Soil water storage dynamics in peatlands with shallow water tables

David R. Lapen[1], Jonathan S. Price[2], and Robert Gilbert[3]

[1]*University of Guelph, Kemptville College, Kemptville, Ontario, Canada K0G 1J0;* [2]*Department of Geography, University of Waterloo, Waterloo, Ontario, Canada N2I 3G1;* [3]*Department of Geography, Queen's University, Kingston, Ontario, Canada K7L 3N6.* *Received 18 February 1999, accepted 9 September 1999.*

Lapen, D. R., Price, J. S. and Gilbert, R. 2000. **Soil water storage dynamics in peatlands with shallow water tables.** Can. J. Soil Sci. **80**: 43–52. **Time domain reflectometry** (**TDR**) was used to estimate soil water storage dynamics in several uncultivated blanket bogs and poor fens in southeastern Newfoundland during the summer growing season. The purpose of the research was to evaluate links between surface moisture conditions, evapotranspiration, and recharge processes in order to elucidate factors that govern blanket peat formation in the region. Water storage changes in the peat/*Sphagnum* above the water table (ΔSWS) were found to be important storage terms in daily water balance estimates. Daily mean ΔSWS values for bog and fen approximated –0.3 and –0.45 mm, respectively. It was also found that, i) fairly high peat water-holding capacities, ii) frequent atmospheric recharge, iii) atmospheric controls on evapotranspiration, and, iv) the transport of water into the unsaturated zone from the shallow water table via capillary and external wicking processes helped to preclude significant de-watering over the bulk of the peatland surfaces. Recharge via groundwater appears to be an important factor governing moisture conditions requisite for peat accrual and the growth of *Sphagnum* spp., especially in the fens.

Key words: Time domain reflectometry, blanket peats, soil water, evapotranspiration, water table depth

Lappen, D. R., Price, J. S. et Gilbert, R. 2000. **Dynamique du stockage de l'eau du sol dans des tourbières à nappe phréatique superficielle**. Can. J. Soil Sci. **80**: 43–52. Nous avons eu recours à la réflectométrie dans le temps (RDT) pour estimer la dynamique du stockage de l'eau du sol durant la saison de végétation dans plusieurs tourbières hautes en couverture et dans des tourbières basses pauvres (non cultivées) du sud-est de Terre-Neuve. Notre but était d'évaluer les rapports éventuels existant entre l'état hydrique en surface, l'évapotranspiration et les mécanismes de reconstitution de la nappe, et ce faisant, d'élucider les facteurs gouvernant la formation des tourbières en couverture dans la région. Les changements affectant le stockage de l'eau dans les tourbières à sphaigne au-dessus de la nappe (ΔSWS) se révélaient être des facteurs importants dans les calculs journaliers du bilan hydrique. Les valeurs ΔSWS moyennes quotidiennes pour les tourbières hautes et les tourbières basses se situaient respectivement, aux abords de –0,3 et –0,45 mm. Nous avons constaté aussi que i) des capacités assez fortes de rétention de l'eau de la tourbe, ii) des épisodes fréquents de réalimentation en eau par voie atmosphérique, iii) les contraintes atmosphériques à l'évapotranspiration et iv) l'adduction de l'eau dans la zone insaturée à partir de la nappe superficielle par capillarité et par des mécanismes de méchage contribuaient à empêcher toute déshydratation importante sur l'ensemble des surfaces en tourbières. La réalimentation hydrique via l'eau du sol semble être un facteur important pour obtenir les conditions hydriques nécessaires au croît des tourbières et à la croissance des sphaignes, en particulier dans les tourbières basses.

Mots clés: Réflectométrie dans le temps, tourbière en couverture, eau du sol, évapotranspiration, profondeur de la nappe

On the southeastern tip of Newfoundland, *Sphagnum* spp. surfaced peat deposits cover extensive expanses of sloping terrain (Wells and Pollett 1983). These peatlands are aptly referred to as blanket bogs or blanket peats (Tansley 1949; Wells 1981). The sequence of processes responsible for peat accumulation on slopes is not entirely clear (Smith and Taylor 1989); however, what is clear is that the immediate cause of peat accumulation of any type is saturation or near-saturation at or very near the ground surface for prolonged periods of time (Ivanov 1978).

Wells (1981) indicated that blanket bogs in the region initially developed in small fens (wet peat-forming areas that receive nutrients from groundwater and precipitation) while Irwin (1994) suggested that initial blanket peat deposits occurred in small water-collecting depressions. Subsequent lateral expansion of these organic deposits may have occurred via paludification, whereby existing peat deposits help to create, in adjacent non-peat environments, moisture and pH conditions suitable for peat accumulation and the growth of bog forming vegetation (Davis 1985; Crum 1988). Taylor and Smith (1972) reported that blanket bogs can develop from the accrual of a "mor humus" layer. As the humus becomes more highly decomposed, its water-holding capacity increases to a point at which moisture conditions suitable for bog formation can be maintained. In a related way, Sjors (1976) noted that peat-forming plants can establish directly on wet, but not necessarily flooded mineral soils. Thus, climate, soil properties, relief, etc., of the locality may combine to form blanket bogs in very different ways.

The soil water dynamics of blanket bogs, and adjacent bio-landscapes that potentially represent pre-bog conditions, can provide valuable insights into blanket-bog-forming mechanisms. This study, which is part of a much larger study on blanket peat-water relationships in southeastern Newfoundland, characterized daily soil water storage dynamics in several uncultivated blanket peat formations and related these dynamics to primary recharge and discharge fluxes. The general purpose of this investigation was to elucidate the environmental mechanisms that govern local moisture conditions requisite for peat formation, paludification, and the growth and establishment of bog forming vegetation (*Sphagnum* spp.) in the region.

STUDY AREA

The study site is located at Cape Race, Newfoundland (Fig. 1). Average annual rain and snow precipitation at Cape Race is 1214 mm and 165 mm, respectively (Environment Canada 1982). Precipitation normals suggest precipitation occurs, on average, nearly half of the year (Environment Canada 1982). Occult precipitation – precipitation such as fog and mist, – that cannot be detected by standard rain gauges, is common in the area (Banfield 1983; Lapen et al. 1998). In fact, visibilities of less than 1 km due primarily to advection fog occur, on average, 155 d yr^{-1} at Cape Race (Banfield 1983). The cool summer temperatures at Cape Race largely reflect cooling by the cold Labrador current (Banfield 1983).

