

An evaluation of the water balance and moisture dynamics within *Sphagnum* mosses
following the restoration (rewetting) of an abandoned block-cut bog

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis,
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Abstract

Artificial drainage networks established throughout peatlands during the peat extraction process often remain active following abandonment, maintaining a water table relatively far from the surface of the peat and hindering the survival and reestablishment of *Sphagnum* mosses. Since cutover peatlands are characterized by low (negative) soil water pressures, sufficient internal water storage and balanced water fluxes are critical for the physiological function of spontaneously regenerated *Sphagnum* mosses. The relative importance of water exchanges between spontaneously regenerated *Sphagnum* moss cushions and their surroundings are addressed through investigation of the sensitivity of moss moisture dynamics to a range of environmental variables. Precipitation waters are poorly retained within the cushions, which indicated that rain event water can only be relied upon by the mosses for a short period of time. An imbalance between water inputs and losses from moss cushions identified that additional (small) sources of water, such as dewfall and distillation, are potentially important for physiological processes under dry conditions, common in disturbed peatland ecosystems.

As an initial restoration effort, rewetting of the peatland by blocking drainage ditches consequently reduced the runoff efficiency and caused the site-average water table to rise by 32 cm. Higher water tables and a blocked drainage network created conditions more favourable for *Sphagnum* survival through increasing the moisture content and soil-water pressures within the remnant peat deposit. The hydrologic connectivity between moss cushions and the remnant peat was strong when conditions were wet and the water table was within 30 cm of the surface of the cutover peat but weakened as conditions became drier, as reflected by weakened upward hydraulic gradients in the unsaturated zone below the moss cushions. Runoff variability increased following rewetting, and displayed a greater dependence upon antecedent conditions (capacity to retain additional water on-site) and event-based precipitation dynamics. Evapotranspiration rates were 25% higher following rewetting (3.6 mm day^{-1}) compared to pre-restoration ET rates of 2.7 mm day^{-1} . Total storage changes were restricted following rewetting, as a factor of the reduced runoff losses limiting

water table drawdown, thereby constraining peat compression and preventing undue drying of the unsaturated zone.

Changes to the system hydrology following rewetting of the peatland by blocking drainage ditches created conditions more favourable for *Sphagnum* survival through increasing the moisture content and soil-water pressures within the remnant peat deposit; although restoration efforts should aim to constrain water table fluctuations to within the upper 30 cm.

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Dedication

This thesis is dedicated to Jenna.

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Note: Sections 4.0 and 5.0 within this thesis are written as independent manuscripts for submission for publication. As such some of the content within the manuscripts repeats previously stated information.

1.0 Context

Peatlands cover approximately 1.136 million km², or 12% of Canada's total land area (Tarnocai, 2006). Exploitation of peatlands for horticultural peat and peat fiber is an important industry in Canada (Keys, 1992), ranking third among the largest peat producing countries world-wide (Bergeron, 1994). Drainage networks established throughout peatlands during the peat extraction process often remain active following abandonment, maintaining a water table relatively far from the surface of the peat (Van Seters and Price, 2001). Consequently, consolidation and enhanced peat oxidation cause changes in the physical properties of the peat, including a more uniform pore structure, higher bulk density, lower saturated hydraulic conductivity and higher water retention capacity, resulting in large water table fluctuations and low (negative) soil-water pressures (Van Seters and Price, 2002). Such harsh physical and hydrological conditions limit the successful recolonization of *Sphagnum* mosses, the most dominant peat-forming plant genus (Kuhry and Vitt, 1996). Consequently, harvested peatlands do not readily recover their hydrologic and ecological (peat-forming) function (Price et al., 2003), making restoration efforts of abandoned sites crucial in order to reduce the impact of peat harvesting on the Canadian landscape.

Water management approaches, such as site rewetting by blocking drainage ditches, can accelerate the restoration of cutover sites by improving the hydrological conditions within the peat substrate (Price et al., 2003). Ombrotrophic bogs are devoid of surface and groundwater inputs typically resulting in a large summer water deficit (Ingram, 1983). In drained peatlands, water loss from drainage coupled with the poor water storage capacity of the remaining peat magnifies the impact on plant-water supply (Lavoie et al., 2005). Price et al. (2003) state that blocking the drainage ditches can significantly restore the summer water budget by retaining more rainfall and snowmelt water. Evapotranspiration can then be sustained by capillary rise from the shallower water table rather than depletion of soil water reserves in the unsaturated zone (Price et al., 2003). This can help ensure sufficiently wet conditions for *Sphagnum* colonization and survival (Price and Whitehead, 2001). However, no standard management prescription for the restoration of cutover sites has yet been developed because each site presents unique challenges (Price et al., 2003).

For *Sphagnum* to successfully recolonize a bare cutover peat surface, it is necessary to have a high and stable water table (within approximately 40 cm of the peat surface), high soil moisture (greater than 50%) and high soil water pressure (greater than -100 mb) (Price and Whitehead, 2001). However, the effect of site rewetting on the physical properties of the remnant peat deposit is not known. Shrinkage, compression and oxidation are the commonly identified volume change mechanisms in peatlands, occurring as a consequence of water table lowering for harvest (Eggelsmann, 1976; Schothorst, 1977). Oxidation is an irreversible process involving the mineralization of carbon to water and CO₂; however shrinkage and compression are the dominant volume change mechanisms for peat soils, accounting for 96-97% of seasonal volume change in a cutover peatland in the Lac-Saint-Jean region of Québec (Kennedy and Price, 2005). Below a material's critical stress level, shrinkage and compression are reversible, though in extremely dry conditions the peat can undergo a permanent structural change that will only partially recover upon rewetting (Kennedy and Price, 2005). Site-scale rewetting experiments documenting the extent of this soil volume recovery in cutover peat deposits are required to quantify the reversibility of these processes. More importantly are the implications of these structural changes on the movement of water and nutrients through the saturated zone, and the availability of water at the top of the unsaturated zone where *Sphagnum* mosses rely upon capillary rise to supply water to their photosynthesizing capitula. Understanding the water fluxes across the interface between the cutover peat surface and the base of the incipient moss cushions will provide valuable information towards our knowledge of the water sources that the moss cushions rely upon. Furthermore, quantifying the components of the water balance, especially the magnitude and distribution of the water losses, for a restored peatland will provide an understanding of the implications of restoration efforts on the movement, and ultimately the availability, of water for newly formed *Sphagnum* mosses. Due to lack of experience, little is known about the implications of restoration efforts on the suitability of restored sites for *Sphagnum* moss regeneration. This is crucial to aid in refining restoration efforts at cutover sites in the future. As such, the specific objectives of this thesis are to:

1. Compare the full water balance of an abandoned block-cut bog prior to and following rewetting;

2. Characterize the impact of peatland restoration (rewetting) on the hydrological conditions of the remnant peat;
3. Address the implications for *Sphagnum* moss recolonization and peatland restoration;
4. Identify and characterize water sources for, and distribution and variability within, newly formed *Sphagnum* moss cushions

2.0 Background

2.1 Cutover Peatlands

Location

Peatlands located at temperate latitudes in Canada are susceptible to anthropogenic disturbances as a consequence of their economic value due to their close proximity to markets (Price and Ketcheson, 2009). In North America, the extraction of peat for horticultural use has been occurring since the beginning of the 20th century (Lavoie and Rochefort, 1996). Since this time, growing industrial harvest and agricultural development pressures within southern Québec have resulted in an increasingly rare occurrence of undisturbed peatland ecosystems (Lavoie and Rochefort, 1996). As such, post-extraction abandoned peatlands are becoming more abundant within areas of intense peat production, such as the Saint Lawrence Lowlands, emphasizing the need for efficient restoration efforts.

Peat Extraction Techniques

Block-cut Method

The development and evolution of peat harvest techniques has largely been a reflection of the technology available at the time of harvest. The extraction of peat by manual block-cutting dominated early horticultural peat harvesting (Price et al., 2003). This technique involved the removal of unwanted vascular vegetation and upper *Sphagnum* layers (skag) from the surface of the peat after site drainage, followed by the extraction of peat blocks using shovels, creating trenches approximately 10 metres wide and up to 200 metres long. The peat blocks were stacked for drying on an uncut strip of peat (balk) 2 – 4 metres wide that separated two adjacent mining trenches (Girard, 2000). Once the extraction of a peat layer was complete the next series of peat blocks were dug from the residual peat deposit, repeating the extraction process 4 – 5 times within a trench, before finally abandoning the trench and restarting the same process in an adjacent, unharvested area (Girard, 2000). The skag was then piled in the centre of the abandoned trench, where it later settled and decomposed to form a convex shape within the trench (Lavoie and Rochefort, 1996). The resultant post-harvest surface profile is characterized by alternating sequences of baulks, raised approximately 0.50 – 1.0 metre above the adjacent,

lower-lying trenches. Although manual block-cutting is no longer used commercially, abandoned block-cut peatlands are abundant in eastern North America (Lavoie et al., 2003).

Vacuum Method

At the end of the 1960s, the introduction of vacuum machines resulted in a rapid shift from the manual block-cutting technique to a more mechanized peat extraction method and the abandonment of most block-cut peatlands (Girard, 2000; Lavoie and Rochefort, 1996). By the mid-1970s, mechanised extraction became the dominant method of peat harvest in North America, greatly increasing the scale that this extraction can occur (Price et al., 2003) and intensifying the hydrological limitations on plant recolonization (Money, 1995). To facilitate the use of tractor-drawn vacuum machines over the surface of the peat, drainage ditches must be deep (0.7 – 1.0 m) and the surface cambered to enhance runoff (Price et al., 2003). The most common mechanised peat extraction technique is milled harvesting, where the surface is milled and harrowed to dry the peat fragments, which are then removed from the surface by large vacuum machines (Price et al., 2003). The regeneration of peatlands harvested in this manner is very slow, with the natural recolonization of *Sphagnum* rarely occurring on the cutover surface (Lavoie and Rochefort, 1996). Following decades of mass peat harvesting using the vacuum technique, an increasing number of peatlands in North America are being abandoned (Lavoie and Rochefort, 1996). Spontaneous revegetation of cutover sites by plants characteristic of natural bogs, including *Sphagnum* species, has been documented (Lavoie et al., 2003; Rochefort et al., 2003; Soro et al., 1999); however, this recolonization is much more common in block-cut peatlands than in vacuum harvested sites (Lavoie et al., 2003). This is because the presence of viable seed and plant source material is greater in block-cut peatlands and there are a large variety of micro-habitats that provide at least some suitable locations for spontaneous *Sphagnum* regeneration (Price et al., 2003). Lavoie and Rochefort (1996) estimated that this was restricted to about 10% of the Cacouna (block-cut) peatland in Québec.

Price and Whitehead (2001) predict that the legacy of past peat extraction will remain far into the future, due in part to the limited effort towards site restoration following abandonment. Without the implementation of suitable site restoration techniques, site improvement through the reestablishment of natural hydrological functions, even within the relatively more favourable block-cut sites, will take a very long time (Van Seters and Price, 2001; Van Seters and Price, 2002). Given the limited natural recolonization of *Sphagnum* species on block-cut peatlands and

the increasing presence of cutover vacuum harvested peatlands throughout North America, efficient site restoration efforts are crucial.

Abandoned Site Characteristics

Physical and Hydrological Properties

Peatlands are subject to drainage during peat extraction, resulting in subsidence due to shrinkage, oxidation and compression, producing cutover sites characterized by a more decomposed and compacted peat substrate (Price and Whitehead, 2001) with a smaller average pore diameter, hence high water retention capacity and low specific yield (Schlotzhauer and Price, 1999). Subsequently, seasonal water table fluctuations are large (Van Seters and Price, 2002), with atmospheric demands for evapotranspiration largely being met by water from storage, which exacerbates low soil-water pressures and low soil-moisture contents of the unsaturated zone throughout the summer months. Because peat is highly compressible, owing to a typically high water content, volume changes can be more than ten times that of swelling clay soils (Schlotzhauer and Price, 1999). Seasonal peat volume changes have a direct effect on the hydraulic parameters and relationships among hydraulic conductivity, porosity and water storage capacity (Schlotzhauer and Price, 1999). An alteration of these parameters has profound consequences regarding the availability of water for non-vascular *Sphagnum* mosses, as they directly influence the movement of water through the peat and dictate the hydrological characteristics of the peatland. These characteristics are common between block-cut and vacuum harvested sites following abandonment (Price et al., 2003). In a comparison of the conditions within an abandoned vacuumed site and those within an abandoned block-cut site, Price et al. (2003) generally found similarities in regards to bulk density, storativity, hydraulic conductivity and water retention characteristic changes due to site degradation. Management of an abandoned cutover peatland will result in the alteration of the hydraulic parameters following water table reestablishment; however, this response is poorly understood (Holden, 2005). Given the similarity in the hydraulic structure of the peat, the processes occurring within cutover sites and their response to rewetting, regardless of harvest technique, are likely similar.

Both of these types of disturbed systems have had the uppermost surface layer of the peat soil, the acrotelm, removed during the extraction process. The acrotelm is defined as the zone that exists above the average minimum WT (Ivanov, 1953). It is composed of living, dead and

poorly decomposed plant material and is the principal site of matter and energy exchange in natural peatland systems (Ingram, 1978). The typical two-layer (diplotelmic) hypothesis developed by Ivanov (1953) breaks down in disturbed systems that have had the acrotelm removed, as they now represent haplotelmic systems, meaning only the lower layer of peat soils, the catotelm, remains. This deeper layer differs from the acrotelm in nature, as it has less abrupt variation in its physical properties, notably its smaller pore sizes. As such, it has a drastically reduced capacity to regulate WT variability and water storage, surface water runoff, capillary rise and evapotranspiration rates, producing a water regime atypical from natural systems and harsh hydrological conditions for recolonizing non-vascular mosses following abandonment. Furthermore, abandoned sites that have yet to recolonize with vegetation are susceptible to soil instability, specifically in the form of frost heaving, which inhibits moss recolonization (Groeneveld and Rochefort, 2005). Restoration efforts have failed in some abandoned vacuum harvested peatlands due in part to the instability of the surface caused by frost heaving (Quinty and Rochefort, 2000). The presence of plants, however, reduces the impact of frost heaving in abandoned peatlands by reducing the number of freeze-thaw cycles and limiting the unfrozen water content of the peat soils during the spring thaw (Groeneveld and Rochefort, 2005). Since abandoned block-cut peatlands are typically more readily recolonized by vegetation, they are less likely to be negatively impacted by surface instability (via frost heaving) than abandoned vacuum harvested sites.

Topography

The baulk – trench topography characteristic of block-cut sites creates spatial variability in the substrate conditions and distinguishes these peatlands from those harvested using the vacuum technique, which are relatively flat (with the exception of the drainage ditches that comprise a proportionately small area of the whole site, and the slightly cambered surface). Extremely harsh (persistently dry) conditions exist on raised baulks and more favourable conditions typically exist within the lower-lying trenches, as they are closer to the water table (Price and Whitehead, 2001). Vacuum harvested sites exhibit fairly uniform conditions that are generally worse (i.e., less moisture, lower soil-water pressure) than the conditions within a block-cut site (Price et al., 2003), thus resulting in the characteristically poor natural regeneration of *Sphagnum* mosses. As a consequence, post-extraction restoration efforts on vacuumed sites typically rely on constructed open water reservoirs and polders to increase the site water storage

capacity, thereby improving the site-wide hydrologic conditions (LaRose et al., 1997; Spieksma, 1999). This desirable increase in site storage capacity is facilitated at block-cut sites by the presence of the wide trenches created during the peat extraction process that are capable of retaining large volumes of water within the site with efficient blocking of drainage ditches. The construction of dams to block drainage ditches at block-cut sites is simplified by the presence of the raised baulk structures that run perpendicular to primary drainage ditches and along the periphery of trenches. The termination of the baulk at the primary drainage ditch provides a narrow point to construct a peat dam, with water retention assisted by the baulks, as they act as efficient flow barriers. The result of this is a series of surficially disconnected water reservoirs across the site.

