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The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Quebec

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Abstract:

Harvested sites rarely return to functional ecosystems after abandonment because drainage and peat extraction lower the water table and expose relatively decomposed peat, which is hydrologically unsuitable for *Sphagnum* moss re-establishment. Some natural regeneration of *Sphagnum* has occurred in isolated pockets on traditionally harvested (block-cut) sites, for reasons that are poorly understood, but are related to natural functions that regulate runoff and evaporation. This study evaluates the water balance of a naturally regenerated cutover bog and compares it with a nearby natural bog of similar size and origin, near Riviere du Loup, Quebec. Water balance results indicated that evapotranspiration was the major water loss from the harvested bog, comprising 92 and 84% of total outputs (2·9 mm day^{-1}) during the 1997 and 1998 seasons, respectively. Despite denser tree cover at the harvested site, evapotranspiration from the natural bog was similar, although less spatially variable. At the harvested site, evaporative losses ranged from 1·9 mm day^{-1} on raised baulks and roads to 3·6 mm day^{-1} from moist surfaces with *Sphagnum*. Although about half of the ditches were inactive or operating at only a fraction of their original efficiency, runoff was still significant at 12 and 24% of precipitation during the 1997 and 1998 study seasons, respectively. This compares with negligible rates of runoff at the natural bog. Thus the cutover bog, although abandoned over 25 years ago, has not regained its hydrological function. This is both a cause and effect of its inability to support renewed *Sphagnum* regeneration. Without suitable management (e.g. blocking ditches), this site is not likely to improve for a very long time. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS peatland; water balance; cutover peatland; peat harvesting; runoff; evapotranspiration

INTRODUCTION

Canada is the third largest peat producer in the world, behind only the former USSR and Germany (Bergeron, 1994). Approximately 16 000 ha of peatlands are currently harvested for horticultural and related products, at a total annual value of $187 million (Bergeron, 1994). Although this represents less than 1% of Canada's total peatland resource (Keys, 1992), areas of intense peat production, such as the St Lawrence Lowlands, face peatland losses of more than 70% (Lavoie and Rochefort, 1996). Harvested sites rarely return to functional peatland ecosystems after abandonment because drainage and peat extraction alters the physical and hydrological conditions necessary for *Sphagnum* moss re-establishment (Heathwaite, 1994; Price, 1996). Surveys of abandoned bogs in Quebec (Rochefort and Lavoie, as cited in Lavoie and Rochefort, 1996) and in the UK and Ireland (Money, 1995) indicate that natural recolonization of *Sphagnum* is poor, rarely covering more than 15% of the surface area (Rochefort and Lavoie, as cited in Lavoie and Rochefort, 1996). A better understanding of relationships between hydrology, morphology, soils and plant growth is required as a basis for restoring peat-forming functions to harvested bogs.

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The low incidence of *Sphagnum* on harvested peatlands reflects the loss of natural functions that previously had limited water table fluctuations to a narrow range near the surface. These functions include the ability of aerobic upper layers to regulate runoff and evaporation losses, and adjust to changes in climate by shrinking and swelling (Ingram, 1983; Heathwaite, 1994). Drainage and peat extraction alter these natural processes by lowering the water table and removing the living and poorly decomposed surface layers. The remaining peat has a more uniform pore structure, characterized by high bulk densities and high water retention capacity (Price, 1996). Consequently, wide water table fluctuations and high water tensions result in a hostile environment for the establishment of non-vascular *Sphagnum* plants (Price, 1997).

Full water balance studies on drained bogs are rare. Most studies are concerned with the efficacy of drainage for forestry or crop production. After drainage, an increase in runoff is generally observed, with a tendency for higher storm peaks (Conway and Millar, 1960; Mikulski and Lesniak, 1975; Nicholson *et al*., 1989) and an increase in baseflow relative to natural conditions (Nicholson *et al*., 1989; Robinson, 1986; Burke, 1975). Other studies (Baden and Eggelsmann, 1968; Burke, 1975) report a decrease in peak flow because of greater available storage capacity in soils drained between storms. During peat production it is assumed that the removal of vegetation causes a decrease in evapotranspiration (Gottlich *et al*., 1993). The magnitude of this effect depends on the depth of the water table and the physical properties of the peat. On a cutover plateau bog in Quebec with drains blocked and a summer water table approximately 40 cm below the surface, Price (1996) found that evaporation from bare peat occurred at potential rates and was similar to that of a nearby natural bog. In contrast, Richardson and McCarthy (1994) found that mining of a peatland in North Carolina with an unspecified water table depth but 46 m ditch spacing resulted in a 26% reduction in evapotranspiration. Ledger and Harper (1987) also found a decrease in evaporation of 30% on a drained bog in Scotland with most ditches from 60 to 90 cm deep and 50% vegetation removal. The spread of vascular plants that are able to withdraw water from deep in the profile increases evapotranspiration, causing the water table to fall further (Ingram, 1987; Heathwaite, 1995). This particularly is true of trees, which also have been found to reduce runoff by intercepting rainfall and influencing antecedent moisture conditions (Robinson, 1986; Ledger and Harper, 1987; Burt *et al*., 1990). To correct imbalances on disturbed peatlands, it is necessary to identify the source, magnitude and distribution of water losses.

The overall objective of this study was to assess the impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog in Quebec. Specifically, the aims were to: (i) provide a full water balance of the site, (ii) evaluate how different regeneration patterns within the bog have influenced individual subcatchment water balances, and (iii) identify temporal hydrological changes by comparing the water balance at the harvested bog with that of a nearby natural one.

STUDY SITES

Harvested bog

The primary study site was an abandoned cutover peatland in Cacouna (47°53′N, 69°27′W) in the maritime floristic region, approximately 10 km north-east of Riviere-du-Loup, Quebec. At an altitude of 83 m a.s.l. (Lavoie and Rochefort, 1996), the abandoned cutover peat was up to 4 m deep and was underlain by a thick deposit of Champlain Sea clay (Lee, 1962). Mean annual precipitation (1963–1990) at a weather station in nearby St Arsène was 924 mm, 27% of which fell as snow. The mean annual temperature (1963–1990) was 3 °C, with mean temperatures in January and July of −12 °C and 18 °C respectively (Environment Canada, 1993).

The Cacouna bog originally covered an area of 210 ha (M. Girard, personal communication, 1999), but has since been reduced in size to 148 ha by agricultural encroachment and the development of roads through the south-west and north-east margins (Figure 1). In the mid-1800s, a railway was constructed roughly along a natural groundwater divide creating a highly compressed peat and flow barrier that separated the bog into two hydrologically distinct halves. This study focused on the larger 80 ha southern half.