The peatlands examined in this study are shown in Fig. 1. The **upland bog** (**UB**) and **lowland bog** (subdivided into **LB1** and **LB2**) are domed ombrotrophic blanket peat formations (Lapen et al. 1996). Bog surfaces consist primarily of *Sphagnum fuscum*. Vascular vegetation such as *Scripus cespitosus*, *Myrica gale*, Ericaceae, and *Empetrum nigrum* are sparsely scattered over the surface. Minor hummock-hollow formations exist. Hummocks are, in general, <0.2 m higher than adjacent hollows within bog interiors. However, the local relief of some *S. fuscum* hummocks can be >0.2 m along bog/fen margins.

The bog peat is composed of highly to poorly decomposed Cyperaceae, *Sphagnum* spp., and Ericaceae plant material; decomposition increases with depth (Lapen et al. 1996). The bogs are generally <2 m deep and are underlain by Placic Humic and Placic Humo-Ferric Podzols (Lapen et al. 1996; Lapen and Wang 1998). On a regional basis, blanket bog water tables typically lie within 0.2 m of the surface throughout the year (Northlands Associates Ltd. 1989; Price 1992).

The **upland poor fen** (**UPF**) is composed of shallow, highly to poorly decomposed peat deposits (0.1 to 0.3 m thick) overlying Placic Humo-Ferric Podzols (Lapen et al. 1996; Lapen and Wang 1998). Unlike the interiors of the UB and LB, the UPF exhibits a greater variety of mosses, Cyperaceae, and Ericaceae vegetation. Minor hummock-hollow (relief generally <0.3 m) gradients exist with *S. fuscum*, *Sphagnum fimbriatum*, and *Sphagnum nemoreum* typically occupying hummocks and *Sphagnum papillosum*, common in poor fens in Newfoundland (Wells and Pollett 1983; Crum 1988), occupying hollows. *Iris versicolor* and *Smilacina trifolia* boldly delimit the UPF from adjacent heathlands (heathland vegetation is mainly Ericaceae, *Myrica gale*, Empetraceae, *Cladina* and *Cladonia* spp., and *Pleurozium schreberi*) and the UB. Water tables in the fen are generally within 0.2 m of the surface.

The major moss type in the **lowland poor fen** (**LPF**) is *Sphagnum tenellum*. Vascular vegetation, which is more variegated in the LPF than in bog, is dominated by *M. gale*, *S. cespitosus*, and *Carex oligosperma*. Relative to bog, evidence of *Aster novi-belgii*, *Lonicera villosa*, and *Sanguisorba canadensis* suggest more mineotrophic conditions. The surface soils are dominated by moderately to highly decomposed peat generally 0.05 to 0.2 m thick. *Carex* spp. tussocks and some organic veneered cobbles make-up a majority of the LPF microrelief (generally < 0.2-m in height). The peats overlie Ortstein Humic and Ortstein Ferro-Humic Podzols (Lapen and Wang 1998). Water tables typically occur within 0.2 m of the surface.

MATERIALS AND METHODS

Rain and Occult Precipitation

Field data were collected between June 24th and August 12th, 1993. **Rainfall** (**R**) was measured by a calibrated Campbell Scientific (Campbell Scientific, Edmonton, AB) Model TE525 tipping-bucket rain gauge. Wet deposition by **occult precipitation** (**OP**) was obtained by a sedimentation-turbulent diffusion model (Unsworth and Crossley 1987) for bog and heath (Lapen et al. 1998). Due to greater similarities in the morphology of heath and fen vegetation associations, relative to bog, it was assumed that OP deposition to the UPF and LPF was the same as that to the heath [See Lapen et al. (1998) for more discussion on OP measurements].

Evapotranspiration

Daily **evapotranspiration** (**ET**) from bog was estimated from a regression model of latent heat flux (Q_c) vs. [net radiation (Q^*)–ground heat flux (Q_g)]. Net radiation, Q_g (two sensors provided average flux values) and air temperature were measured on site, and the regression model was applicable for the bog water table elevations observed in this study (unpublished data). Net radiation and Q_g measurements were made every 10 s and averaged every 0.5 h. See Lapen et al. (1998) for specifics on ET instrumentation and measurement protocols.

Lysimeters [0.3 m (width) by 0.3 (length) by 0.12 m (thick)] filled with vegetated fen peat/*Sphagnum* spp. were used to measure ET from fens according to

$$ET = R + OP - \Delta LWS \tag{1}$$

where, ΔLWS = water storage change in the lysimeter.

The lysimeters, of the type described in Lapen et al. (1998) with overflow reservoirs, were placed flush with fen surfaces and weighed each day with a calibrated scale. Lysimeter bottoms were impermeable to vertical flow. Whenever possible, lysimeter water levels were adjusted so that they were consistent with those in the surrounding soil. Regressions between bog (Q^*–Q_g) and fen lysimeter ET were used to estimate fen ET for periods when lysimeter measurements were problematic (e.g., the largest rain event observed during the study period).

Water Storage Changes above the Water Table

Daily changes in the volumetric water content (θ_v) of peat/*Sphagnum* spp. above the water table in all bio-land-

