HYDROLOGY AND MICROCLIMATE OF A PARTLY RESTORED CUTOVER BOG, QUÉBEC

JONATHAN S. PRICE

Wetlands Research Centre, Department of Geography, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada

ABSTRACT

Peatlands do not readily return to functional wetland ecosystems after harvesting (cutting), because the harsh hydrological and microclimatic conditions are unsuitable for *Sphagnum* regeneration. In this study, drainage ditches blocked after harvesting restored the water balance to a condition similar to a nearby natural bog. Evaporation averaged 2·9 and 2·7 mm day^{-1} on the cutover and natural bog, respectively. Evaporation consumed most of the rainfall input (86 and 80%, respectively), whereas runoff was minor at both sites (6 and 4%, respectively). However, the water table position was markedly different at these sites. Median water table depth was 0·05 m below the surface in the natural bog, compared with 0·44 m in the cutover bog (ditches blocked). Changes to the peak soil matrix owing to drainage and cutting reduced the specific yield (Sy) of the peat to 0·04–0·06 from 0·35–0·55, causing exaggerated water table changes in the cutover site. Nevertheless, volumetric soil moisture in the cutover site (0·67 ± ·08) had low variability, and was maintained above moisture contents found in *Sphagnum* hummocks in the natural bog (0·48 ± ·10), although less than on *Sphagnum* lawn (0·84 ± ·11). Poor *Sphagnum* regeneration on cutover surfaces can therefore be attributed to its inability to extract water from the underlying peat, which retains water at matric suction greater than the non-vascular *Sphagnum* can generate.

The corrupted iron pan under main ditches has permitted partial recharge of the underlying aquifer, reducing local hydraulic gradients, thereby decreasing vertical seepage loss.

KEY WORDS wetland ecosystems; peatland; cutover bog; hydrology; microclimate; *Sphagnum* regeneration; restoration

INTRODUCTION

In Canada, few cutover peat sites have reverted to functional wetland ecosystems because the disturbed hydrological and microclimatic conditions appear to be unsuitable for *Sphagnum* regeneration. This study compares the hydrological and microclimate conditions in a natural and recently cutover bog.

Canadian *Sphagnum* peat harvesting operations generate about $180 000 000 of sales per year, and another $45 000 000 in economic 'spin-off' (G. Hood, Canadian *Sphagnum* Peat Moss Association, personal communication, 1995). In Canada, most peat extraction activity occurs in Quebec, New Brunswick and Alberta (Keys, 1992). At present, peat harvesting is not managed as a sustainable resource, and exhausted sites are simply abandoned. Few of these have regenerated to functional bog ecosystems (Famous *et al.*, 1991) because the disturbed hydrological and microclimatic conditions are unsuitable for *Sphagnum* regeneration.

Vegetation succession occurring since abandonment reflects the range of edaphic, hydrological and ecological processes operating at the site. In Quebec, this has resulted in less than 10% of the area of abandoned bogs showing any *Sphagnum* regeneration (Lavoie and Rochefort, 1996). In comparison, a completely developed moss carpet can be achieved in a greenhouse within 4–6 months depending on the water level (Campeau and Rochefort, 1996). Therefore, given the appropriate hydrological and microclimatic conditions, it should be possible to regenerate a *Sphagnum* cover under field conditions. Artificial shading devices or mulches ameliorate these processes to increase the survival of hand-sown *Sphagnum* fragments (diaspores) (Quinty and Rochefort, 1997). However, the threshold conditions are as yet undefined.

Peat extraction, and the consequent water table drop, alters the surface conditions and groundwater flow dynamics that govern the bog's relationship to the surrounding landscape (Bragg, 1995). This alters the physical, hydrological and chemical environment of the cutover surface on which *Sphagnum* re-establishment must occur (Heathwaite, 1994; Schouwenaars, 1993).

Shrinkage, oxidation and compression of the drained peat (Schothorst 1977) alter the pore structure of the peat matrix. The smaller pores thus formed, decrease the plant-available water in the unsaturated zone (Okruszko, 1995), and increase the variability of the water table elevation (Schouwenaars, 1993), by altering the way in which water is stored in the peat. Hydrological changes relating to runoff from drained peatlands are well documented (Boelter, 1972; Burke, 1972; Mulqueen, 1986), and are characterized by a more regulated flow regime. Blocking ditches in a drained peatland is an essential step in restoring the water balance (Rowell, 1989), but the efficacy of this procedure has not been quantified.

Other components of the water balance such as seepage and evaporation must also be considered. Seepage losses may be high because of changes to the regional water pressure caused by activities outside the peatland, and as a consequence of removing peat, which, in its decomposed state, has a low hydraulic conductivity. Egglesman (in Schouwenaars, 1988) suggests that for European peatlands, seepage losses in excess of 50 mm year^{-1} preclude restoration in most cases.

There is a paucity of data regarding evaporation from bare peat surfaces. O'Kane (1992) discusses a theoretical approach that suggests that the potential evaporation rate occurs from bare peat surfaces following saturation, and is sustained for approximately 30 hours before the evaporative efficiency drops off as a result of a vapour 'bottle-neck' in the drying layer. Over the longer term, Heathwaite (1994) suggested that the change in vegetation to predominantly vascular plants, associated with a deeper water table, may favour greater evapotranspiration loss.