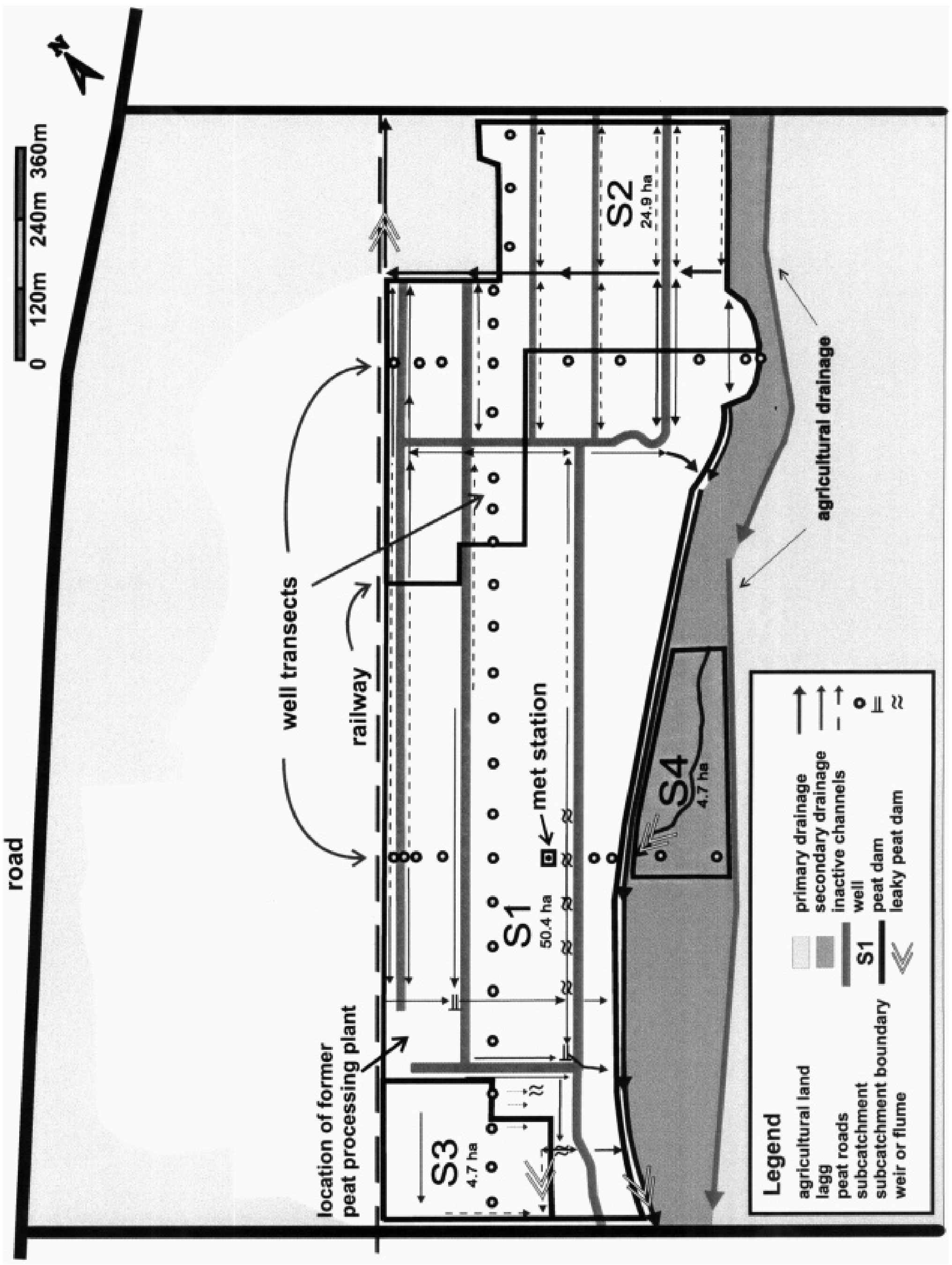

Figure 1. Experimental set-up at the Cacouna bog showing location of weirs, meteorological station, well transects and the areal boundaries of individual subcatchments (S1–S4)

Harvesting of peat on the Cacouna bog started in 1942 and continued until 1975 using the traditional 'block-cut' method. The post-harvest surface profile is characterized by alternating sequences of peat ridges, or 'baulks' (approximately 2 m wide), on to which blocks of peat were piled for subsequent removal, and lower lying convex cutover surfaces, or 'trenches' (approximately 10 m wide), from which the peat blocks were cut. During the course of harvesting, new sections were opened and old ones abandoned, introducing a complex historical component to the revegetation of the bog. The south side was completely abandoned by 1972, with most of the cutting between 1968 and 1972 occurring in the western sections (Girard, 2000). An attempt was made at that time to block some ditches with peat in the south-west portion of the bog (Figure 1), presumably to aid regeneration of the former vegetation. The last major disturbance occurred in the 1990s, when mineral soil and rock from the construction of a hydroelectric station on a small remnant west of the road was dumped and levelled immediately south of the former peat processing plant (Figure 1).

By 1997, twenty-two years after abandonment (longer in many areas), vegetation typical of raised bogs in the Riviere-de-Loup region had recolonized the bare peat surface (Lavoie and Rochefort, 1996). Trees are especially dense on the bog periphery, near major drainage ditches and in areas abandoned longest. Dominant tree species include black spruce (*Picea mariana*), tamarack (*Larix laricina*), white birch (*Betula papyrifera*), grey birch (*Betula populifolia*) and jack pine (*Pinus banksiana*). Dwarf shrubs (*Ericaceae* spp.) and cotton grass (*Eriophorum spissum*) are well distributed except under closed canopy forest and at the bottom of a slope in the south-west, where sedge (*Carex* spp.) dominates, probably because of seasonal flooding. The re-establishment of mosses (*Sphagnum* spp.) is sparse and irregular, occurring mostly in a few wet trenches and topographic depressions. A more detailed description of plant species and distribution can be found in Lavoie and Rochefort (1996).

The southern margin of the bog (hereafter referred to as the 'lagg') is situated within a topographic low separating the bog from adjacent mineral soils (Figure 1), and supports a distinct mix of eutrophic vegetation. Aerial photographs indicate that a part of this area was actively managed for timber from the 1960s to the present. The shallow winding stream was probably deepened in sections and extended towards the main channel to help lower the water table and promote forest growth (Figure 1). A section of this area was recently logged, but the area around the stream has regenerated naturally with a dense stand of speckled alder (*Alnus rugosa*), trembling aspen (*Populus tremuloides*), tamarack (*Larix laricina*), black spruce (*Picea mariana*), mountain ash (*Sorbus americana*), white birch (*Betula papyrifera*) and white cedar (*Thuja occidentalis*). Groundcover consists predominantly of sedge (*Carex* spp.), and various herbaceous plants including meadow rue (*Thalictrum pubescens*), raspberry (*Rubus pubescens* and *Rubus idaeus*) and various species of fern (especially *Dryopteris carthusiana* and *Thelypteris palustris*).

