by a deep, less conductive and more humified, anaerobic layer of peat (catotelm) (Ingram, 1978; Ivanov, 1981). The sharp physical gradients in the acrotelm (Figure 5) controlled the short-term stability of the bog by imposing strict limits on the availability of moisture at the surface (Heathwaite, 1995). Investigations at the natural bog suggest that prior to disturbance the specific yield at the Cacouna bog graded from 0·25 near the surface to 0·06 at −50 cm, whereas bulk density increased from 0·07 to 0·13 g cm^{-3}. Evapotranspiration was the major output, runoff was low or negligible (Table II) and the water table fluctuated narrowly around a mean of about 31 cm below the surface. Botanically, *Sphagnum* and a mix of vascular plants dominated the bog, but trees were sparse. These hydrophysical characteristics are typical of relatively undisturbed raised mires in Europe and North America (Ingram, 1982).

Disturbance typically begins with drainage, which causes a depletion of long-term water storage, reflected by a lower water table. The associated loss of buoyancy in the upper layers produces higher loads and subsequent consolidation of macro- and microsoil-pores in the saturated zone (Figure 3). The consequence is a rapid initial decrease in surface elevation and a corresponding reduction in hydraulic conductivity (Figure 6) as water is expelled from the system. The literature suggests an immediate increase in runoff (e.g. Conway and Millar, 1960; Nicholson *et al.*, 1989), especially in baseflow (Burke, 1975) as the long-term water storage is released. Runoff usually declines after the mean water table drops to a new lower position (Burt *et al.*, 1990), but remains higher than before drainage (e.g. Heikurainen *et al.*, 1978; Ahti, 1987). Peatland type, climate and drain characteristics control the magnitude and nature of runoff. Depletion of long-term water storage by runoff is offset by lower evapotranspiration, which occurs when water levels in bogs are low (Romanov, 1962; Williams, 1970).

Natural revegetation of the site beginning before final abandonment results in gradually rising evapotranspiration with the spread of vascular plants, which is especially important when the water table is low. As ditches fill with sediment and mosses, and hydraulic conductivity continues to decrease (Figure 7), annual runoff declines. Regeneration of *Sphagnum* mosses is poor because changes to soil physical properties (Figure 5) promotes wide water table fluctuations and concurrent variations in capillary pressure and soil moisture at the surface. During this period, the mean annual water table may change very little because interception and transpiration by trees promotes lower water tables (Tables III and IV), but on the other hand, natural ditch occlusion and lower hydraulic conductivity reduce lateral water loss. Thus, meso-scale water balance fluxes tend towards pre-disturbance levels following exploitation, but only after a very long time, and within the context of wider seasonal fluctuations in water levels associated with a denser tree cover and a more humified and compressed peat matrix.