The general objective of this paper is to compare the hydrological and microclimatic processes on a natural undisturbed peatland, and a cutover peatland in the intial stages of restoration. Within this setting, the specific goals are to quantify the nature of (i) water table changes and water storage, (ii) the surface energy balance and evaporation, and (iii) the water balance.

STUDY AREA

The study was done at the Toubière Fafard peatland, near Sainte-Margeurite-Marie, in the Lac Saint-Jean area of Quebec, Canada (48°47′N, 72°10′W). The peatland is part of a 4315-ha bog-poor fen complex (Campeau and Rochefort, 1996), situated on a terrace of deltaic sands (Morin, 1981) in the Lac Saint-Jean lowland. The 1951–1980 climatic normals (Environment Canada, 1982) indicate that the average annual temperature is 1·7°C, with average January and July temperature of −17·1 and 17·3°C, respectively. Mean annual total precipitation during this period was 906 mm (32% falling as snow). Mean annual runoff in the nearby Mistassini River is 623 mm (Environment Canada, 1992).

The peatland is part of the Low Boreal Wetland region (NWWG, 1986), and can be classified as Plateau Bog (NWWG, 1987). Two sites within this bog, approximately 2 km apart, were studied — a natural and a cutover site. The surface cover of the natural bog is dominated by *Sphagnum fuscum*, *S. angustifolium*, *S. magellanicum* and *S. capillifolium*. The specific area selected for study is open (no trees), with *Sphagnum* hummocks typically 0·3 m above the *Sphagnum* lawn. The disturbed area is essentially devoid of vegetation. It was drained in 1990, and the upper 0·35 m was cutover in 1991 by block cutting with heavy machinery. Ditches (30 m spacing) were blocked in spring 1993, but were not back-filled. The post-harvest surface profile is characterized by a central ridge called a 'balk', upon which peak cuttings were piled for later removal, and a lower lying flat cutover surface, which rises into a slight berm near the ditch (milled cuttings from the ditch excavator). The peat forming the balk was never harvested, but the surface is irregular because of scattered residual peak blocks.

METHODS

The measurement period was 14 July to 21 September 1993. The surface energy balance was measured at both the natural and disturbed sites. At both locations evapotranspiration was determined with the Bowen

ratio–energy balance method, which consisted of a net radiometer, two soil heat flux plates embedded 1 cm below the surface, and a four-level aspirated psychrometer (at 0·5, 1·0, 1·5 and 2·0 m) to measure dry and wet bulb temperature. There was at least 300 m of fetch in all directions. The theoretical approach and instrumental set-up is identical to that described in detail by Price (1991). Soil temperature was measured with thermocouples at 0·001, 0·01, 0·05, 0·10, 0·25, 0·50 and 1·00 m beneath the surface.

At both sites, rain was measured with a tipping bucket rain gauge 0·5 m above the surface. The water level was monitored continuously with a float-potentiometer device, and also daily using wells and piezometers as described below. Wells were constructed of 19 mm (i.d.) PVC slotted throughout their length, and covered with a 200 μm geotextile. At the natural site, only one well was used, and its elevation was referenced to the surface of the *Sphagnum* lawn. At the cutover site, wells were organized in a transect perpendicular to a ditch, at a distance of 1, 2, 5, 10 and 15 m from the ditch edge. Piezometers were installed in the peat at 1 and 2 m below the surface, constructed similarly to the wells described above, but were slotted only along the lower 30 cm. Deeper piezometers installed into the underlying mineral soil were 30 cm stainless steel drive-point piezometers (19 mm i.d.), and were set at depths of 3 and 5 m below the surface.

Soil moisture was determined gravimetrically, by using a cutter to sample the upper 50 mm of soil. Three to five samples were taken daily at each location, and pooled to determine the daily average soil moisture there. Deeper soil cores were taken to determine specific yield (Sy). The core was cut into 50 mm sections, saturated in standing water to determine the saturated weight ($M_{\text{saturated}}$), drained for 24 hours to determine the drained weight (M_{drained}) and then

$$Sy = \frac{(M_{\text{saturated}} - M_{\text{drained}})/\rho_{\text{w}}}{M_{\text{saturated}}/\rho_{\text{w}}} \qquad (1)$$

where ρ_{w} is the density of water, assumed to be 1000 kg m^{-3}.

A water balance calculation was performed for the period 14 July to 21 September using

$$RO + \varepsilon = P - E - \Delta S \qquad (2)$$

where precipitation (P) and evapotranspiration (E) were measured at both sites, and storage change (ΔS) was determined from the change in water level (Δh), as $\Delta h \cdot Sy$. Since runoff (RO) cannot be determined from these sites, it was calculated as a residual. The error term is represented by ε. The magnitude of probable errors is discussed later.