In spite of these differences between vacuum and block-cut peatlands, comparable processes occur within the peat substrate and similar restoration goals are shared, so restoration principles should be common to both types of disturbed ecosystems. However, despite sharing the same fundamental problem of restricted water availability, recent work by Price et al. (2003) has identified problems in developing standard management recommendations for site restoration efforts, due to site-specific challenges. An increased understanding of the fundamental processes occurring within cutover peatlands and how these change following site management approaches, such as rewetting, is essential to the improvement of current restoration techniques. Additionally, this will aid in improving the applicability of new restoration techniques to a wider variety of cutover sites (e.g., block-cut and vacuum harvested).

Vegetation

Abandoned sites allowed to naturally regenerate typically favour the growth of vascular species better suited for the deeper water table and moisture deficiency of the uppermost peat layer, including Ericaceous shrubs (e.g., Labrador tea (*Ledum groenlandicum*), leatherleaf (*Chamaedaphne calyculata*), sheep laurel (*Kalmia angustifolia*)), and tree species (e.g., tamarack (*Larix laricina*), black spruce (*Picea mariana*), grey birch (*Betula populifolia*)) (Lavoie and Rochefort, 1996). A few variables, such as water level and peat thickness, can be used to provide a decent prediction for the revegetation of abandoned peatlands (Girard, 2000). Within the trenches of an abandoned block-cut site (the Cacouna bog), Lavoie and Rochefort (1996) observed greater than 50% plant cover by spontaneous revegetation of typical peatland species twenty years after abandonment; findings that concurred with over 90% of all abandoned block-

cut sites surveyed throughout central and eastern North America. Conversely, the harsh, dry conditions present in cutover sites limits the successful spontaneous recolonization of non-vascular *Sphagnum* mosses, as the mosses are not able to generate the capillary pressure necessary to access water from within the substrate (Price and Whitehead, 2001). Girard (2000) observed that only 10% of the total harvested area at the Cacouna bog had been recolonized by *Sphagnum* species, with the growth being largely limited to the lowest lying portions of the trenches. Based on vegetation surveys in Québec, just 17.5% of the trenches and 0.1% of the baulks of abandoned block-cut peatlands had a *Sphagnum* cover of more than 50% (Lavoie and Rochefort, 1996)). Additionally, unmanaged sites harvested using the vacuum technique have conditions generally harsher than those within block-cut sites, resulting in an increased restriction of natural recolonization of *Sphagnum* mosses (Lavoie et al., 2003).

2.2 Peatland Restoration and Hydrology

Rewetting is a site management approach implemented in cutover peatlands during the restoration process that involves blocking the site drainage ditches, thereby altering water distribution and site drainage dynamics and changing the site hydrology. These changes have direct implications for the components of the water balance, inevitably impacting the character and magnitude of water losses from the site. The water balance, or water budget, is a water accounting tool which allows for an evaluation of the quantity of inputs and outputs for a system (e.g., study site). Simply stated, the water balance can be written as

$$INPUTS = OUTPUTS \pm \Delta S \quad \text{Equation 2-1}$$

where ΔS is the change in soil (water) storage within the system. More specifically, within bog peatlands which are typically devoid of groundwater exchanges, the water balance can be stated as

$$P = ET + R \pm \Delta S + \varepsilon \quad \text{Equation 2-2}$$

where P is precipitation, ET is evapotranspiration, R is runoff and ε is the residual term. The water balance provides a good indication of the relative importance of hydrological processes and their spatial variation throughout the site (Van Seters and Price, 2001). However, full water balance studies of managed (rewet) cutover bogs are rare. Rewetting the site involves blocking the drainage ditches (affecting R), altering site water distribution (affecting ET) and increasing

site water storage capacity (affecting ΔS and ET), hence changing the site hydrology. These changes can be quantified by evaluating the individual components of the water balance prior to and following rewetting, thereby quantifying the altered distribution and magnitude of water losses from a site as a consequence of rewetting.

Evapotranspiration

The term evapotranspiration (ET) represents the composite loss of water to the air from all sources (Oke, 1987). As the moisture content of the unsaturated zone increases, water availability at the surface increases, and the actual evapotranspiration rate approaches the potential rate (Oke, 1987). ET typically represents the largest water loss from harvested peatland systems (Price, 1996; Van Seters and Price, 2001), with the rate of ET losses being controlled by the water table level and vegetation cover for a given energy supply (Lafleur and Roulet, 1992). Van Seters and Price (2001) found that ET losses from an abandoned cutover bog represented an average of 88% of post-snowmelt water losses over two years. Further, ET rates were nearly twice as high from surfaces with a water table closer to the surface (-35 cm) than surfaces with a water table level further from the surface (-80 cm) within the same study site (ET rates of 3.6 and 1.9 mm day⁻¹, respectively). The Priestley and Taylor (1972) combination method, commonly used in estimations of daily equilibrium ET, accounts for the effect of spatially variable moisture conditions and vegetation cover on ET rates. Splitting a study season into shorter time periods accounts for the dynamic insensitivity of the Priestley-Taylor method, reducing the insensitivity to temporal changes in moisture conditions, as the shorter time period allows for similar moisture conditions and plant physiological stages (i.e., bud burst, growth/flowering and senescence) to be grouped together. Clearly, an altered water table depth as a consequence of site management (rewetting), coupled with the inevitable shift in vegetation cover, has implications for the rates of ET. Greater evaporation rates can be expected following rewetting, due to the increased abundance of water as well as the potential for areas of pooled water, a freely evaporating surface. However, the relationship between the increased water availability and transpiration rates through woody vascular plants (mainly *ericaceous* shrubs) is not as clear. Inevitably, the perpetually wet, and in some areas flooded, conditions on the site will cause a shift in vegetation cover, favouring *Sphagnum* mosses over woody shrubs following rewetting. Studies addressing the relationship between this vegetation shift and mid-to-long term ET rates are uncommon.

ET Variability

Since ET rates are partially controlled by the depth to the water table and block-cut sites are characterized by a highly variable topography (i.e., baulks and trenches), ET rates within these sites exhibit large spatial variability. For example, Van Seters and Price (2001) observed evapotranspiration rates 53% lower from locations where the water table position was 45 cm further from the peat surface (i.e., on a baulk) within an abandoned block-cut bog. However, vascular vegetation located atop the baulks is able to tap into the deeper water supply and contributes to transpiration losses. Nonetheless, ET rates are higher in the relatively moist trenches, since the water table is closer to the surface, and the *Sphagnum* mosses present cannot actively control their evaporative losses, as they lack stomata. *Sphagnum* mosses are, however, able to passively control the water losses due to evaporation as a consequence of the reduced capillary capability as the surface of the moss dries (Price, 1991) and the increase in albedo that accompanies the whitening of the surface of the drying mosses (Ingram, 1983). Comparatively, in vacuum harvested sites, the topography is fairly uniform, resulting in relatively homogeneous ET rates across the site (Petroni et al., 2001). The vegetation cover is relatively sparse, though the narrow pore diameters of the degraded remnant peat deposit can typically generate the capillary transport necessary to sustain ET near potential rates when the water table is near to the surface (Price and Ketcheson, 2009). Dry summer seasons coupled with remnant peat deposits characterized by low specific yields create conditions where it is possible for the water table to be drawn down sufficiently to decouple it from surficial water exchanges with the atmosphere (Price, 1997), thus curtailing ET rates drastically (Lafleur and Roulet, 1992). At this point, atmospheric demands for ET are largely met by water from storage above the water table, exacerbating low (i.e., strongly negative) soil-water pressures and low soil-moisture contents of the unsaturated zone as it dries, which further restricts water availability for mosses and shrubs at the surface of the peat. Thus, in addition to plant physiological controls (e.g., stomatal response to moisture conditions; seasonal phases – see below), temporally variable ET rates are exhibited within most cutover peatlands. Furthermore, seasonal peat volume changes and the accompanying effect on the hydraulic parameters of the peat (Price, 2003) affects the availability of water at the surface of the peat, as this is influenced by pore diameters, with greater potential for capillary rise in peat deposits exhibiting narrow pore diameters as a consequence of shrinkage as the peat deposit dries.

In addition to water availability at the surface of the peat, the vegetation cover also has a large influence on the observed ET rates. This control also exhibits temporal variability trends, as the transpiration from vegetation is influenced by the position of the water table and the physiological characteristics of the vegetation (Lafleur and Roulet, 1992). ET rates are greatly reduced as the water table drops below the limit of capillary rise, or below the rooting zone, from surfaces dominated by non-vascular and vascular plants, respectively (Lafleur and Roulet, 1992). Further, physiological responses to atmospheric conditions can greatly influence evapotranspiration rates from vegetation, with reduction in transpiration to the atmosphere when the atmosphere is dry or very humid. This control usually follows seasonal trends throughout the summer months, as atmospheric demands increase with warmer, drier air (Lafleur and Roulet, 1992). This, however, would also depend on precipitation dynamics, as this would be reflected in the physiological responses of the vegetation to moisture stress, or lack thereof. Also, different stages of plant growth, such as bud burst, growth/flowering and senescence, throughout the growing season influences the physiological characteristics, and hence transpiration rates, from the vegetation cover (Lafleur and Roulet, 1992). A highly temporally and spatially (see below) variable water table position, in combination with differing vegetation cover, are responsible for the highly variable ET rates from block-cut peatlands, which must be properly accounted for when evaluating site-scale ET rates.

Water Table

The water table (WT) within unrestored cutover peatlands is further from the peat surface than within natural peatlands due to the construction of a drainage network to facilitate peat extraction during the harvesting process. Price (1996) also showed that the degraded peat, with lower specific yield, resulted in a lower (and more variable) water table during the summer within a cutover site than in an undisturbed site. The WT beneath baulks and trenches within block-cut sites is, on a microtopographical scale, relatively flat (Price and Whitehead, 2001), resulting in substantial differences in the WT position beneath each of the features. Raised baulks are relatively dry, with a WT depth at least 0.5 m further from the peat surface than the adjacent low-lying trenches. In addition, the convex shape within the trenches creates variation in the depth to the WT from the edges to the centre of the trench. The dominant vegetation cover present on each of these features is also reflective of the moisture characteristics of the topographical position. Vascular vegetation more suited for a deeper WT tends to occupy higher,

drier areas such as baulks and the centre of the trenches, while non-vascular mosses occupy lower-lying trench edges. On a larger scale, topographical variability throughout a site gives rise to differences in WT depths within the site. Previous restoration efforts (e.g., LaRose et al., 1997; Shantz and Price, 2006b; Spiexsma, 1999) have resulted in higher WT levels following restoration.

Runoff

Runoff represents a substantial loss of water from disturbed peatlands. Van Seters and Price (2001) found that runoff losses corresponded to 18% of annual precipitation (two year average; snowmelt runoff excluded) for an abandoned cutover bog. Typically, increases in runoff, event peak flows and baseflow 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 (Baden and Eggesman, 1968; Burke, 1972). Holden (2005) found that changes in peatland management can result in dramatic changes to runoff from disturbed sites, characterized by high stream peak flows and rapid response to rainfall. The responsiveness of this system, however, tended to be dependent upon antecedent moisture conditions (Holden, 2005). As such, runoff exhibits seasonal variation, typically greatest during snowmelt periods (Fraser et al., 2001) and conditions with high water table levels (Evans et al., 1999), which are anticipated following rewetting. Despite this, the effect of blocking drainage ditches on runoff has not been well-documented (Spiexsma, 1999). Price (1996) found summer runoff to represent only 6% of precipitation inputs following the blocking of site drainage ditches in a disturbed peatland. Similarly, restricted water losses through site runoff were observed by Shantz and Price (2006a) following site rewetting, with post-restoration losses reduced to 25% of those from a nearby unrestored site. The responsive behaviour of these systems following site management is a topic of substantial concern for both cutover and restored sites, since flood management and maintenance of base flow have considerable ecological consequences downstream of the disturbed system. As such, this lack of knowledge must be suitably addressed. Though snowmelt represents a predominant component of seasonal runoff and considering that few studies evaluate runoff control techniques (i.e., blocking drainage ditches) during the snowmelt period (Shantz and Price, 2006a), the snowmelt period is not included in this thesis.

Water Storage and Peat Volume Change

Following disturbance and peat extraction, the remnant peat deposit (with the exception of the skag) comprises well-decomposed peat from the former catotelm. This peat is characterized by small pore diameters, hence reduced specific yield, resulting in a rapid decline in WT levels (Price, 1996) and thickening of the unsaturated zone after the snowmelt period. Specific yield is the ratio of the volume of water drained from a soil by gravity and tension (after being saturated) to the total volume of the soil. Accordingly, it is inversely related to pore diameter, as more narrow pores are able to more effectively retain water due to stronger capillary forces. Furthermore, smaller, narrow pores have less space to hold water and thus are responsible for the large WT variability in cutover peat, as the addition or removal of a given volume of water will result in a greater change in water level in peat soils with smaller pores. Estimates of seasonal storage changes within peatlands need to include the loss of water from soil storage as a consequence of the draining/filling of pores with water table change (specific yield), as well as the volume of water released from storage by compression of the peat matrix during seasonal surface subsidence (specific storage) and the change in moisture content within the unsaturated zone. The specific storage component is often omitted from storage change estimates due to the relatively large specific yield from unconfined aquifers (Price and Schlotzhauer, 1999). However, the high compressibility of peat soils results in a significant contribution of the specific storage term in estimates of storativity, with specific storage values up to 170% higher than specific yield values in cutover peat (Price and Schlotzhauer, 1999).

The subsequent changes to the physical properties of the remnant peat deposit following harvest (higher bulk density and reduced porosity, soil moisture and soil water pressures) significantly alter the water storage capacity of the peatland, particularly through decreases to the specific yield and, hence, water holding capacity of the peat deposit (Price et al., 2003). Increased rates of ET coupled with low WT levels can result in a shortage of water within cutover sites during the summer months, as ET demands are largely met by water from storage (Price et al., 2003), resulting in increased surface subsidence due to the contracting peat deposit. For example, Schlotzhauer and Price (1999) observed seasonal surface subsidence in excess of 10 cm in a cutover peatland. The two main factors contributing to this subsidence include: a deeper water table, exacerbated by a low specific yield, causing increased effective stress on peat layers below the water table (compression); and drier moisture conditions within the unsaturated

zone causing the development of negative soil water pressures as the peat above the water table dries (shrinkage) (Kennedy and Price, 2005). Consequently, the volume of larger pores is greatly reduced throughout the entire remnant peat deposit, thus increasing the retention capacity of the peat and reducing the availability of water for *Sphagnum* mosses (Schlotzhauer and Price, 1999). Decreasing the summer water deficit would reduce the severity of the seasonal pore size reduction and associated water retention through increasing the abundance of water within the site, resulting in evaporation demands being met by the shallow water table as opposed to moisture from soil storage. This should result in higher soil moisture and higher soil water pressures throughout the summer months following rewetting, thus reducing seasonal shrinkage and maintaining conditions favourable for *Sphagnum* survival (Price and Whitehead, 2001). Furthermore, a water table much closer to the surface following rewetting of the peat will subsequently increase the buoyancy of the peat, reducing the overburden stress and the associated peat compression, which could result in surface rebound as the peat deposit expands. These volume changes have a profound impact on the hydrological functioning of cutover peatlands; however site-scale impacts investigating their reversibility are rare.