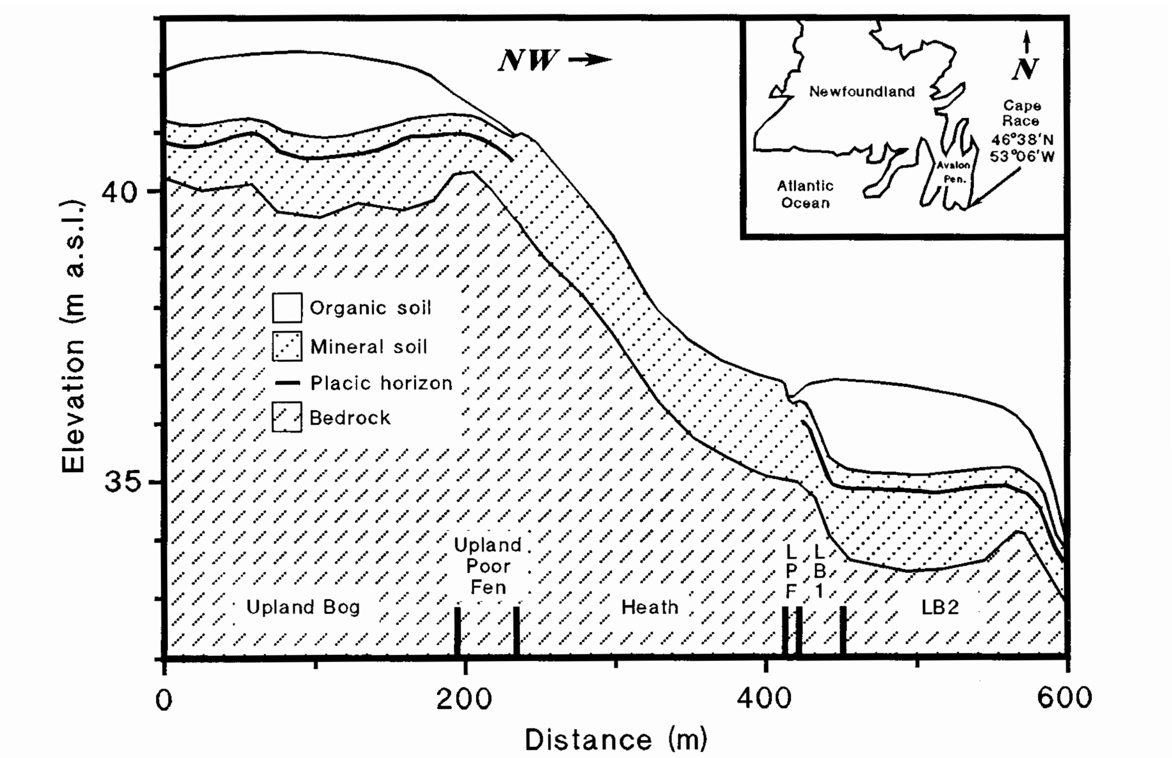

Fig. 1. Study site at Cape Race, Newfoundland, Canada. LPF = lowland poor fen, LB1 = lowland bog 1, and LB2 = lowland bog 2.

scapes were determined by TDR and associated calibration techniques. Apparent dielectric constants (K_a) of the peats/*Sphagnum* spp. were estimated with a Tektronix 1502B cable tester (Tektronix, Beaverton, OR, USA) and two-pronged 0.30-m, 0.15-m, and 0.10-m stainless steel soil probes (baluns were employed). The probes were 5 or 3 mm in diameter and probe spacings varied between 0.05 and 0.02 m K_a was estimated from wave forms according to the methods described in Topp (1993).

Bulk K_a was measured for the entire peat/*Sphagnum* spp. profile above the water table using variable length probes inserted at an angle, and at 0.00 to 0.05 m (0.10-m-long probes were inserted at an angle), 0.00 to 0.10 m (0.10-m probes were inserted perpendicular to soil surface), 0.00 to 0.15-m (0.15-m probes were inserted perpendicular to soil surface), 0.00 to 0.20 m (0.30-m-long probes were inserted at an angle) depth intervals when possible. Groundwater wells made of PVC pipe and small pits near to the measurement sites served to delineate the surface of the water table.

For each bio-landscape, up to 10 spatially distributed (made within approximately 10-m distance of each other) K_a estimates for each depth interval were made and averaged. The TDR measurements made in the UB, UPF, LPF, LB1 and LB2 centered around the 130-m, 217-m, 419-m, 441-m, and 480-m mark along the hillslope transect shown in Fig. 1. When there were daily decreases in water table elevation, bulk K_a was estimated for peat/*Sphagnum* spp. above the water table at time 1 (t_1) and for the same peat/*Sphagnum* spp. depth interval approximately 24 h later (t_2).

For periods when there were daily increases in water table elevation (i.e., during and after precipitation events), bulk estimates of changes in K_a above the depth of water table fluctuation were more difficult to attain because portions of the peat/*Sphagnum* spp. profile above the water table at t_1 were below the water table at t_2. Thus, bulk estimates of daily changes in K_a for peats/*Sphagnum* spp. above the water table at a particular measurement site were approximated via TDR measurements for depth intervals (given above) that were immediately above the water table fluctuation zone.

TDR Calibration

The K_a measurements were translated to volumetric water contents (θ_v) from calibrations between θ_v and K_a. For the bogs, peat/*Sphagnum* spp. samples having dimensions of approximately 0.20 m (width) by 0.20 m (length) by 0.11 m (thickness) were carefully cut from the UB at around the 120-m mark along the hillslope transect (Fig. 1). Three samples were respectively acquired for depths of 0.0 to 0.11 m and 0.11 to 0.22 m. The 0.11-m depth corresponded, very approximately, to a natural break between live *Sphagnum* spp./poorly decomposed peats (<0.11-m depth) and more highly decomposed peats (>0.11-m depth) representing the lower portion of the water table fluctuation zone. Three 0.20-m (width) by 0.20-m (length) by ≈0.15-m (thickness) peat/*Sphagnum* spp. samples were cut from each fen for TDR calibration.

After the peat/*Sphagnum* spp. samples were acquired, they were immediately wrapped in plastic wrap and frozen.

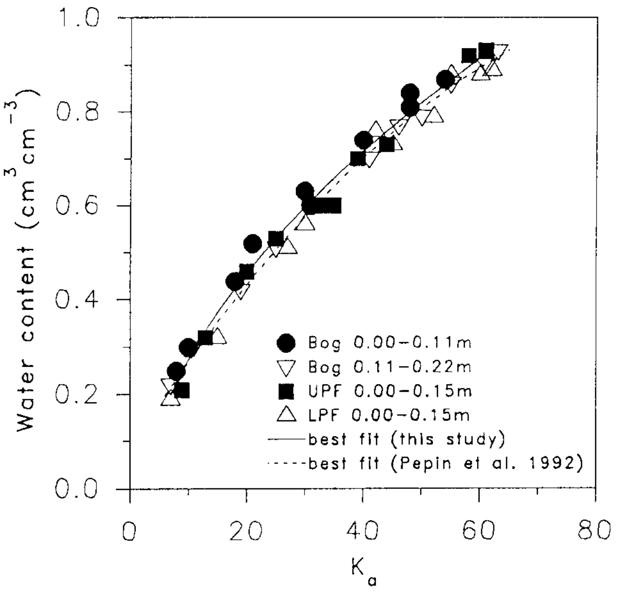

Fig. 2. TDR calibration relationships for peat materials examined in this study.