RESULTS

Soil cores in the natural and drained soil had markedly different water storage characteristics (Figure 1). Specific yield (Sy) in the natural bog is highly depth dependant, ranging from 0·55 near the surface, dropping to about 0·25 at 0·3 m, and remaining between 0·2 and 0·3 with greater depth. In contrast, the cutover peat has had its upper (high Sy) layer mechanically removed. The remaining peat has very low Sy, displaying little variability with depth, and ranging between 0·04 and 0·06.

During the period 14 July to 21 September there was a general rise in the water table as the soil moisture reservoir was recharged. Water table variations were caused by steady evapotranspiration losses, punctuated by rain events (Figure 2). Average water table depth below the surface ($\pm$ standard deviation) was 0·053 ($\pm$·042) m and 0·440 ($\pm$·082) m in the natural and cutover bog, respectively. Corresponding median water table depths are shown in Table I, along with the percentage time the water level was within 0·4 m of the surface. By late August, the water table rose to, and remained near, the surface in the natural site, but complete recovery was never attained in the cutover bog. Piezometers located in the peat (1 m below the surface), and below the iron pan in the mineral soil underlying the peat (3 m below the surface) had an average hydraulic gradient during the measurement period, of −0·48 and −0·14, in the natural and cutover bog respectively (negative sign indicates downward gradient).

Typical configurations of the water table along the transect in the drained site are shown in Figure 3. During the wetter period (26 August) the water table was about 0·3 m below the surface, and sloped
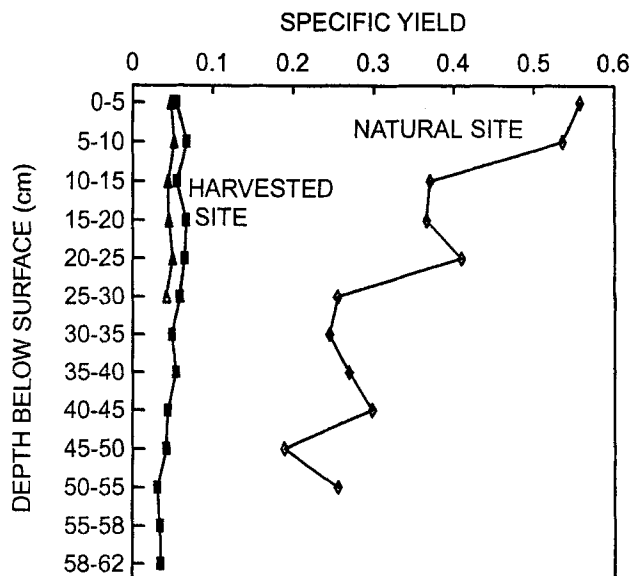
SPECIFIC YIELD

Figure 1. Depth profiles of specific yield (Sy)

towards the ditch. At a drier time (19 July) the water table was about 0·5 m below the surface, and sloped away from the ditch.

Evapotranspiration was calculated from the surface energy balance (Figure 4). Average net radiation (Q^*) was almost identical at both the natural and cutover surfaces. The ground heat flux (Q_G) was lower in the cutover bog. The lower heat flux across the cutover peat surface is reflected in the lower soil temperatures there. The average soil temperature gradients in the natural and drained sites, between depths of 0·01 m and 0·50 m were −8·0 and −15·5 °C m^{-1}, respectively. The latent heat flux (Q_E) was generally higher from the cutover bog surface. The latent heat flux was used to determine the evapotranspiration rate, which averaged 2·9 and 2·7 mm day^{-1} in the cutover and natural bog, respectively.

The water balance was determined to see if mesoscale site hydrological differences could explain the lower water table in the cutover site (Table II). At both sites, evapotranspiration consumed most of the rainfall input (80–86%), whereas runoff was calculated at only (4–6%). Note that this is less than the measurement error for any of the fluxes.

Surface soil moisture (0–5 cm) varied considerably from site to site, and over time (Figure 5). The general trend was similar to that of the water table, increasing into September. The *Sphagnum* lawn had the highest average volumetric moisture content (0·84 ± ·11), whereas the natural hummocks had the lowest (0·48 ± ·10) (see Table I). The average moisture content at the cutover site (0·67 ± ·08) had the lowest variability. The volumetric soil moisture in the central ridge (balk) of the cutover site (not shown in Figure 5) had a similar pattern to the *Sphagnum* hummocks, but was slightly higher (average 0·54 ± 0·11). The daily volumetric soil moisture at the cutover site is plotted against that at the natural site (*Sphagnum* lawn) in Figure 6. The larger range of volumetric soil moisture at the natural site is evident, even though both achieved full saturation during this period.

