

Water Relations in Cutover Peatlands

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Sphagnum mosses, the dominant peat-forming plant in many northern peatlands, generally do not regenerate spontaneously in mined peatlands because water transfer between the cutover peat and incipient moss diaspores cannot overcome the capillary barrier effect between the two hydraulically distinct layers. Artificial drainage networks established throughout peatlands, coupled with the removal of the acrotelm during the peat extraction process, drastically alter the natural system function through the exposure of more decomposed catotelm peat and increased compression, oxidation, and shrinkage, subsequently decreasing average pore diameter and enhancing this capillary barrier effect. Water table (WT) fluctuations, constrained within the reduced specific yield of the altered catotelm, exhibit increased variability and rapid decline. The increased effective stress caused by a declining WT can result in seasonal surface subsidence of 8 to 10 cm, thereby reducing saturated hydraulic conductivity by three orders of magnitude. Restoration efforts aim to alter the disturbed hydrological regime, creating conditions more favorable for the recolonization of *Sphagnum* mosses and the ultimate reestablishment of an upper acrotelm layer. Due to the large areal coverage and high organic carbon content, the response of peatlands to disturbances caused by resource extraction, and their return to functioning ecosystems, must be thoroughly addressed. This paper integrates both published and unpublished work to facilitate an overview of our understanding of the hydrological impact of peat cutting and its implications for restoration.

1. INTRODUCTION

Cutover peatlands are those exploited for their peat resource and sometimes for agriculture. The common feature is that the surface layer, previously the most biologically and hydrologically active zone [Ingram, 1983], has been removed. The hydraulic structure of this upper layer of living, dead, and poorly decomposed plant material is essential to maintaining the storage and fluxes of water that define its

ecosystem functions including its hydrologic function, native plant community, geochemical attributes, and carbon balance. These functions are either lost or profoundly altered with peat cutting such that their ecohydrological trajectory may be forever altered.

Peat cutting is widespread in parts of Scandinavia, British Isles, Russia, and North America. Peatlands cover over 1 million km² in North America, with most (97%) of the total peatland-covered area located within the boreal and subarctic wetland regions [Tarnocai, 2006]. The peatlands located at temperate latitudes, though proportionately less, are more susceptible to disturbances due to anthropogenic activities as a consequence of their proximity to markets; hence, their economic value. For example, approximately

16,000 ha of Canada's peatlands have been or are currently being exploited for peat resources [Bergeron, 1994; Keys, 1992]. While peatlands include bogs, fens, and some swamps [NWWG, 1997], the primary target of peat extraction activities is on bogs for the production of *Sphagnum* peat because of its superior water-holding properties and resistance to decay [Read et al., 2004]. There is a need to understand the impacts of peat cutting on the system ecohydrology in order to better manage the industrial exploitation, particularly in devising appropriate restoration strategies. Thus, the objective of this paper is to establish our current state of understanding of the hydrological impact of peat cutting and its implications for restoration. Price et al. [2003] provided a review of hydrological processes in abandoned and restored peatlands, and provide details of restoration attempts in Europe and North America. This paper includes some of the essential aspects outlined by Price et al. [2003] but includes more recent work, both published and unpublished, to highlight our current state of understanding.

2. ECOHYDROLOGICAL FUNCTIONS IN UNDISTURBED PEATLANDS

Peatlands are fundamentally an ecohydrological construct. Their ecological function is both an outcome and a determinant of their hydrogeomorphic setting, since plant materials contribute to peat development and accumulation. Undisturbed peatlands are typically characterized by an upper layer of living, dead, and poorly decomposed plant material (acrotelm) that is defined as the zone that exists above the average minimum annual WT [Ingram, 1978]. While the existence, development, and vertical extent of this layer are variable depending on peatland form and location, it has a disproportionately large influence on the ecohydrological and biogeochemical function. Toward the surface, there is an increase in porosity, hydraulic conductivity, and specific yield which regulates WT variability, infiltration capacity and water storage, groundwater and surface water runoff (RO), capillary rise, and evapotranspiration (ET) [Ingram, 1983]. Removal of the acrotelm exposes the more decomposed catotelm peat [Ingram, 1978] that previously existed in an anoxic state below the WT. This layer is characterized by lower hydraulic conductivity and lower porosity that imparts a low specific yield [Price, 1996] when it is drained. Consequently, the water regime no longer supports the original ecology and carbon regulation function of the peatland.

The structure of the acrotelm that arises from the vegetation community that formed it and the decomposition processes that transform it eventually into peat provide the ideal medium for sustaining that plant community. Near the surface the hydraulic matrix is characterized by relatively large

pores derived from growing and dead undecomposed plant material as yet uncompressed by the weight of overlying materials over time. The large pores have a high saturated hydraulic conductivity, K_s [Boelter, 1968; Hayward and Clymo, 1982; Hobbs, 1986], which can effectively transmit water when a hydraulic gradient is present. Thus, natural drainage following large storms or snowmelt reduces the duration of surface flooding [Spieksma, 1999], conditions which are less than ideal for many plants even in wetlands [Rochefort et al., 2002]. As drainage occurs and the WT falls, the effective K_s decreases sharply below the surface, and the ability to shed groundwater diminishes accordingly, a mechanism which ensures sufficient wetness is sustained. Hoag and Price [1995] noted that K_s of a bog acrotelm can decrease five orders of magnitude from the surface to 50-cm depth.