Natural bog

The natural bog near St Arsène is situated approximately 2 km north of the harvested bog at approximately 53 m above sea level. The bog covers an area of 242 ha and formed under similar climatic and geological conditions (Auer, 1930). Investigations at the natural site were used as a proxy of pre-disturbance conditions at Cacouna. The St Arsène peatland is the smaller of at least two bogs that formed in adjacent clay basins (Auer, 1930). A road separates the two, and a drainage ditch cuts through the eastern margin. Aerial photographs from 1948 to 1994 indicate a progressive increase in the size and number of trees on the bog. The dominant tree and shrub species are similar to that of the Cacouna bog, with the exception of birch (*Betula* spp.), which typically invades after abandonment of harvested bogs (Lavoie and Rochefort, 1996). *Sphagnum* spp., and reindeer moss (*Cladina rangiferina*) form a typical hummock and hollow topography. *Sphagnum* spp. on both bogs are dominated by *S. capillifolium, S. fuscum, S. magellanicum* and *S. fallax*. Plant identification follows Crum and Anderson (1981) for mosses, and Scoggan (1978) for herbaceous plants, trees and shrubs.

METHODS

Data were collected from 18 June to 15 August in 1997 and from 9 May to 13 August in 1998, to evaluate hydrological processes during the main growing period. Energy balance data and water table fluctuations were monitored continuously with a Campbell Scientific Inc.™ data logger at a meteorological station set up on the south side of the bog (Figure 1). Precipitation was measured with a tipping bucket and manual rain gauge elevated approximately 0.5m above the soil surface. Comparative measurements were made at the St Arsène bog in 1998 along a 520 m well transect from the centre of the bog to the forested margin. Instrumentation included four manual wells spaced approximately 130 m apart, and a continuous well recorder and manual rain gauge in the centre of the bog.

Evapotranspiration

Actual evapotranspiration (Et_a) was determined using three plastic bucket lysimeters (each 0·12 $m^2 \times$ 0·2 m deep) filled with peat monoliths and supporting vegetation representative of each of three major surface types within the trench-baulk sequence. Surface type was differentiated on the basis of vegetation and moisture content. The 'moist' trench lysimeter maintained a water table 15 to 20 cm below the surface and was covered by *Sphagnum* spp. with some *Ericaceae* spp. The 'damp' trench and 'dry' baulk lysimeters contained *Ericaceae* spp., bare peat and a sparse cover of leaf litter. Unlike the *Sphagnum* lysimeter, these were perforated through their bases and a second bucket below captured the drainage water so as to prevent undue moisture build-up. All lysimeters were sunk level to the surface in representative locations and weighed daily (including drainage water when applicable) to determine the rate of evapotranspiration during the previous 24 h. The moisture content in the lysimeters and the surrounding soil was monitored regularly using time-domain reflectometry (TDR) probes with 20 cm wave-guides. Water was added when lysimeter soil moisture content fell below that of its immediate surroundings. At the end of the study period, bulk density for each lysimeter was calculated by dividing the oven-dried weight of lysimeter monoliths by their saturated volumes. These data were combined with daily weight measurements in the field to determine the volumetric moisture content of lysimeters throughout the summer.

Daily equilibrium evapotranspiration (Et_{eq}) was estimated using the Priestley and Taylor (1972) combination method where

$$Et_{eq} = \alpha[s/(s+q)][Q^* - Q_G)/L\rho] \qquad (1)$$

and where L is the latent heat of vaporization (J kg^{-1}), ρ is the density of water (kg m^{-3}), s is the slope of the saturation vapour pressure–temperature curve (Pa °C^{-1}), q is the psychometric constant (0·0662 kPa °C^{-1} at 20 °C), Q^* is the net radiation flux (J day^{-1}), and Q_G is the ground heat flux (J day^{-1}). When the near-surface atmospheric vapour pressure deficit is zero, evaporation occurs at the equilibrium rate, and $\alpha = 1$ in Equation 1. The slope of the regression line relating actual (lysimeter) to equilibrium evapotranspiration ($\alpha = Et_a/Et_{eq}$) provides an empirical estimate of α that can be substituted into Equation 1 to determine evapotranspiration (*Et*) when only energy balance data are available (Price and Maloney, 1994).

The α parameter in Equation 1 for evapotranspiration from forested sections of the bog (20% of study area) was derived from the literature. Observations of ground water levels before and after tree harvesting in undrained bogs have shown that mean annual water tables are similar if the pre-cut water level is within 20–30 cm of *Sphagnum* hollows (Bay, 1969; Verry, 1981; Dube *et al*., 1995). This implies that net water loss by evaporation, including interception losses, is not greatly different between *Sphagnum* and tree-covered bogs. Based on the measured evaporation rate from the *Sphagnum* lysimeter, a value of $\alpha = 1{\cdot}07$ was assumed. Raising or lowering the α value by 0·1 would change the areally weighted evaporation rate from the bog by only ±2%.

The α values for the four surface types (moist, damp, dry and forest) were weighted by area and used in conjunction with the Priestley and Taylor (1972) method to determine total evapotranspiration from the Cacouna bog. Areal estimates were based on a detailed vegetation survey performed by M. Girard in 1997 and aerial photograph interpretation using geographical information systems (GIS) software (Girard, 2000). Trench designations were differentiated on the basis of the presence of *Sphagnum*, where a trench was considered moist if *Sphagnum* covered 10% or more of the surface and damp if *Sphagnum* covered less than 10%. Dry surfaces (baulks, roads and factory area) and drained forests could be readily discerned (via GIS) from air photographs.

Net radiation was recorded using two net radiometers installed 1·5 m above *Sphagnum–Ericaceae* and bare peat–*Ericaceae* surfaces. Soil heat flux was measured with two soil heat flux plates inserted 1 cm beneath bare peat and *Sphagnum* moss in 1997, and with only one beneath bare peat in 1998. Air temperature was measured with a shielded thermistor located approximately 1 m above the surface.

Runoff

Runoff was measured at three locations with V-notch weirs and at one location in the south-west corner with a current meter in an earth bottom flume (Figure 1). Water stages were measured continuously with potentiometric water level recorders connected to data loggers, except at the lagg stream in 1998, where a Stevens™ Recorder was used instead. The stage–discharge relationship for each stream gauging station was used to calculate average discharge rates for 1-h intervals over the two study periods. The ditches were mapped by direct observation and classed as active or inactive according to whether they transmitted drainage water during and after heavy storms. The ditch water levels at the junction between primary and secondary channels (Figure 1) were also monitored manually during and after storm events to determine relationships between bog water levels and primary/secondary channel contributions to discharge.