DISCUSSION

The water balance indicates that there were no large differences in the net water fluxes at either the natural or harvested site. However, interpretation of the water balance requires consideration of the possible errors. Precipitation was probably within ±15% (Gray, 1970). The error associated with evapotranspiration depends on the reliability of measurements of available energy (net radiation, Q^*, less ground heat flux, Q_G) and the Bowen ratio (β) measurements. Assuming Q^* was accurate within ±5% (Latimer, 1972),
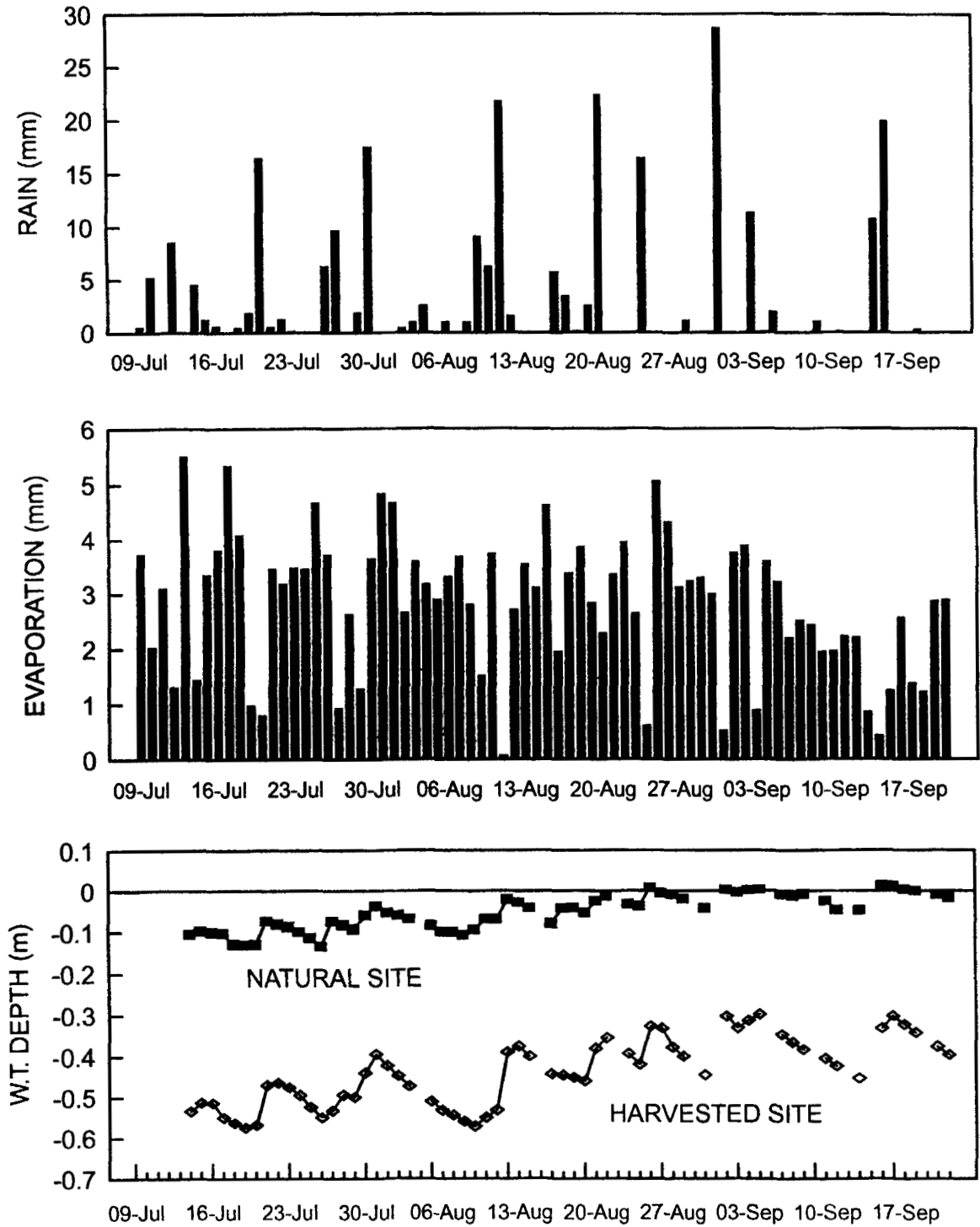
Figure 2. Rain (top), evaporation at the harvested site (centre) and water table depth below the surface (bottom)

Table I. Seasonal average soil moisture (dimensionless) in the upper 50 mm, median water table depth below the surface, percentage of time the water table was within 0·4 m of the surface and average bulk density (ρ_b), values given as ± SD

	Soil moisture	Median w.t. depth (m)	% time w.t. < 0·4 m	ρ_b (kg m^{-3})
Sphagnum lawn	0·84 ± ·11	0·05	100	36·7 ± 7·7
Sphagnum hum.	0·48 ± 0·10	0·35	82	46·8 ± 9·1
Cutover peat	0·67 ± ·08	0·44	40	109·1 ± 20·2
Balk (ridge)	0·54 ± 0·11	0·69	0	85·6 ± 24·9

Q_G within ±20%, and given that Q_G was 9 and 12% of Q^* at the cutover and natural sites, respectively, the error in available energy ($Q^* - Q_G$) was within ±10% for both sites (Angus and Watts, 1984). Under moist conditions, where the Bowen ratio is small, the significance of errors in the gradient measurements (used to determine β) is minimized (Fuchs and Tanner, 1970). Therefore, considering the average available energy at the cutover and natural sites (204 and 207 W m^{-2}) and β (0·2 at both sites), the total error of the latent heat term, and hence evapotranspiration, was within ±16%.