The poorly decomposed organic material in the upper acrotelm has low water retention capacity [Boelter, 1969]; thus, a high specific yield (S_y). Specific yield is the ratio of the volume of water drained from a soil by gravity (after being saturated) to the total volume of the soil. Large pore sizes dominate the upper acrotelm, resulting in the drainage of a large proportion of the pore space by gravity, consequently increasing the specific yield. On the one hand, this high storativity dampens the WT drawdown response to drainage and, thus, sustains the WT relatively close to the surface (a definitive factor for wetlands and especially peatlands where anoxic conditions must prevail), but the sharp decrease in volumetric water content (θ) with pore drainage rapidly reduces the unsaturated hydraulic conductivity of the moss [Price et al., 2008], since hydraulic conductivity is a function of water content, $K(\theta)$. Thus, water flow in the matrix above the WT, especially near the surface of moss-dominated peatlands, is suppressed when the WT falls. Various studies have shown, for example, that evaporation from moss-dominated systems is sharply reduced when the WT declines [Lafleur and Roulet, 1992; Price, 1991; Romanov, 1968], since $K(\theta)$ becomes very low and upward capillary flows cannot effectively replenish water at a rate that meets the evaporative demand. One consequence of the reduced evaporation due to the low $K(\theta)$ is that the system retains a relatively high WT. Thus, the ability to readily shed water when the WT is high, while also preventing a large WT drawdown and reducing the groundwater efflux when the WT does drop, is an essential self-regulating feature of undisturbed bog peatlands. Another self-regulating feature of many peatlands is the ability to shrink and swell to adjust to changes in seasonal wetness [Ingram, 1983] or drainage [Whittington and Price, 2006].

The intimate relationship between ecology and hydrology of peatlands is a vital feature that both defines and regulates their function. Drainage and removal of the acrotelm ob-

literates the ecology and severely impairs the hydrological function. The characteristic hydrology of drained cutover peatlands is described below and then examined in the context of restoration.

3. NATURE AND EXTENT OF HYDROLOGICAL CHANGE EXPERIENCED BY CUTOVER PEATLANDS

Peat harvesting typically begins with the installation of a drainage network designed to dewater the peat. The dewatering is necessary to increase the bearing capacity for extraction operations [Hobbs, 1986] and additionally removes water that must otherwise be shed in the drying process for the commercial product. Drainage causes a short-term pulse in water flow as water is released from storage, but can also lead to an increase in base flow, at least on the short-term [Conway and Millar, 1960]. Drainage ditches are typically spaced ~30 m apart [Mulqueen, 1989]. Following the initial drainage and WT lowering, drainage must occur through catotelm peat where the low hydraulic conductivity impedes drainage. Moreover, with drainage, the effective stress on the peat increases causing peat compression and consolidation [Price, 2003], reducing the average pore size and further reducing the hydraulic conductivity of the peat and its drainage [Prevost et al., 1997]. Boelter [1972] showed ditches have little effect beyond 50 m in a forested peatland and that drainage was most effective within 5 m of the ditch. This was supported by a simple model [Price, 2003] that demonstrated the drainage of uniform cutover peat was rapid near the ditch, but largely ineffective beyond 10 m.

Most peat cutting directly removes the acrotelm. Once the surface of a bog is stripped and peat is harvested, the acrotelm/catotelm divisions no longer apply. What remains is a peat matrix that initially has the relatively uniform (with depth) hydraulic attributes of the catotelm peat. The relatively small pore size of the older, more decomposed peat has a high water retention capacity, low specific yield, and low hydraulic conductivity [Price, 1996]. Consequently, with drainage and evaporative water loss, the WT falls quickly [Price, 1996], unregulated as in the former acrotelm. The consequent alterations to the cutover peat matrix has a positive feedback loop, since the lower WT facilitates aerobic decomposition to greater depths, which can increase the efflux of carbon dioxide (CO₂) by 400% [Waddington and Price, 2000]. This further reduces pore size, with the consequent effect on water retention, specific yield, hydraulic conductivity, etc. Price [1996] reported the S_y of acrotelm mosses as 0.6, diminishing to 0.2 by 50-cm depth within the acrotelm peat. The exposed catotelm peat underwent compression and oxidation, and S_y declined to 0.06 in approximately 5 years. The consequence was a more variable

WT [Price, 1996]. The higher water retention capacity of the smaller pores results in higher volumetric water content at a given pressure $\theta(\psi)$, since the smaller pore radii are able to hold more water at a higher tension (more negative pressure). Peat with a higher bulk density (hence smaller pore size) has a greater soil water retention [Boelter, 1968], resulting in the typical shape of the soil moisture-pressure characteristic curve [see Price, 1997]. The impact of the increased $\theta(\psi)$ is that more of the pores contain water, thus increasing the number and thickness of water films that conduct water flow, resulting in a higher unsaturated hydraulic conductivity at a given pressure, $K(\psi)$ [Price et al., 2008]. This increase in $K(\psi)$, coupled with stronger capillary rise, results in increased availability of water at the cutover peat surface, consequently increasing ET losses and enhancing the WT decline.