2.3 Ecohydrology

Hydrological Conditions and Successful Sphagnum Reestablishment

Sphagnum mosses are non-vascular vegetation (bryophytes) that, in addition to meteoric water inputs, rely upon capillary flow, mainly in the spaces between individual plants (Hayward and Clymo, 1982), for the transport of water upwards to the photosynthesizing capitula (McNeil and Waddington, 2003). In cutover sites characterized by low, negative soil water pressures, *Sphagnum* is unable to generate the capillary forces necessary for the adequate extraction of water from the underlying peat substrate (Price, 1997; Price and Whitehead, 2001). Price and Whitehead (2001) developed hydrologic thresholds for *Sphagnum* survival, through evaluating the conditions of the underlying substrate in areas within an abandoned cutover site that were naturally recolonized by groups (cushions) of *Sphagnum* mosses. They concluded that *Sphagnum* recolonized where there was a high water table (mean depth -24.9 ± 14.3 cm), high soil moisture (greater than 50%) and high soil water pressure (greater than -100 cm). These areas were mostly in shallow ditches and lower parts of the in-trench skag. The mosses initially recolonize as isolated, hemispherical cushions that are closely tied to the moisture regime of the cutover peat

substrate (Price and Whitehead, 2004) and the influence of the Ericaceae canopy (Farrick and Price, 2009), and are able to amalgamate into larger carpets in wetter areas (Price and Whitehead, 2004). *Sphagnum*, however, is unable to survive extended dry periods (Sagot and Rochefort, 1996), and even short periods with conditions beyond the specified thresholds can be detrimental (Price and Whitehead, 2001). The highest soil water pressures, thus most easily accessible water, were found under cushions, as the presence of the mosses on the surface of the peat protects the underlying substrate from evaporative demands, thus indicating that the presence of *Sphagnum* improves its own environment (Price and Whitehead, 2004). Accordingly, Price and Whitehead (2004) also found that soil moisture content beneath cushions was 5 – 14% higher than in bare cutover peat directly adjacent to it. However, soil water pressure provides a better indication of moisture availability for *Sphagnum*, since the pressure gradients that drying *Sphagnum* can generate can result in a range of soil-moistures that are dependent upon the condition of the peat (Thompson and Waddington, 2008). Further, peat volume decreases due to shrinkage during drying, resulting in similar volumetric moisture content values, despite water being held more tightly (thus less available for *Sphagnum*) in smaller pores (Price and Whitehead, 2001).

Water availability and fluxes in shrub-dominated cutover peatlands are inevitably influenced by the abundance and distribution of the ericaceous vegetation (Farrick and Price, 2009). Farrick and Price (2009) observed higher soil moisture and soil-water pressures in the upper soil layers within shrub-covered peat as compared to bare peat. The presence of ericaceous shrubs was considered hydrologically advantageous because of reduced water losses from the upper unsaturated zone due to the presence of a fine leaf litter layer and reduced net radiation received at the surface (Farrick and Price, 2009). This is in spite of the combined interception from the canopy and leaf litter, accounting for 23% of the seasonal rainfall. Nevertheless, the relationship between recolonized *Sphagnum* cushions and ericaceous vegetation is poorly understood. Lavoie et al. (2003) state that the vegetation that is able to first colonize the dry peat surface helps in stabilizing it, thus facilitating the establishment of other species. Also, Groenvelde and Rochefort (2005) have shown that the presence of plants reduces the impact of frost heaving in abandoned peatlands. However, the leaf litter from Ericaceae could interfere with the establishment of incipient moss diaspores (Price and Ketcheson, 2009), and *Sphagnum* cushions desiccate following removal of the shrubs (McNeil and Waddington, 2003). This is

partly due to the essential shading that the ericaceous canopy provides to the mosses (Malmer et al., 2003), although little is known about the water dynamics within cushions. As such, an increased understanding of this relationship is required in order to recognize the implications of the presence of Ericaceous vegetation on *Sphagnum* moss establishment and survival within disturbed peatland ecosystems.

As previously mentioned, spontaneous regeneration of *Sphagnum* on unmanaged cutover sites is typically poor, owing to harsh physical and hydrological conditions. In most cases, peatland restoration efforts face a common fundamental problem: availability of water (Price et al., 2003). Water management efforts, such as blocking drainage ditches, have been found to substantially increase the availability of moisture for use by *Sphagnum*, thus creating conditions more favourable for *Sphagnum* recolonization. However, the specific conditions present immediately following rewetting are poorly understood. An improved understanding of these conditions is a necessary component for the development of suitable site restoration techniques.

Moisture Dynamics within Sphagnum Cushions

While much work has been done characterizing hydraulic properties of both undisturbed peat and remnant cutover peat deposits, little is known about water variability and transport processes in mosses, particularly in the unsaturated condition and with regards to changes caused by restoration efforts and *Sphagnum* cushion health. Price and Ketcheson (2009) recently reported that moisture variability increased with depth within newly formed *Sphagnum* moss cushions, with smaller cushions exhibiting the most variability overall. They hypothesized that the upper and lower parts of the larger cushions may be only weakly coupled, limiting vertical growth, and favouring lateral spreading and coalescing of cushions; though water exchanges between the base of the cushion and underlying peat substrate have yet to be sufficiently characterized. More importantly, from an ecosystem restoration perspective, the impact of peatland restoration and rewetting on the health of, and moisture dynamics within, naturally recolonized *Sphagnum* cushions has not been documented.

3.0 Site Description

The study site is an abandoned block-cut bog in Cacouna (47°53' N, 69°27' W), approximately 10 km north-east of Rivière-du-Loup, Québec, Canada. Mean annual precipitation (1971 – 2000) recorded at a meteorological station in St. Arsène (< 2 km from study site) is 962.9 mm, 29% of which falls as snow (Environment Canada, 2003). The mean annual temperature is 3.2°C, ranging from -10.9°C in February to 16.5°C in August (Environment Canada, 2003).

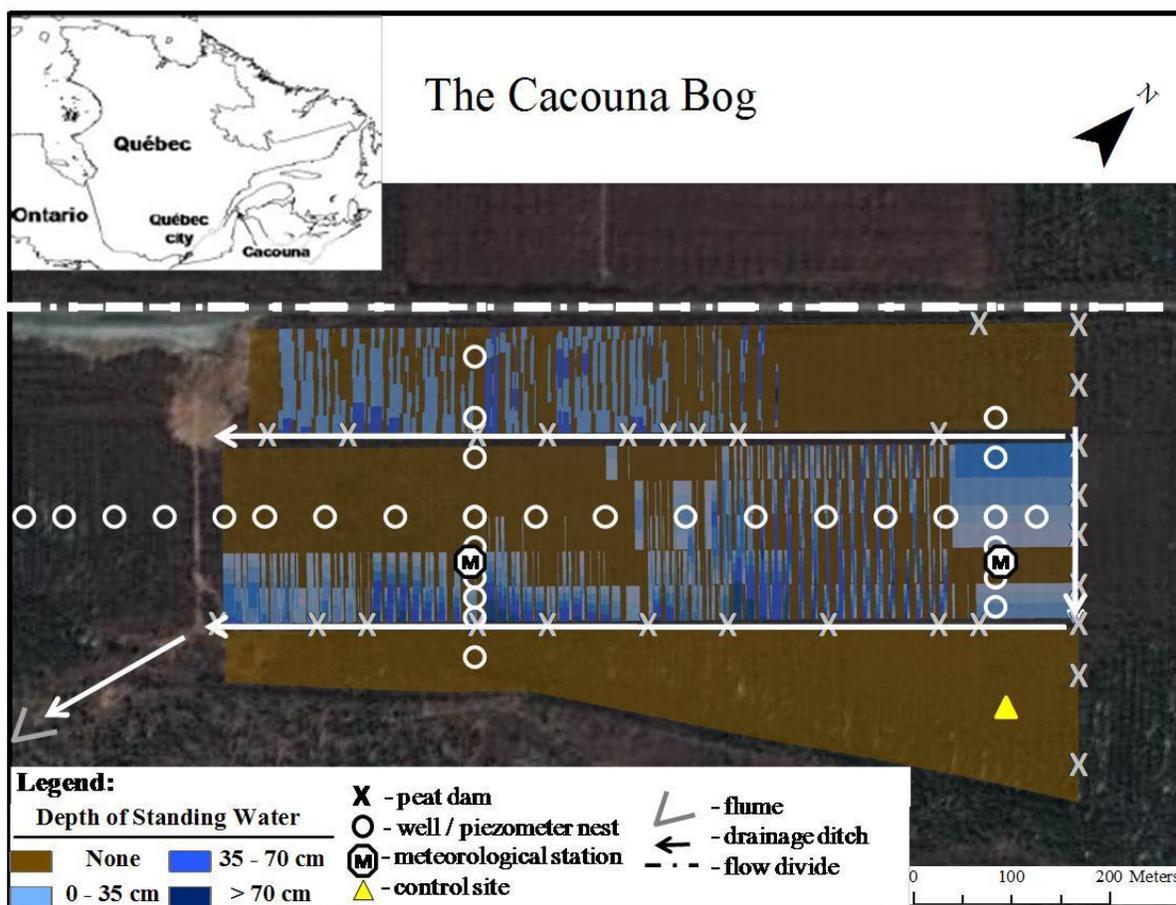


Figure 3-1 Map of the Cacouna bog. Standing water depth is indicated by areas shaded proportional to the depth of water observed following rewetting; brown indicates that there was no standing water. Baulks and trenches are situated in an approximately north-south direction, producing the striped pattern of narrow brown (dry) baulks between mostly flooded trenches (blue) throughout much of the site. Note the deepest water is located just upstream of the location of a peat dam, with no standing water (hence drier peat) further from the peat dam. A more gradual slope in the northeast end of the site resulted in a transition towards more uniform standing water depths

Located within the St. Lawrence Lowlands, the Cacouna peatland is a domed bog of the Low Boreal Wetland Region (NWWG, 1997), underlain by thick deposits of marine clay from the former Goldthwait Sea (Dionne, 1977). Extensive auger sampling by Van Seters and Price (2002) indicate that the clay layers are continuous. Given the low hydraulic conductivity of the clay deposit (10^{-8} cm s⁻¹), water exchanges between the bog and the regional aquifer are restricted (Price and Whitehead, 2001). Common to this region, domed bogs are characterized by thick, dome-shaped accumulations of peat in which the water table is at a higher elevation than the surrounding areas (Glaser and Janssens, 1986). At an altitude of 83 m a.s.l., the Cacouna bog originally covered an area of 210 ha, but has since been reduced in size to 148 ha as a result of agricultural encroachment and the development of roads through the bog margins (Girard et al., 2002). In the mid-1880s, a railway was constructed approximately along a natural groundwater divide, creating a flow barrier, separating the bog into two hydrologically distinct halves (Van Seters and Price, 2001). This study focused on a 55 ha section within the 80 ha southern half (Figure 3-1).

Peat harvesting began in 1945 and continued until 1975, using the traditional block-cut extraction technique, resulting in a cutover landscape of alternating baulks, 2 – 4 m wide and raised approximately 0.5 – 1.0 m above adjacent, lower-lying trenches of 10 – 12 m width. These baulk-trench combinations occur in parallel, with typical lengths of 180 m, and are situated in an approximately north-south direction. The remaining cutover peat is up to 4 m thick (Van Seters and Price, 2001), with average bulk density and specific yield values of 0.12 g cm⁻³ and 0.08, respectively, for residual peat within the trenches (Price and Whitehead, 2001). Following final abandonment, an attempt was made to block some drainage ditches with peat in the south-west portion of the bog; however, about half of the ditches still remained operational, resulting in runoff losses amounting to a significant proportion of precipitation (two-year average of 18%, snowmelt excluded) (Van Seters and Price, 2001).

Since final abandonment, the site has been spontaneously recolonized by vegetation typical of raised bogs in the Rivière-du-Loup region (Lavoie and Rochefort, 1996). The relatively dry conditions of the cutover peat favoured the growth of vascular vegetation, including Ericaceous shrub species, predominantly Labrador tea (*Ledum groenlandicum*), leatherleaf (*Chamaedaphne calyculata*), sheep laurel (*Kalmia angustifolia*) and blueberry (*Vaccinium angustifolium*) (Lavoie and Rochefort, 1996). Additionally, prolific tree species

included tamarack (*Larix laricina*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*) and grey birch (*Betula populifolia*), with tree cover being denser in areas abandoned longest as well as along the margins of the bog. A total of 90 – 100% of the harvested area has been recolonized by vascular vegetation (Girard et al., 2002). Conversely, only 10% of the harvested area has been recolonized by *Sphagnum* species (most commonly *S. capillifolium*, *S. magellanicum*, and *S. fallax*), largely limited to the lowest lying moist portions of the trenches (Girard et al., 2002). A more detailed description of plant species can be found in Lavoie and Rochfort (1996).

In October of 2006, peat dams were constructed throughout the southern section of Cacouna bog (Figure 3-1) thereby blocking the remaining active ditches within the site drainage network and consequently flooding the lower portions of some of the trenches. This thesis includes data from two years prior to (2005, 2006), and one year following (2007) the site rewetting. A small portion in the south-east corner of the site remained unaffected by the rewetting, providing a suitable control site.

4.0 Manuscript 1: The impact of peatland restoration (rewetting) on the site hydrology and water balance of an abandoned block-cut bog in Québec.

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4.1 Summary

Artificial drainage networks established throughout peatlands during the peat extraction process often remain active following abandonment, maintaining a water table relatively far from the surface of the peat and hindering the survival and reestablishment of *Sphagnum* mosses. As an initial restoration effort, the primary drainage network of an abandoned cutover peatland was blocked with a series of peat dams, consequently reducing the runoff efficiency and causing the site-average water table to rise by 32 cm. Higher water tables and a blocked drainage network resulted in increased runoff variability, dependent upon antecedent conditions (capacity to retain additional water on-site) and event-based precipitation dynamics. Evapotranspiration (ET) rates were 25% higher following rewetting (3.6 mm day^{-1}) compared to pre-restoration ET rates of 2.7 mm day^{-1} . Total storage changes were restricted following rewetting, as a factor of the reduced runoff losses limiting water table drawdown, thereby constraining peat compression and preventing undue drying of the unsaturated zone. An average surface level rebound of 3 cm was observed, increasing the mean hydraulic conductivity by an order of magnitude. Changes to the system hydrology following restoration efforts produced hydrological conditions more favourable for the recolonization of *Sphagnum* mosses.

4.2 Introduction

Peatlands cover over 12% of Canada's total land area (Tarnocai, 2006). Exploitation of peatlands for horticultural peat (Bergeron, 1994; Keys, 1992) and, more recently, the potential of peat as a fuel source (Gleeson et al., 2006) is an important industry in Canada. Peat mining activities primarily focus on extracting *Sphagnum* peat from bogs due to its desirable water-holding properties and resistance to decay (Read et al., 2004). Prior to extraction, peatlands are subject to drainage that lowers the water table, resulting in subsidence due to shrinkage and oxidation in the unsaturated zone and compression below the water table (Kennedy and Price, 2005). Consequently, cutover sites are characterized by a more decomposed and compacted peat

substrate (Price and Whitehead, 2001) with a high water retention capacity and low specific yield (Schlotzhauer and Price, 1999), resulting in harsh physical and hydrological conditions that limit the successful recolonization of *Sphagnum* mosses, the most dominant peat-forming plant genus (Kuhry and Vitt, 1996). Inadequate spontaneous reestablishment of *Sphagnum* in cutover sites inhibits the restoration of natural peatland functions. In undisturbed peatland ecosystems, the uppermost layers of living, dead and poorly decomposed plant material exist as the acrotelm, which represents the principal site of matter and energy exchange in natural peatland systems (Ingram, 1978). Towards the surface within the acrotelm, there is an increase in porosity (n), with typically larger pore-sizes consequently increasing specific yield (S_y) and saturated hydraulic conductivity (K_{sat}), thereby regulating surface runoff and evaporation losses and reducing water table fluctuations to a narrow limit near the surface of the peat (Van Seters and Price, 2001). Cutover peatland systems, however, lack these self-regulating characteristics, as the former acrotelm is removed during the peat extraction process. The remnant catotelmic peat differs from the acrotelm in character as it has less abrupt variation in its physical properties and has smaller average pore size. As such, it has a drastically reduced capacity to regulate WT variability, water storage, surface water runoff, and evapotranspiration rates, producing a water regime atypical of natural systems and harsh hydrological conditions for recolonizing plants, especially non-vascular mosses, following abandonment.

