Use of Shallow Basins to Restore Cutover Peatlands: Hydrology

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Abstract

Basins 20-, 10-, and 4-m wide were excavated 15 to 20 cm into cutover peat fields near Lac Saint Jean, Québec, Canada to facilitate the establishment of *Sphagnum* mosses. *Sphagnum* diaspores (fragments) and straw mulch were spread over the excavated surfaces, a control peat field, and a mulch-protected site without basins. Mean water tables in the 20-, 10-, and 4-m wide basins and the mulch-protected site were 27.2, 8.3, 11.4, and 9.7 cm higher, respectively, than in the control peat field in May to August 1996. Similar improvements were observed in 1997 (a drier summer). The higher water table was due to lowering of the peat surface with respect to the local water table, retention of meltwater and stormwater by the peripheral ridges formed during excavation, retention of water during drier periods by the groundwater mound beneath the ridges, and mulch. Soil moisture was always higher in the experimental basins than in the control peat field or in the mulch-protected site, demonstrating the superior soil wetness characteristic of sites with basins and straw mulch. Water tension data signaled the absence of the capillary fringe (i.e., capillary drainage) near the surface for some finite period, thus possibly limiting water for best *Sphagnum* growth. At the experimental basins and mulch-protected site, 100% of these periods lasted four or fewer days. In the control peat field, 20% of the periods when capillary drainage had occurred lasted more than four days, with one period of 17 days. The mulch protection alone provided considerable improvement in hydrological conditions compared with the control peat field, but the additional water retained in the experimental basins protected against *Sphagnum* desiccation and loss during more extreme dry periods.

Key words: cutover peatland, hydrology, restoration, rewetting, trenches.

Introduction

The exploitation of peatlands for *Sphagnum* is widespread in North America and Europe (Lappalainen 1996). Hydrological, microclimatic, and ecological changes associated with peat harvesting destroy the original ecosystem functions (Wheeler & Shaw 1995). These functions are dominantly attributable to the layer of living, dead, and poorly decomposed *Sphagnum* mosses and peat occurring above the water table, known as the acrotelm (Ingram 1978). The hydraulic properties of the acrotelm modulate water table fluctuations (Ingram 1983), sustaining a critical level of humidity, probably by both capillary rise of water from the water table and downward percolation from precipitation. Drainage of the site, accompanied by removal of the acrotelm during harvesting, lowers the water table into the underlying catotelm (Ingram 1978) peat, where the water table is unstable (Price 1996). Evaporation and drainage from the well-decomposed peat soil exposed by cutting results in capillary forces within the soil that are sufficient to limit water availability to *Sphagnum* mosses (Price 1997). Consequently, water management strategies are required to improve the hydraulic conditions.

Water management strategies previously used include blocking ditches (Eggelsmann 1988; Price 1997), passive (LaRose et al. 1997) or pumped seepage reservoirs (Price 1998), shading devices (Quinty & Rochefort 1997a), companion species (Ferland & Rochefort 1997), and straw mulch (Price 1997; Quinty & Rochefort 1997a). Price et al. (1998) reported on the use of artificial microtopography and straw mulch to improve water availability. They found that microtopographic relief provided no net benefit for the site to be revegetated, compared with the use of protective mulch, although narrow trenches caused by bulldozer tracks had significantly greater soil moisture and *Sphagnum* revegetation (Price et al. 1998).

In eastern Canada, the spontaneous recolonization of *Sphagnum* communities onto large, abandoned, vacuum-harvested peatland does not readily occur. However, the regeneration of *Sphagnum* hummocks or lawns has been recorded in some basins of abandoned block-cut peatlands (Lavoie & Rochefort 1996; Robert et al. 1999). This, along with the success of *Sphagnum* recolo-

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nization in narrow trenches as described above, was the impetus for this research. The experiment described here was designed to expand the scale of the trenches into shallow basins to evaluate their suitability for large-scale restoration. Specifically, the objective of this research was to evaluate how basin design affects seasonal and interannual water flows and storage and to determine whether shallow basins provide a significant advantage for recolonization of *Sphagnum* mosses. This article presents the hydrological evaluation.

Study Area

The study was performed near Lac-Saint-Jean, Québec, Canada (48°47′N, 72°10′W). The average annual temperature is 2.2°C, with average January and July temperatures of −15.9 and 18.1°C, respectively (Environment Canada 1992a). Mean annual total precipitation is 909 mm (36% falling as snow). Mean annual run-off in the nearby Mistassini River is 623 mm (Environment Canada 1992b); thus, mean annual evapotranspiration (precipitation minus run-off) is approximately 286 mm, assuming no net storage change.