The increase in WT variability, and especially the accentuated drawdown during dry periods, has a number of important hydrological and ecological implications. As noted above, lowering the WT reduces the pressure (ψ) throughout the profile. This increases the effective stress (σ_e) at a given point below the WT, since

$$\sigma_e = \rho_T gh - \psi, \quad (1)$$

where ρ_T is the total density of the column of air, water, and peat of height, h , overlying that point, and where g is gravitational acceleration. The increase in σ_e results in “normal consolidation” of peat [McLay et al., 1992; Pyatt and John, 1989], where the volumetric change is equivalent to the amount of water lost [Terzaghi, 1943], resulting in initially rapid peat subsidence [Whittington and Price, 2006]. Price and Schlotzhauer [1999] mapped the subsidence to account for water storage change by normal consolidation (volume change equivalent to the volume of water lost) in an abandoned section of the cutover Lac St. Jean, Québec (LSJ) peatland. They found water storage change (ΔS_{tot}) was a function of pore drainage (S_y) and specific storage (S_s) times the saturated thickness of the aquifer (b) such that $\Delta S_{\text{tot}} = \Delta h (S_y + bS_s)$, where bS_s is the slope of the relationship between surface subsidence and WT, and Δh is the change in head (WT). At this site, bS_s (0.13) was greater than specific yield (0.05), underscoring the importance of including the storage change associated with peat compression (S_s) in estimates of total water storage change if the water balance is to be correctly specified [Price and Schlotzhauer, 1999]. The ability of the peatland to subside and dilate seasonally diminishes after prolonged drainage, but this mechanism is partly restored with rewetting [Shantz and Price, 2006a]. They also found the water storage change due to peat volume change over the post-snowmelt period in a rewetted site was equivalent

to the volume of water lost as RO, while in the drained site, the volume change was nil.

Peat volume change affects the hydraulic properties of the soil. *Schlottzauer and Price [1999]* and *Price [2003]* showed at LSJ that the seasonal subsidence of 8 to 10 cm caused up to a three order of magnitude decline in K_s , attributing this to collapse of the larger pores as the WT declined. This seasonal variation in K_s diminishes over time in synch with the reduced volume change over time [*Kennedy and Price, 2004*]. Long-term decrease in K_s was also noted by *Van Seters and Price [2002]* as a consequence of peat degradation. Despite the diminishing response with time, an abandoned block-cut bog near Cacouna, Québec (the Cacouna bog) exhibited surface subsidence of up to 5 cm at some locations within a single season 30 years after abandonment.

One important consequence of higher $K(\psi)$ and water retention, $\theta(\psi)$, in cutover peatlands is that evaporation remains relatively high when the WT drops, even in the absence of plants because of the greater availability of water, and the relatively effective capillary flow in the unsaturated zone near the surface. For example, *Price [1996]* found summer ET losses averaging 2.7 and 2.9 mm d⁻¹ from an undisturbed and an adjacent unvegetated cutover bog (LSJ), respectively. *Shantz and Price [2006a]* found evaporation from bare cutover peat was about 20% greater than in a relatively wet restored section of the same peatland, although this was partly attributed to the effect of mulch applied to the surface of the restored section [*Petrone et al., 2004*]. ET from the Cacouna bog increased during the summer of 2005, averaging 2.5 and 3.0 mm d⁻¹ for the time periods 19 May to 1 July and 2 July to 16 August, respectively. This increase came despite an average WT decline of 19 cm over the same time period (S. Ketcheson, unpublished data, 2008). Increased atmospheric demands over the latter portion of the summer provide the explanation, as a 26% increase in daily net radiation flux was coupled with a 5°C increase in average air temperature. Further, with the exception of the last day of measurement, the average site WT remained within the upper 60 cm of the peat. This is within the lower limit of the shrub rooting structure [*Laflleur et al., 2005*], indicating that transpiration through vascular vegetation was not substantially restricted due to physiological responses to water stress. Prolonged atmospheric demands for ET results in an eventual disconnect of the WT from the atmosphere [*Price, 1997*], at which point water is lost from soil storage in the unsaturated zone, and the WT becomes relatively stable.