Evapotranspiration was the major flux within the water balance, and there was only 0·2 mm day^{-1} difference between sites. The larger value at the cutover site is attributable to the smaller soil heat flux there. This was confirmed indirectly by the presence of ground frost, which persisted until early July in the previously drained site, and by the colder soil temperatures there. Lower soil temperatures in drained soils have been described elsewhere (e.g. Swanson and Rothwell, 1989).

Recognizing the limitations of the water balance approach (i.e. runoff was calculated as a residual in Equation (2)), there may be significant error in the runoff terms. However, since the values are so small, the magnitude of the errors is probably unimportant. The seasonal runoff calculated from the water balance is less than half of the potential error in evapotranspiration. The comparable runoff values on the natural and cutover bog imply that blocking the ditches at the latter site significantly restored the mesoscale hydrology. However, irreparable damage may have been caused during installation of the main ditches that border the site, because tailings contained fragmented iron pan. The breach of this placic horizon, which is considered impermeable (Damman, 1965), permits leakage into the permeable deltaic sands underlying the bogs. The large hydraulic gradient registered in piezometers above and below the iron
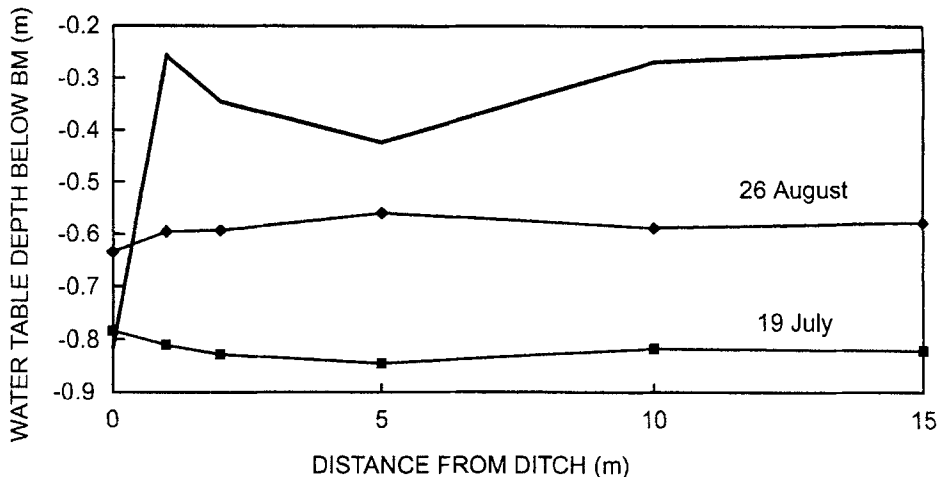

Figure 3. Relative elevation of the surface and water table along a transect perpendicular to the (blocked) ditch, to the mid-point between the adjacent ditch. Note the characteristics surface profile
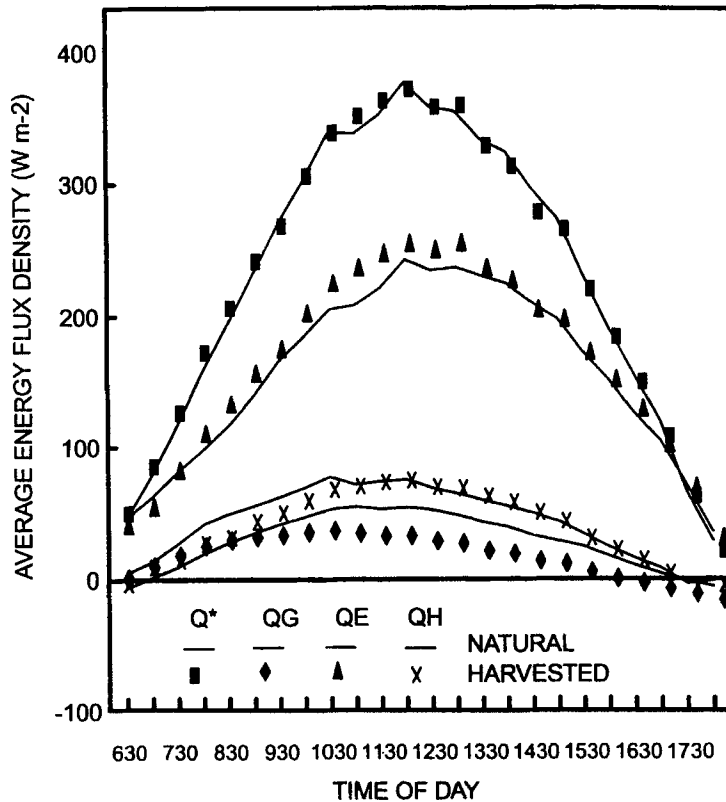
Figure 4. Daytime surface energy balance at both sites. Data represent the seasonal average values. Fluxes shown are net radiation (Q^*), latent heat (Q_E), sensible heat (Q_H) and the ground heat flux (Q_G). Standard error ($\sigma/\sqrt{N}$) at noon for these variables at the cutover (natural) site were 20·0 (20·0), 13·7 (13·2), 5·8 (6·7) and 2·4 (3·2) W m^{-2}, respectively

pan (−0·48 and −0·14 in the natural and cutover bog, respectively), confirm its importance in this area. The lower head difference in the cutover bog may indicate that the regional water table is being recharged by leakage from the main ditches (not blocked) where the iron pan is no longer present. There are no data to confirm this.