The peatland is part of a 4,315-ha bog-poor fen complex, classified as "plateau bog" (National Wetland Working Group 1997). The peat deposit has developed over permeable deltaic sands (Morin 1981) where a well-developed iron pan limits seepage losses (Price 1996). This study examined a cutover portion of the peatland. Drainage operations began in 1990. The upper 0.35 to 0.6 m was removed by block cutting with heavy machinery in 1991, and then the ditches were blocked with peat dams of approximately 5-m width set every 100 m along the drainage system in the fall of 1992. Residual peat thickness currently ranges from 1.2 to 1.8 m and has suffered oxidation and compression due to drainage and mining activities.

Methods

Experimental Design

Basins were installed between 23 and 29 April 1996 when the peat was thawed to a depth of approximately 15 to 20 cm. The surface peat was scraped down to the frozen layer and the spoil pushed into ridges bordering the plots. The basins were installed longitudinally along the center line of the 30-m wide peat fields, at widths of 4, 10, and 20 m (Fig. 1). The 10- and 4-m basins were adjacent to one another, and whereas the 30-m basin was located in an adjacent peat field, site restrictions required that it was placed at the other end of the field (Fig. 1). The height and breadth of the ridges increased for the wider basins, ranging from 40 to 50 cm high and 1 to 2 m wide. The 20-m basin and lateral ridges covered almost the entire width of the peat field. The 4- and 10-m basins occupied only the medial portion of the field and thus were bordered by "untrenched" flat cutover peat that received no further treatment. All experimental basins were sown with *Sphagnum* diaspores (fragments) and covered with straw mulch. As a fourth treatment, four 15 × 15-m plots without basins were covered with *Sphagnum* diaspores and mulch protected (mulch-protected site). These were located on peat fields 200 m northwest of the 10- and 4-m basins but at the same end of the field (not shown in Fig. 1). The general restoration method to reestablish a *Sphagnum* lawn was described in more detail by Quinty and Rochefort (1997b). Finally, for comparative purposes, a control section of peat field (Fig. 1) with no basins or straw mulch was monitored (control peat field).

Hydrological and Microclimatic Variables

An intensive measurement program was carried out during the 1996 vegetative growing season (May to August). Microclimatic data were logged hourly, whereas water table, soil moisture, and water tension were measured approximately daily between May and August and several times during September and October. Weekly monitoring of the same variables was done between June and August 1997. Rain was measured with

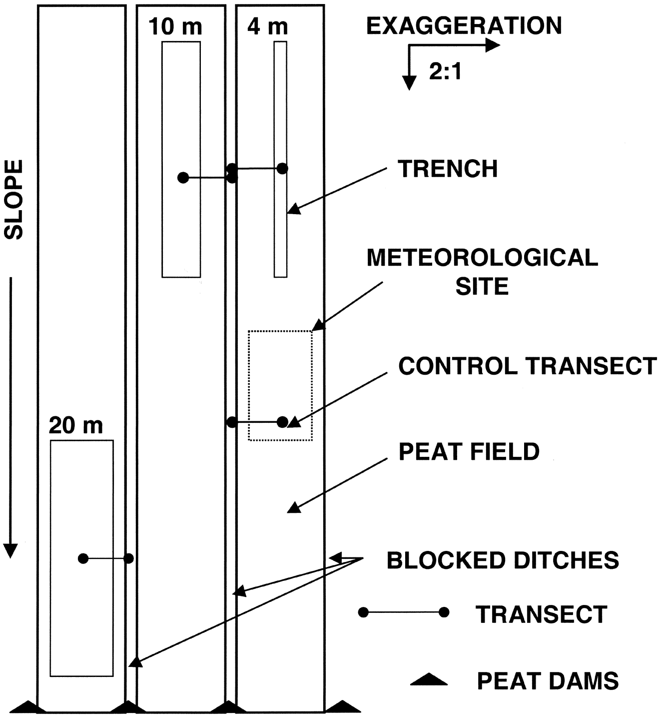

Figure 1. Experimental setup showing location of treated and control sites and location of meteorological observations. Mulch-protected site not shown.

a tipping bucket rain gauge 0.5 m above the surface at the meteorological station (all years).