4. POSTHARVEST CHANGES

As noted above, there are various mechanistic changes in the hydrological character of peatlands on the short-term

that are a direct consequence of drainage and cutting. Over the longer-term, change occurs as a consequence of soil creep [*Price, 2003*], decomposition [*Van Seters and Price, 2002*], changes to RO due to drainage ditch collapse and infilling [*Van Seters and Price, 2001*], as well as macropore activity [*Holden, 2005*], and because of changes in vegetation [*Girard et al., 2002*]. Following the abandonment of peat-cutting operations, cutover peatlands were often left without action to facilitate restoration. While this is less common nowadays, there are numerous abandoned peatlands that have solely spontaneously regenerated vegetation [*Lavoie et al., 2003*]. In addition to invasive species, those plants common in peatlands return (e.g., *Sphagnum* mosses and Ericaceae), although not in the original proportion [*Lavoie and Rochefort, 1996*]. The hydrological conditions are typically too harsh to allow substantial recolonization of *Sphagnum*, which is the dominant peat-forming plant in undisturbed bogs [*Kuhry and Vitt, 1996*]. For example, at the Cacouna bog, a manually block-cut peatland, less than 10% of the area supported *Sphagnum* mosses 25 years after abandonment [*Lavoie and Rochefort, 1996*]. This recolonization was limited to the relatively low areas adjacent to occluded ditches and where cutting was greatest, which had soil water pressure >-100 mb and $\theta > 50\%$ in the upper 5 cm [*Price and Whitehead, 2001*]. In peatlands exploited with modern (vacuum harvesting) machines, spontaneous revegetation is much less successful than in block-cut sites [*Lavoie et al., 2005b*]. *Price et al. [2003]* attributed this to the relative lack of hydrological variability in vacuum harvested sites, being uniformly poor for vegetation regeneration.

The recolonization of *Sphagnum* is related to moisture relations associated with position in the cutover landscape, typically relative elevation [*Price and Whitehead, 2001*]. The mode of recolonization is initially as isolated cushions, which in the wetter areas coalesce into a carpet. In areas less suitable, isolated cushions develop in a hemispherical form and exist as a microcosm closely tied to the moisture regime of the substrate and the influence of the Ericaceae canopy [*Price and Whitehead, 2004*]. The presence of the cushion itself affects the substrate, which compared to bare peat immediately adjacent, has a higher ψ and θ [*Price and Whitehead, 2004*]. Still, little is known about the water transfer between the peat substrate and moss cushion.

While much work has been done characterizing hydraulic properties of undisturbed peat [*Kellner et al., 2005*; *Kennedy and Van Geel, 2000*; *Silins and Rothwell, 1998*], little is known of the hydraulic properties of the mosses themselves. Water retention characteristics [*Hayward and Clymo, 1982*] and, more recently, measurements of the unsaturated hydraulic conductivity function [*Price et al., 2008*] for *Sphagnum* mosses have been published, providing the foundation for

more in-depth characterization and modeling of water fluxes within the living and poorly decomposed mosses. Access to water is essential for the nonvascular *Sphagnum* mosses that are limited to relying on typically weak capillary pressure in its hyaline cells and interstitial spaces [Hayward and Clymo, 1982] to maintain a water supply to the growing part of the plant (capitula). *Sphagnum* is relatively intolerant to desiccation [Sagot and Rochefort, 1996]; thus, a lack of available water has implications for plant metabolic processes, such as photosynthesis and soil respiration (plant matter decomposition) [McNeil and Waddington, 2003]. Strack and Price [2009] have shown that photosynthesis is strongly coupled to the wetness of the moss surface, such that plant metabolic activity increases significantly with small additions of water (e.g., dew) that are insufficient to cause a change in volumetric water content 5 cm below the surface.

During the summer of 2005, 11 naturally recolonized *Sphagnum* cushions sitting atop the cutover peat substrate at the Cacouna bog were instrumented with time domain reflectometry (TDR) probes to measure moisture content at 5-cm intervals, centered at 2.5, 7.5, 12.5, and 17.5 cm below the cushion surface. The moisture content was fairly consistent near the surface of the cushions throughout the summer months, with variability increasing substantially with depth (Figure 1). The seasonal volumetric water content (θ) fluctuated within a small range ($\pm 10\%$) in the uppermost portion of the cushion, nearest to the capitula, where the cushions were driest. In contrast, the greatest range of θ ($\pm 60\%$) was exhibited across the 15- to 20-cm interval, where water was the most abundant, a trend evident in most of the cushions investigated (Table 1). A similar moisture profile was observed by McNeil and Waddington [2003].

An investigation of cushion size and its influence on moisture dynamics was conducted, lumping the cushions

Table 1. Seasonal Moisture Variability Across Four Depths Within Naturally Regenerated *Sphagnum* Cushions at the Cacouna Bog^a

Depth Interval ^b (cm)	Standard		Maximum θ	Minimum θ	Range
	Mean θ	Deviation			
0–5	0.19	0.012	0.28	0.18	0.10
5–10	0.23	0.025	0.38	0.16	0.22
10–15	0.33	0.071	0.65	0.22	0.43
15–20	0.48	0.134	0.79	0.19	0.60

^aData are for time period 8 June to 18 August 2005.

^bFor each depth interval, $n = 72$.