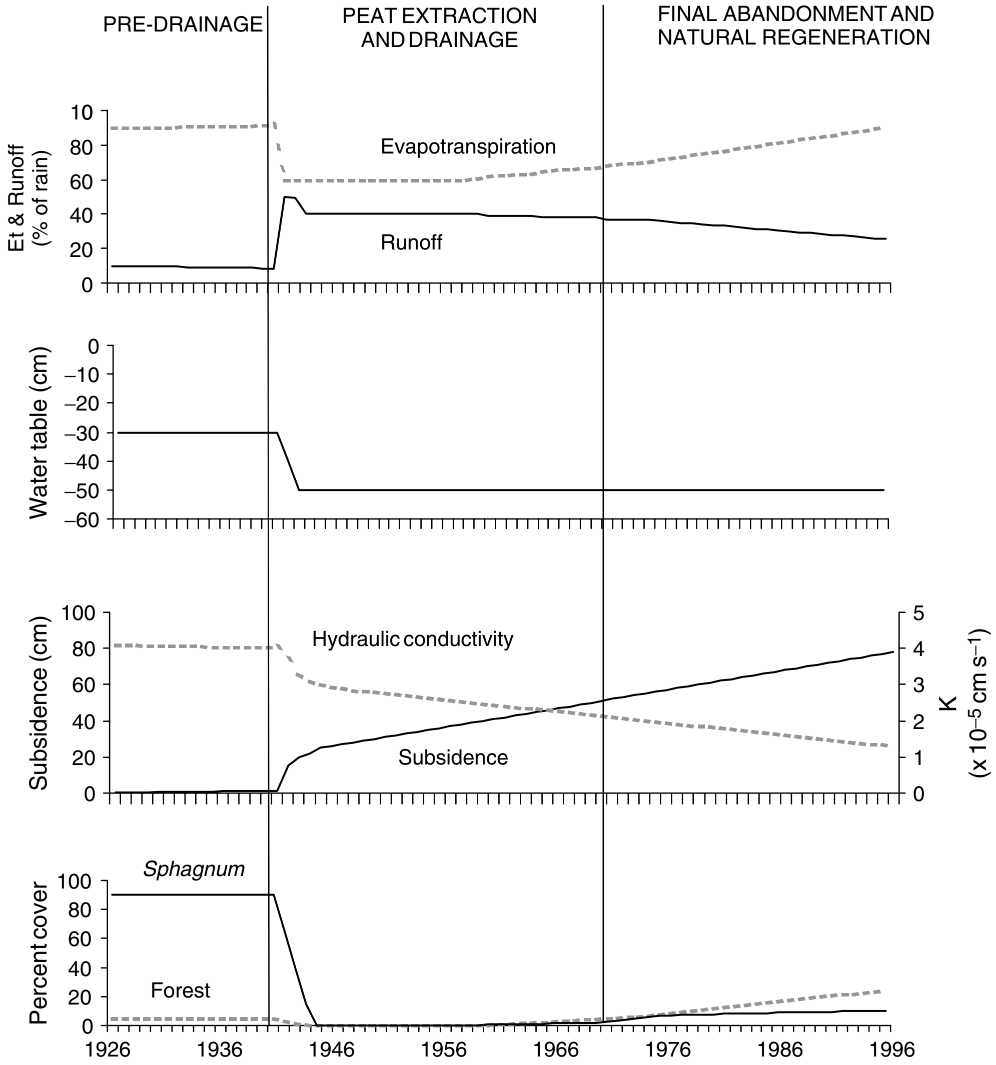

Figure 7. A schematic representation of changes in hydrology, vegetation and hydrophysical properties of the peat from before disturbance to after natural revegetation of the Cacouna bog. Precipitation is assumed to be constant. Vertical axis values are approximations based on the data and analysis presented in this paper. To simplify, drainage of the bog is depicted as a single event occurring over a period of only a few years

CONCLUSION

The results of this study document significant impacts to the hydrology and physical structure of the Cacouna bog and lend insights into how specific hydrophysical variables changed following exploitation and abandonment. The conceptual model (Figure 7) illustrates the sequence of changes. When exploitation commences, the water budget changes as drainage enhances runoff at the expense of evapotranspiration losses. The lower water table causes irreversible changes in the soil properties (lower K and Sy) that increase water table variability. As vascular plants colonize, especially trees, evapotranspiration losses increase, and summer runoff may continue, enhancing the summer water deficit. This may be offset if ditches become occluded, or intentionally blocked, but the water table (thus capillary pressure and soil moisture at the surface) variability remains large, and thus frequently unsuitable for *Sphagnum* recolonization.

Management of the site will be required if natural peatland functions are to be restored in the short-term. Comparison between water balances at a natural and cutover sites suggests that blocking ditches would raise mean water levels during the summer and largely restore meso-scale water fluxes to pre-disturbance conditions (e.g. Price, 1997). The same could be achieved through natural ditch occlusion processes if drainage ditches originally were designed to be shallow with gentle gradients. Most drainage canals with these characteristics were no longer active in 1998.

Good natural regeneration of *Sphagnum* in zones of groundwater discharge implies that these areas could be the focus of restoration where management of the entire site is not practical. In appropriate circumstances, topographic contours of new and abandoned sites could be designed or re-shaped to create larger discharge zones with similar characteristics. Subsidence also could play a role in restoration by lowering the surface relative to the water table and slowing groundwater flow to drainage canals. The role of subsidence in promoting moisture conditions suitable for *Sphagnum* growth and establishing a new stable equilibrium should be considered in the design of restoration strategies. Further research is required on the conflicting roles of lower hydraulic conductivity, shortened base dimensions and changes in the water balance on the long-term stability of disturbed bog ecosystems.

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REFERENCES

Ahti E. 1987. Water balance of drained peatlands on the basis of water table simulation during the snowless period. *Communicationes Instituti Forestalis Fenniae* **141**: 1–53.

Auer V. 1929. Present peat bogs in southeastern Canada. *Communicationes Instituto Quaestionum Forestalium Finlandiae* **13**: 1–54.

Auer V. 1930. Peat bogs in southeastern Canada. *Geological Survey of Canada Memoir* **162**: 1–32.