While frozen, the samples were trimmed with a saw to eliminate marginal perturbations (e.g., roots etc.). Samples were then thawed and their volumes estimated via water volume displacement. This displacement procedure involved tightly sealing the samples in pliable plastic bags and displacing water in a calibrated container. The samples were then saturated, weighed, and allowed to naturally drain until rapid gravity drainage had ceased. Samples were then wrapped in plastic wrap and rotated on a daily basis to augment as much moisture uniformity as possible. Immediately prior to TDR measurements, sample volumes and weights were estimated by the methods described above. The TDR measurements were then acquired by inserting 0.10-m-long probes into the tops of the samples; only two TDR measurements were made in each sample to minimize sample disturbance. The estimated K_a values were then averaged. Subsequent TDR measurements were made after the samples were allowed to air dry at room temperature and subsequently sealed in plastic wrap for moisture uniformity purposes. The length of the drying period was on the order of days/weeks. The TDR estimates were performed on the duplicate samples in manners similar to those described above.

After the last TDR estimate for each sample, the samples were oven-dried (100°C) and their volumes and weights were determined. Water contents of the samples during the TDR estimates were then determined to acquire the θ_v vs. K_a relationships for the various materials.

Physical Analysis of Peat

Bulk density (**BD**), **drainable porosity over a 24-h period** (**DP$_{(24h)}$**), and degree of humification (von Post tests) were estimated on peat/*Sphagnum* spp. samples from each bio-landscape type. Bulk density (0.12-m length by 0.10-m diameter cores) and von Post measurements were made according to the methods described in Parent and Caron (1993). The DP$_{(24\ h)}$ data were estimated from peat/*Sphagnum* spp. cores (0.12 m length by 0.10 m diameter) via

$$DP_{(24\ h)} = V_w/V_s \qquad (2)$$

where, V_w = volume of water drained from saturated sample of known volume (V_s) over 24 h.

Table 1. Ranges of bog and fen peat/*Sphagnum* spp. physical properties taken at TDR measurement locations. There were ten observations per property measured

Bio-landscape	Depth (m)	BD (g cm^{-3})	von Post	DP$_{(24\ h)}$ (cm^3 cm^{-3})
Bog	0.00–0.11	0.02–0.06	1–3	0.17–0.51
Bog	0.11–0.22	0.06–0.12	2–5	0.11–0.30
UPF	0.00–0.15	0.03–0.25	2–7	0.06–0.42
LPF	0.00–0.15	0.02–0.29	4–8	0.05–0.18

UPF = upland poor fen, LPF = lowland poor fen, BD = bulk density, DP$_{(24\ h)}$ = drainable porosity over a 24-h period, von Post = von Post decomposition scale (1 = unaltered plant residues to 10 = nonrecognizable plant residues) (Parent and Caron 1993).

RESULTS AND DISCUSSION

TDR Calibration

The K_a vs. θ_v relationships for the peat sample materials described above, were plotted and fit with a model of the form described by Ledieu et al. (1986) (Fig. 2). Given the similarities in the calibration results between the different bog and fen peat/*Sphagnum* spp. materials (Fig. 2 and Table 1), one model was fit, by eye, to the pooled data:

$$\theta_v = a\sqrt{K_a} - b \qquad (3)$$

where, a = 0.14, b = 0.17.

Differences in duplicate K_a readings for individual samples were less than 3. Such differences were not surprising considering natural variability in porosity, root structures, air gaps, etc. The calibration curve developed for this study is very similar to that developed by Pepin et al. (1992) for peat derived from a forested bog in Quebec. Pepin et al. (1992) used a polynomial best-fit model of the form;

$$\theta_v = 0.85 \times 10^{-1} + 1.92 \times 10^{-2} K_a - 0.95 \times 10^{-4} K_a^2 \qquad (4)$$

R, OP, ET, D and h Observations

Daily water balances were developed for all peat bio-landscapes; the water balance model has the form:

$$\Delta SWS = R + OP - ET - D \qquad (5)$$

where D = drainage.

In this study, D was determined as a residual in the water balance equation. Thus, D represented net daily fluxes. Moreover, ΔSWS equaled zero if the entire unsaturated zone became saturated by a rising water table (i.e., total water storage changes at the site were due directly to *groundwater*).