In each basin, water levels were measured in wells along transects perpendicular to the long axis of the basin. The transects ran from the ditch, which had been blocked 4 years previously, to the center of the basin. In each transect, wells were located at the center line, on both sides of the ridge, on top of the ridge, and adjacent to the ditch. In the 20-m basin, the well on the ridge also represented the position adjacent to the ditch. A single well was also used at both ends of each experimental basin. At the control peat field, a transect had wells at 0.5, 1, 2, 3.5, 5, 10, and 15 m from the ditch. Wells were constructed of 25 mm i.d. polyvinyl chloride pipes slotted over their entire length, covered with geotextile, and inserted in predrilled holes of the same diameter to approximately 0.75 m below the surface.

Soil moisture and bulk density were determined gravimetrically on samples retrieved with a cutter that sampled the upper 3 cm of soil. Samples were taken in triplicate at each location and returned to the lab for analysis (daily in 1996, weekly in 1997). Matric tension was measured daily in 1996 at the control peat field, the 4- and 10-m basins, and the mulch-covered site. In 1996 tension was measured at −1, −3, −10, −30 and −50 cm with a 1-cm o.d. porous ceramic cup inserted horizontally into a pit wall, connected to a partially water filled L-shaped tube protruding above the peat surface. The pit was back-filled with peat. Pressure was measured with a Tensimeter (Soil Measurement Systems, Tucson, AZ, U.S.A.) pressure transducer accurate to 1 mb and adjusted to account for the height of the water column above the ceramic cup. Values herein are expressed in cm of water (1 cm = mb). In the same pits, time domain reflectrometry was used to measure soil moisture at −2, −10, −30, and −50 cm (1996 only). In 1997 time domain reflectrometry was not used, and tension was measured weekly at −2 cm at all experimental sites.

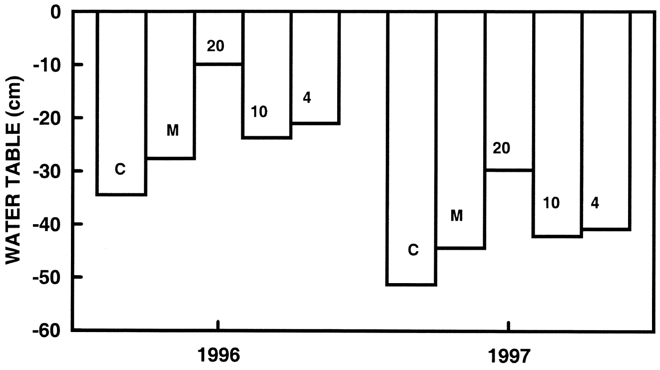

Figure 2. Summary of water table levels for the period June to August 1996 to 1997, based on weekly water table measurements at the control site (C), mulch-covered site (M), and 20-, 10-, and 4-m basins.

Results

Monthly total precipitation at nearby Péribonca for May, June, July, August, and September 1996 deviated from the long-term normals by −13.3, −11.8, +79.9,