While the water balance fluxes are similar at both sites, the nature of water storage is very different. At the natural site, living, dead and poorly decomposed *Sphagnum* imparts a very high specific yield (Sy) to the soil matrix (Figure 1), which controls the water storage characteristics of the site. The high specific yield of the upper layer in the natural bog minimizes water table fluctuations in response to the withdrawal or addition of water. Consequently, the water table remained near the surface, even during dry periods. At the cutover site, the (high Sy) surface layer has been mechanically removed, and drainage has increased the oxidation and compression of the soil (Schothorst, 1977). The specific yield of the remaining soil

Table II. The water balance for the period 14 July to 21 September (74 days) at the natural and cutover site. Precipitation (P), evaporation (E) and change in storage (ΔS) were measured. Runoff (RO) was calculated as a residual

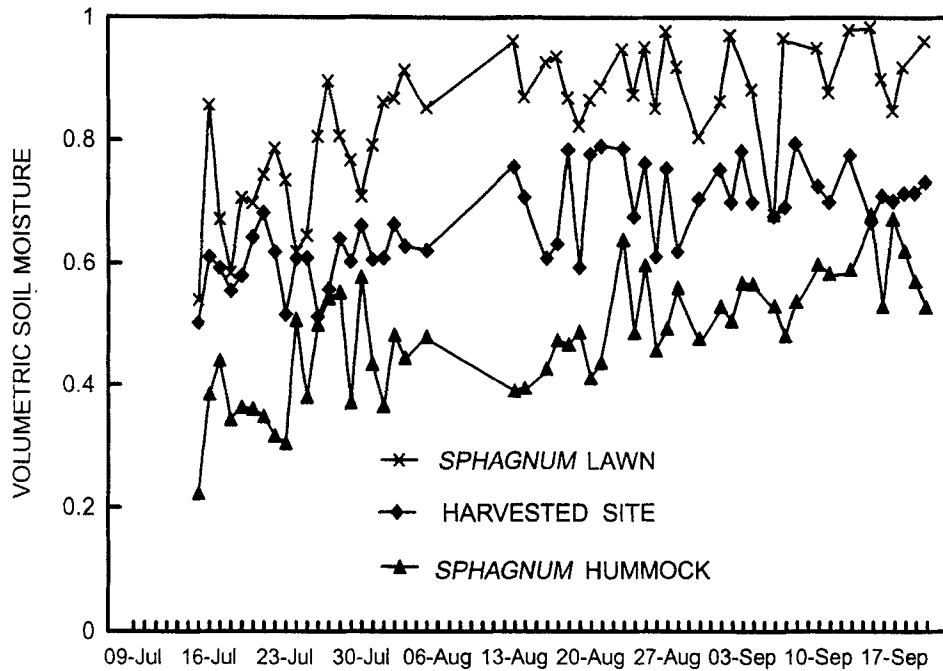|	P (mm)	E (mm)	ΔS (mm)	RO (mm)
Natural	250	200	40	10
Harvested	250	215	19	16

Figure 5. Volumetric soil moisture in the upper 50 mm of peat. Data for the balk were not plotted, but the average values are given in Table I

shows little vertical variation, and averages 0·048. With comparable water fluxes at both sites, water table fluctuations at the cutover site are calculated to be approximately one order of magnitude greater (i.e. 0·55/ 0·048 = 11·5 ×). Therefore, the seasonal water deficit produced a greater water table drawdown at the cut-over site.
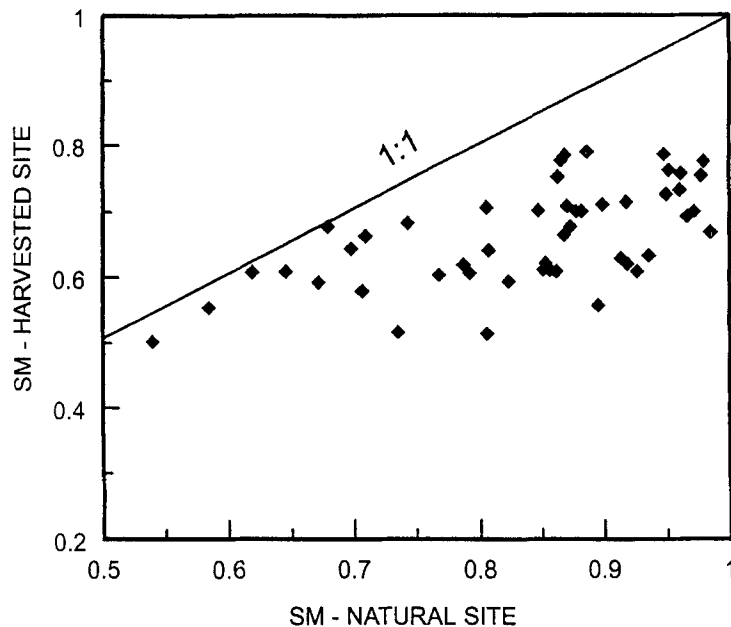

Figure 6. Daily average soil moisture at the harvested site plotted against that measured in the *Sphagnum* lawn. Note the limited range of the harvested site data caused by changes to the soil matrix

The water table profile in the cutover site (Figure 3) indicates lateral drainage of the peat occurred during wet periods. During dry periods, the trend was reversed, and water seeped into the peak from the ditch. Since the specific yield of the water in the open ditch is unity, its water level drop from a unit loss of water is much less than occurred in the peat ($Sy = 0.048$). This sets up a hydraulic gradient that recharges water from the ditch to the peat. The net effect on the average water table position needs further attention. A study is underway to test this.