Storage changes

The change in storage (ΔS) over the study periods was determined as

$$\Delta S = \mathrm{d}h(S_y + bS_s) \pm \mathrm{d}\theta \tag{2}$$

where dh is the change in the water table, S_y is specific yield, b is the aquifer thickness, S_s is specific storage, and dθ is the change in moisture content in the unsaturated zone. The S_s term is defined as the amount of water that is expelled from aquifer storage due to compressibility of the soil matrix per unit change in head (Fetter, 1994), and is calculated as:

$$S_s = (\mathrm{d}b/\mathrm{d}h)/b \tag{3}$$

where db is the change in aquifer thickness, measured as a change in surface elevation (Schlotzhauer and Price, 1999). The S_s component is often omitted from estimates of storage change because S_y in unconfined aquifers is typically large relative to S_s. However, peat is much more compressible than mineral soils and thus S_s can be significant. Price and Schlotzhuaer (1999) found that S_s was from 67 to 170% higher than S_y in cutover peat, and that storage changes could be characterized adequately only if both terms were evaluated.

Water level changes (dh) were measured manually at 10-day intervals and after significant rain events to capture storm peaks 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. During the 1998 study season, average water levels from manual (PVC) wells were regressed on continuous well recorder data to estimate water levels when direct measurements were not available (see Figure 2). Transects were surveyed in 1997 using a level and compass. Surface elevation changes (db) were monitored at eight well locations with different peat depths by measuring the distance between a $0{\cdot}15 \times 0{\cdot}15$ m board resting on the ground surface and the top of an iron rod firmly set into the clay substrate.

The specific yield was determined in the laboratory using eight cores (80 cm × 120 cm^2) extracted from a representative sample of surface types at the Cacouna and St Arsène bogs. Cores cut into 5–10 cm sections

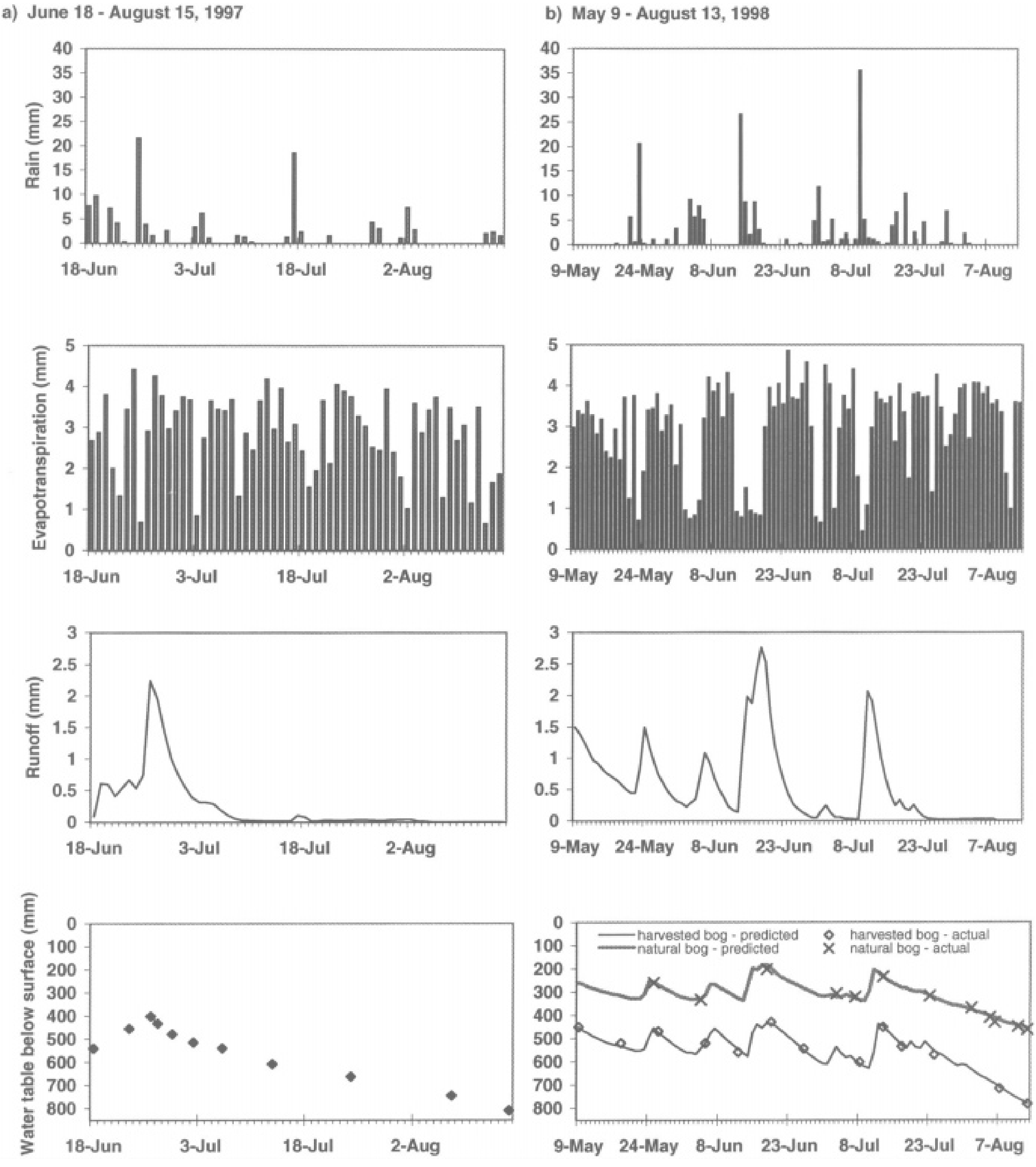

Figure 2. Daily rainfall, evapotranspiration, runoff and average water tables at the Cacouna bog from (a) 18 June to 15 August 1997 and (b) 9 May to 13 August 1998. Mean water table levels in 1998 are also shown for the natural bog. The 'predicted' water table fluctuations were determined by regressing mean values of all manual wells on data from the continuous water level recorder at each of the two study sites

were saturated in standing water and weighed (W_s), drained for 24 h, then weighed again (W_d). The specific yield (S_y) was calculated as

$$S_y = [(W_s - W_d)/\rho]/(W_s/\rho) \quad (4)$$

where ρ is the density of water (Price, 1996). Results were averaged to provide a final measure of S_y for substitution into Equation 2.

Volumetric moisture content changes in the unsaturated zone (dθ) were estimated by TDR and gravimetrically in 1997 and 1998, respectively. A block of peat extracted from the site was used to calibrate the TDR. Measurements by TDR (1997) and samples of known volume (1998) were taken at 2, 10, 30 and, where the water table was lower, at 50 and 75 cm depths in areas representative of each of the major surface types described above. The change in moisture content was calculated as the depth-averaged difference in moisture content between the first and last day of the two study periods.