(*Sphagnum capillifolium*) according to approximate cushion volume (mean cushion size shown in brackets), resulting in three groups: largest ($\sim 125,000 \text{ cm}^3$), mid-sized ($\sim 36,000 \text{ cm}^3$), and smallest ($\sim 13,000 \text{ cm}^3$). On average, the smallest-sized cushions had the highest moisture content (34%) compared to the larger sized (30%) and mid-sized (30%) cushions, though no direct relationship between cushion size and θ could be established. The least amount of moisture variability occurred in the uppermost portion of the cushion from each group, with increasing variability with depth. The smallest cushions exhibited the most variability overall, reflected in a comparatively large standard deviation with depth (Figure 2). The maximum and minimum θ values observed (79 and 16%, respectively) occurred within the smallest- and mid-sized cushion groupings, respectively.

Hummocks within natural peatland (i.e., hummock-hollow) landscapes can become isolated from the surrounding hydrologic system once more than 8 cm of peat has been deposited beneath the hummock, as this weakens the capillary rise to mosses near the top of the hummock [Bellamy and Rieley, 1967]. A similar restriction may apply to

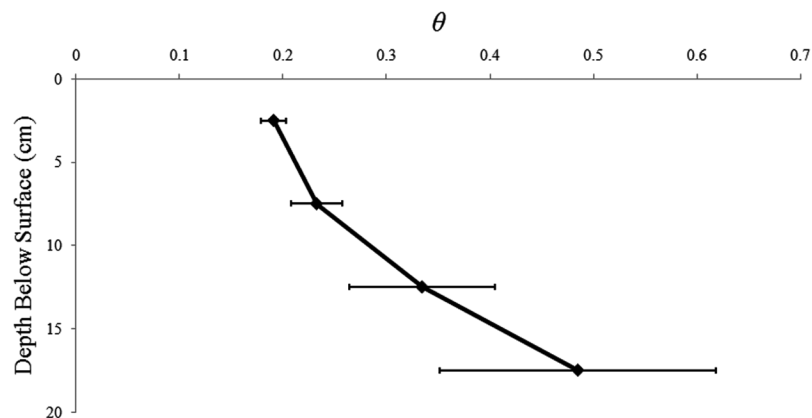


Figure 1. Average θ values within 11 naturally regenerated cushions at the Cacouna bog for the time period 8 June to 18 August 2005. Error bars indicate standard deviation ($n = 72$ for each depth).

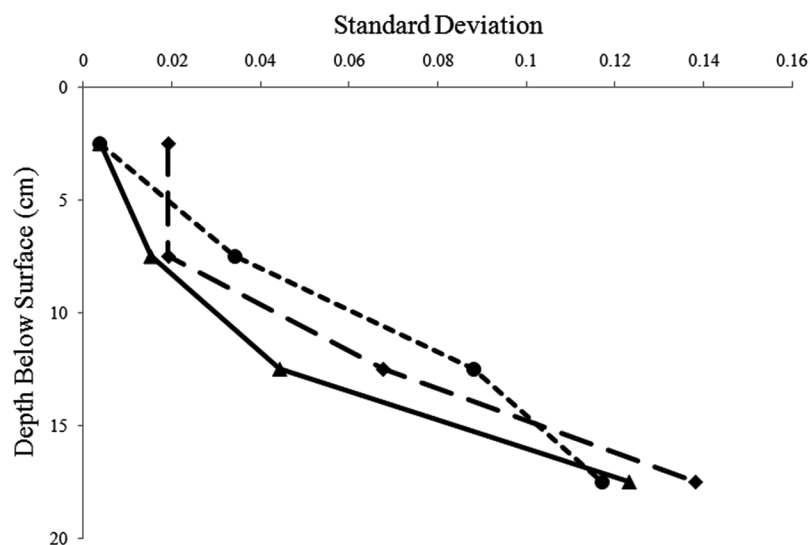


Figure 2. Variability in θ with depth for the largest (solid line; $n = 25$), mid-sized (large dashed line; $n = 26$), and smallest (small dashed line; $n = 21$) size cushion groupings in the Cacouna bog for the time period 8 June to 18 August 2005.

recolonized *Sphagnum* cushions. Considering the very low values of unsaturated hydraulic conductivity within living and poorly decomposed mosses [Price *et al.*, 2008], such as those comprising the newly formed cushions, regular water exchanges between the cutover peat substrate and the overlying moss cushions may occur only periodically. The abrupt change in pore size at the substrate-moss interface may create a capillary barrier effect [cf. Kennedy and Van Geel, 2000], where water exchange cannot occur until the pressure in the cutover peat is at or near zero (i.e., near saturation). Given the highly variable moisture content at depth within the recolonized cushions at the Cacouna bog and the small fluctuations of θ near the moss capitula, the upper and lower parts of the cushion may be only weakly coupled, so vertical extension (growth) is limited, and lateral spreading and coalescing of cushions is more favorable.