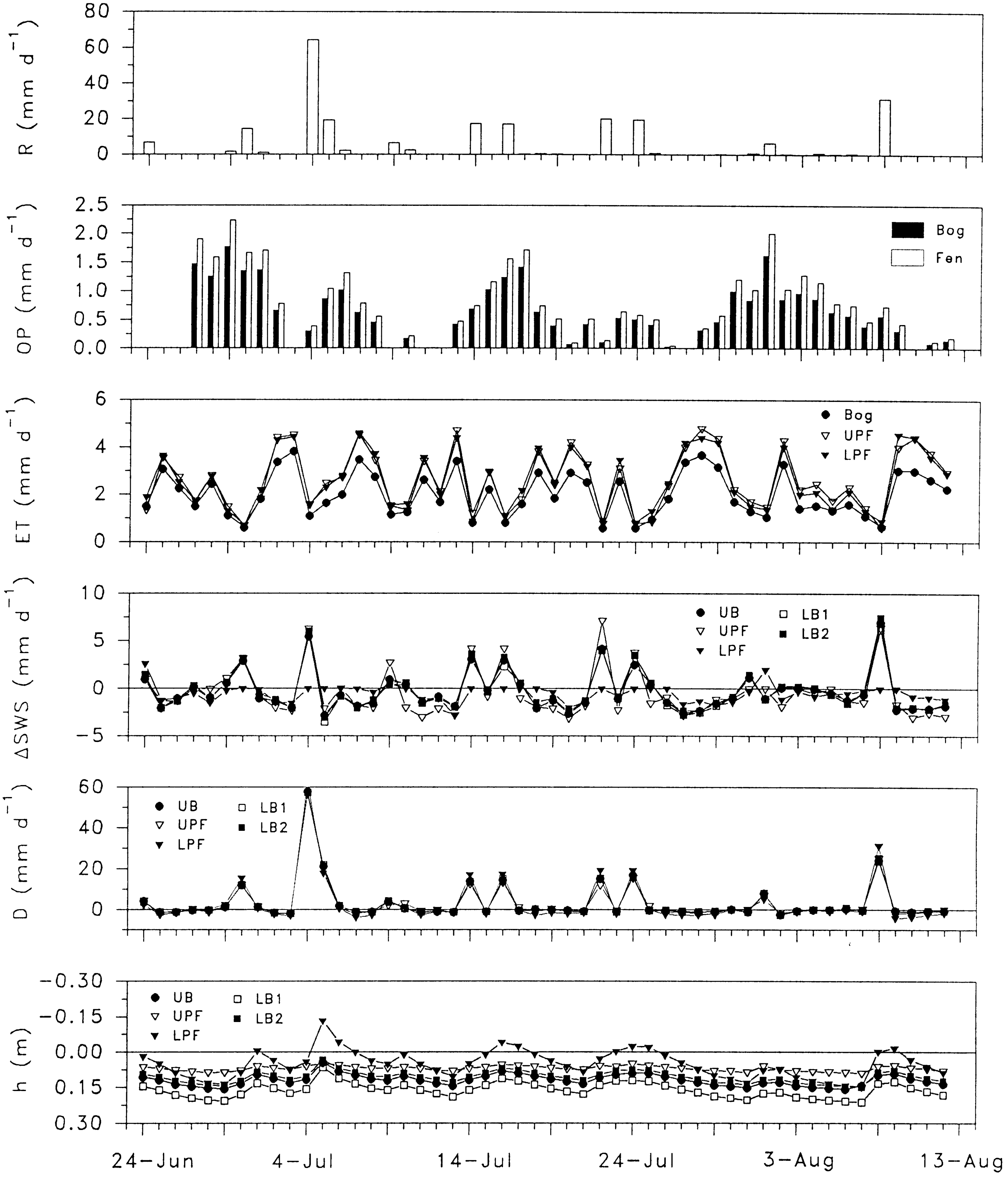

Fig. 3. Daily estimates of R (rain), OP (occult precipitation), ET (evapotranspiration), ΔSWS (changes in soil water storage), D (drainage), and average daily water table depth (h) during the study period. Water table depths were recorded at locations given in Table 2.

Daily and study period R, OP, ET, ΔSWS, D, and daily average water table depth (h) are given in Fig. 3 and Table 2, respectively. Total R during the study period was approximately 235 mm, or approximately 5 mm d^{-1}. The storm with the greatest intensity occurred on 4 and 5 July, when 83 mm of rain fell in 19 h. Occult precipitation during the study period, as estimated via the turbulent transfer-sedimentation model (Lapen et al. 1998), was approximately 29 and 36 mm for bog and fen, respectively; these values translate to approximately 0.6 mm d^{-1} of OP deposition to bog and 0.7 mm d^{-1} of OP deposition to fen.

Figure 3 shows surprisingly strong temporal coherence between bog and fen ET. Evapotranspiration from bog, UPF, and LPF amounted to 2.0, 2.6, and 2.6 mm d^{-1}, respectively. Study period D values ranged between 177.1 to 171.4 mm for the bogs and 164.7 to 161.4 mm for fens. Thus, there was net recharge to the water table over the study period.

There are strong temporal trends between the average daily h data. Average daily h was typically less than 0.2 m depth in all bio-landscapes; however, the LPF was the only bio-landscape in which average daily h was above the ground surface.

Bog ΔSWS and θ_v Observations

Positive ΔSWS values, for all bio-landscapes, most strongly reflect R inputs and capillary recharge from the shallow water table. Storage increases due exclusively to OP were not directly evident from field observations; however, they may not have been detectable by the TDR techniques employed or they may have been offset by preferential evaporation of OP droplets deposited at the surface.

Water loss above the zone of water table fluctuation was attributed to a combination of gravity drainage, ET, and plant uptake. Daily storage increases and decreases were typically <7 and >–3 mm d^{-1}, respectively. Positive (recharge) daily ΔSWS maxima were considerably greater than negative (water loss) daily ΔSWS maxima. The larger recharge peaks were considered due to the temporary filling of the larger peat/*Sphagnum* spp. pores and capillary/wicking inputs (Ingram 1983; Lafleur 1990) from the water table during and immediately following recharge by rain. The largest recharge peaks were associated with high water table elevations.

Study period ΔSWS totals (Table 2) indicate that water loss in the peat/*Sphagnum* spp. above the water table was modest; indeed it is likely that the negative ΔSWS terms most strongly reflect the timing of precipitation events. Nevertheless, ΔSWS appears significant with regard to explaining *daily* water storage dynamics in the bogs; hence, daily blanket bog water balances. For instance, during 24-h periods with no rain, a fairly strong linear relationship existed between ET and ΔSWS (Fig. 4 and Table 3). In fact, during these periods, the D values indicate that there was a net upward flow of water from the water table (Fig. 3). Positive daily D terms (net drainage was downward) were almost exclusively associated with days with rain precipitation. Although this particular study did not independently estimate unsaturated flow terms or plant uptake of water from the groundwater, and thus precisely determine how much ΔSWS was accounted for by individual source and sink terms, i) the consistent relationships in Fig. 4, ii) the predominantly negative D terms associated with them, and iii) the fact that a majority of the drainable pore water of live *Sphagnum* spp. and poorly decomposed peat will occur at very low suctions (Boelter (1964), underscores the potential for ΔSWS to strongly reflect ET losses.

Figure 5 shows that during the study period, dramatic drops in average daily θ_v did not occur in the top 0.0–0.05 m of the bog surface. During periods with minimal rain precipitation, such as between 24 July and 7 August, average θ_v at 0.0- to 0.05-m depth was essentially invariant. Coincidently, frequent OP that occurred during this period reduced Q^* inputs and vapor pressure gradients; and moreover, OP provided wet deposition to surface features. Regional controls on ET, i.e., factors that limit Q^* inputs and reduce vapor pressure gradients such as frequent dense advection fog (Lapen et al. 1998), may in fact be critical to the growth of *Sphagnum* spp. on sloping blanket peat formations in the Cape Race area. This contention is reinforced by the fact that when the effects of OP were minimal and ET high, such as on 3 and 27 July, and 10–12 August for example, daily ΔSWS values were around –2 mm. It is also noteworthy that the general lack of water content change between 24 July and 7 August may reflect to some degree the spatial domination of non-vascular *Sphagnum* spp. at the bog surface. The sparseness of vascular vegetation over these bogs, relative to many continental formations (Crum 1988), makes these bogs different from treed or shrub covered bogs where water uptake by plants from the unsaturated peats/*Sphagnum* spp. may comprise a greater proportion of total ET (Romanov 1968).

The potential importance of atmospheric constraints on ET to *Sphagnum* spp. growth, especially during periods of minimal precipitation, are supported by observations that most drainage of live *Sphagnum* spp. and poorly decomposed peat will occur at very low suctions (Boelter 1964). Moreover, due to large pore sizes, capillary inputs from the water table to live *Sphagnum* spp. at the very surface will be small. This indicates that droughty conditions and/or high potential ET could compromise the health of bog surface features.