RESULTS

Water inputs and outputs

Hydrological observations during the summers of 1997 and 1998 were used to calculate the water balance. The sole water input to the Cacouna bog was precipitation, and the only losses were streamflow and evapotranspiration. A low permeability clay floor (5×10^{-8} cm s^{-1}) restricted water exchanges between the bog and the regional aquifer. Auger sampling at over 100 locations within the study area revealed a continuous clay base. Even if the hydraulic gradient was as high as 1, the seepage loss would be negligible, at 0·004 cm day^{-1}. Lateral flow towards the margins was intercepted by 1 to 2 m deep drainage canals (Figure 1), which were monitored frequently during the study periods. Hydrological data collected simultaneously in 1998 from the St Arsène natural bog are presented for purposes of comparison.

Precipitation

Daily precipitation, evapotranspiration, runoff and water table levels from 18 June to 15 August 1997 and from 9 May to 13 August 1998 are presented in Figure 2. Total rainfall was 120 and 219 mm for the 1997 and 1998 seasons, respectively. Precipitation in June and July was 71 and 44 mm in 1997, and 83 and 102 mm in 1998, respectively. This compares with the 28-year average (1963–1990) from the St Arsène meteorological station of 83 and 87 mm for the same two months (Environment Canada, 1993). The wetter conditions in July of 1998 were followed by a dry spell in August (Figure 2). The difference between tipping bucket and manual rain gauges at Cacouna was less than 3%. Rainfall recorded at the St Arsène bog was 4% less than at Cacouna during the 1998 season. Mean daily temperatures for June and July of both years were slightly lower but still within 0·5 °C of climate normals.

Runoff

The total areas of the lagg (S4) and three bog drainage basins (S1, S2 and S3) are 4·7, 50·4, 24·9 and 4·7 ha respectively (Figure 1). The S4 catchment consisted of a single winding stream that was less than 0·5 m deep and approximately 310 m in length. The S1 and S2 channel outlets were connected to a network of primary and secondary drains that were approximately 3740 and 1697 m in length respectively. Secondary drains were typically shallow, moss filled drains that transmitted water only during large rain events (>20 mm). A few drains had been blocked with peat (Figure 1), but often with only partial success. Secondary drains constituted roughly 59, 31 and 10% of the S1, S2 and S3 drainage networks respectively. These statistics do not include shallow ditches draining individual trenches. All of the catchments had similar drainage densities (*c.* 0·01 m m^{-2}).

Runoff from the S1 outlet accounted for 64% of the 14 mm measured from 18 June to 18 August 1997 and 69% of the total measured bog runoff depth of 54 mm from 9 May to 13 August 1998. Drainage slowed considerably in the latter part of the summer (Figure 2). Table I presents basin runoff ratios and lag-to-peak times for storms preceded by high, intermediate and low water table elevations. The hydrographs for each of the storms are shown in Figure 3. The runoff ratios for the lagg basin (S4) decreased with water table position, whereas those from the bog basins (S1 and S2) decreased with storm size.

Shorter lag times were generally associated with lower water table positions. The S4 (lagg) basin was the most responsive, with the exception of the last storm when lag times for all weirs were relatively short.

Table I. The runoff ratios and lag times of bog (S1 and S2) and lagg (S4) catchments for storms with antecedent water tables at high, intermediate and low positions

	Date (1998)	Antecedent water level (mm)	Rain (mm)	Runoff (mm)[a]	Runoff ratio	Lag-to-peak (h)[b]
S1 (area = 50 ha)						
High	23 May	−573	22·9	3·8	0·17	20
Intermediate	14 June	−601	50·5	19·4	0·38	9[c]
Low	10 July	−647	43·7	8·0	0·18	6[d]
S2 (area = 25 ha)						
High	23 May	−509	22·9	3·7	0·16	16
Intermediate	14 June	−542	50·5	17·6	0·35	11[c]
Low	10 July	−597	43·7	11·3	0·26	8[d]
S4 (area = 5 ha)						
High	23 May	−301[e]	21·8	7·8	0·36	11
Intermediate	14 June	−342	49·3	16·5	0·33	5[c]
Low	10 July	−401	43·5	10·4	0·24	7[d]

[a] Runoff calculated over time required for stream discharge to return to pre-storm levels.
[b] Time from centre mass of the rain storm to peak, as described by Burt (1992).
[c,d] Lag time to first peak after 23 mm and 36 mm of rain, respectively.
[e] Based on water level measurements from one well approximately 20 m from the shallow stream. These do not represent the average for the basin.

Although the S2 basin was smaller than S1, lag times were shorter only for the 23 May storm. Discharge volumes from both bog channel networks were similar and required up to 7 days to return to pre-storm levels, approximately twice as long as was required for the S4 (lagg) basin stream (Figure 3). A secondary peak in the S1 hydrographs was evident for storms greater than 25 mm (Figure 3 and other hydrographs not shown). Direct channel precipitation ranged from 2 to 4% of total runoff losses based on estimated channel areas for each basin. Runoff from the natural bog was assumed to be negligible because of the relatively dense peat within the zone of water table fluctuations, the upper limit of which never exceeded 100 mm below the peat surface, and the absence of a drainage channel.

Evapotranspiration

The rate of wetland evapotranspiration for a given energy supply is controlled by water table levels and vegetation cover (Lafleur and Roulet, 1992). The effect of these variables on evapotranspiration is represented in the Priestley and Taylor (1972) equation by the coefficient of evaporability (α). An estimate of the coefficient is provided by the slope of the best-fit line relating equilibrium to actual (lysimeter) evaporation (Figure 4). Estimated α values and associated evaporation rates for various surface types (see Methods section) at Cacouna are presented in Table II. Daily evaporation from 'dry' surfaces (baulks, roads and factory area) (1·9 mm day^{-1}) was 66% that of 'damp' surfaces (2·9 mm day^{-1}) and just over half that of the 'moist' trenches with *Sphagnum* (3·6 mm day^{-1}). Forest evapotranspiration was estimated to be 3·6 mm day^{-1} (see Methods section for rationale). The relative proportion of the study area covered by moist, damp, dry and forested surfaces for the bog, and individual subcatchments is given in Table III. Based on these estimates, the areal average evapotranspiration rates were 2·9, 2·8, 3·1, 3·5 and 3·0 mm day^{-1} for the bog area and subcatchments S1 to S4, respectively. Results from the shorter 1997 season were similar, except for a slightly lower evapotranspiration rate of 3·4 mm day^{-1} from the S3 basin.