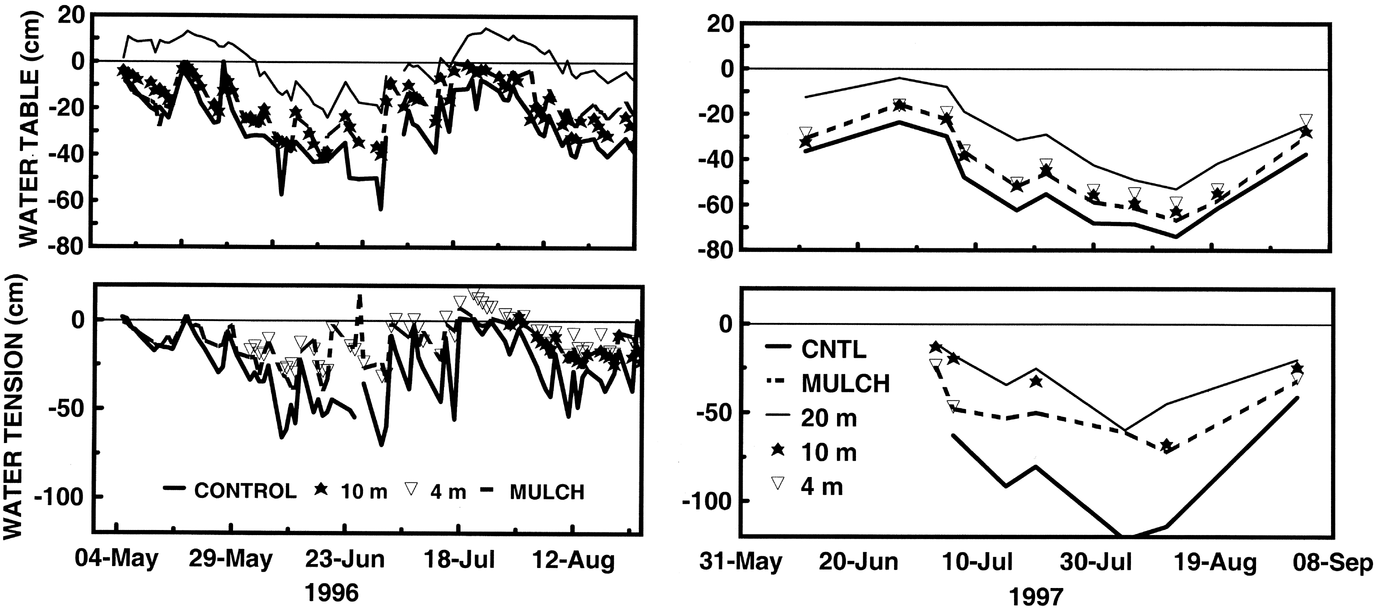

Figure 3. Water table and water tension for 1996 and 1997. Note the vertical axis of water tension is not the same in 1996 and 1997. Measurements in 1996 were approximately daily, whereas in 1997 were weekly.

Table 1. Summary of changes to water table, soil moisture at −2 cm, and water tension at −1 cm.

1996	*Water Table (cm)*	*Soil Moisture (TDR)*	*Tension (cm)*
Control	−27.5 ± 13.2 (−30.2)	0.67 ± 0.07 (0.65)	−26.4 ± 19.3 (−25.7)
20-m basin	−0.3 ± 10.3 (1.2)	ND	ND
10-m basin	−19.2 ± 11.4 (−19.2)	0.80 ± 0.05 (0.72)	−15.4 ± 9.3 (−15.5)*
4-m basin	−16.1 ± 12.1 (−16.5)	0.78 ± 0.06 (0.71)	−8.2 ± 11.7 (−7.4)
Mulch site	−17.8 ± 10.5 (−18.6)	ND	−13.5 ± 11.0 (−13.5)

Values are means ± SD, with medians in parentheses, collected daily between 6 May and 28 August 1996.
ND, data for this variable were not collected at this location.
*Data missing but generated by regression ($r^2 = 0.92$).

−7.0, and +13.2 mm of rain, respectively (Sommaire Climatologique du Québec 1996). Conditions in 1997 were somewhat drier toward the end of summer, with precipitation deviating + 63.0, +12.8, −60.4, and −13.5 mm from May to August normals, respectively (Sommaire Climatologique du Québec 1997).

The intensive July 1996 rainfall resulted in higher average water table conditions compared with 1997 (Fig. 2). The water table in the experimental basins was distinctly higher than at the control peat field. Furthermore, the mulch-protected site also had an improvement in water table height over the control peat field, but not as much as in the experimental basins. The pattern of water table depths among sites was consistent from year to year.

Seasonal fluctuations in water table depth (Fig. 3) showed significant flooding in 1996 in the 20-m basin after spring run-off and after a major storm on 19 and 20 July (70 mm in 48 hr). Patchy flooding occurred in all experimental basins during these periods but was most persistent in the 20-m basin. Surface run-off and patchy flooding also occurred at the control peat field and mulch-protected sites. In 1997 measurements began later (Fig. 3), although surface ponding did occur after snowmelt run-off. The lowest water table in 1996 occurred on 2 July, measuring approximately −63, −39, −22, −39, and −38 cm for the control, mulch, 20-, 10-, and 4-m locations, respectively. In 1997 the comparable values (12 August) were –74, –67, –53, –62, and –59 cm, respectively. The standard deviation of water table elevations (1996) was greatest for the control site and least for the 20-m basin (Table 1). Water table responses (1996) at the treated experimental sites were regressed against those at the control peat field (Fig. 4). The responses had smaller slopes than the 1:1 line of the control.