Schouwenaars and Gossen [2007] used a model to demonstrate that a thin layer of recolonized *Sphagnum* can be well-supplied by water, but once it grows to 5–15 cm thick, it is more susceptible to water stress because of the ineffective delivery of water to the moss from the substrate. However, at greater thicknesses, the water storage capacity of the thicker moss is sufficient to maintain an adequate water supply. Price (unpublished results) used Hydrus 1-D to simulate water flux in a moss layer subject to evaporation with a WT depth of 30 cm, using the hydraulic parameters presented by Price *et al.* [2008]. The results indicate that the mosses were unable to sustain evaporation at the (imposed) potential rate of 5 mm d⁻¹ for more than 1 h, eventually equilibrating

at about half that rate. The five order of magnitude drop in hydraulic conductivity with drainage results in resistance to water flow in the upper moss layers. In addition to the liquid flux, there is a vapor flow, although this amounts to <2% of the former [Price *et al.*, 2009].

Vascular plants, especially ericaceous shrubs, more readily recolonize cutover sites, thriving in areas where ψ is much lower than -100 mb [Farrick, 2008]. Further, shrubs cleared from the original peatland surface were typically piled in the center of trenches during the abandonment process in block-cut peatlands, forming large seed banks and enhancing Ericaceae-dominated recolonization of manually cutover peat surfaces [Girard *et al.*, 2002]. Girard *et al.* [2002] reported that the spontaneous revegetation of the Cacouna bog by vascular plants resulted in 90–100% surface cover, while *Sphagnum* mosses recolonized less than 10% of the surface area.

Water availability and fluxes within cutover peatlands are influenced by the high abundance and distribution of shrubs [Farrick, 2008]. The presence of the shrub canopy and subsequent development of a leaf litter layer results in increased interception, transpiration, and altered peat surface evaporation dynamics [Crockford and Richardson, 2000; Dingman, 2002], consequently impacting ψ and θ in the upper portion of the peat substrate. Ψ below -100 mb results in the desiccation of *Sphagnum* mosses as water is removed from storage within hyaline cells [Hayward and Clymo, 1982]; however, the vascular shrubs are not only able to extract water and thrive under conditions with ψ much lower than this

[Farrick, 2008], but their presence might prevent extremely low ψ from occurring. In a lab investigation using peat monoliths extracted from the Cacouna bog, Farrick [2008] found that, under a falling WT, monoliths with shrubs present maintained $\psi > -100$ mb throughout the sampling period (85 days), while monoliths of bare peat (also from the Cacouna bog) subjected to similar conditions exceeded the $\psi < -100$ mb threshold after only 57 days. Lower net radiation under a shrub canopy cover and the presence of a thin litter layer (consequently reducing ET) accounted for the reduced water losses (thus higher ψ) from the shrub-covered peat surface. These reductions in water losses were able to offset the interception (I) from both the canopy ($I = 33\%$ of precipitation) and the leaf litter ($I = 7\%$ of precipitation), and Ericaceae were deemed beneficial, from a hydrological perspective, in the successful reestablishment of a *Sphagnum* cover [Farrick, 2008]. The benefits of an ericaceous cover, however, may be partially offset due to the potential interference of the leaf litter on the establishment of the incipient moss diaspores.

RO has been found to represent a substantial loss of water from disturbed peatlands. Van Seters and Price [2001] found in an old abandoned bog (the Cacouna bog) that RO losses corresponded to 18% of precipitation during the study period (2-year average; snow excluded). A snow survey and snowmelt RO study also at the Cacouna bog (March/April 2006) found average snow depths of 67–81 cm, with snowmelt waters accounting for approximately 109 mm of RO over a 29-day melt period (S. Ketcheson, unpublished data, 2008). During the following summer (19 May to 16 August 2006), RO from the same site was 73 mm (S. Ketcheson, unpublished data, 2008). The relatively short (29 days) snowmelt period resulted in 50% more RO in comparison to the 89-day summer study period. Thus, the snowmelt period represents a substantial proportion of the annual RO from a disturbed system and should be included in such estimations.

Typically, increases in RO, peak flows, and base flow relative to natural conditions are observed following drainage [Price et al., 2003]. However, contradictory hydrological responses, such as decreased peak flow due to increased storage capacity in drained soils between storms, have also been observed [Burke, 1975]. Over the long-term, permanent structural changes can take place following WT lowering including soil-pipe formation and macropore development, which increases throughflow and correspondingly reduces overland flow [Holden and Burt, 2002]. Further, in a study comparing data from the 1950s to the early 2000s, Holden et al. [2006] identified long-term changes to the hydrology of disturbed (drained) catchments that were not apparent in the few years immediately following drainage [Conway and Millar, 1960].

5. HYDROLOGICAL PROCESSES RELATED TO SYSTEM RESTORATION

Given the desire to recolonize cutover peatlands with peat-forming *Sphagnum* moss, a variety of techniques including ditch-blocking, surface scarification, shallow excavation, low bunds, etc. are used to increase surface water detention [Price et al., 2003]. The application of straw mulch has been shown to reduce evaporation [Petroni et al., 2004] and thereby increase the surface wetness and consequently the survival and growth of reintroduced *Sphagnum* mosses [Price et al., 1998].