Seasonal peat volume changes have a direct effect on the hydraulic parameters (e.g. K_{sat}) and water storage capacity of the peat deposit (Kennedy and Price, 2004), thereby influencing the availability of water for non-vascular *Sphagnum* mosses. Shrinkage and compression are the dominant volume change mechanisms for peat soils that occur as a consequence of water table lowering for harvest (Eggelsmann, 1976; Schothorst, 1977), accounting for 96-97% of seasonal volume change in some cutover peatland systems (see Kennedy and Price, 2005). Below a material's critical stress level, shrinkage and compression are reversible, though in extremely dry conditions the peat can undergo a permanent structural change, preventing a peat layer from recovering 100% of its prior volume, even if completely rewetted to saturation (Kennedy and Price, 2005). Site-scale rewetting experiments documenting the extent of this soil volume recovery in cutover peat deposits are required to quantify the reversibility of these processes. More importantly are the implications of these structural changes on the movement of water and nutrients through the saturated zone and the availability of water at the top of the unsaturated

zone, where *Sphagnum* mosses rely upon capillary rise to supply water to their photosynthesizing capitula (Price et al., 2009). However, the effect of site rewetting on the physical properties of the remnant peat deposit is not known.

Successful *Sphagnum* recolonization is dependent upon restoration efforts of abandoned sites (Lavoie et al., 2003; Price et al., 2003; Rochefort et al., 2003). This is an essential step towards re-establishing the critical self-regulating processes of the acrotelm layer, allowing for the recovery of the peatland hydrological and ecological (peat-forming) function. Natural recolonization of abandoned sites may take decades or may not occur at all (Price et al., 2003), necessitating the implementation of proper site management techniques to reduce the impact of peat harvesting. Water management approaches, such as site rewetting by blocking drainage ditches, can accelerate the restoration of cutover sites by improving the hydrological conditions within the peat substrate (LaRose et al., 1997; Price et al., 2003; Shantz and Price, 2006b); however, the response of the hydraulic parameters of the substrate (e.g. K_{sat}) following water table reestablishment is poorly understood (Holden, 2005). Furthermore, altered water dynamics and distribution within a bog following rewetting has direct implications for the components of the water balance, inevitably changing the distribution and magnitude of water losses from the site. The water balance provides a good indication of the relative importance of hydrological processes and their spatial variation throughout the site (Van Seters and Price, 2001); however, full water balance studies of managed (rewet) cutover bogs are rare.

As yet, no standard management prescription for the restoration of cutover sites has been developed because each site presents unique challenges (Price et al., 2003). To improve peatland restoration strategies, there is a need to understand the impact of site rewetting on the system hydrology. Therefore, the specific objectives of this study are to (i) compare the full water balance of an abandoned block-cut bog prior to and following rewetting; (ii) characterize the impact of peatland restoration (rewetting) on the hydrological conditions of the remnant peat; and (iii) address the implications for *Sphagnum* moss recolonization.

4.3 Study Area

The study site is an abandoned block-cut bog near Cacouna (47°53' N, 69°27' W), approximately 10 km north-east of Rivière-du-Loup, Québec, Canada. Mean annual precipitation (1971 – 2000) recorded at a meteorological station in St. Arsène (< 2 km from study site) is 963

mm, 29% of which falls as snow (Environment Canada, 2003). The mean annual temperature is 3.2°C, ranging from -10.9°C in February to 16.5°C in August (Environment Canada, 2003).

Located within the St. Lawrence Lowlands, the Cacouna peatland is a domed bog of the Low Boreal Wetland Region (NWWG, 1997), an area underlain by thick deposits of marine clay from the former Goldthwait Sea (Dionne, 1977). Extensive auger sampling by Van Seters and Price (2002) indicate that the clay layers are continuous. Given the low hydraulic conductivity of the clay deposit ($10^{-8} \text{ cm s}^{-1}$), water exchanges between the bog and the regional aquifer are restricted (Price and Whitehead, 2001). Common to this region, domed bogs are characterized by thick, dome-shaped accumulations of peat in which the water table is at a higher elevation than the surrounding areas (Glaser and Janssens, 1986). At an altitude of 83 m a.s.l., the Cacouna bog originally covered an area of 210 ha, but has since been reduced in size to 148 ha as a result of agricultural encroachment and the development of roads through the bog margins (Girard et al., 2002). In the mid-1880s, a railway was constructed approximately along a natural groundwater divide, creating a flow barrier that separates the bog into two hydrologically distinct halves (Van Seters and Price, 2001). This study focused on a 55 ha section within the larger 80 ha southern half (Figure 3-1).

Peat harvesting began in 1945 and continued until 1975, using the traditional block-cut extraction technique, resulting in a cutover landscape of alternating baulks 2 – 4 m wide and raised approximately 0.5 – 1.0 m above adjacent, lower-lying trenches of 10 – 12 m width. These baulk-trench combinations occur in parallel, with typical lengths of 180 m, and are situated in an approximately north-south direction. The remaining cutover peat is up to 4 m thick (Van Seters and Price, 2001) with average bulk density and specific yield values of 0.12 g cm^{-3} and 0.08, respectively, for residual peat within the trenches (Price and Whitehead, 2001). Following final abandonment, an attempt was made to block some drainage ditches with peat in the southwest portion of the bog; however, about half of the ditches still remained operational, resulting in runoff losses amounting to a significant proportion of precipitation (two-year average of 18%, snowmelt excluded) (Van Seters and Price, 2001).

Since final abandonment, the site has been naturally recolonized by vegetation typical of raised bogs in the Rivière-du-Loup region (Lavoie and Rochefort, 1996). The relatively dry conditions of the cutover peat favoured the growth of vascular vegetation, especially Ericaceous shrub species such as Labrador tea (*Ledum groenlandicum*), leatherleaf (*Chamaedaphne*

calyculata), sheep laurel (*Kalmia angustifolia*) and blueberry (*Vaccinium angustifolium*) (Lavoie and Rochefort, 1996). Additionally, prolific tree species included tamarack (*Larix laricina*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*) and grey birch (*Betula populifolia*); tree cover was denser in areas abandoned longest as well as along the margins of the bog. A total of 90 – 100% of the harvested area has been recolonized by vascular vegetation (Girard et al., 2002). Conversely, only 10% of the harvested area has been recolonized by *Sphagnum* species (most commonly *S. capillifolium*, *S. magellanicum*, *S. rubellum* and *S. fallax*), which are largely limited to the lowest, moist portions of the trenches (Girard et al., 2002). A more detailed description of plant species can be found in Lavoie and Rochefort (1996).

In October of 2006, peat dams were constructed within the southern portion of the Cacouna bog (Figure 3-1), thereby blocking the remaining active ditches within the site drainage network and consequently flooding the lower portions of some of the trenches. The current study includes data from two years prior to (2005, 2006) and one year following (2007) the site rewetting. A small section in the south-east corner of the site remained unaffected by the rewetting, providing a suitable control site.

4.4 Methods

Site Rewetting and Hydrology

The primary drainage network within the Cacouna bog (previously moderately functional) was blocked in October of 2006 through the construction of 29 peat dams, which were located predominantly along the length of the two primary drainage ditches that run approximately east-west (perpendicular to trenches – see Figure 3-1). No other restoration measures were undertaken. Average spacing between peat dams was approximately 75 m, which corresponded to an approximate change in elevation of 25 cm between dams. The terminal end of raised balk structures that run perpendicular to primary drainage ditches and along the periphery of trenches provided a suitable location for peat dam construction as the baulks act as efficient flow barriers. As part of the dam construction technique, the upper vegetation mat (including rooting layer) was removed from both the surface of the drainage ditch and the borrow area and put aside. Deeper, well-decomposed peat was dug from the borrow area and tamped into place in the centre of the drainage ditch until the top of the peat dam protruded slightly above the surrounding peat surface. Finally, the uppermost vegetation and root layer

(previously removed) was placed atop the dam to stabilize the surface through revegetation. Piezometers were installed in seven of the constructed peat dams, and cores were extracted from three dams for estimates of hydraulic conductivity and bulk density.

Water table levels were monitored on a weekly basis throughout the three study periods with a network of over 70 PVC wells slotted along their entire length and arranged in transects running approximately north-south and east-west throughout the site (Figure 3-1). Since trenches dominated spatially over baulks in the Cacouna bog, and to be consistent, all wells were installed in trenches. Surface level changes were monitored concurrently by measuring the distance between the top of a stationary steel rod (firmly set in the underlying clay layer) and a 25 cm diameter plastic disc resting on the surface of the peat. Nine nests of piezometers were installed throughout the site (Figure 3-1) and consisted of PVC pipes slotted along only the bottom 20 cm; pipe intakes were situated at varying heights above the peat-mineral interface. The altitude of all well and piezometer pipe tops were referenced to a common datum using a total station and standard surveying techniques. Field estimates of saturated hydraulic conductivity (K_{sat}) were conducted in each study period using bail tests following Hvorslev's (1951) hydrostatic time-lag method. Piezometers remained in the ground throughout the three-year study period to allow for a direct comparison of the saturated hydraulic conductivity values between seasons.

Micrometeorological Conditions

Meteorological data were monitored continuously from 19 May to 16 August in three consecutive years (2005 – 2007) using a Campbell Scientific Inc.™ data logger at a meteorological station established within the central portion of the site (see Figure 3-1). All meteorological instruments were connected to loggers (with the exception of the manual rain gauges) and measured at 60-second intervals with average and total outputs every 20 minutes. Precipitation was automatically measured with two tipping bucket rain gauges, and data checks were made using a manual rain gauge adjacent to each of the tipping bucket rain gauges. Values were within $\pm 10\%$. Measurements were compared to climate averages for the region (1971 – 2000) as recorded at the nearby (< 2 km) St. Arsène meteorological station. Air temperature and relative humidity (RH) were measured using copper-constantan thermocouples (air temperature) and a self-logging Hobo™ Temperature and RH logger. The thermocouples were housed in a Styrofoam cup covered in aluminum foil (to minimize heating by radiation) located

approximately 1 m from the ground surface, and the Hobo™ logger was housed in an enclosure approximately 2 m from the ground surface that was equipped with flow-through ventilation.

Evapotranspiration

A net radiometer was installed 1.5 m above the cutover peat surface and centred in an 11 m wide trench that exhibited typical shape and vegetation cover. This created an approximate footprint diameter of 15 m, thus, sufficiently covering the different surface and vegetation types of the trench and adjacent baulks to either side. This provides a representative measurement of the net radiation flux (Q^*). Additionally, two soil heat flux plates were installed (in the trench) at the meteorological station to provide measurements of ground heat flux (Q_G). These measurements of Q^* and Q_G were used for estimation of daily equilibrium evapotranspiration (ET_{eq}) using the Priestley and Taylor (1972) combination method where

$$ET_{eq} = \alpha \left[\frac{s}{(s + q)} \right] \left[\frac{(Q^* - Q_G - Q_W)}{L\rho} \right]$$

Equation 4-1

and where L is the latent heat of vaporization (J kg^{-1}), ρ is the density of water (kg m^{-3}), s is the slope of the saturation vapour pressure-temperature curve ($\text{Pa } ^\circ\text{C}^{-1}$), q is the psychrometric constant (assumed to be $0.0662 \text{ kPa } ^\circ\text{C}^{-1}$ at 20°C), Q^* is the net radiation flux (J day^{-1}), Q_G is the ground heat flux (J day^{-1}), and Q_W is the pool heat storage (J day^{-1}). Where standing water was present (2007 only), Q_W was determined based on changes in water temperature and the depth of the standing water (Price and Maloney, 1994). The α coefficient is the Priestley-Taylor coefficient of evaporability, which represents the slope of the regression line relating actual (ET_a) to equilibrium (ET_{eq}) evapotranspiration. This empirical estimate of α can be substituted into Equation 4-1 to determine evapotranspiration when only energy balance data are available (Price and Maloney, 1994). It is equal to unity when evaporation is occurring at the equilibrium rate, when the near-surface atmospheric vapour pressure deficit is zero.

ET_a was determined using an evaporation pan (representing standing water only) and nine weighing lysimeters filled with peat monoliths and supporting vegetation representative of four of the major surface types and dominant vegetation covers (three repetitions each) for use in deriving the α coefficient. The α parameter for evapotranspiration from forested sections of the bog (less than 20% of the study area) was derived from the literature. In a previous study, Van

Seters and Price (2001) used an α value of 1.07 for evapotranspiration calculations from forested sections within the Cacouna bog. Raising or lowering the forest alpha value by 0.1 (i.e. 1.17 and 0.97) would change the aerially weighted evapotranspiration value from the site by $\pm 1\%$.

The study area was approximately divided into five surface classes (open water, wet, moist, dry and forest), based on field observations of vegetation cover, the topographical position of each lysimeter (thus moisture conditions), and previous studies in the Cacouna bog involving detailed vegetation surveys and aerial photograph interpretation (Girard et al., 2002; Van Seters and Price, 2001). The ‘wet’ trench lysimeters maintained an approximate water table within the upper 5 - 15 cm with a surface cover dominated by *Sphagnum* moss and bare peat. The ‘moist’ lysimeters exhibited water table depths between 20 - 30cm below the surface and contained a combination of *Sphagnum* moss, bare peat and Ericaceous shrub cover, while the ‘dry’ lysimeters (approx. water table > -50 cm) were limited to Ericaceous shrubs and bare peat. The extent and depth of standing water (2007 only) was quantified through manual staff gauge measurements along ten transects (25 – 30 m spacing between transects) spanning the entire length of the site.

Individual α values were derived for each surface type, and an aerially weighted α value was derived for the Cacouna bog where

$$Site \alpha = \sum_{i=1,5} (\alpha_i A_i)$$

Equation 4-2

and A_i is the fractional aerial coverage of i surface class (1-5 representing dry, moist, wet, open water and forest) with an α_i coefficient of evaporability. Each study period was temporally divided into four separate time periods (approximately 20 – 30 days each, with the exception of 2005, which was divided into only two periods) with separate *Site α* values determined for each period. This provided an estimation of total evapotranspiration from the Cacouna bog. Following site rewetting (i.e., 2007 study period), the relative aerial coverage of the different surface types of the previous two years was altered as a consequence of a rise in the average site water table level (~30 cm) and the flooding of low-lying portions of the site. The magnitude of this water table rise and consequent alteration of the surface type distribution varied according to the site topography in addition to the proximity to a peat dam. Based on water table levels and field observations of moisture content, the proportion of wet sites in the 2007 study period was

increased by 25% as compared to 2005/2006, with dry sites being reduced by 25% accordingly. A sensitivity analysis determined that raising or lowering this percent change by 10% (i.e. 15% and 35% change in surface type proportions) would change the aerially weighted evapotranspiration rate by only $\pm 1\%$.

Runoff

Runoff was measured with a current meter in a box flume located in the southwest corner of the site at the outlet of the primary drainage network (Figure 3-1). Water stage was continuously measured with a Remote Data Systems Inc. TM water level monitoring device secured to a staff gage for manual verification. A stage-discharge relationship was developed and applied to allow for the empirical derivation of hourly discharge rates for each of the study periods. Although snowmelt represents a predominant component of seasonal runoff, few studies evaluate runoff control techniques (i.e., blocking drainage ditches) during the snowmelt period (Shantz and Price, 2006a); the snowmelt period is not included in this study.