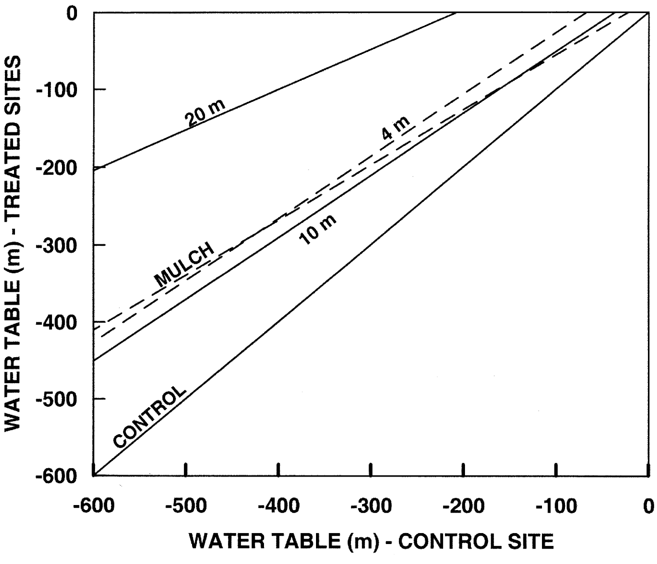

Figure 4. Water table responses at the treated sites regressed against those at the control site.

To facilitate comparison of water table variability, the median water table depth at each site was subtracted from respective daily values (i.e., data were normalized) and the frequency of the deviation summarized (Fig. 5). In general, the normalized frequency distribution of water table in experimental basins and the mulch-covered site were not greatly different. The control peat field had the most variable water table, covering the widest range of water table fluctuations. Of the treated sites, the 4-m basin had the greatest range of fluctuations.

Water table profiles along transects (Fig. 6) during high and low water tables were generally parallel. However, a groundwater mound developed beneath the ridges at the 10- and 4-m experimental basins during low water table periods. This was not evident in the 20-m experimental basin, whose ridge was adjacent to, and more strongly under the influence of, the ditch water level. In the 10- and 4-m experimental basins the water table was perceptibly higher within the basin than outside it during the dry period.

Frequency distributions of soil moisture (Fig. 7) indicate more variability between sites than do the frequency distributions of water table. The control peat field site had distinctly lower soil moisture and an asymmetrical distribution with predominance of soil moisture values in the range of 51 to 70%. In the mulch-covered site (straw) the distribution was shifted upward and was flatter than in the control peat field. In the experimental basins, the distribution was shifted

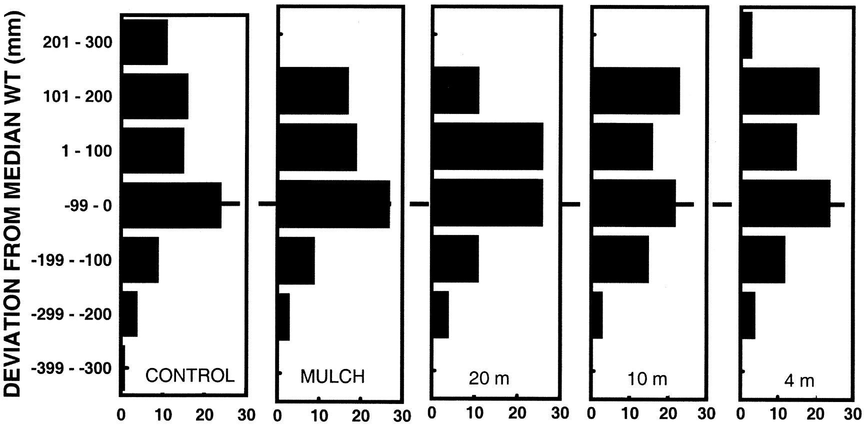

Figure 5. Normalized frequency distributions of water table (WT) variations at all sites (1996). Values were based on 76 days of data at each site. The horizontal dashed line represents the normalized median, 0 cm.

upward yet again, with a progressively shorter (drying) tail for wider basins. The sections of peat field adjacent to the 4- and 10-m experimental basins were significantly drier than their respective basins yet moister than the control site.

Soil water tension was most negative in the control peat field, markedly less negative in the mulch-protected site, and less again in the experimental basins (Fig. 3). The effect of the experimental basins on tension, compared with that in the mulch-covered site, was small in 1996 and moderate in 1997. Overall, the soil water tension near the surface exhibited a very similar pattern of rises and falls as the water table in both 1996 and 1997 (Fig. 3). However, during the driest part of the 1996 summer (late June to early July), when the water table was low, tension still responded quickly to rainstorms, approaching (but not reaching) zero tension, suggesting capillary saturation. The tension at the control peat field did not drop lower than −65 cm (mb) in 1996, whereas in 1997 it was lower than −100 cm (mb) almost all of July and August.