An essential first step is the blockage of drainage ditches. This provides wetter conditions more suitable for nonvascular mosses. Blocking the drainage network at the Cacouna bog (October 2006) resulted in a rise in the average seasonal WT level by nearly 30 cm and made the substrate in previously marginal areas more favorable to *Sphagnum* mosses through increased ψ and θ at the cutover surface. However, previously established *Sphagnum* cushions in low areas were flooded (S. Ketcheson, unpublished data, 2008). Following the blockage there were substantial reductions in RO efficiency (percentage of precipitation produced as stream discharge). The average RO efficiency during the summer months of 2007 (following ditch blocking) was reduced to 10% from a 2-year average (2005 and 2006) preblockage efficiency of 23%.

No comparative studies of water budgets of undisturbed and drained sites including snowmelt RO are available, to our knowledge. However, snowmelt RO from both drained and restored sections of cutover peatland at Bois des Bel (BdB) peatland (also near Cacouna, Québec) amounted to 79% of the annual RO, but in the post-snowmelt period, the restored section lost only 25% of that experienced by the drained site [Shantz and Price, 2006b]. During snowmelt, the RO at both sites was dominated by surface water inputs (~85%), but surface water input declined to about 60% later in the summer [Shantz and Price, 2006b]. During the summer period, the restored site had wetter antecedent conditions; thus, RO was more responsive to rainfall, being larger and having a shorter time lag.

Rewetting at BdB significantly raised the WT, resulting in θ and ψ conditions suitable for the regeneration of a plant cover, notably with *Sphagnum* mosses. Rewetting restored some of the previous peat volume within 1 year, as the peat dilated in accordance with the higher pore water pressure, and consequently, the ability to change volume seasonally increased in response to WT variations [Shantz and Price, 2006a]. The greatest volume change within each layer occurred in the upper 30 cm (4.8–9.6%), while the 30- to 150-cm layer experienced 1.1–2.4% change over 3 years of

monitoring. The unrestored section had <0.3% total volume change. At the restored site, the volume change was accompanied by a seasonal reduction of K_s of nearly one order of magnitude. Despite the growing layer of poorly decomposed mosses and nonvascular plants, the WT regularly falls below the cutover peat surface [Shantz and Price, 2006a], the CO_2 efflux continues to be high, and the essential water regulation function of an acrotelm are not yet present.

While site reconfiguration (blocking ditches, bunds, etc.) is effective when used in combination with straw mulch application, the use of companion species to nurse *Sphagnum* also has a benefit [Lavoie et al., 2005a], as they provide shading. McNeil and Waddington [2003] found *Sphagnum* cushions (at the Cacouna bog) with the Ericaceae cover removed performed poorly, and it was assumed that shading was responsible. Price (unpublished data) used Hydrus 1-D (as noted previously) to model unsaturated flow in *Sphagnum* and found that splitting the potential evaporation demand between soil evaporation and transpiration resulted in higher ET losses, but accessed water from deeper within the cushion and resulted in a higher θ at the surface than if plants were absent (no transpiration).

Kennedy and Price [2004] developed a numerical model (FLOCOPS) to simulate surface elevation, WT, and soil moisture and pressure (at 5 cm below the surface) of a partly

restored peatland (LSJ). They found the simulations to be most sensitive to the water retention and consolidation characteristics. A good fit was made to surface elevation, WT, and soil moisture, but only a reasonable fit to soil-water pressure, likely because of the difficulty in accounting for its high spatial variability [Shantz and Price, 2006a]. The analysis also revealed that the reduction in K_s due to compression resulted in less efficient transport of water to the surface in response to evaporation. This can reduce the evaporation loss, but increase the variability in θ . More variable θ increases soil respiration, thus carbon efflux [Waddington et al., 2002]. However, in general, the compressibility of peatlands, including (but to a lesser extent) cutover peatlands, results in synchronous rise and fall of the surface and WT, thus maintaining higher levels of saturation than would otherwise be the case [Whittington and Price, 2006], with a consequent reduction in CO_2 loss [Strack and Waddington, 2007].

6. SUMMARY AND CONCLUSION

The changes in WT, ET, RO, and net carbon exchange caused by drainage, abandonment, and restoration are summarized in a conceptual model (Figure 3). In the undisturbed state, the WT is relatively high and stable, since it is regulated by the acrotelm. Consequently, methane (CH_4) fluxes