Storage Changes

According to Van Seters and Price (2001), seasonal changes in storage within peatlands can be determined by

$$\Delta S = dh(S_y + bS_s) \pm d\theta \quad \text{Equation 4-3}$$

where dh is the change in the water table, S_y is the specific yield, b is the aquifer thickness, S_s is the specific storage, and $d\theta$ is the change in moisture content of the unsaturated zone. The S_s parameter characterizes the volume of water released from storage by compression of the peat matrix where

$$S_s = (db/dh)/b \quad \text{Equation 4-4}$$

and db/dh represents the slope of the surface subsidence versus water table level relation (Price and Schlotzhauer, 1999). This component is often omitted from storage change estimates due to the relatively large specific yield from unconfined aquifers (Van Seters and Price, 2001); however, the high compressibility of peat soils results in a significant contribution of the specific storage term in estimates of storativity (Price and Schlotzhauer, 1999). As such, Equation 4-3 includes the effects of water table changes on aquifer compression and moisture content changes in the unsaturated zone in seasonal estimates of storage change.

Water table levels (dh) and relative changes in surface elevation (db) were monitored on a weekly basis along the transect of wells and surface level monitors running approximately east-west through the centre portion of the site (Figure 3-1). In the unsaturated zone, $d\theta$ was estimated by *in situ* volumetric moisture content surveys conducted within a representative trench using a HydroSense® soil water content measurement system that was calibrated in the lab using peat extracted from the same area. Seasonal $d\theta$ was calculated as the difference in average θ at the end of the study period compared to that at the start. During each study period, five cores were extracted from the surface to depths of 50 – 80 cm from representative surface types within the Cacouna bog. The cores were carefully transported back to the laboratory where they were sliced into 5 cm sections and analysed for bulk density and S_y using standard methods (e.g., Price, 1996).

4.5 Results

The hydrological data reported below quantify the water inputs and outputs from the Cacouna bog during the time period 19 May – 16 August of 2005, 2006 and 2007 for use in the calculation of the full water balance for each study period. The 2005 and 2006 seasons represent the water balance of the Cacouna bog ~30 years after abandonment, while 2007 facilitates a comparison of the components of the water balance and the hydraulic parameters of the Cacouna bog following site management (rewetting).

Water Distribution Following Rewetting

Water ponding was evident behind peat dams and between baulks, producing a series of water reservoirs across the site (Figure 3-1). The K_{sat} of the constructed peat dams was comparable to that of the borrow peat deposit, with geometric mean values of 2×10^{-4} and $6 \times 10^{-4} \text{ cm s}^{-1}$ (at 75 and 100 cm below the surface of the peat dam, respectively) and 2×10^{-4} and $5 \times 10^{-4} \text{ cm s}^{-1}$ (at 75 and 100 cm within the remnant peat deposit, respectively). However, the K_{sat} at 150 cm depth was an order of magnitude higher within the peat dam ($3 \times 10^{-2} \text{ cm s}^{-1}$) than the borrow peat deposit ($1 \times 10^{-3} \text{ cm s}^{-1}$). Failure of several peat dams occurred prior to the summer of 2008 (i.e., following this study) with no obvious signs of failure via washout, indicating a failure of the dam either at depth within the dam or via an undercut beneath the dam. Average bulk density values within the upper 80 cm of the peat dam structures ranged from 0.08 to 0.20 g cm^{-3} , which were more dense (with one exception) than the borrow peat deposit. The hydraulic

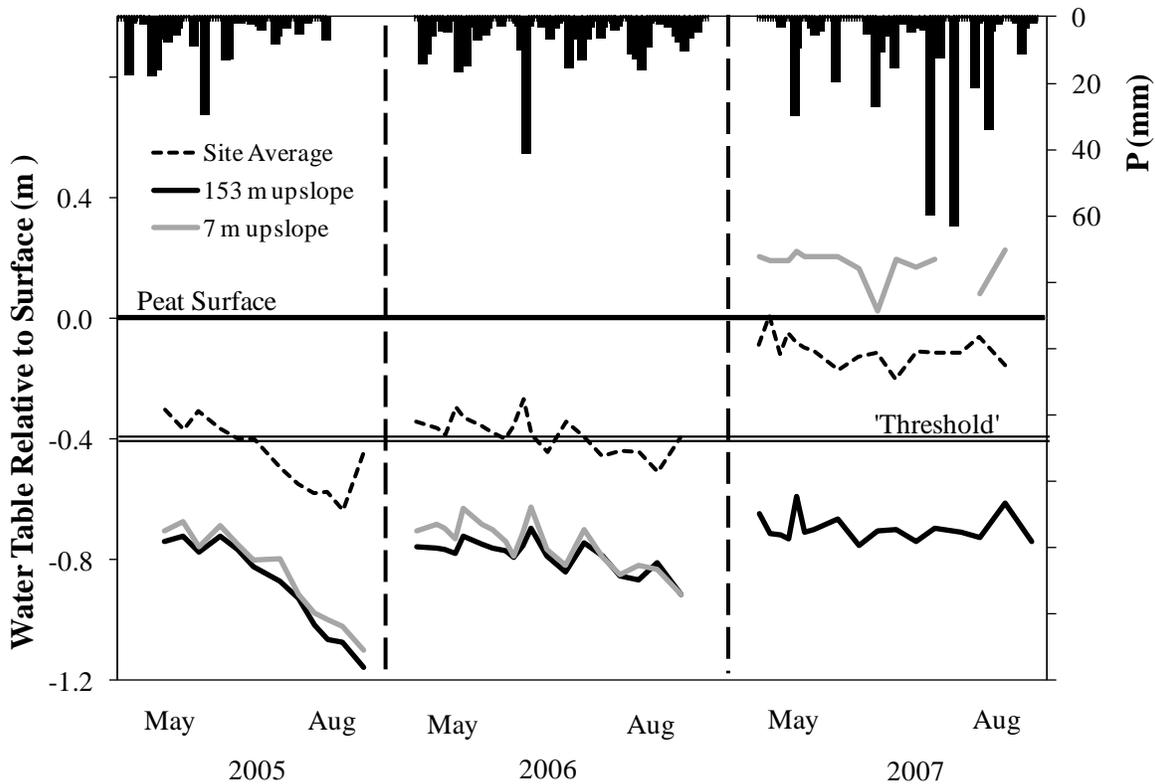


Figure 4-1 Water table levels at the Cacouna bog (dashed line represents the average site water table). The ‘threshold’ level (> -0.4 m) identifies water table levels which are generally suitable for moss survival at the Cacouna bog (Price and Whitehead, 2001). Water table levels near to (7 m upslope; grey) and far from (153 m upslope, black) a peat dam illustrate the non-uniform rise of water table levels following rewetting. Black bars represent precipitation (P)

parameters of the constructed peat dams were sufficient for detention of spring snowmelt and summer precipitation waters on-site up to the site water-holding capacity (see *Runoff* section below). Consequently, the average site depth to water table increased from approximately -44 and -39 cm (with reference to the cutover peat surface) during the 2005 and 2006 study periods, respectively, to -10 cm in the 2007 study period (Figure 4-1). Topographical variability within the study site, in combination with the location of the constructed peat dams, had a profound influence on the magnitude of the water table rise at any given location within the site. A typical trench exhibited an elevation change of over 2 m along an approximate 180 m length, resulting in a slope of 0.013. The low elevation ends of the trenches were disproportionately wet given their proximal location to the main drainage ditch and the peat dams compared to the upper reaches of the trenches that were farthest from the peat dams. For example, the water table level

rose by 112 cm at a well situated in the lower end of a trench, 7 m upslope from a peat dam, while a well situated 153 m upslope in the same trench exhibited a rise in water table level of only 26 cm (Figure 4-1). Similarly, topographical changes between peat dams in an east-west direction (i.e., perpendicular to trenches) complicated the variable influence of site rewetting. Prior to rewetting, standing water occupied a small (<5%) proportion of the site; however, in the 2007 study period, standing water covered 37% of the study site, with an average depth of 24 cm, and occupied some trenches along their entire length and others not at all (see Figure 3-1).

Water Inputs and Outputs

Cacouna bog is underlain by a low permeability continuous clay base ($5 \times 10^{-8} \text{ cm s}^{-1}$) that restricts water exchanges with the regional aquifer (Van Seters and Price, 2001). The drainage network established during the peat extraction process was sufficiently deep (1-2 m) to intercept any lateral flow towards the margins of the bog. As such, in each year, the only water input to the Cacouna bog was precipitation; evapotranspiration and runoff accounted for the only water losses from the site.

Precipitation

Precipitation (P) recorded during the 2005, 2006 and 2007 study periods totalled 200, 222 and 327 mm, respectively. Precipitation occurred predominantly as small events in 2005, the driest year, with only one event exceeding 16 mm. Similarly, only 1 event exceeded 16 mm in 2006, during which nearly 60 mm of rain fell over a 4-day period. The wettest year, 2007, was dominated by large, numerous precipitation events; in which six separate events exceeded 16 mm, including a 50 mm rainfall event in a 24-hour time period. The 30-year average (1971 – 2000) precipitation for the months of June and July total 179 mm as recorded at the St. Arsene meteorological station (Environment Canada). Precipitation for the same two months of 2005, 2006 and 2007 totalled 137, 158 and 216 mm, respectively.

Evapotranspiration

Owing to the highly variable surface microtopography within the Cacouna bog (baulks and trenches) and a relatively flat water table beneath this microtopography, substantial differences in the water table, and thus ET rate, exist on a small scale (metres). During α derivation, the best relationships (highest R^2 values) were typically achieved from wet surfaces (see *Methods* section for surface classification description); α values, and hence ET rates, trended

open water > forest > wet > moist > dry for each of the study periods (Table 4-1). As such, ET losses from open water and wet surfaces were the largest (the forest makes up only a small portion of the site) since these were the areas within the site where moisture was generally the most available. Aerially weighted α values ranged between 0.72 and 1.11 over the three study periods (Table 4-2). The highest estimated average α value was from open water ($\alpha = 1.37$). ET rates were 25% higher following rewetting in 2007 (3.6 mm day^{-1}) as compared to pre-restoration ET rates of 2.7 mm day^{-1} during both the 2005 and 2006 study periods (Table 4-2).

Table 4-1 Percent cover and ET rates for the Cacouna bog for 19 May to 16 August, 2005 – 2007. Note: open water was only present during the 2007 study period

Surface Type	Dominant Surface Cover	Percent Cover 05/06 (07)	ET Rate (mm day^{-1})			Average ET Rate (mm day^{-1})
			2005	2006	2007	
Wet trenches	<i>Sphagnum</i> spp. and bare peat	21 (29)	3.0	3.0	3.2	3.1
Moist trenches	Ericaceae spp. and some <i>Sphagnum</i> spp.	24 (15)	2.4	2.8	2.8	2.7
Dry baulks and roads	Ericaceae spp. and bare peat	35 (7)	2.3	2.3	2.5	2.4
Forest	Various tree species	19 (12)	3.7	3.1	3.7	3.5
Open Water		(37)	-	-	4.6	4.6
	Aerially Averaged Seasonal ET Rate (mm day^{-1})		2.7	2.7	3.6	

Table 4-2 Alpha values and ET losses for the Cacouna bog for 19-May to 16-August, 2005 – 2007

Year	Total ET Losses (mm)	Average ET Rate (mm day^{-1})	Aerially weighted alpha for time period			
			Julian Day			
			139 – 156	157 - 182	183 – 211	212 - 228
2005	246	2.7	0.78	0.78	0.72	0.72
2006	227	2.7	0.96	0.89	0.94	0.91
2007	328	3.6	0.72	0.73	1.07	1.11
			Water α	Forest α		
			1.36	1.07		

Storage Changes

The greatest storage change was due to the deepening water table during the course of each study period. The water table declined by 258, 215 and 113 mm during the 2005 – 2007 study periods, respectively. The specific yield value for the substrate was estimated at 0.18 (three year average), which generated water losses due to the drainage of soil pores of approximately 47, 39 and 20 mm over each study period, respectively. Over the three study seasons a total of 186 samples were analysed for S_y , with a standard deviation of 0.05. The values used represent an average S_y estimate for the upper 80 cm of the peat deposit, which encompasses the zone within which the site-averaged water table fluctuated over the entire study period. Storage changes associated with compression of the peat matrix, as estimated by Equation 4-4, were 16, 10 and 5 mm (see *Surface Elevation Change* section for explanation). Good R^2 values (> 0.75) were obtained during calculation of the slope of the surface subsidence versus water table level relation. Changes in moisture content (drying) of the unsaturated zone throughout each study period resulted in storage losses of 12, 23 and 5 mm. Using Equation 4-3, total storage change during the 2005, 2006, 2007 study periods was estimated to be 75, 71 and 31 mm, respectively.

Runoff

A network of primary and secondary drains transmitted runoff from the site. Runoff was 25 and 73 mm in the 2005 and 2006 study periods. After construction of the peat dams in the fall of 2006, runoff during the 2007 study period was 32 mm.. Runoff losses were the largest in 2006, due mainly to the occurrence of one large (60 mm) precipitation event and an active primary drainage network. An average runoff efficiency (percent precipitation produced as stream discharge) of 10% was observed following drainage ditch blocking (2007), which was reduced from 23% during the 05/06 study periods (Price and Ketcheson, 2009). Storm hydrograph lag-times were also generally shortest in 2007. Table 4-3 presents the runoff efficiency and lag-times for storms with similar antecedent water levels in each year. Antecedent water levels were measured a few days prior to the event at the same location each year, which remained unaffected by the site rewetting. The control site had not been established prior to the storm event in 2005 so it was unsuitable for this application; however, water levels at the control site were similar in 2006 (-52 cm) and 2007 (-50 cm) prior to the respective events. The hydrographs for each of the storms (Figure 4-2) indicates that stream flow returned to pre-storm conditions rapidly following ditch blocking (2007). Moreover, a notable difference between the

daily flow duration curves of 2005/2006 and 2007 illustrates the impact of a blocked drainage network on the site flow regime (Figure 4-3). The storage capacity of the Cacouna bog exhibited an increased storage capacity in 2007, whereby a critical storage threshold had to be exceeded for the system to respond rapidly to precipitation inputs. For example, precipitation produced deepening pools within trenches during a 60 mm precipitation event in 2007 until the site storage capacity was reached, as indicated by an increasing discharge and decreasing rate of water rise in the trench (Figure 4-4). Hysteresis was apparent, as similar discharge depths were observed at different standing water levels for the rising and receding limbs.