The equilibrium rate of evapotranspiration at the natural bog was calculated using energy flux data over a partially *Sphagnum* covered surface at the harvested site. The α coefficient of evaporability was assumed to be similar to that of a damp trench (2·9 mm day^{-1}) because the lysimeter representing this surface type was maintained at a moisture content comparable to an area with mean water levels only 4 cm lower than

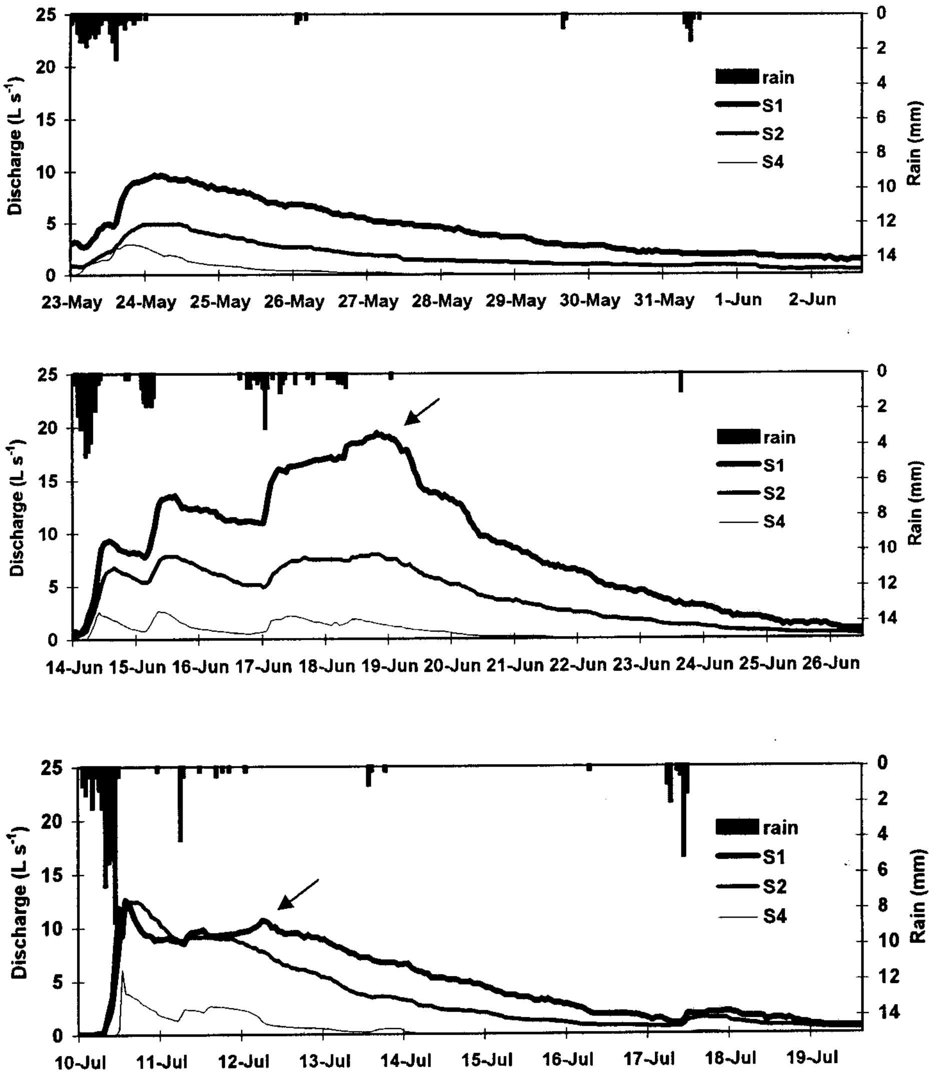

Figure 3. Lagg (S4) and bog subcatchment (S1 and S2) hydrographs for three storms during the 1998 study period. Arrows indicate secondary peaks

the natural bog (−35 cm compared with −31 cm at the natural site), and the difference between equilibrium evapotranspiration over surfaces with and without *Sphagnum* was only 0·06 mm day^{-1}. The slightly lower water levels beneath damp surfaces was likely offset by the tendency for *Sphagnum* plants to dry out and resist further losses of moisture to evaporation as water levels fall below −20 to −30 cm (e.g. Romanov, 1968; Nichols and Brown, 1980).

Storage changes

Storage change was estimated using Equation 2, which includes the effects of water table changes on aquifer compression and moisture content changes in the unsaturated zone. The mean water table declined by 264 mm and 337 mm at Cacouna over the 1997 and 1998 study periods, respectively. Using the mean laboratory specific yield estimate of 0·08, the storage change associated with drainage of soil pores was 22

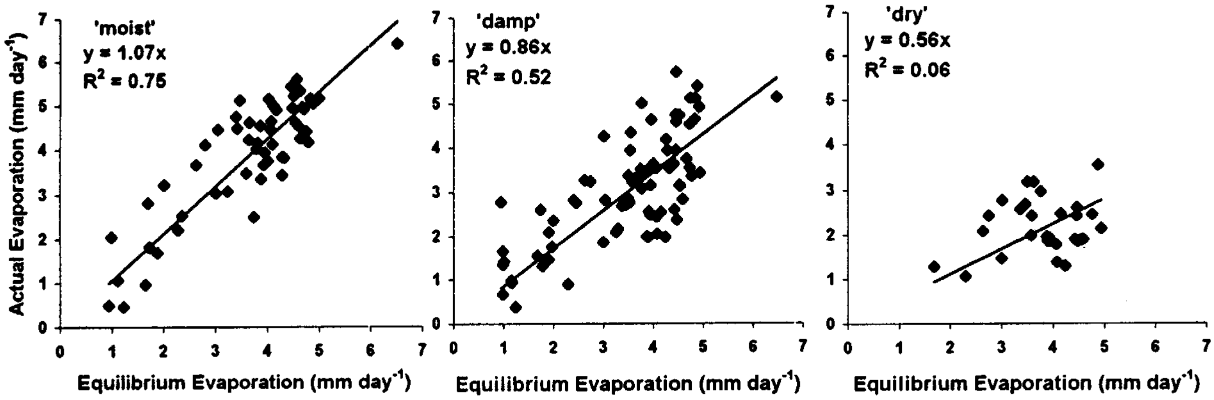

Figure 4. Actual (lysimeter) versus equilibrium evaporation for moist, damp and dry surface types (see Table II) at the harvested bog from 17 May to 13 August 1998

Table II. The mean (± standard deviation) of the Priestley and Taylor (1972) α value, moisture content and daily evapotranspiration (*Et*) for various surface types at Cacouna, between 9 May and 13 August 1998. Surface types are as defined in the Methods section

Surface type	Dominant surface cover	n[a]	α	Moisture content (%)	*Et* rate (mm day^{-1})[b]
Moist trenches	*Sphagnum* spp. and *Ericacae* spp.	55	1·07 (±0·28)	64·2 (±8·2)	3·6 (±1·5)
Damp trenches and uncut areas	*Ericacae* spp. and bare peat	78	0·85 (±0·32)	55·3 (±5·6)	2·9 (±1·2)
Dry baulks and roads	*Ericacae* spp. and bare peat	29	0·56 (±0·18)	41·8 (±4·6)	1·9 (±0·8)
Forest	Various tree species	—	1·07[c]	—	3·6 (±1·5)

[a] n = number of days of lysimeter data.
[b] Includes entire study period (97 days).
[c] Value derived from literature.