Tension data of 1996 were subjected to a frequency and duration analysis to determine the probability that the capillary fringe was absent from the peat at −1 cm depth. The capillary fringe was judged to be absent when the tension was below the air-entry value of −25 mb (Schlotzhauer & Price 1999). In treated sites, 100% of these periods were less than or equal to 4 days (Fig. 8). At the control site, 80% of the periods with no capillary fringe near the surface were 4 days or less. Furthermore, periods of up to 17 days with no capillary fringe near the surface were experienced at the control site.

Discussion

On the basis of water table elevations one could easily jump to the conclusion that the 20-m basin configuration most improved the site wetness. The 20-m experimental basin was clearly the wettest, but this was likely an artifact of the method (unintentional) rather than an attribute of the configuration (width). Preparation of the basins with a bulldozer produced only roughly similar excavation depths (controlled by local frost table position). Furthermore, the height and width of the ridges formed from the excavated spoil material was directly related to the volume of material removed, so wider basins had larger

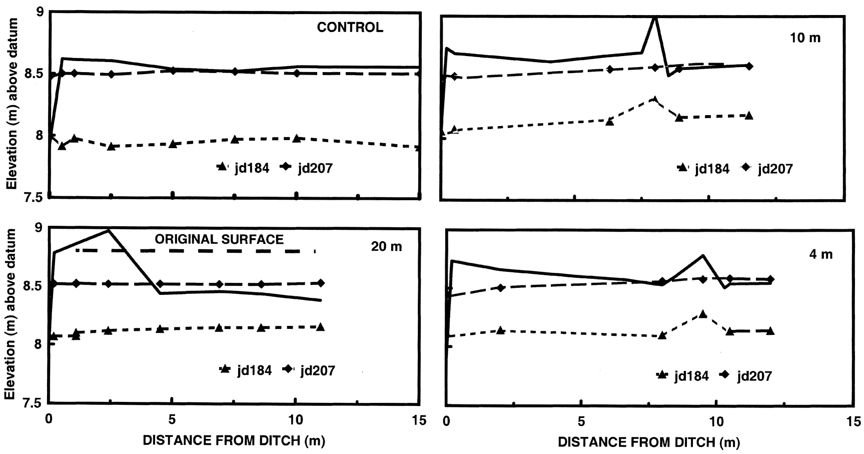

Figure 6. Water table profiles along transects (Fig. 1) during a wet (jd207) and dry (jd184) period in 1996. jd, Julian day. The solid line represents the surface.

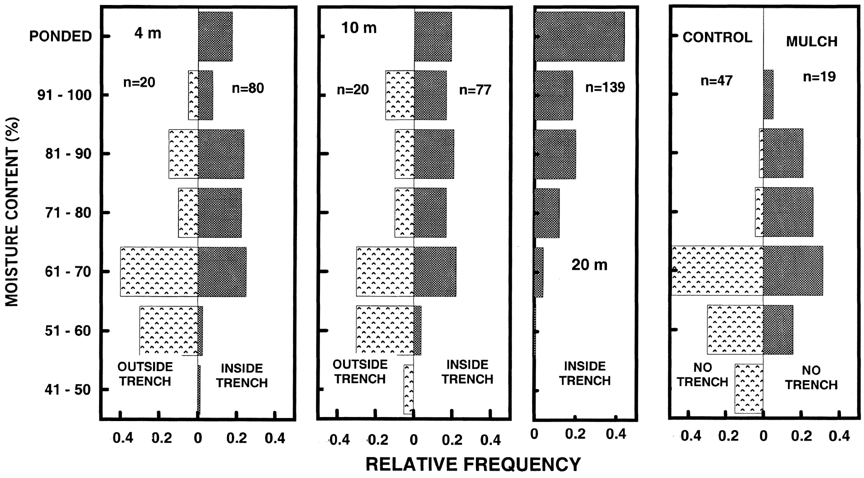

Figure 7. Frequency distribution of soil moisture at all sites including the area of peat field outside the 4- and 10-m experimental basins. Data are from weekly sampling, 20 samples per site, analyzed gravimetrically.

ridges and were thus theoretically more effective at retaining surface water. Moreover, the depths to the water table were not the same throughout the study site (even before manipulation) because of a gentle slope of the peatland. The ditches had been blocked (flat water surface in ditches); thus, the water tables were higher on the adjacent downslope section of the peat fields. The 20-m and control site were located closer to the downslope side and thus had higher water tables than the 10-m, 4-m, and mulch-covered plots. This situation was not anticipated or the experimental design would have been different. Despite this, careful evaluation of the data can provide insight into the hydrological processes, which is useful for planning restoration strategies.