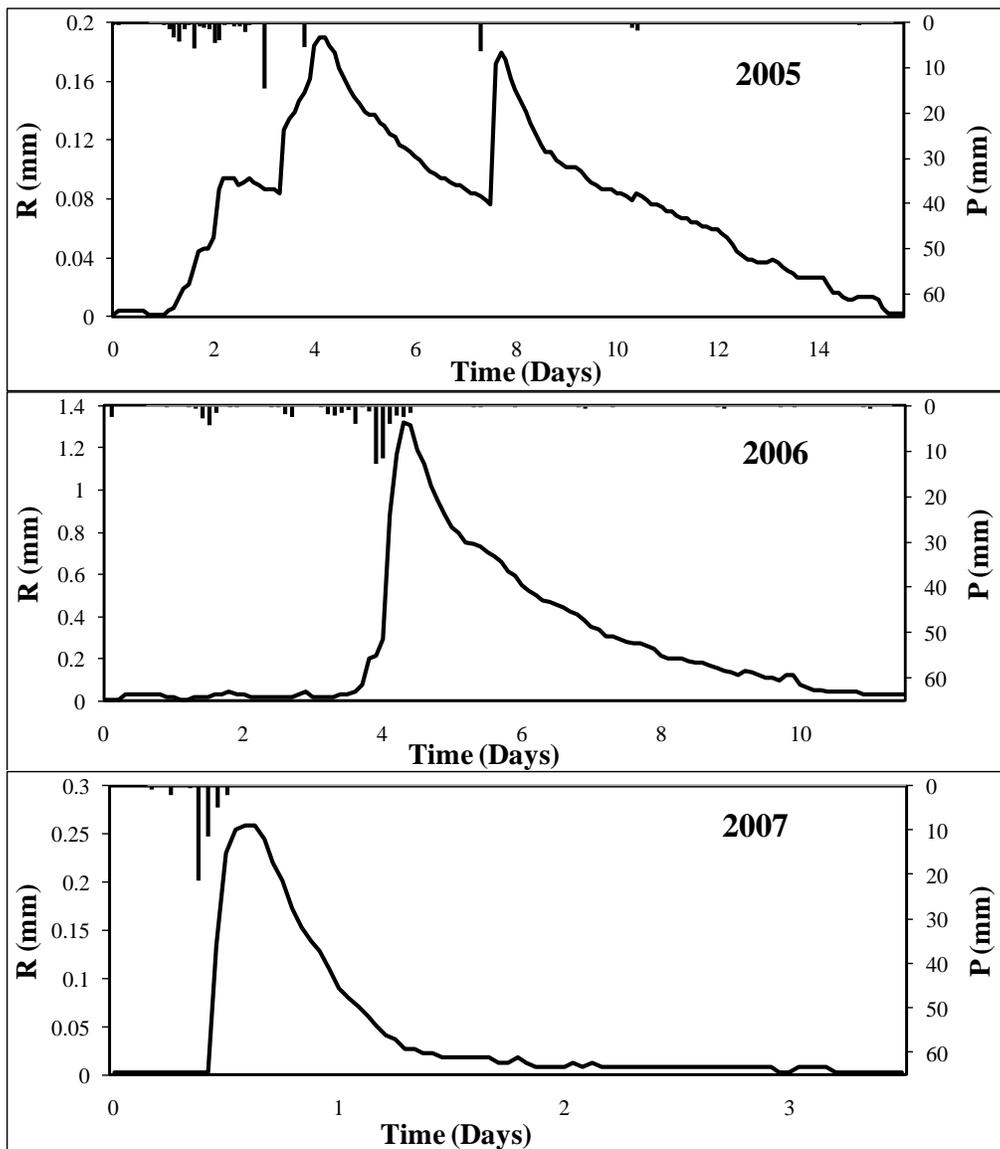


Figure 4-2 Hydrographs for storms during the 2005, 2006 and 2007 study periods (similar antecedent water levels)

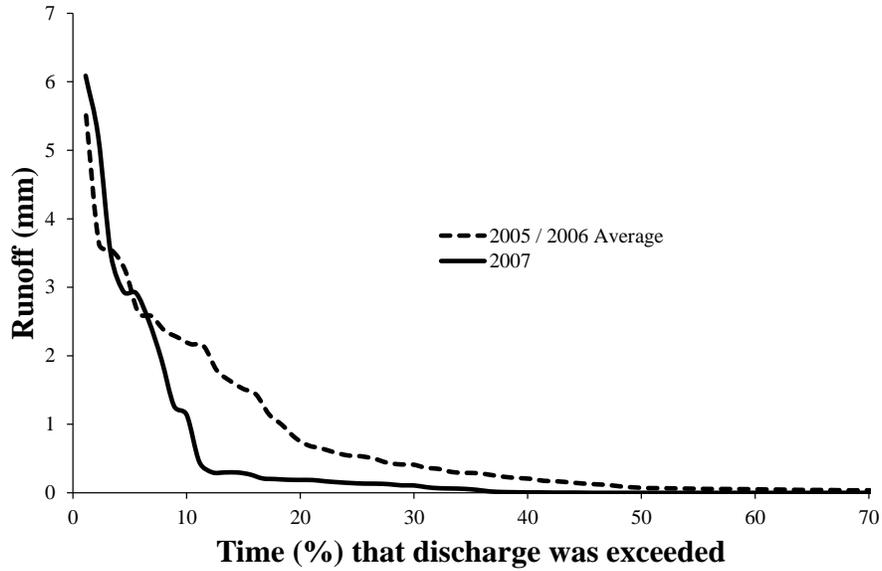


Figure 4-3 Daily flow duration curves for the Cacouna bog. The steeper curve following rewetting (2007) indicates a tendency towards low-flow conditions

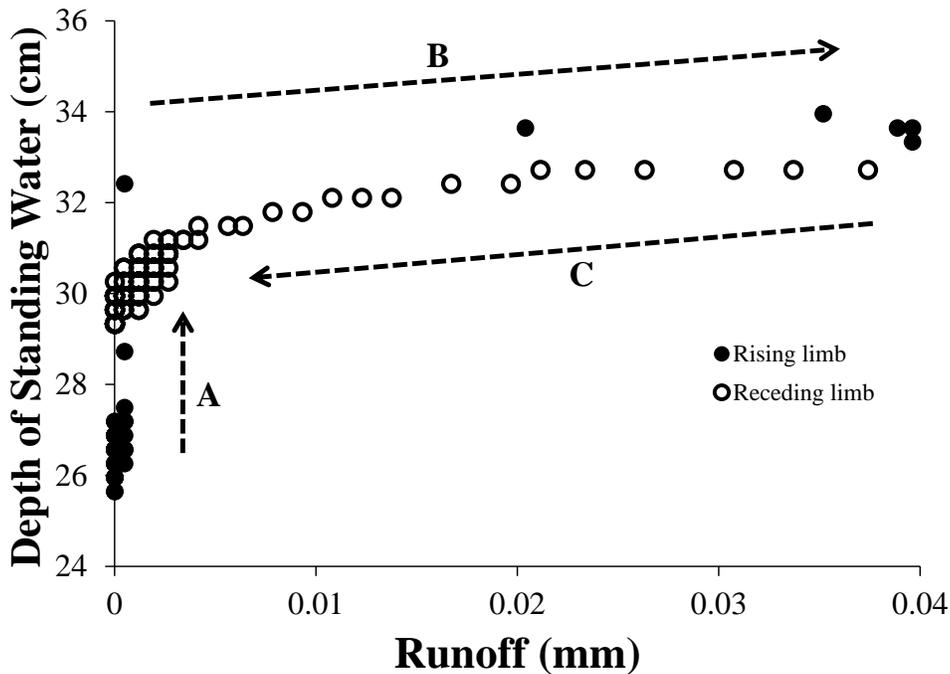


Figure 4-4 Standing water depth within a trench versus discharge during a 60 mm precipitation event in 2007. **A** – Depth of standing water within a flooded trench increases during the precipitation event, as water is detained on-site due to the blocked drainage network (closed symbols); **B** – the site water storage capacity is exceeded and precipitation inputs produce site runoff (closed symbols); **C** – runoff from the site recedes as precipitation inputs cease and the site returns to its maximum water holding capacity (open symbols)

Table 4-3 Runoff efficiency, lag-times and storm characteristics for events with similar antecedent water levels each year. Note: a small (9 mm) secondary precipitation event occurred in 2005, which increased the time from peak to baseflow

Year (Julian Day)	Antecedent water level (cm)	Event duration (hrs)	Average event intensity (mm/hour)	P (mm)	R (mm)	Runoff Efficiency (%)	Lag-time (hrs)*	Time from peak to baseflow (hrs)
2005 (165)	-89.2	106	0.5	51	12	24	50	245
2006 (158)	-93.4	79	0.7	59	30	51	14	158
2007 (192)	-88.3	12	3.6	43	4	9	6	32

* Time from centre mass of rain storm to peak

Surface Elevation Change and Hydraulic Conductivity

Site-averaged seasonal surface level adjustment (relative to the first measurement of each respective study period) was found to be -2.3, -0.6 and +0.2 cm in 2005, 2006 and 2007, respectively, with a maximum subsidence of over 5 cm at one location in a single season (2005). The surface level rebounded by an average of 3.2 cm following rewetting (relative to the 2005/2006 average level) (Figure 4-5).

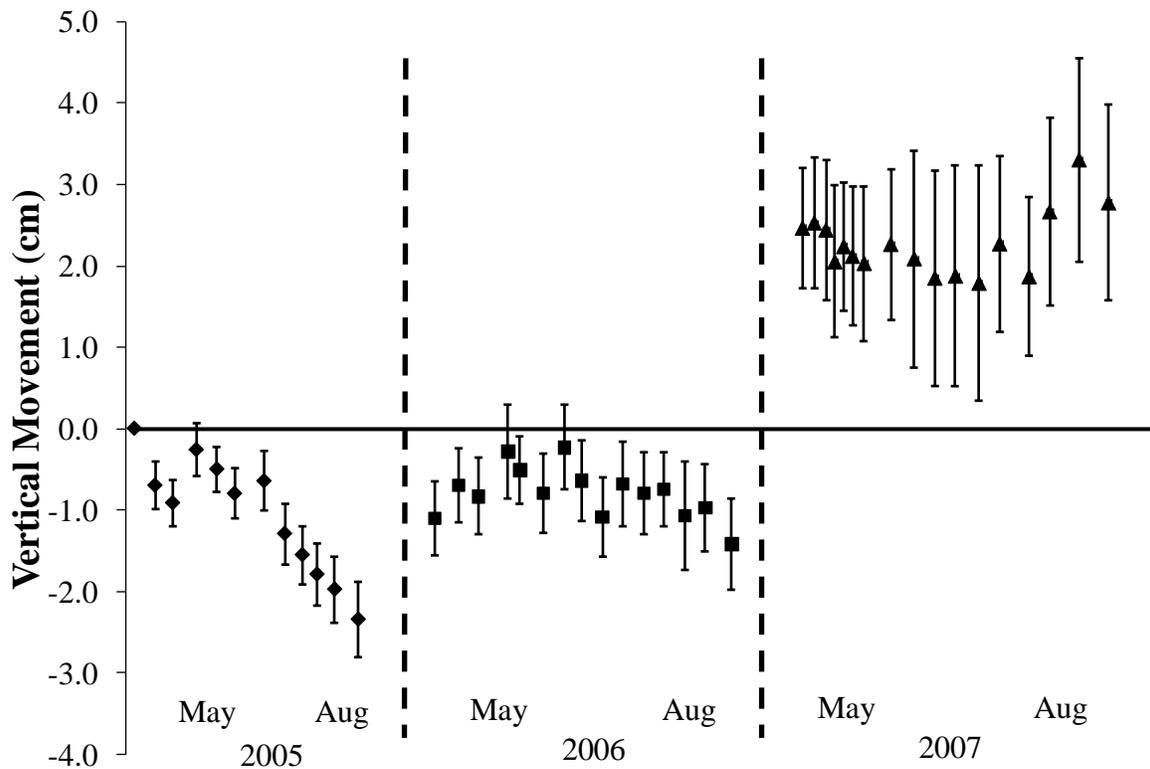


Figure 4-5 Surface elevation changes (relative to the first measurement in 2005) over the three study periods. Error bars represent the standard error of the mean

Contemporaneous with peat surface rebound following site rewetting, the mean K_{sat} increased by an order of magnitude (2007) both at the site scale (55.1 ha) and within an instrumented trench (the ‘study trench’ ~0.2 ha) (Figure 4-6). Values of K_{sat} within the control section of the Cacouna bog (hence not affected by the rewetting) increased only slightly (32% higher than 05/06 average) as compared to the site average K_{sat} , which showed an increase of 269% (higher than 05/06 average) (Table 4-4).

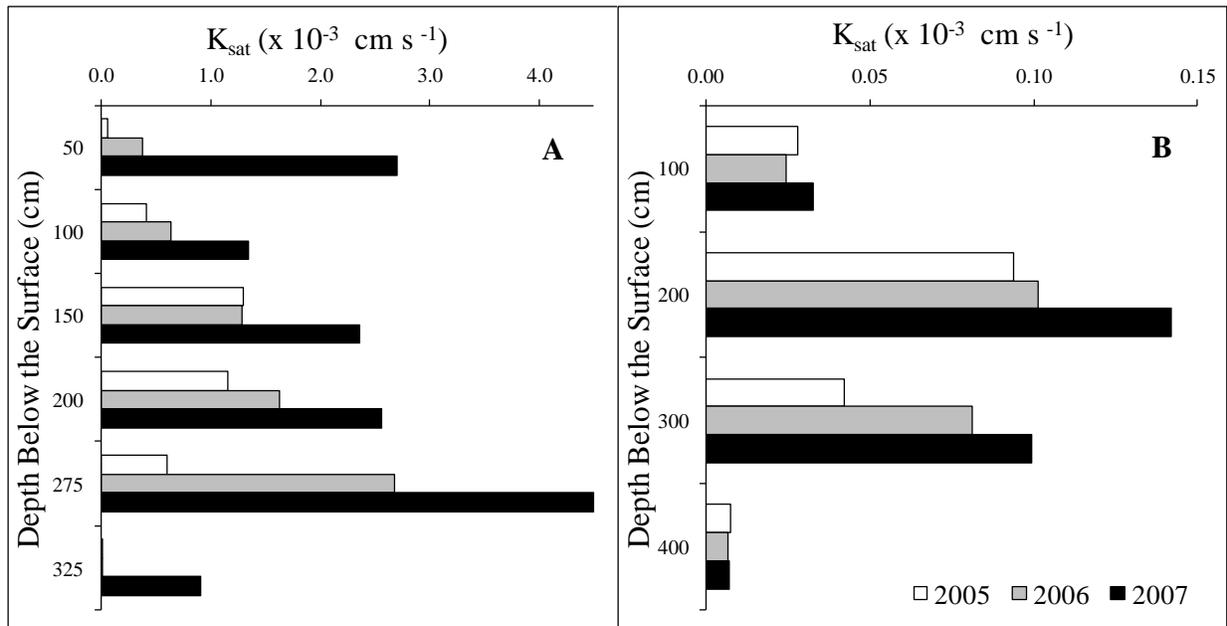


Figure 4-6 K_{sat} with depth within a trench at the Cacouna Bog (A; left) and at the control site (B; right). Note the different scales (X and Y axes)

Table 4-4 The geometric mean K_{sat} values (in cm s^{-1} , all depths included in calculation) for the entire Cacouna Bog (‘site average’), for within the study trench, and at the control site (standard error of the mean in brackets)

Year	Site Average		Study Trench		Control Site	
	K_{sat}	n	K_{sat}	n	K_{sat}	n
2005	$2.7 (\pm 3.4) \times 10^{-4}$	136	$3.1 (\pm 4.6) \times 10^{-4}$	98	$3.0 (\pm 1.8) \times 10^{-5}$	20
2006	$3.8 (\pm 4.4) \times 10^{-4}$	130	$4.5 (\pm 5.1) \times 10^{-4}$	100	$3.4 (\pm 2.3) \times 10^{-5}$	14
2007	$12 (\pm 17) \times 10^{-4}$	134	$15 (\pm 15) \times 10^{-4}$	101	$4.2 (\pm 3.1) \times 10^{-5}$	10
Change (%)	+ 269		+ 284		+ 32	

4.6 Water Balance

The seasonal water balance of the Cacouna bog (devoid of surface and ground water inputs) is estimated as

$$P = ET + R \pm \Delta S + \varepsilon \quad \text{Equation 4-5}$$

where P is precipitation, ET is evapotranspiration, R is runoff, ΔS is change in soil storage and ε is the residual term. Each of the components used in the water balance (with the exception of P) were influenced by rewetting (Table 4-5). ET was the dominant water loss from the site each year and exceeded precipitation inputs in both years prior to rewetting, which resulted in a summer water deficit. The cumulative P minus ET during the 2005, 2006 and 2007 study periods was -46, -21 and -1 mm, respectively, indicating a shortage of water in each of the two study periods prior to rewetting and the absence of a summer water deficit in 2007 following rewetting. A water deficit did not occur in 2007 despite the substantial increase in ET losses due to above average precipitation. Runoff losses were the largest in 2006 due mainly to the occurrence of one large (60 mm) precipitation event and an active primary drainage network. Even though more precipitation occurred in 2007 (327 mm) as compared to 2005 (200 mm), runoff was similar due to the reduced runoff efficiency following blockage of the drainage network. Both the storage changes and the residual term were smallest in 2007. The residual terms in 2005, 2006 and 2007 represented 2, 10 and <1% of water inputs, respectively.