A lower water table beneath bare peat surfaces has been shown to be detrimental to the survival and growth of *Sphagnum* diaspores (Campeau and Rochefort, 1996). Schouwenaars (1988) suggests that during the growing period, the water table should not drop below 0.4 m. Indeed, this was the case for the *Sphagnum* lawn and hummock, where the water table was above the 0.4 m level for 100% and 82% of the time, respectively (Table I). In the cutover site the water table was above the 0.4 m level only 40% of the time in the cutover area, and 0% of the time in the balk. Nevertheless, average soil moisture in both balk and cutover peat was greater than in *Sphagnum* hummocks (Figure 5). Therefore, the soil water relationships in the unsaturated zone may be more relevant to the viability of *Sphagnum* than is explicable simply by the position of the water table. The higher dry bulk density of the drained peat (Table I) and the smaller average pore diameter (Okruszko, 1995), result in greater matric potential generated within the small pores of the cutover peat, causing water to be retained upon drainage. The higher bulk density of the cutover peat also limits the upper range of volumetric moisture, because more space is occupied by soil material.

Figure 6 demonstrates that cutover peat has a lower moisture content in the saturated state. The higher dry bulk density of the drained peat and the smaller average pore size diameter (Okruszko, 1995) result in greater matric potential and hence greater water retention after drainage. These same properties, however, make most of the soil water unavailable to *Sphagnum* diaspores, which have a weak capillary connection to the surface. *Sphagnum*, a non-vascular plant, must draw its water by the capillarity it generates within its cellular structure (Clymo and Hayward, 1982). Since the capillarity of live *Sphagnum* is very low (e.g. Boelter, 1968), it cannot extract water from well-decomposed peat unless the peat is near saturation. More work needs to be done to identify the soil water relationships associated with *Sphagnum*.

CONCLUSIONS

The results of this study indicate that changes of the *water balance* that occurred following drainage of the peat, were largely reversible, simply by blocking the drainage ditches. Evaporation and runoff from the natural and cutover sites were similar. However, microscale changes to the soil structure produced irreversible changes to the manner in which water storage occurred. The moss cover in the natural site is well adapted to sustaining a high water table. Even so, it experienced a relatively large soil moisture variation, but since matric suction remained low under these conditions, water was still available for plant use. In contrast, the water table in the cutover peat dropped well below the surface (even though the ditches are blocked) because of the irreversible change to a lower specific yield. Strong capillary flow of water from the water table to the surface must occur, as indicated by the sustained evaporation from the bare peat surface. Judging from poor *Sphagnum* recolonization (Campeau and Rochefort, 1996), moisture is unavailable to *Sphagnum* diaspores. The weak capillary uptake capability of *Sphagnum* (Romanov, 1968) denies it access to moisture from the cutover peat in all but the wettest conditions. Thus *Sphagnum* is unable to tap water during periods of strong evaporative demand.

The water blocked in ditches supplied moisture to the peat during dry periods. The additional (unconnected) ditches may be a useful strategy to employ for bog restoration.

While this study has quantified some of the mesoscale hydrological variables associated with peatland restoration, much remains unknown about the soil–water–plant relationships of *Sphagnum*. Further study must be done both to characterize the capillary flows and soil water storage in the unsaturated zone of cutover peat, and the capillary processes that control water supply and retention in *Sphagnum* and *Sphagnum* diaspores.