The frequency distribution of the mean deviation of the water table (which removed the bias caused by location along the regional slope) shows that the experimental basins and mulch-covered treatments stabilized the water table compared with the control peat field. The slope of the regression lines of the water tables also shows this. The regression slopes of less than unity for all treated sites (i.e., vs. the control water table) indicate that the treated experimental sites did not experience the same degree of water table lowering in response to drying. This results from several hydrological processes. First, a large amount of snowmelt water was retained in all experimental basins, whereas surface run-off from the control peat field and mulch-covered sites left only small patches of ponded water. The prevalence of ponded water early in the season in experimental basins, and its persistence in the 20-m basin, had the effect of stabilizing the water level fluctuations (i.e., specific yield = unity), compared with water table fluctuations that occur beneath the surface at all other sites (specific yield $<<1$). Second, experimental basins all had a protective mulch cover, which reduced evaporative water loss (Price et al. 1998). Third, during periods of low water table, groundwater mounds developed beneath the lateral ridges, bounding the 10- and 4-m experimental basins. These mounds restricted lateral groundwater seepage losses and thus assisted in sustaining the water table within the basins compared with the adjacent section of the respective peat field outside the basin. The 4-m basin was the least effective of the experimental basins in stabilizing the water table, because the volume of water it retained relative to its perimeter length was less than at wider basins. Finally, the wetter peat in the basins (as compared with drier peat elsewhere) was more likely to undergo bulk density changes (subsidence) in response to water losses (Price & Schlotzhauer 1999), resulting in a dampened water table response.

The pattern of interannual variation in water table shows that for the drier conditions of 1997, the water table in the control peat field was 11 cm lower than in 1996. In contrast, the water table in the mulch and 20-, 10-, and 4-m experimental basins was lower by 28, 31, 23, and 21 cm, respectively. The experimental sites suffered a greater water table drop than the control peat field. This does not suggest that they were less effective during drier conditions. Price (1997) noted that when the water table was relatively deep (approximately 60 cm), as in the control peat field, vertical water fluxes to and from the atmosphere were manifest primarily as changes in soil moisture storage. Once a certain water table depth was reached, further evaporative water losses were supplied from the zone above the water table. This is evident from Figure 3, which shows that water tension at the control peat field was much lower (more negative) than at the experimental basins during the dry summer than would be suggested by changes in water table. The presence of mulch cover clearly improved the site wetness, but the experimental basins provided yet further protection against drying of the surface peat, which should be favorable to *Sphagnum* establishment and survival.

Soil moisture characteristics associated with the experimental basins were related to the position of the

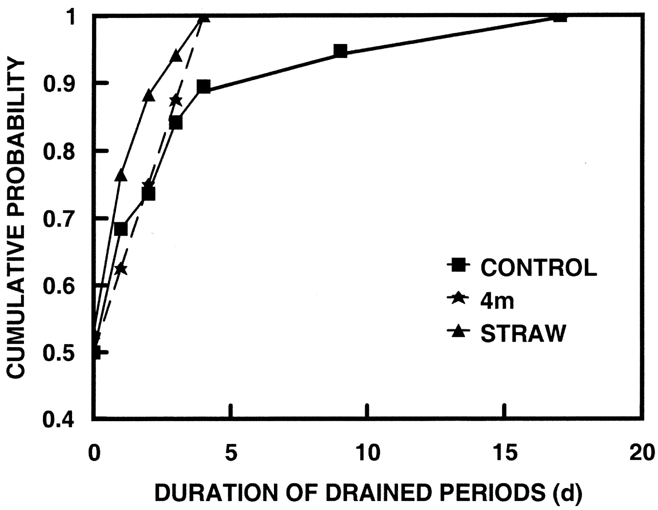

Figure 8. Frequency-duration analysis of the periods when the water tension in the peat at 1 cm below the surface was no more than −25 mb. For example, at the 4-m basin 100% of these periods were less than or equal to 4 days.

water table at each site, and therefore the bias associated with position of the experimental sites along the local gradient cannot be ignored. The soil moisture frequency distributions of the experimental basins are flatter than those of locations outside experimental basins and, in the case of the 20-m site, dominated by sample locations that were flooded. The flatter distributions are related to the proximity of the water table, because soil moisture varies more consistently with water table fluctuations when the water table is high (Price 1997). The higher moisture within the basins was the obvious consequence of retaining the spring moisture surplus. The lateral leakage of the water retained by basins evidently raised the soil moisture adjacent to the basin (i.e., compared with the control peat field) to a level similar to that at the mulch-protected site.