Table 4-5 The components of the water balance for the Cacouna bog (all values in mm). Percent error was calculated by dividing the residual term by the precipitation amount for each year

Year	P	ET	R	Delta S	Residual	% Error
2005	200	246	25	-75	-4	2
2006	222	243	73	-71	23	10
2007	327	328	32	-31	1	<1

The largest probable source of error in the water balance estimation is likely within the ET term, as it represents the largest individual component of Equation 4-5 and, thus, has the potential to impact the water budget estimation the most if estimated inaccurately. The ET estimation is impacted by the accuracy of the lysimeter measurements, which likely included error induced by slight differences in heat and moisture conditions within the lysimeters, errors in the Priestley and Taylor (1972) method and the combined error in the Q^* and Q_G measurement, which is typically within 10% (Price, 1996). Coefficient of determination for the

stage-discharge relationship remained above 0.9 and encompassed a range of high to low-flow conditions, and P measurements made with the automated tipping bucket rain gauge were within $\pm 10\%$ of manual rain gauge measurements. Random error (human and measurement) in the field likely resulted in measurements representing actual values within approximately $\pm 15\%$, although every effort was made to keep this source of error low.

4.7 Discussion and Conclusions

Hydrological Consequences

The rewetting of the Cacouna bog caused the water table to rise and flood lower-lying trenches (Figure 3-1). Topographical variability and the location of the constructed peat dams strongly influenced the magnitude of the water table rise at any given location (Figure 4-1). A similar trend was observed following blockage of the main drainage ditch in a block-cut peatland; where the impact of the main ditch dam on water table level decreased with increasing distance from the dam (Roul, 2004). Peat dams effectively detained P waters on-site and exhibited K_{sat} values similar to those of the borrow peat for the upper $\sim 100+$ cm of the dams; however, K_{sat} values were an order of magnitude higher at 150 cm within the peat dams. Several peat dams failed via deep through-flow or undercut in 2009 (personal observation) where the K_{sat} was much higher. This portion of the dam near to its base is more likely to have macropore flow, as it is composed of peat from the upper portion of the borrow area. This peat has been above the water table consistently for decades and, through oxidation, compression and shrinkage, has become quite dense and structurally sound (i.e., less amorphous) and, hence, more resistant to being tamped into place. Further, differences in standing water levels across some peat dams consistently exceeded 0.5 m. This large pressure difference across the peat dam could result in hydraulic lifting and separation of the peat dam material at depth, which would allow water to flow through the dam more easily. Closer peat dam spacing would reduce these large pressure differences and thereby restrict the water flow through the dam as a consequence of hydraulic lifting. Nonetheless, the average site water table rose by 32 cm following construction of the peat dams (Figure 4-1).

ET losses were the greatest following rewetting due to the increased abundance of water as well as the addition of pooled (open) water within flooded trenches (Figure 3-1). The inevitable ecological succession as a consequence of the new moisture regime should favour *Sphagnum*

mosses over vascular vegetation (see *Implications for Sphagnum moss recolonization* section), and, thus, limit the contribution and associated physiological control of plant transpiration to site ET rates. Farrick and Price (2009) noted that transpiration dominated ET losses at the Cacouna bog; however, this only occurred at WT depths of ≥ -30 cm. The average site water table in 2007 remained within the upper 30 cm (Figure 4-1) where bare peat evaporation losses dominated over transpiration losses through ericaceous shrubs (Farrick and Price, 2009). These are also areas that will likely become dominated by a *Sphagnum* moss cover. Since water transport occurs passively through *Sphagnum* mosses as water conduction through the capillary spaces between individual plants, which do not possess stomata, they are unable to actively control the rate of their water losses to counter atmospheric conditions (Hayward and Clymo, 1982). *Sphagnum* mosses are, however, able to passively control the water losses due to evaporation as a consequence of the reduced capillary capability as the surface of the moss dries (Price, 1991) and the increase in albedo that accompanies the whitening of the surface of the drying mosses (Ingram, 1983). Considering the variable impact of the water table rise (Figure 4-1), many areas within the site will become sufficiently wet to reduce the shrub cover in favour of *Sphagnum* mosses. However, other drier areas (i.e., locations farther from dams; baulks) will indeed continue to favour an ericaceous shrub cover. Nonetheless, these areas will have increased water availability, as the seasonal water table is likely to remain within the rooting zone, with the consequence of increased transpiration losses in drier areas. Further, an increase in ET variability should be expected, as newly recolonized mosses exhibit a widely variable ability to transport water to the surface for evaporation (Price and Ketcheson, 2009).

Despite the increased ET rates drying of the unsaturated zone was reduced in 2007. Increased P amounts (in 2007) are partially responsible for this; however, the reduced runoff efficiency following ditch blocking is likely the most important factor. Storm hydrographs returned to pre-event conditions quickly following rewetting (Figure 4-2) and, despite having the highest event intensity and shortest lag-time, the storm event in 2007 produced the smallest amount of runoff (Table 4-3). Holden (2005) documented dramatic changes to the runoff regime in disturbed peatlands that included high stream peak flows, rapid responses to rainfall and a strong dependency upon antecedent moisture conditions. These characteristics become more prevalent at the Cacouna bog following rewetting. This is a factor of the concept of a maximum site water storage capacity where, following blockage, the site has an increased yet finite storage

capacity. The discharge regime remains somewhat unresponsive to precipitation, as these water inputs are detained within the site until the site storage capacity has been reached (i.e., the system can hold no additional water); after which the system becomes more responsive to precipitation inputs (see Figure 4-4). Large discharge rates are produced and time lags are shortened (Figure 4-2), which are characteristics more typical of a surface-flow dominated regime. Thus, despite the substantial reduction in the efficiency of the primary drainage network, the behaviour of the system depends upon a critical storage threshold. Once this threshold is exceeded the system responds rapidly to precipitation inputs following rewetting. As such, antecedent moisture conditions within the site had a greater impact on the runoff regime following rewetting. Nonetheless, 127 mm more precipitation fell in 2007 (327 mm) as compared to 2005 (200 mm); however, R losses were similar (25 mm in 2005; 32 mm in 2007) due to the reduced runoff efficiency following blockage of the drainage network. These changes to the system flow regime are apparent in the daily flow duration curves (Figure 4-3). For the largest discharge rates similar curves are observed; however, following blockage, the flow duration curve shifts to the left and exhibits a much steeper slope, which indicates a reduction in daily discharge rates in all but extreme conditions.

Seasonal storage change was reduced by over 60% following rewetting as a result of increased water abundance within the site. This is in part a consequence of the large amount of P in 2007, which was accompanied by increased ET losses and a very slight water deficit; and in part a consequence of the reduced runoff efficiency resulting in the detention of more P waters on-site. This subsequently restricted seasonal water table drawdown and constrained the amount of water lost from storage due to pore drainage (58, 38 and 16 mm in 2005, 2006 and 2007, respectively). Prior to restoration, higher R losses resulted in increased drying of the unsaturated zone and large water table drawdown during the summer season, as less precipitation inputs were detained on-site due to the active drainage network (i.e., higher runoff efficiency) facilitating the removal of these water inputs. The volume change associated with the surface rebound during the rewetting of the Cacouna bog (32 mm; Figure 4-5) caused the saturated hydraulic conductivity of the remnant peat deposit to increase by an order of magnitude (Figure 4-6). The higher K_{sat} could increase subsurface site drainage; however, the blocked drainage network is sufficiently deep to intercept this subsurface flow, thus, providing no outlet for consistent discharge as a consequence of the increased K_{sat} .

Implications for Sphagnum moss recolonization

Initially, restoration efforts aim to create hydrological conditions more favourable for the recolonization of non-vascular *Sphagnum* mosses to ultimately facilitate the reestablishment of an upper acrotelm layer and a self-sustaining (peat accumulating) ecosystem. At the Cacouna bog, the drying of the unsaturated zone and concurrent water table decline throughout the summers of 2005 and 2006 (Figure 4-1) are an excellent illustration of why the natural recolonization of the peatland following abandonment favoured vascular vegetation (90 – 100% coverage) over *Sphagnum* moss recolonization (<10% coverage; Girard et al., 2002). Price and Whitehead (2001) determined hydrologic thresholds for *Sphagnum* recolonization at the Cacouna bog and identified that *Sphagnum* recolonized areas where soil water pressures were greater than -100 cm and water tables remained high (-24.9 ± 14.3 cm). Water tables deeper than -40 cm were found to be imperfectly related to soil water pressures; however, this appears to be the lower limit of water table levels within which *Sphagnum* mosses are able to survive. It is therefore reasonable to use a water table depth of -40 cm as a general indicator of site suitability for *Sphagnum* moss recolonization at the Cacouna bog, wherein water table fluctuations within the upper 40 cm of the peat deposit represent suitable conditions for *Sphagnum* moss recolonization and survival. The average site water table level in both 2005 and 2006 was drawn below the -40 cm threshold level (labelled 'threshold' in Figure 4-1). This signifies that, in general, the site was not suitable for *Sphagnum* recolonization and survival in the years prior to rewetting. However, in 2007 the average site water table remained above -25 cm for the entire season (Figure 4-1), which indicates that the site is suitable for the survival of *Sphagnum* moss following rewetting. A more accurate estimation of the proportion of the site suitable for *Sphagnum* survival following rewetting is difficult to quantify given the logistical limitations of spatial measurements in the field and the complicating influence of site topography and proximity to a peat dam on the disproportionate water table rise.

Prior to rewetting, the *Sphagnum* mosses that were able to recolonize naturally on the surface of the Cacouna bog were mostly limited to the lowest lying moist portions of the trenches (Girard et al., 2002). Following rewetting, these areas became inundated with water (e.g., Figure 4-1) that was up to over 100 cm deep in some trenches, which resulted in the death of much of the naturally recolonized mosses. Despite the flooding of the sites that were previously the most suitable for *Sphagnum* recolonization, the water table rise increased the proportion of the site that

is suitable for moss survival by raising and maintaining high water table levels throughout most of the site over the span of the summer months, which typically represent the most harsh hydrological conditions. In the years following the rewetting of the Cacouna bog, especially where flooded conditions prevail, an ecological succession should occur. Favourable conditions will shift away from vascular vegetation and towards non-vascular *Sphagnum* mosses. Signs of vascular vegetation stress (dying leaves and needles on shrubs and trees growing in newly waterlogged areas) were apparent during the summer of 2007. It is anticipated that much of the vascular vegetation will die off due to the persistently waterlogged conditions following rewetting. Conversely, aquatic *Sphagnum* spp. growth was observed within flooded portions of many trenches by late August 2007. By 2009, >50% of the flooded areas appeared (visual observation) to be colonized by *S. fallax*.

The baulk – trench topography at the Cacouna bog produced spatially variable conditions in the substrate prior to rewetting. The water table beneath baulks and trenches is relatively flat on a microtopographical scale, which results in substantial differences in the water table position beneath each of the features. Prior to rewetting, raised baulk structures were relatively dry, with a water table depth at least 0.5 m further from the peat surface than the adjacent low-lying moist trenches. This characteristic distinguishes block-cut peatlands from those harvested using the vacuum technique, which are relatively flat and exhibit fairly uniform conditions that are generally worse for *Sphagnum* moss recolonization (i.e., less moisture and lower soil-water pressure) than the conditions within a block-cut site (Price et al., 2003). Ideally, for the successful recolonization of *Sphagnum* mosses, site rewetting (i.e., water table rise) would occur uniformly throughout the entire site and surface topographical features would be minimized. Increasing the number of peat dams would thereby reduce the spacing between them and assist in achieving a more uniform rewetting. Typically, post-extraction restoration efforts on vacuumed sites rely on ditch-blocking (Price et al., 2003), constructed open water reservoirs (Spieksma, 1999) and bunds (Shantz and Price, 2006b) to increase the site water storage capacity. At the Cacouna bog, the increased site water storage capacity was facilitated by the presence of relatively wide trenches as a legacy of the peat extraction process. In spite of the differences between vacuum and block-cut peatlands, the importance of maintaining water availability on restored sites is paramount.

In conclusion, rewetting transformed the system hydrology and altered water relations within the Cacouna bog. In comparing the components of the water balance prior to (2005/2006) and following (2007) site rewetting (Table 4-5) it is beneficial to limit the ET losses from a restored site, since it is the dominant water loss each year. The most important impact of site rewetting on the system hydrology, however, was the reduction in runoff efficiency following blockage of the drainage network. The restricted water losses via the site drainage network (i.e., R) resulted in an increased water abundance following site management. The new runoff regime was more dependent upon antecedent water table levels following rewetting; as the system responded rapidly once the site water holding capacity was exceeded and low-flow conditions dominated otherwise. The site is generally well-suited for *Sphagnum* moss survival due to the higher water table levels following rewetting; however, the site topography and location of peat dams caused the impact of rewetting to be highly spatially variable. Flooded portions of the site are rapidly recolonizing with aquatic *Sphagnum* species, while more time will be required for *Sphagnum* to colonize the cutover peat surface where moisture is more limited.

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5.0 Manuscript 2: Characterization of the fluxes and stores of water within newly formed *Sphagnum* moss cushions and their environment

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5.1 Summary

Internal water storage and balanced water fluxes are critical for the physiological function of *Sphagnum* mosses that have recolonized cutover peatlands characterized by low soil water pressures. The relative importance of water exchanges between spontaneously regenerated *Sphagnum* moss cushions and their surroundings are addressed through investigation of the sensitivity of moss moisture dynamics to a range of environmental variables. Precipitation waters are poorly retained within the cushions, which indicated that rain event water can only be relied upon by the mosses for a short period of time. The connectivity between moss cushions and the remnant cutover peat deposit was strong when conditions were wet and the water table was within 30 cm of the surface of the cutover peat but weakened as conditions became drier, as reflected by weakened upward hydraulic gradients in the unsaturated zone below the moss cushions. Calculation of a water budget for the moss cushion identified an imbalance between water inputs and losses that exceeded the change in moss soil water storage. As such, additional (small) sources of water, such as dewfall and distillation, are hypothesized as being important for physiological processes when conditions are dry. Rewetting of the peatland by blocking drainage ditches created conditions more favourable for *Sphagnum* survival through increasing the moisture content and soil-water pressures within the remnant peat deposit; although restoration efforts should aim to constrain water table fluctuations to within the upper 30 cm.

5.2 Introduction

Sphagnum mosses are non-vascular vegetation (bryophytes) that, in addition to meteoric water inputs, rely upon capillary retention and water flow in the spaces between individual plants (Hayward and Clymo, 1982) to sustain hydration of the photosynthesizing capitula (McNeil and Waddington, 2003). They are the primary peat-forming plants in northern peatlands (Kuhry and Vitt, 1996), which cover over 12% of Canada's total land area (Tarnocai, 2006). In cutover sites

characterized by low soil water pressures (Price, 1997), *Sphagnum* is unable colonize spontaneously because it cannot generate the capillary forces sufficient to extract water from the underlying peat substrate (Price and Whitehead, 2001). Price and Whitehead (2001) developed hydrologic thresholds for *Sphagnum* recolonization on abandoned cutover sites by evaluating the conditions of the underlying substrate in areas of the Cacouna bog (same site as in this study) that were (and were not) spontaneously recolonized by *Sphagnum* mosses. They concluded that *Sphagnum* recolonized where there was a high water table (mean depth -24.9 ± 14.3 cm), high soil moisture (greater than 50%) and high soil water pressure (greater than -100 mb). These areas were mostly in shallow ditches and low-lying areas within the site, where the surface was closer to the site water table.