REFERENCES

Angus, D. E. and Watts, P. J. 1984. 'Evapotranspiration — How good is the Bowen ratio system' *Agric Water Manage.*, **8**, 133–150.
Boelter, D. H. 1968. 'Important physical properties of peat materials', *Proc. 3rd Int. Peat Congr.*, Quebec City, 1967, pp. 150–156.
Boelter, D. H. 1972. 'Water table drawdown around and open ditch in organic soils', *J. Hydrol.*, **15**, 329–340.
Bragg, O. M. 1995. 'Towards an ecohydrological basis for mire restoration', in Wheeler, D, Shaw, S. C., Fojt, W. J., and Robertson, R. A. (Eds), *Restoration of Temperate Wetlands*. John Wiley and Sons, Chichester. pp. 305–314.
Burke, W. 1972. 'Aspects of the hydrology of blanket bog', in *Hydrology of Marsh Ridden Areas, Proc. Minsk. Symp., UNESCOIAHS*, pp. 171–182.
Campeau, S. and Rochefort, L. 1996. '*Sphagnum* regeneration on bare peat surfaces: field and greenhouse results', *J. Appl. Ecol.*, **33**, 599–608.
Clymo, R. S. and Hayward, P. M. 1982. 'The ecology of *Sphagnum*', in *Bryophyte Ecology*, Smith, A. J. E. (Ed.). Chapman and Hall, London. pp. 229–289.
Damman, A. W. H. 1965. 'Thin iron pans: their occurrence and the conditions leading to their development'. *Information Report N-X-2*, Department of Forestry, Newfoundland Region, St. John's, 14 pp.
Environment Canada, 1982. *Canadian Climatic Normals 1951–1980: Temperature and Precipitation, Quebec*. Atmospheric Environment Service, Downsview. 216 pp.
Environment Canada, 1992. *Historical Streamflow Summary, Quebec*. Water Survey of Canada, Ottawa. 526 pp.
Famous, N. C., Spencer, M., and Nilsson, H. 1991. 'Revegetation patterns in harvested peatlands in central and eastern North America', in Grubich, D. N. and Malterer, T. J. (Eds), *Peat and Peatlands: The Resource and Its Utilization. Proc. 1991 Int. Peat Symp.*, Duluth, Minnesota, pp. 48–66.
Fuchs, M. and Tanner, C. B. 1970. 'Error analysis of Bowen ratios measured by differential psychrometry'. *Agr. Meteorol.*, **7**, 329–334.
Gray, D. M. 1970. *Handbook on the Principles in Hydrology*. Water Information Center, Inc., New York.
Heathwaite, A. L. 1994. 'Hydrological management of a cutover peatland', *Hydrol. Process.*, **8**, 245–262.
Keys, D. 1992. 'Canadian peat harvesting and the environment', *Sustaining Wetlands Issues Paper No, 1992–3*, North American Wetlands Conservation Council (Canada), Ottawa. 29 pp.
Latimer, J. M. 1972. *Radiation Measurement* International Field Year for the Great Lakes, Technical Manual Series No. 2, CNC-IHD, National Research Council of Canada, 53 p.
Lavoie, C. and Rochefort, L. 1996. 'The natural revegetation of a harvested peatland in southern Québec: a spatial and dendro-chronological analysis', *Ecoscience*, **3**, 101–111.
Morin, G. 1981. *Atlas Régional du Saguenay-Lac-Saint-Jean*. Les Laboratoires de Géographie de L'université du Québec, Chicoutimi.
Mulqueen, J. 1986. 'Hydrology and drainage of peatland', *Environ Geol. Water Sci.*, **9**, 15–22.
NWWG (National Wetland Working Group), 1986. *Canada's Wetlands*, Map folio. Energy Mines and Resources and Environment Canada. Ottawa.
NWWG (National Wetland Working Group), 1987. *The Canadian Wetland Classification System*, Ecological Land Classification Series, Inland Waters/Land Directorate. Environment Canada, Ottawa. 18 pp.
O'Kane, J. P. 1992. 'The hydrology of milled pet production', in O'Kane, J. P. (Ed.), *Advances in Theoretical Hydrology*. Elsevier, Amsterdam. pp. 27–46.
Okruszko, H. 1995. 'Influence of hydrological differentiation of fens on their transformation after dehydration and on possibilities for restoration', in Wheeler, D., Shaw, S. C., Fojt, W. J., and Robertson, R. A. (Eds), *Restoration of Temperate Wetlands*. John Wiley & Sons, Chichester. pp. 113–120.
Price, J. S. 1991. 'Evaporation from a blanket bog in a foggy coastal environment', *Boundary-Layer Meteorol.*, **57**, 391–406.
Quinty, F. and Rochefort, L. 1997. 'Plant re-introduction on a harvested peat bog', in Trettin *et al.* (Eds), *Ecology and Management: Forested Wetlands*. Lewis Publishers, New York, 137–150.
Romanov, V. V. 1968. *Hydrophysics of Bogs*. Israel Program for Scientific Translations, Jerusalem. 299 pp.
Rowell, T. A. 1989. 'Practical aspects of the restoration of damaged mires', in Fojt, W. and Meade, R. (Eds), *Cut-over Lowland Raised Mires*. Research & Survey in Nature Conservation No. 24, Nature Conservancy Council, Peterborough. pp. 112–123.
Schothorst, C. J. 1977. 'Subsidence of low moor peat soil in the western Netherlands', *Geoderma*, **17**, 265–291.
Schouwenaars, J. M. 1988. 'Hydrological research in disturbed bogs and its role in decisions on water management in the Netherlands', *Proc. Int. Symp. on the Hydrology of Wetlands in Temperate and Cold Regions*, Joensuu, Finland, 6–8 June 1988, pp. 170–177.
Schouwenaars, J. M. 1993. 'Hydrological differences between bogs and bog-relicts and consequences for bog restoration', *Hydrobiologia*, **265**, 217–244.
Swanson, L. E. and Rothwell, R. L. 1989. 'Substrate freeze-thaw in a drained Alberta fen', *Can. J. For. Res.*, **19**, 353–373.