The surface (top 0.1 m) moisture conditions in some large *Sphagnum* spp. hummocks along bog/fen margins displayed markedly lower θ_v values than average θ_v (0.0–0.05 m) values observed within the blanket bog interiors. For instance, spot measures of θ_v in large isolated *Sphagnum* spp. hummocks (>0.2 m above adjacent hollows) along bog/fen margins (193-m and 237-m mark along the hillslope transect) between 5 and 7 August, had θ_v values <0.2 $cm^3\ cm^{-3}$ at 0.0- to 0.05-m depth while θ_v in some bog hollows (0.0- to 0.05-m depth) were concurrently observed to be >0.8 $cm^3\ cm^{-3}$. Daily changes in hummock θ_v during this period did not vary. It is generally accepted that water will not rise more than 0.2 m by capillarity in undecomposed peat; considerably less in live *Sphagnum* spp. (Boelter 1964; Romanov 1968). The majority of the large *Sphagnum* spp. hummocks previously described were well above the water

Table 2. Summary statistics of R (rain), OP (occult precipitation), ET (evapotranspiration), ΔSWS (change in soil water storage), D (drainage), and daily average h (water table elevations) for each bio-landscape during the study period. Meter marks for h data refer to locations along the hillslope transect (Fig. 1) at which the water levels were recorded

Variable and bio-landscape		Total (mm)	Mean (mm d^{-1})	Min. (mm d^{-1})	Max. (mm d^{-1})	St. dev. (mm d^{-1})
R		234.6	4.7	0.0	64.2	11.0
OP						
	Bog	29.2	0.6	0.0	1.8	0.5
	Fen	36.0	0.7	0.0	2.2	0.6
ET						
	Bog	100.9	2.0	0.6	3.8	0.9
	UPF	130.5	2.6	0.6	4.8	1.2
	LPF	130.3	2.6	0.7	4.6	1.2
ΔSWS						
	UB	–13.5	–0.3	–2.8	7.0	2.1
	UPF	–21.6	–0.4	–3.2	7.2	2.6
	LPF	–24.7	–0.5	–2.8	2.6	0.9
	LB1	–14.2	–0.2	–3.0	7.5	2.2
	LB2	–8.5	–0.3	–3.5	6.2	2.1
D						
	UB	176.4	3.5	–2.3	57.9	10.0
	UPF	161.4	3.2	–2.5	56.7	9.8
	LPF	164.7	3.3	–4.1	62.9	11.4
	LB1	177.1	3.5	–2.4	57.4	9.9
	LB2	171.5	3.4	–2.5	57.4	9.9
			(m depth)	(m depth)	(m depth)	(m depth)
h						
	UB (130-m mark)		0.12	0.04	0.16	0.02
	UPF (217-m mark)		0.07	0.05	0.09	0.01
	LPF (419-m mark)		0.06	–0.13	0.18	0.07
	LB1 (441-m mark)		0.16	0.07	0.21	0.03
	LB2 (480-m mark)		0.11	0.03	0.15	0.02

UB = upland bog, UPF = upland poor fen, LPF = lowland poor fen, LB1 = lowland bog 1, LB2 = lowland bog 2.

table fluctuation zone and probably had water retention characteristics similar to those of live *Sphagnum* spp. (Boelter 1964). Due to the inefficient water transport and retention mechanisms of live *Sphagnum* spp. and poorly decomposed peat, and that many marginal hummock formations were observed to be isolated from the influence of the water table, some of these *Sphagnum* spp. hummocks exhibited signs of water stress. Water stress was evidenced by significant desiccation and the whitening of the moss surface (Bavina 1967; Ingram 1983). It should be noted that the largest hummocks were generally isolated to bog/fen margins and were not representative of the majority of the bog surface; hence, daily TDR measurements were not performed on these formations. Bog hollows, which were closer to the water table, were more strongly protected by surrounding hummocks and were, in general, composed of more highly decomposed peats than the *Sphagnum* spp. hummocks. Greater decomposition can significantly increase moisture-holding capacities and capillarity in peat. Moreover, shallow rooting plants in hollows would more readily tap into saturated peats, thus reducing further localized water losses in the unsaturated peat/*Sphagnum* spp.

Fen ΔSWS and θ_v Observations

Daily ΔSWS fluctuations in the UPF were similar to those for the bogs (Fig. 3); however, study period ΔSWS totals indicate greater overall water loss from the UPF, relative to bog (Table 2). At first, this finding was somewhat surprising, considering that UPF water tables were very shallow. Although, as will be discussed later, greater UPF water loss may have been related to greater establishment of shallow-rooting vascular vegetation. It should be noted that most water storage increases in the LPF were accounted for by groundwater (saturating previously unsaturated peats/*Sphagnum* spp.), since the water table often rose above the ground surface during and after recharge by rain. Thus, total study period ΔSWS reflects, primarily, storage losses. Notwithstanding this bias, daily ΔSWS values for the LPF during non-rain conditions were, on average, less strongly negative than those for bog and UPF (Fig. 3). Like the bogs, recharge maxima in both fens were significantly greater than water loss maxima. This points to the role capillary/wicking from the groundwater may have played in recharging unsaturated peats/*Sphagnum* spp., especially immediately after rain recharge when water tables were high. As previously described, the more highly decomposed peats in the fens would tend to augment capillary recharge.