Bergeron M. 1994. Peat. In *Canadian Minerals Yearbook*. Natural Resources Canada: Ottawa; 37.1–37.8.

Boelter DH. 1975. Methods for analyzing the hydrological characteristics of organic soils in marsh-ridden areas. In *Hydrology of Marsh-ridden Areas*. Proceedings of the Minsk Symposium, 1972, IASH, UNESCO: Paris; 161–169.

Bragg OM. 1995. Towards an ecohydrological basis for raised mire restoration. In *Restoration of Temperate Wetlands*, Wheeler BD, Shaw SC, Fojt W, Robertson RA (eds). Wiley: Chichester; 305–313.

Bragg O, Steiner GM. 1995. Applying groundwater mound theory to bog management on Puergschachenmoos in Austria. *Gunneria* **70**: 83–96.

Burke W. 1975. Aspects of the hydrology of blanket peat in Ireland. In *Hydrology of Marsh-ridden Areas*. Proceedings of the Minsk Symposium, 1972, IASH, UNESCO: Paris; 171–182.

Burt TP, Heathwaite AL, Labadz JC. 1990. Runoff production in peat-covered catchments. In *Process Studies in Hillslope Hydrology*, Anderson MG, Burt TP (eds). Wiley: Chichester; 463–500.

Chow TL, Rees HW, Ghanem I, Cormier R. 1992. Compactibility of cultivated Sphagnum peat material and its influence on hydrologic characteristics. *Soil Science* **153**(4): 300–306.

Clymo RS. 1984. The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London* **303**: 605–654.

Conway VM, Millar A. 1960. The hydrology of some small peat-covered catchments in the N. Pennines. *Journal of the Institute of Water Engineering* **14**: 415–424.

Devito KJ, Waddington JM, Branfireun BA. 1997. Flow reversals in peatlands influenced by local groundwater systems. *Hydrological Processes* **11**: 103–110.

Dionne J-C. 1977. La mer de Goldthwait au Québec. *Géographie physique et Quaternaire* **31**: 61–80.

Elson BA. 1988. The Champlain Sea: evolution of concepts and bibliography in the late Quaternary. In *The Late Quaternary Development of the Champlain Sea Basin*, Gadd NR (ed.), Geological Association of Canada: St Johns, Newfoundland; 5–12.

Environment Canada. 1993. Canadian Climate Normals, *1961–1990. Quebec*. Atmospheric Environment Service, Canadian Climate Program, Environment Canada: Ottawa.

Girard H. 1947. Report on Allied Peat Moss, Ltd. Cacouna. Province of Quebec. Unpublished report. Quebec.

Girard M. 2000. *La Régénération Naturelle d'Écosystemes Fortement Perturbés: Le Cas Des Tourbieres Exploitees Du Bas-Saint-Laurent.* MA Thesis, Department of Geography, Université Laval, Sainte-Foy, Quebec.

Heathwaite AL. 1995. The impact of disturbance on Mire Hydrology. In *Hydrology and Hydrochemistry of British Wetlands*, Hughes JMR, Heathwaite AL (eds). Wiley: Chichester; 401–417.

Heathwaite AL. 1994. Hydrological management of a cutover peatland. *Hydrological Processes* **8**: 245–262.

Heathwaite AL, Eggelsmann R, Gottlich K (with a contribution from Kaule G). 1993. Ecohydrology, mire drainage and mire conservation. In *Mires: Process, Exploitation and Conservation*, Heathwaite AL (ed.). Wiley: Chichester; 417–484.

Heikurainen L, Kenttamies K, Laine J. 1978. The environmental effects of forest drainage. *Suo* **29**: 49–58.

Hobbs NB. 1986. Mire morphology and the properties and behavior of some British and foreign peats. *Quarterly Journal of Engineering Geology* **19**: 7–80.

Hvorslev MJ. 1951. *Time Lag and Soil Permeability in Groundwater Observations. Waterways Experimental Station Bulletin 36, U.S.* Army Corps of Engineers: Vickburg, Ms.

Ingram HAP. 1978. Soil layers in mires: function and terminology. *Journal of Soil Science* **29**: 224–227.

Ingram HAP. 1982. Size and shape in raised mire ecosystems: a geophysical model. *Nature* **297**: 300–303.

Ingram HAP. 1983. Hydrology. In *Ecosystems of the World 4A—Mires: Swamp, Bog, Fen and Moor*, Gore AJP (ed.). Elsevier: New York; 67–159.