Table III. The estimated percentage area of four surface types and weighted average α value and daily evapotranspiration for indicated catchments for the period 9 May to 13 August 1998

	Area by surface type (%)				Areally weighted average	
	Forest	Moist	Damp	Dry	α	*Et* rate (mm day^{-1})
Total study area	20	25	23	32	0·86	2·9 (±1·2)
S1	16	20	26	37	0·82	2·8 (±1·1)
S2	21	32	22	25	0·90	3·1 (±1·2)
S3	51	36	0	13	1·00	3·5 (±1·4)
S4	70	0	0	30	0·87[a]	3·0 (±1·2)
Natural bog	—	—	100	—	0·85	2·9 (±1·2)

[a] The α value was assumed to equal 1 for the short scrub forest (70% by area) in the S4 (lagg) basin.

and 27 mm. The effect of aquifer compression on storage was estimated by a coefficient equal to the slope of the best-fit line of surface elevation plotted against water table elevation (d*b*/d*h*) (see Methods section). Mean 1998 coefficient values for the 1997 and 1998 seasons were 0·037 (10 mm, $R^2 = 0{\cdot}90$) and 0·046 (16 mm, $R^2 = 0{\cdot}88$) respectively. The depth-integrated moisture contents were determined for each surface type and weighted by area to provide an estimate of change (dθ) over the two study periods. The areal average change in moisture content at Cacouna was 43 and 57 mm in 1997 and 1998 respectively. From Equation 2, total storage change was 75 mm for 1997 and 100 mm for the 1998 season.

In contrast to the Cacouna bog, the natural bog water table fell by 195 mm in 1998 and desaturation of pores resulted in a 21 mm loss in storage ($S_y = 0{\cdot}11$). Change in storage related to aquifer compression was 11 mm ($db/dh = 0{\cdot}054$, $R^2 = 0{\cdot}91$). The change in volumetric moisture content in the unsaturated zone was assumed to be similar to that of a 'moist' trench at the harvested site, or 26 mm. Substituting again into Equation 2, the approximate change in storage for the natural bog was 58 mm.

Water balance

The water balance was estimated as

$$P = Et + R + \Delta S + \varepsilon \tag{5}$$

where P is precipitation, Et is evapotranspiration, R is runoff, ΔS is change in storage and ε is the residual term. Water budgets for the entire study area, each of the four drainage basins (Figure 1), and the natural bog in 1998 are presented in Table IV. Calculation of Et and ΔS was based on the vegetation cover and moisture content of the soil. Evapotranspiration was the dominant water loss from the system, accounting for 169 mm in 1997 and 285 mm in 1998. Runoff depths of 15 and 54 mm were small in comparison to storage changes of −75 and −100 mm for the two study periods respectively. Residual errors were 11 and −19 mm, or 9% of water inputs, in 1997 and 1998 respectively. The difference in residuals between the two years was influenced by the period over which measurements were taken. Recalculation of the 1998 water budget for the spring and summer periods indicated a residual of −34 mm from 9 May to 16 June and, like the 1997 season (18 June to 15 August), a positive residual of 18 mm from 16 June to 13 August. The discrepancy in residuals between the two periods was probably the result of an overestimate of evapotranspiration during the early spring, before tree and shrub canopies were fully formed. From 9 May to 20 May, total outputs were 47 mm (36 mm of evaporation and 11 mm of runoff), but over the same period less than 1 mm of rain fell, and changes in storage amounted to only 13 mm ($S_y = 0.08$, $db/dh = 0.02$, $d\theta = 6$ mm). Thus, approximately 33 mm of moisture were not accounted for in the 1998 water budget analysis.

Table IV. The relative magnitude of water budget components (in mm) over the 1997 and 1998 study periods for the harvested bog, its subcatchments, the lagg basin and the natural bog (1998 only)

	Variable				
	P	Et	R	ΔS	ε
18 June to 15 August 1997					
Harvested bog	120	169	15	−75	11
S1	120	161	19	−71	11
S2	120	177	14	−70	−1
S3	120	197	0	−91	14
S4	120	171	20	−61	−10
9 May to 13 August 1998					
Harvested bog	220	285	54	−100	−19
S1	220	271	58	−96	−13
S2	220	298	54	−101	−31
S3	220	331	0	−100	−11
S4	220	288	51	−104	−15
Natural bog	212	281	0	−58	−11

DISCUSSION

Drainage and peat cutting have dramatically altered the hydrological functions of the Cacouna peatland. Lower water tables and modifications in surface topography and vegetation were responsible for many of the changes observed. The centrifugal pattern of shallow subsurface runoff typical of natural raised bogs was replaced by a network of deep drains that withdrew water from deep within the peat matrix and transmitted it by various routes to the two major outlets. After abandonment, many of the secondary drains were operating at only a fraction of their original efficiency because of sedimentation, natural ditch occlusion and, in a few instances, deliberate attempts to block ditches (Figure 1). The observed patterns of storm runoff response from the harvested surface (Figure 3) were largely a reflection of these drainage characteristics.

In the S1 and S2 basins this was evident in the varying response produced by primary and secondary channel networks, the latter of which were generally less efficient and further away from the stream gauging stations. During wet conditions, the two networks were well connected and responded as a single integrated unit (23 May storm in Figure 3). At this time, the single peak of storm hydrographs at the S1 and S2 outlets represented runoff from both primary and secondary channels, and thus lag times were relatively long (16 to 20 h). Following storms at periods of low water table, partially occluded and blocked secondary channels responded more slowly as water flowed through the loosely packed sediment and debris, creating a secondary peak in the S1 basin hydrograph (14 June and 10 July storms in Figure 3). Lag-to-peak times declined because runoff contributions to the first peak were principally from primary channels closer to the drainage outlets (Table I). In contrast to the S1 basin, secondary and primary channel response times of the S2 basin were more integrated owing to its smaller size and the greater efficiency of its secondary drain network (i.e. ditches and culverts had not been blocked). In this basin, hydrographs lacked secondary peaks (Figure 3) and combined discharge from a greater proportion of active channels (both secondary and primary), producing lag times of 8 and 9 h at low and intermediate water table positions compared with 6 and 9 for the larger S1 subcatchment. These relatively long lag times are in contrast to more recently drained bogs with more efficient ditch networks, where storm peaks typically occur within a few hours of rainfall (Conway and Millar, 1960; Burke, 1975; Ledger and Harper, 1987).