The data show that the basins improved the substrate wetness over both the control site and the straw mulch site. However, an important consideration for *Sphagnum* viability is not simply the average value of water table, soil moisture, or even water tension but the persistence of suitably saturated conditions near the surface. Perhaps more importantly, the occurrence of excessively dry conditions that can result in desiccation and death of these plants (Sagot & Rochefort 1996) must be investigated. Because *Sphagnum* species are nonvascular, it is essential that water tension of the contact soil remains very small to ensure adequate water availability. Previous attempts to characterize the duration (e.g., LaRose et al. 1997; Price 1997) using standard duration analysis (e.g., Dingman 1994) fail to take into account the periodicity of wetting and drying. For example, it is possible to have half of the seasonal water tension values below a stated threshold occurring as a single prolonged dry period or as a series of brief dry spells. Thus, a frequency-duration analysis (e.g., Hunt et al. 1999) was done to determine the probability that the capillary fringe was absent from the peat at −1 cm depth. The capillary fringe was judged to be absent when the tension was below the air-entry value of −25 mb (Schlotzhauer & Price 1999). At these tensions intercellular pores of the poorly decomposed peat begin to drain, and air enters the peat soil. As previously noted, the analysis found that the experimental basins and the mulch-protected site sustained water tension sufficiently so that the capillary fringe (hence pore saturation) was never absent from the surface peat for a period longer than 4 days. In contrast, at the untreated control peat field one such period lasted 17 days.

The selection of −25 mb, corresponding to the air-entry pressure for this peat, represents the probable upper limit of tension that could negatively influence water availability for vigorous *Sphagnum* growth. Although it is a nonvascular plant, Hayward and Clymo (1982) found that intracellular drainage (i.e., of hyaline cells) does not occur until −100 mb. Occurrence of these tensions in the peat soil is likely to be a more realistic limit to *Sphagnum* survival, because this will force prolonged desiccation of the *Sphagnum*, which can result in plant mortality (Clymo 1973; Wagner & Titus 1984; Sagot & Rochefort 1996). However, the task of determining the critical duration and tension for *Sphagnum* survival and growth remains. Different species are likely to have different thresholds. It should be noted that the relatively wet conditions of 1996 were favorable for *Sphagnum* growth (Rochefort, unpublished data), and tensions did not reach −100 mb at any site. However, the duration of drier conditions was considerably less at treated sites, increasing the productivity of *Sphagnum* compared with control conditions. Although tension did drop below −100 mb in 1997, the weekly measurements did not provide sufficient data for a frequency-duration analysis.

Conclusions

The water table was consistently higher at sites where basins were used. The "improvement" in water table height was due to lowering of the surface with respect to the local water table, retention of meltwater and floodwater by the ridges, and retention of water during drier periods by the groundwater mound beneath the ridges (10- and 4-m basins). The highest water table depth was recorded at the 20-m site. This may have been partly due to its larger ridges but was largely due to the higher local water table where this basin was located. It is important to note that high water table, when characterized by periods of flooding, is not necessarily desirable for *Sphagnum* regeneration.

Soil moisture was always higher in the experimental basins than in the control peat field or in the mulch-protected site. The improvement in soil moisture at the basin sites extended beyond the ridges bounding the basins, indicating that some seepage was replenishing the adjacent part of the peat field.

Water tension in the experimental basins and mulch-protected site did not drop below -100 mb in either year but did so in the control peat field in 1997. The frequency and duration of periods of capillary drainage (tensions less than -25 mb) from the cutover peat surface were considerably less in the experimental basin and mulch-protected site than in those from the control peat field.

Straw mulch has previously been shown to provide adequate conditions for *Sphagnum* revegetation under the range of experimental conditions tested (e.g., Price 1997; Quinty & Rochefort 1997a; Rochefort et al. 1997), but the additional water retention provided by basins provided further protection against desiccation and moisture loss during extreme conditions.

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