Relative to the bogs, the ΔSWS vs. ET plots for the fens are much more scattered (Fig. 4). Greater scatter could have resulted from inadequate sampling representation of fen ΔSWS and ET. Plant species and soil properties are much more varied in the fens, relative to bog (Lapen and Wang 1998). Nevertheless, regression *b* coefficients given in Table 3 could be interpreted to indicate that a greater major-

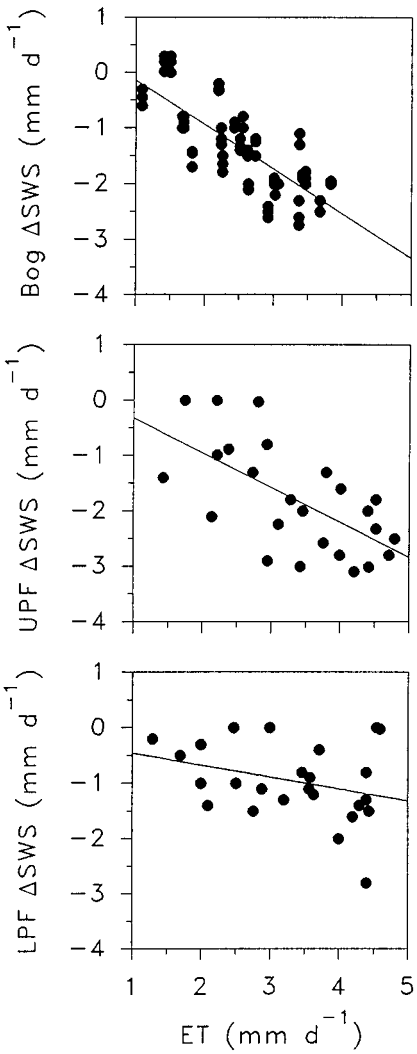

Fig. 4. ΔSWS vs. ET for non-rain periods during the study period. Best-fit lines correspond to regression estimates given in Table 3.

ity of water used for ET, relative to bog, came from groundwater sources. It is likely that during most non-rain days, the contribution of vertical drainage in the ΔSWS term was modest, or sufficiently offset by vertical inputs. This speculation is supported by observations of very small $DP_{(24\ h)}$ for some fen peat materials (Table 1) and that the drainage of live *Sphagnum* spp. would be greatest during and immediately following recharge by rain (Boelter 1964). This appears to be most evident in the LPF, which has a greater proportion of more highly decomposed sedge-dominated peats than bog and UPF. In addition, the LPF had, on average, shallower water tables. Hence, there may have been greater capillary/wicking recharge into surface peats/*Sphagnum* spp. Speculation of this sort is complimented by observations that LPF D values during days with no rain were, in general, more strongly negative than those for bog and UPF (Fig. 3).

Table 3. Coefficients and r^2 for linear regressions between ΔSWS and ET (ΔSWS=*a*+(b×ET)) during non-rain conditions

Bio-landscape	*a*	*b*	r^2
Bog	0.66	−0.80	0.61
UPF	0.30	−0.63	0.41
LPF	−0.25	−0.21	0.10

UPF = upland poor fen, LPF = lowland poor fen.

Average LPF and UPF daily θ_v (0.0–0.05-m) values (Fig. 5) were greater than those in the bog because i) the more highly decomposed fen surface peats/*Sphagnum* spp. tended to have greater moisture retention capacities than the *S. fuscum* dominated surface of the bogs (Table 1), ii) fen *Sphagnum* spp. formations may have been more protected from excessive drying by over story vegetation (Crum 1988) and leaf remains over the surface, and iii) there was greater recharge from groundwater sources in the fens. Changes in average daily θ_v (0.0–0.05-m) for the LPF were less extreme than those for bog and UPF (Fig. 5). These observations likely resulted from the greater water retention characteristics of the LPF peats as compared with the less highly decomposed surface peats in the UPF and bog (Table 1). Moreover, the surface peats in the LPF were often directly recharged via groundwater. Visual observations suggested that the LPF, as a whole, also had less coverage by vascular vegetation than the UPF. As a result, there was likely less root uptake of water from unsaturated surface peat layers. In fact, relative to bog and LPF, the greater rate of water loss in the UPF 0.0 to 0.05-m surface layers between 29 July and 7 August can be interpreted to support the latter contention.

The occurence of hydrophillic *S. papillosum* and *S. tenellum* in the fens suggests that surface moisture conditions remain fairly high over time periods greater than that of the study period (Wells and Pollett 1983; Crum 1988). Nevertheless, the tops of some *Sphagnum* spp. hummocks did show signs of water stress during the latter part of the study period (5–7 August). *S. nemoreum* and *S. fuscum* on the tops of hummock formations (hummocks >0.2 m above adjacent hollows and above maximum water table elevations) in the UPF were observed to be whitened and, in several cases, highly desiccated. Moisture contents in some of these formations were <0.2 $cm^3\ cm^{-3}$, presumably because they were hydrologically disconnected from water table fluctuations, had very high $DP_{(24\ h)}$ (> 0.7 $cm^3\ cm^{-3}$), and were generally more exposed to the elements. There were no observations of water stress in LPF *S. tenellum* formations, presumably because they were not hummocky (carpet type of formation) and were frequently recharged directly by groundwater.

RELEVANCE TO PEATLAND PROCESSES

Using spatially and temporally limited field observations, this study compared soil water storage dynamics in fen and blanket bog. Relationships between soil water storage changes and primary water fluxes were used to help relate wetland vegetation associations to the local hydrological environment. Moreover, this study demonstrated that the

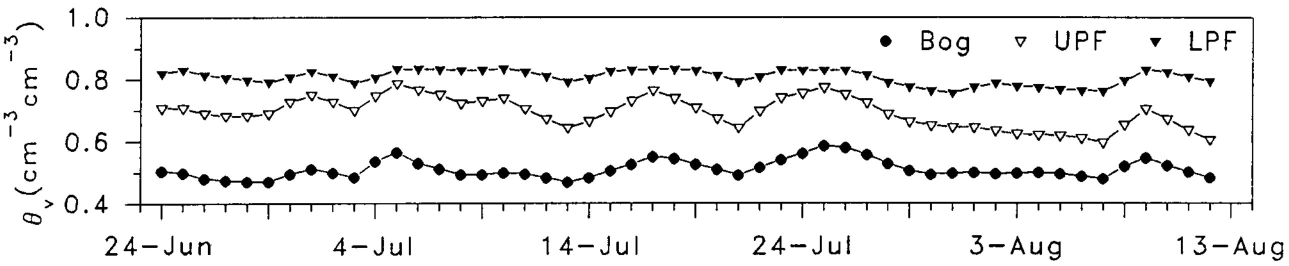

Fig. 5. Daily average θ_v for 0.0- to 0.05-m depths for bog, UPF, and LPF. Values for bog represent the average of all values derived from the UB, LB1 and LB2.

soil water storage term is an important and physically meaningful parameter in daily water budgets of peatlands with shallow water tables.