A positive relationship between water table levels and streamflow generation in undisturbed peatlands has been noted by several researchers. Bay (1969) reported runoff ratios for a 9·7 ha forested bog of approximately 0·1 and 0·4 for low and high water table positions respectively. These compare with average runoff ratios for storms greater than 15 mm on a small Ontario headwater peatland of 0·06 during 'dry' conditions and 0·52 during 'wet' ones (Branfireun and Roulet, 1998). In the present study, runoff ratios for the bog basins were controlled primarily by storm size and only slightly by the antecedent water table during dry conditions (Table I). The difference between drained and natural peatlands in this regard may be attributed to differences in the structure of the peat matrix and the effects this has on the transport of runoff to the margins. In natural bogs, the upper layers of living and weakly decomposed *Sphagnum* act as an effective overflow system, rapidly transporting excess water to lagg streams during wet conditions (Bragg, 1989). When the water table falls into the more decomposed peat layers, flow decreases dramatically and all or parts of subsequent rainfall inputs are retained in storage (Bay, 1967). Conversely, the drained bog discharges water predominantly from a deep but narrow zone of dense peat on either side of ditches, where the mean hydraulic conductivity and storage capacity is very low (Boelter, 1972). After a rain event, the peat profile is quickly saturated and runoff is transported over a period of several days to the nearest outlet. Hence the water table has less influence on discharge volumes in drained bogs.

The lagg basin (S4) has a slightly concave shape with a shallow stream that cuts through the centre and drains into the main channel. Slow internal groundwater flow inputs from within the basin maintained high water levels approximately 15 m on either side of the stream for most of the summer. During rain events, water levels in these zones rose to the surface and water was transported quickly to the stream through overland and shallow subsurface channels. The processes involved are similar to the variable source area concept outlined by Dunne and Black (1970). This mechanism of stream flow generation was reflected in short lag and recession times (Figure 3) and a cessation in runoff during dry periods. As the water table fell, runoff ratios declined because the size of the area contributing water to the stream during storms contracted and thus a greater proportion of rainfall inputs were absorbed into storage. During these periods, the water table elevation fell below the shallow, overgrown stream bed, and thus unlike some bogs with deep drains (e.g. Burke, 1975; Robinson, 1986), baseflows were not sustained.

Variations in evaporation among lysimeters (1·9 to 3·6 mm day^{-1}) reflected differences in soil moisture content and vegetation. Baulks and roads were very dry because low water tables (mean −80 cm) prevented a constant supply of capillary water from reaching the surface. Despite its separation from the water table, the baulk lysimeter never required artificial additions of water to maintain moisture conditions similar to its undisturbed surroundings. Under these circumstances, evaporation was controlled more by soil matric forces than by available radiant energy, which may explain the low R^2 for the baulk α value plot (Figure 4). Some trench skags, with mean water tables greater than 40 cm below the surface experienced similar surface moisture deficits during spells of drought (G. Whitehead, personal communication, 1999). Low evaporation from such surfaces may play a role in promoting the regeneration of *Sphagnum* mosses by reducing water table fluctuations and helping to maintain wetter conditions in adjacent less elevated areas of cutover trenches. In the long term, the continued spread of trees threatens to reverse this role by intercepting and transpiring water that was previously unavailable for atmospheric consumption.

The water balance data indicated that evapotranspiration was the major water loss from the harvested bog, comprising 92 and 84% of total outputs (2·9 mm day^{-1}) for the 1997 and 1998 study periods respectively. The loss was more significant from very moist surfaces and forested parts of the basin. Trees are particularly dense around the main channels where early abandonment and deep drainage facilitated forest growth. These trees act as a form of 'biological drainage' (Heikurainen and Paivanen, 1970) and were found to intercept 32% of precipitation inputs, thereby inhibiting runoff during dry periods (Van Seters, 1999). Perhaps this partly explains why the S3 basin, with 51% forest cover but a drainage density similar to that of other basins (0·01 m m^{-2}), produced negligible runoff. Forest cover in the S1 and S2 catchments was similar (16 and 21% respectively), but the larger S1 basin was drier, more steeply sloped and had a higher proportion of blocked drains than S2. The drier conditions of the S1 catchment produced lower evaporation (by 9%), whereas the steeper surface gradients, in spite of the blocked ditches, may explain the 26 and 7% higher runoff depths during the 1997 and 1998 study periods, respectively. Overall, however, the water balances for the two major bog catchments were similar (Table IV).

The natural bog was assumed to evapotranspire at rates similar to a damp trench (2·9 mm day^{-1}) because of the low water table (mean = 31 cm below the surface). This is well below the potential evapotranspiration rate typical for natural bogs (Ingram, 1983) with high water tables and was the same as the areal average rate for the cutover site. The low water table at the natural site also prevented moisture losses from runoff. Research on undisturbed peatlands has shown that runoff decreases significantly when the water table falls lower than 10 to 15 cm below *Sphagnum* hollows (Bay, 1970; Verry *et al*., 1988). This zone is characterized by more decomposed peat relative to the upper horizons and therefore water is retained more effectively. As the water table at the natural site was below 15 cm for 97% of the 1998 study season, runoff was assumed to be negligible. Thus, although evapotranspiration at the natural and harvested sites was similar, low runoff rates and high specific yield of the undisturbed peat limited water table fluctuations to within a narrower range (Figure 2) and ensured moisture conditions were not limiting for *Sphagnum* plant growth.

The potential errors of individual water balance components must be assessed in relative terms, as there is no absolute standard against which comparisons can be made. Precipitation from two gauges at the harvested site differed by only 7%. The accuracy of evapotranspiration estimates depends on errors in the Priestley and Taylor (1972) method and in the lysimetric analysis used to obtain values of the α term. The combined errors in net radiation and soil heat flux are typically within ±10% (Price, 1996) and small lysimeters (<1 m^2) provide a reasonable measure of actual evaporation during the growing season (Dugas and Bland, 1989). The areas for each surface type used to estimate evapotranspiration and soil moisture change were determined with GIS combined with extensive ground surveys of topography and vegetation. Although this method was reasonably accurate (Girard, 2000), the averaging process probably introduced an error of at least ±10%. Stream gauging station rating curves were the same for both years and had coefficients of determination ranging from 0·96 for the flume to 0·99 for the weirs. Data points included several high flow measurements, the largest of which was less than 20% lower than the highest estimated discharge rate. The catchment areas for all of the basins were accurately determined through topographic surveys and drainage water mapping. Thus, although the error cannot be determined explicitly, the general water balance results provided a good overall indication of the relative importance of hydrological processes and how these varied spatially in areas with different hydrophysical and botanical characteristics.

CONCLUSION

Strong spatial variations in water losses were a distinctive feature of the Cacouna bog. Within a distance of less than 10 m, evaporation increased from 1·9 mm day^{-1} from baulks to 3·6 mm day^{-1} from moist ditches (Table III). Strong losses from forests around the periphery were in contrast to much lower areal average losses from the open bog expanse. In the S3 basin, with 51% forest cover, runoff was negligible, whereas in the S2 basin, summer runoff losses consumed 26% of precipitation inputs (Table IV). These spatial variations are in contrast to the relatively uniform distribution of losses characteristic of natural bog ecosystems. Thus, although management strategies such as blocking ditches would be effective in restoring areal average water balance levels to those of the natural bog (Table IV), their effectiveness in specific locations may vary significantly.

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