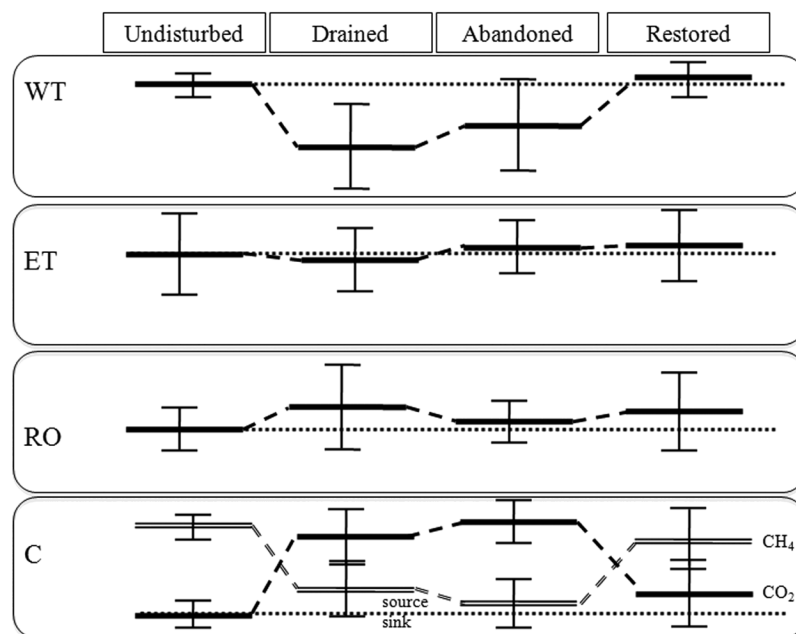


Figure 3. Changes in water table (WT), evapotranspiration (ET), runoff (RO), and net carbon exchange (C) relative to the undisturbed state. Vertical bar represents relative variability. Small dashed line represents natural levels, while larger dashed lines represent the transition between disturbance stages (slope not reflective of time for transition). Adapted from Van Seters and Price [2002] and Waddington and Price [2000].

to the atmosphere are high, while decomposition of the peat is low, resulting in a net atmospheric CO₂ sink [Gorham, 1991]. RO from bogs is quite variable, being highly dependent on the antecedent condition. Similarly, ET is highly variable, since *Sphagnum* relies solely on capillary transport of water to the surface, which is poor when the WT is low. Drainage lowers WT, and the decrease in S_y caused by peat consolidation increases WT variability. The drainage network is efficient, and water flows are transmitted quickly, increasing the flashiness of the hydrograph (variability). ET may drop slightly with the loss of vascular plants, but higher water retention strengthens the capillary transport of water, so bare-soil evaporation satisfies the potential ET demand; thus, the relative ET rate is similar to the undisturbed condition. ET variability is lower because capillary transport maintains water availability at the evaporating surface. Plant production (net ecosystem productivity) is eliminated completely (i.e., zero) following the removal of vegetation at mined sites [Waddington and Price, 2000]. The lower WT increases the depth of the aerobic zone and decreases soil moisture content, subsequently increasing soil respiration and decreasing CH₄ production, resulting in a large increase in net CO₂ loss to the atmosphere, and reduced CH₄ fluxes [Waddington and Price, 2000]. Over longer time periods in abandoned cutover bogs, WT will rise as the drainage network loses efficiency due to infilling and occlusion, which also reduces RO. However, WT variability is still high, since ET is the primary water loss, and it (ET) remains high, perhaps even increasing because of the spontaneous regeneration of ericaceous plants. Restoration measures to raise the WT often result in flooding, which is highly spatially variable but temporally less variable than in the drained and abandoned state because of the increased water retention by dams and bunds. The higher WT results in wetter antecedent conditions, which can increase RO and will increase RO variability. The RO efficiency, however, will be dependant upon antecedent conditions (capacity to retain additional water on-site) and event-based precipitation dynamics. CH₄ production increases in the wetter conditions following restoration, and recolonization of vegetation increases plant production and reduces net CO₂ losses to the atmosphere. ET in this wetter system may change little as the capillary transport in the drained and abandoned state was relatively efficient, although partial flooding of lower-lying areas will consequently increase ET, as open water is a freely evaporating surface. The return to a moss-dominated system may increase ET variability, as the newly emerging mosses with their huge range of $K(\psi)$ begin to control water delivery to the evaporating surface. In addition, the much wetter environment will likely cause a vegetation shift away from vascular vegetation, reducing transpiration losses from the

system, which is typically quite consistent. Over the long-term, once the WT resides in the newly developed moss layer, other system functions will return to a state similar to the undisturbed condition.

Cutover peatlands function very differently than undisturbed ones because stripping of the acrotelm during peat-cutting operations removes the essential self-regulating mechanisms characteristic of peatlands, including the ability to regulate WT and the water supply to vascular and nonvascular plants. Drainage ditches that lower the WT increase peat compression by normal consolidation and enhanced decomposition. This increases the WT variability and the water retention of cutover peat so that artificially or spontaneously introduced *Sphagnum* mosses have a limited ability to access water stored in the cutover peat. The presence of mosses does, however, increase the wetness of the substrate, which, if sufficient, will support the initiation and expansion of *Sphagnum* cushions that may eventually coalesce into a carpet. Restoration measures to detain water on-site for longer duration are effective and, coupled with reintroduction of plant materials, can begin to return ecohydrological functions to the peatland. Few, if any, of such restoration attempts have returned all such functions; presumably, this will have to wait until a layer with properties similar to the acrotelm is developed.

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