Although the field hydrological observations are limited, some very general speculations can be made regarding these observations and peatland processes and *Sphagnum* spp. growth in the region. First, the hydrophillic vegetation covering the vast majority of each bio-landscape appeared healthy. This observation suggests that over longer periods of time, the peatland surfaces (i.e., peats and live *Sphagnum* spp.) are, on average, not water limited with regard to the growth of bog forming vegetation (i.e., *Sphagnum* spp.). Several factors contribute to the health of these bio-landscapes: i) high water-holding capacities of the peat, especially in the fens, ii) atmospheric constraints on ET fluxes, iii) frequent recharge by rain and OP, and iv) storage recharge via groundwater sources. Nevertheless, peatland-forming processes in the region appear to occur only where water tables are at or near the surface. Thus, soil water storage recharge via groundwater sources likely plays a predominant role in maintaining suitably wet moisture conditions for peat accrual and the growth and establishment of peat-forming vegetation at the surface. Irwin (1994) suggests that water table depth largely determines community distribution in the blanket bog region of Newfoundland.

In support of the speculation put forth above, the limited TDR sampling and visual observations of large hummocky *Sphagnum* spp. formations along bog/fen margins indicated that *Sphagnum* spp. hydrologically disconnected from groundwater recharge could become water stressed. While excessive water loss may inhibit *Sphagnum* spp. growth at certain locales along the peatland complexes, it can accelerate organic matter decay which, consequently, can increase the water-holding capacities of the decaying formation. In this way, the water-stressed hummock formations along the bog/fen margins may indeed help perpetuate the lateral development of blanket peats by providing a suitably wet organic platform for the establishment of bog-forming vegetation. This type of regime is analogous to hummock/hollow regeneration cycles whereby, i) the more rapid growth of bog-forming vegetation in the wetter hollows turns hollows into hummocks, and, ii) greater degradation of water-stressed hummocks turns hummocks into wet hollows (Crum 1988).

ACKNOWLEDGMENTS

Funding for this project was provided by individual Natural Science and Engineering Research Council Grants awarded to J. S. Price and R. Gilbert, and an American Geophysical Union Horton Research Grant awarded to D. R. Lapen. The technical help of R. Hoag is also appreciated. Helpful comments and suggestions were provided by G. C. Topp and H. N. Hayhoe of the Eastern Cereal and Oilseed Research Centre, Ottawa, Ontario.

Banfield, C. E. 1983. Climate. Pages 37–106 *in* R. South, ed. Biogeography and ecology of the island of Newfoundland. Dr. W. Junk Publishers, The Hague, The Netherlands.

Bavina, L. G. 1967. Refinement parameters for calculating evaporation from bogs on the basis of observations at bog stations. Sov. Hydrol. **1967**: 348–370.

Boelter, D. H. 1964. Important physical properties of peat materials. Int. Peat Congress, Quebec. Can. pp. 150–154.

Crum, H. 1988. A focus on peatlands and peat mosses. University of Michigan Press, Ann Arbor, MI.

Davis, A. M. 1985. Causes and character of paludification in Newfoundland. Can. Georgr. **32**: 77–79.

Environment Canada. 1982. Canadian climatic normals 1951–1980: Temperature and precipitation, Atlantic Provinces. Atmospheric Environment Service, Downsview, ON.

Ingram, H. A. P. 1983. Hydrology. Pages 67–158 *in* A. J. P. Gore, ed. Mires: Swamp, bog, fen, and moor. Elsevier, New York, NY.

Irwin, T. E. 1994. Development of a blanket bog at St. Shotts, Avalon Peninsula, Newfoundland. Ph.D Dissertation, University of Toronto, Toronto, ON.

Ivanov, K. E. 1978. Water movement in morelands. Academic Press, London, UK.

Lafleur, P. 1990. Evaporation from wetlands. Can. Geogr. **34**: 79–82.

Lapen, D. R., Price, J. S. and Gilbert, R. 1998. Occult precipitation and Cl-deposition to bog and heath surfaces, Cape Race, Newfoundland. Atmos. Ocean (in press).

Lapen, D. R., Moorman, B. J. and Price, J. S. 1996. Using ground-penetrating radar to delineate subsurface features along a wetland catena. Soil Sci. Soc. Am. J. **60**: 923–931.

Lapen, D. R. and Wang, C. 1998. Placic and ortstein genesis and peatland development, southeastern Newfoundland. Soil Sci. Soc. Am. J. **22**: 1472–1482.

Ledieu, J., De Ridder, P., de Clerck, P. and Dautrebande, S. 1986. A method of measuring soil moisture by time domain reflectometry. J. Hydrol. **88**: 319–328.

Northlands Associates Ltd. 1989. Research on bog preparation and peat sod drying techniques in Newfoundland (1986–1988). Northlands Assoc. Ltd., St. John's, NF.

Parent, L. E. and Caron, J. 1993. Physical properties of organic soils. Pages 441–458 *in* M. R. Carter, ed. Soil sampling and methods of analysis. Lewis Publisher, Boca Raton, FL.

Pepin, S., Plamondon, A. P. and Stein, J. 1992. Peat water content measurement using time domain reflectometry. Can. J. For. Res. **22**: 534–540.

Price, J. S. 1992. Blanket bog in Newfoundland. Part II. Hydrological processes. J. Hydrol. **135**: 103–119.

Romanov, V. V. 1968. Hydrophysics of bogs. Israel Program for Sci. Translations, Jerusalem, Israel.

Sjors, H. 1976. Successional trends in boreal peatlands. Pages 22–28 *in* Proc. 5th Internat. Peat. Congr, Poland.

Smith, R. T. and Taylor, J. A. 1989. Biopedological processes in the inception of peat formation. Int. Peat J. **3**: 1–24.

Tansley, A. G. 1949. The British Isles and their vegetation. Vol. 2. Cambridge University Press, London, UK.

Taylor, J. A. and Smith, R. T. 1972. Climatic peat — a misnomer? Proc. 4th Int. Peat Cong. International Peat Society, Helsinki, Finland. pp. 471–483.

Topp, G. C. 1993. Soil water content Pages 541–557 *in* M. R. Carter, ed. Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

Unsworth, M. H. and Crossley, A. 1987. Consequences of cloud water deposition on vegetation at high elevation. Pages 171–188 *in* T. C. Hutchinson and K. M. Meema, eds. Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems. Springer-Verlag, Berlin, Germany.

Wells, E. D. 1981. Peatlands of eastern Newfoundland: distribution, morphology, vegetation, and nutrient status. Can. J. Bot. **59**: 1978–1997.

Wells, E. D. and Pollett, F. C. 1983. Peatlands. Pages 207–265 *in* R. South, ed. Biogeography and ecology of the island of Newfoundland. Dr. W. Junk Publishers, The Hague, The Netherlands.