Ingram HAP. 1987. Ecohydrology of Scottish peatlands. *Transactions of the Royal Society Edinburgh: Earth Sciences* **78**: 287–296.

Ivanov KE. 1981. *Water Movement in Mirelands*. Academic Press: London; 276 pp.

Lavoie C, Rochefort L. 1996. The natural re-vegetation of a harvested peatland in Southern Quebec: a spatial and dendrochronological analysis. *Ecoscience* **3**: 101–111.

Ledger DC, Harper SE. 1987. The hydrology of a drained, afforested peat bog in southern Scotland, 1977–1986. *Transactions of the Royal Society Edinburgh: Earth Sciences*, **78**: 297–303.

Linacre ET, Hicks BB, Sainty GR, Grauze G. 1970. Evaporation from a swamp. *Agricultural Meteorology* **7**: 375–386.

Money RP. 1995. Re-establishment of a Sphagnum dominated flora on cut-over lowland raised mires. In *Restoration of Temperate Wetlands* Wheeler BD, Shaw SC, Fojt W, Robertson RA (eds). Wiley: Chichester; 405–422.

Nicholson IA, Robertson RA, Robinson M. 1989. The effects of drainage on the hydrology of a peat bog. *International Peat Journal* **3**: 59–83.

Price JS. 1996. Hydrology and microclimate of a partly restored cutover bog, Quebec. *Hydrological Processes* **10**: 1263–1272.

Price JS. 1997. Soil moisture, water tension, and water table relationships in a managed cutover bog. *Journal of Hydrology* **202**: 21–32.

Price JS, Schlotzhauer SM. 1999. Importance of shrinkage and compression in determining water storage changes in peat: The case of a mined peatland. *Hydrological Processes* **13**: 2591–2601.

Price JS, Waddington JM. 2000. Advances in Canadian wetland hydrology and biogeochemistry. *Hydrological Processes* **14**: 1579–1589.

Price JS, Whitehead GS. 2001. Developing hydrological thresholds for Sphagnum recolonization on an abandoned cutover bog. *Wetlands* **21**: 32–42.

Priestley CHB, Taylor RJ. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* **100**(2): 81–92.

Quebec Ministry of Mines. 1946. Cacouna Peat Bog, Riviere-du-Loup County. Ottawa

Rochefort L, Gauthier R, LeQuere D. 1995. Sphagnum regeneration—toward an optimization of bog restoration. In *Restoration of Temperate Wetlands*. Wheeler BD, Shaw SC, Foigt WJ (eds). Wiley: Chichester; 423–434.

Romanov VV. 1962. Evaporation from Bogs in the European Territory of the USSR. In *Israel Programme for Scientific Translations*, Heiman A (ed.). Jerusalem; 299 pp.

Rothwell RL, Silins U, Hillman GR. 1996. The effects of drainage on substrate water content at several forested Alberta peatlands. *Canadian Journal of Forest Research* **26**: 53–62.

Schlotzhauer SM, Price JS. 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: Field and laboratory investigations. *Water Resources Research* **35**: 3675–3684.

Schothorst CJ. 1977. Subsidence of low moor peat soils in the western Netherlands. *Geoderma* **17**: 265–291.

Siegel DI, Reeve AS, Glaser PH, Romanowicz EA. 1995. Climate-driven flushing of pore water in peatlands. *Nature* **374**: 531–533.

Stewart AJA, Lance AN. 1983. Moor draining: a review of impacts on land use. *Journal of Environment Management* **17**: 81–99.

Stuiver M, Reimer PJ. 1993. Radiocarbon calibration program, revision 3.0. *Radiocarbon* **35**: 215–230.

Van Seters TE. 1999. *Linking the past to the present: the hydrological impacts of peat harvesting and natural regeneration on an abandoned cutover bog, Quebec*. MES Thesis, Department of Geography, University of Waterloo: Ontario; 79 pp.

Van Seters TE, Price JS. 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned bog, Quebec. *Hydrology Processes* **15**: 233–248.

Verry ES. 1986. Forest harvesting and water: the lake states experience. *Water Resource Bulletin* **22**(6): 1039–1047.

Waddington JM, Price JS. 2001. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography* **21**: 433–451.

Williams GP. 1970. The thermal regime of *Sphagnum* peat bog. Proceedings of the 3rd International Peat Congress, August 18–23, 1968, Quebec, Canada. Department of Energy, Mines and Resources, and National Research Council of Canada, Ottawa, 195–200.