Sphagnum mosses initially recolonize cutover peatlands as isolated, hemispherical cushions that are closely tied to the moisture regime of the cutover peat substrate (Price and Whitehead, 2004) and the influence of the Ericaceae canopy (Farrick and Price, 2009). The newly formed *Sphagnum* cushions are able to coalesce into larger carpets in wetter areas, with the highest soil water pressures. There appears to be a positive feedback in which the development of *Sphagnum* cushions protects the underlying substrate (already relatively wet) from evaporative demands, thus engineering its own environment (Price and Whitehead, 2004). Price and Whitehead (2004) found that soil moisture content beneath cushions was 5 – 14% higher than in bare cutover peat directly adjacent to it. While these studies have documented the hydrological conditions required for *Sphagnum* moss recolonization and survival, few field-based studies were found that quantified the role of capillary rise from cutover peat versus water from precipitation on the moisture dynamics within moss cushions. Modelling work by Shouwenaars and Gosen (2007) suggested that restricted water transport within *Sphagnum* cushions increased their vulnerability to water stress; however, unreliable measurements of soil-water pressure in the unsaturated zone limited the ability for proper characterization of the connectivity between the mosses and the underlying substrate. Therefore, it remains uncertain if the substrate is an important source or sink of water for the recolonized mosses.

The moisture exchanges at the moss – atmosphere interface are dominated by evaporation losses and precipitation inputs. However, small yet potentially critical sources of water, such as dewfall (Csintalan et al., 2000), distillation (Carleton and Dunham, 2003) and vapour transport (Price et al., 2009) may be physiologically important to prevent desiccation. Carleton and

Dunham (2003) found that, under certain microclimatic conditions, condensation of upwardly transported vapour from within the moss matrix (distillation) hydrated the uppermost parts of forest (feather) mosses. Price et al. (2009) estimated that (upward) vapour flux in *Sphagnum* mosses was about 1% of capillary rise. Within *Sphagnum* moss cushions on cutover peat, Price and Ketcheson (2009) reported that moisture variability increased with depth to the base of the cushion, with smaller cushions exhibiting the most variability overall. They hypothesize that the upper and lower parts of the larger cushions may be only weakly coupled, limiting vertical growth, and favouring lateral spreading and coalescing of cushions; though water exchanges between the base of the cushion and underlying peat substrate have not been well-characterized. Since rewetting of cutover peatlands will increase the water content of the cutover peat (Price, 1997), the direction and magnitude of water exchanges between *Sphagnum* cushions and the substrate could be affected. An increased understanding of the moisture dynamics within and exchanges of water between moss cushions and their surroundings is required. Consequently, the specific objectives of this study are to: 1) Characterize the distribution and variability of moisture within newly formed *Sphagnum* moss cushions; 2) Identify potential water sources for the moss cushions; and 3) Compare substrate moisture and pressure conditions before and following rewetting.

5.3 Study area

The study site is an abandoned block-cut bog domed bog of the Low Boreal Wetland Region (NWWG, 1997) in Cacouna (47°53' N, 69°27' W), approximately 10 km north-east of Rivière-du-Loup, Québec, Canada. Mean annual precipitation (1971 – 2000) recorded at a meteorological station in St. Arsène (< 2 km from study site) is 963 mm, 29% of which falls as snow (Environment Canada, 2003). Average monthly temperatures range from -10.9°C in February to 16.5°C in August (Environment Canada, 2003). Peat was harvested at Cacouna using the traditional block-cut extraction technique, resulting in alternating sequences of narrow (2-4 m wide) baulks that were raised 0.5-1.0 m above the adjacent 10-12 m wide trenches when harvesting ceased in 1975. At the Cacouna bog, this topographical pattern occurred in parallel in an approximately north-south direction. The remnant peat is up to 4 m thick (Van Seters and Price, 2001), with average bulk density and specific yield values of 0.12 g cm⁻³ and 0.08, respectively (Price and Whitehead, 2001). Following agricultural encroachment and the development of roads and a railway line (Girard et al., 2002), the Cacouna bog was reduced from

an area of 210 ha to 148 ha and divided into two hydrologically distinct halves (Van Seters and Price, 2001). This study focused on a 55 ha section within the larger 80 ha southern half. See Ketcheson and Price (2011) for a full site description.

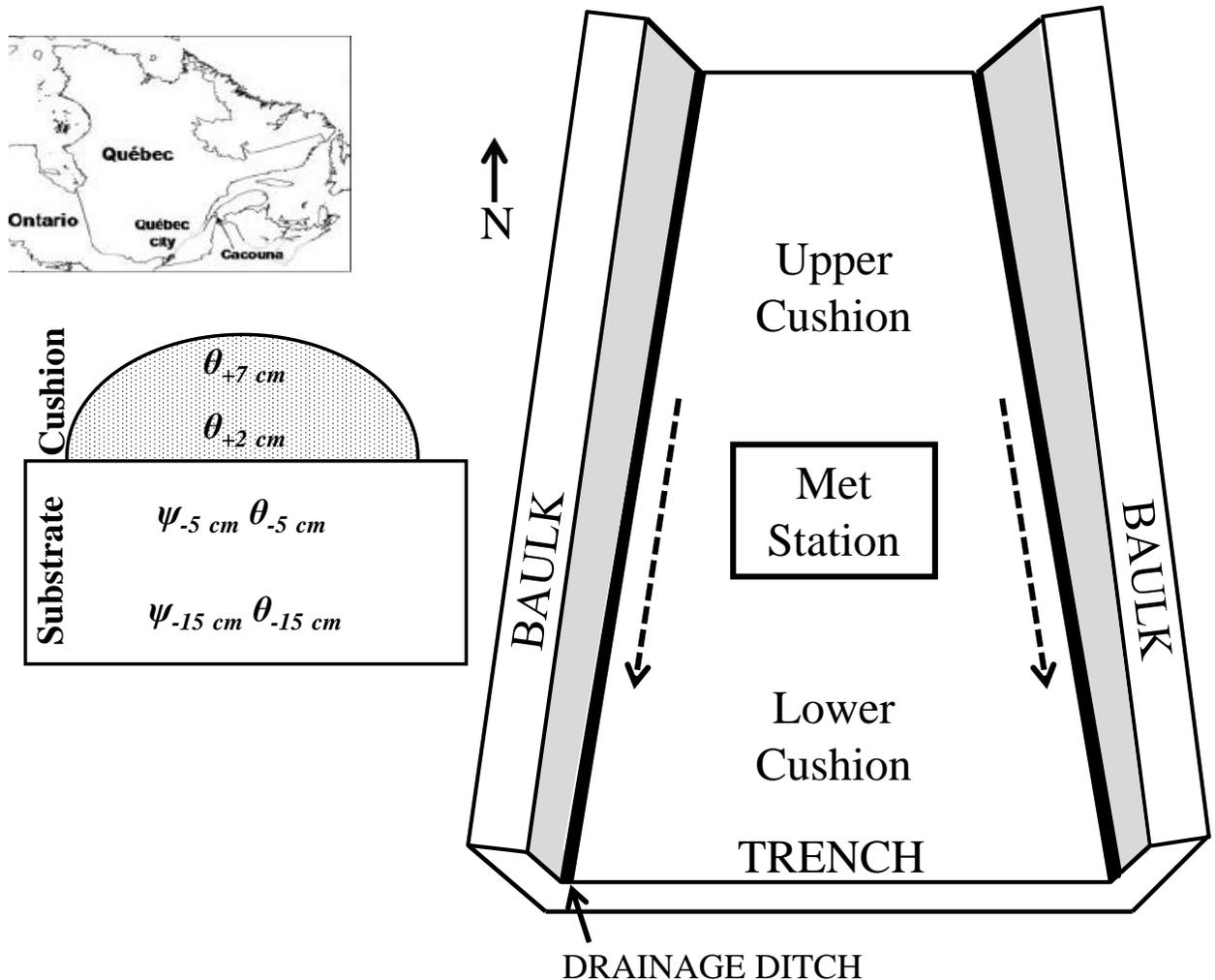


Figure 5-1 Location of the Cacouna bog and schematic representation of a baulk-trench topography and the relative location of the upper and lower cushions in the study trench. Dashed arrows indicate the direction of drainage. Cross-section indicates the relative location of measurements made both within and beneath the cushions

An 11 m wide, 180 m long trench within the Cacouna bog that exhibited structure and vegetation cover typical of this peatland was selected for study (herein referred to as the study trench (ST); see Figure 5-1). Multiple *Sphagnum* moss cushions have successfully recolonized on the surface of the remnant peat deposit within the study trench, ranging in size from large (diameter = ~100 cm; height = ~40 cm) to small (diameter = ~15 cm; height = ~5 cm). The study

trench had a slope of 0.013 along its long axis (approximately North-South orientation), with *Sphagnum* prevalence and cushion size generally increasing in the lower (south) end of the trench, where conditions were more consistently moist. Cushions were dominated by *Sphagnum* species, most commonly *S. capillifolium* and *S. rubellum* in the upper portion of the trench and *S. capillifolium* and *S. magellanicum* in the lower end. Ericaceous shrub species, predominantly Labrador tea (*Ledum groenlandicum*), leatherleaf (*Chamaedaphne calyculata*), sheep laurel (*Kalmia angustifolia*) and blueberry (*Vaccinium angustifolium*), proliferate both on the peat surrounding and beneath the moss cushions, with plant stems protruding out of the top of many of the cushions.

In October of 2006, peat dams were constructed throughout the southern section of the Cacouna bog that consequently flooded the lower portions of some of the trenches (see Ketcheson and Price, 2011 for full description of the rewetting). This study includes data from the summer prior to (2006) and following (2007) the site rewetting.

5.4 Field methods

Data were collected from 19-May to 16-August in 2006 and 2007. Meteorological data was monitored continuously using a Campbell Scientific Inc.™ data logger at a meteorological station established within the study trench (see Figure 5-1). Precipitation (P; rainfall only) was automatically measured with a tipping bucket rain gauge paired with an adjacent manual rain gauge for data checks. A net radiometer was installed in the center of the study trench, 1.5 m above the surface of the remnant peat deposit; over a typical vegetation cover dominated by ericaceous vegetation and sporadic moss cushions, providing a representative measurement of the net radiation flux (Q^* ; $J\ day^{-1}$). Two soil heat flux plates were installed (in the trench) at the meteorological station to provide measurements of ground heat flux (Q_G ; $J\ day^{-1}$), and temperatures were recorded in a profile within pooled water (2007 only) and paired with regular depth measurements for calculation of pool heat storage (Q_W ; $J\ day^{-1}$).

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

$$ET_{eq} = \alpha \left[\frac{s}{(s + q)} \right] \left[\frac{(Q^* - Q_G - Q_W)}{L\rho} \right] \quad \text{Equation 5-1}$$

and where L is the latent heat of vaporization (J kg^{-1}), ρ is the density of water (kg m^{-3}), s is the slope of the saturation vapour pressure-temperature curve ($\text{Pa } ^\circ\text{C}^{-1}$) and q is the psychrometric constant (assumed to be $0.0662 \text{ kPa } ^\circ\text{C}^{-1}$ at 20°C). The α coefficient is the Priestley-Taylor coefficient of evaporability, and represents the slope of the regression line relating actual (ET) to equilibrium (ET_{eq}) evapotranspiration. Individual α values were derived from lysimeters for each of the dominant surface and vegetation cover types at the Cacouna bog. This included five surface classes (open water, wet, moist, dry and forest) based on field observations of vegetation cover, predominant moisture conditions and previous studies in the Cacouna bog that involved detailed vegetation surveys and aerial photograph interpretation (Van Seters and Price 2001; Girard et al. 2002). An aerially weighted α value was derived for the Cacouna bog, which was used for the calculation of an aerially averaged ET rate for the site.

Volumetric soil moisture (θ) and soil-water pressure (ψ) were monitored at two *Sphagnum* cushions located along a topographical gradient and situated atop the remnant cutover peat substrate within the south portion of the study trench (Figure 5-1). Both cushions were approximately 60 cm in diameter and 12 cm in height. One cushion was dominated by *Sphagnum capillifolium* (with some *Sphagnum magellanicum*), which was located farther down the topographical gradient (south) within the study trench where the shallow water table results in prevalently moist conditions at the surface (the ‘lower’ cushion). The other cushion was located approximately 100 m upslope (north) of the lower cushion (still within the study trench) where conditions were generally drier, and was dominated by *Sphagnum rubellum* (the ‘upper’ cushion; see Figure 5-1).

To quantify the relationship between the moisture regime of the moss cushion and that of the cutover peat substrate, measurements were made at two points within the moss (+7 and +2 cm) and the substrate (-5 and -15 cm); with sampling depths referenced to the moss - substrate interface (Figure 5-1). The +7 cm measurement point is approximately 5 cm below the surface of

the moss cushion. θ was measured using Campbell Scientific Inc.TM water content probes (CS615), each paired with a copper-constantan thermocouple, connected to a Campbell Scientific Inc.TM data logger and recording data every 20 minutes. Water content information is derived from the effect of changing dielectric constant on electromagnetic waves propagating along two 30 cm parallel stainless steel rods (Campbell Scientific, 1996). Probes were calibrated using the measured dielectric permittivity of the peat/air/water matrix in a mixing model expression (Roth et al., 1990) which incorporates the individual dielectric permittivity of each the probe, peat, air and water as well as the influence of temperature and the porosity and geometry of the soil (cf Kellner and Lundin, 2001). Tensiometers were installed within the peat substrate at depths of -5 and -15 cm beneath the base of the *Sphagnum* moss cushions. Soil-water pressure ψ was measured on a regular basis (approximately every two or three days, when possible) with a TensimeterTM pressure transducer accurate to ± 1 millibar and adjusted to account for the height of water in the column above the porous ceramic cup (1 cm water is equal to 1 millibar pressure). The water table beneath each cushion was monitored continuously using a Remote Data Systems Inc.TM water level monitoring device adjacent to a manual well for verification.

Additionally, manual measurements of θ , ψ and water table position were made daily or every other day beneath two additional, smaller (approximate diameter 15 to 40 cm; approximate height 10 to 20 cm) *Sphagnum* moss cushions (dominated by *S. capillifolium* and *S. rubellum*) that had spontaneously recolonized the upslope portion of the study trench, where drier conditions were generally more prevalent. ψ measurements were made using L-shaped tensiometers installed at -5 and -12 cm beneath cushions and measured in the same manner as described above. θ measurements were made using a Campbell Scientific Inc. HydroSenseTM soil water measurement system and a calibration coefficient that was determined in the laboratory, based on measurements using an independent measurement of water content and peat cores extracted from the Cacouna bog (accuracy ± 0.03). Three replicate measurements were taken in the peat substrate surrounding each moss cushion, with θ averaged over the 12 cm probe length. Concurrent measurements of water table position were made using a manual well.

As an initial restoration measure, a series of peat dams were constructed within the Cacouna bog (Fall 2006), causing the site-average water table to rise by 32 cm (Ketcheson and Price, 2011). During the 2006 study period, standing water occupied a small ($< 5\%$) proportion of the

site; however, in the 2007 study period, standing water covered 37% of the southern (rewetted portion) of the Cacouna bog (average depth = 24 cm), occupying some trenches along their entire length and others not at all. This resulted in flooding of many locations within the site where *Sphagnum* mosses had successfully recolonized prior to rewetting, including parts of the study trench. Consequently, inundation throughout the 2007 study period caused the death of the upper and lower cushions from this study. Nonetheless, characterization of the substrate moisture and pressure conditions before and following rewetting is possible at the smaller cushions that were manually monitored during both study periods. No other restoration measures were undertaken.

5.5 Results

Environmental variables

Less precipitation (P) was received during the summer of 2006 than 2007 resulting in a larger cumulative seasonal site water deficit (precipitation minus evapotranspiration; $P - ET$) of -21 mm compared to nil for 2007 (Figure 5-2). ET rates from moss-covered surfaces (3.0 mm d^{-1}) exceeded the site-averaged ET rate (2.7 mm d^{-1}). The greatest number of daily rain events was in 2006 (67% of days); however these were predominantly small rain events. Only 1 event exceeded 16 mm in 2006; with the largest rain event recording nearly 60 mm of precipitation over a 4-day period. The wetter year, 2007, was dominated by large, less frequent precipitation events (46% of days); in which six separate events exceeded 16 mm. Precipitation for June and July 2006 and 2007 was 88% and 121% of the 30-year average (Environment Canada, 2003). Data checks made using manual rain gauges were within $\pm 10\%$.

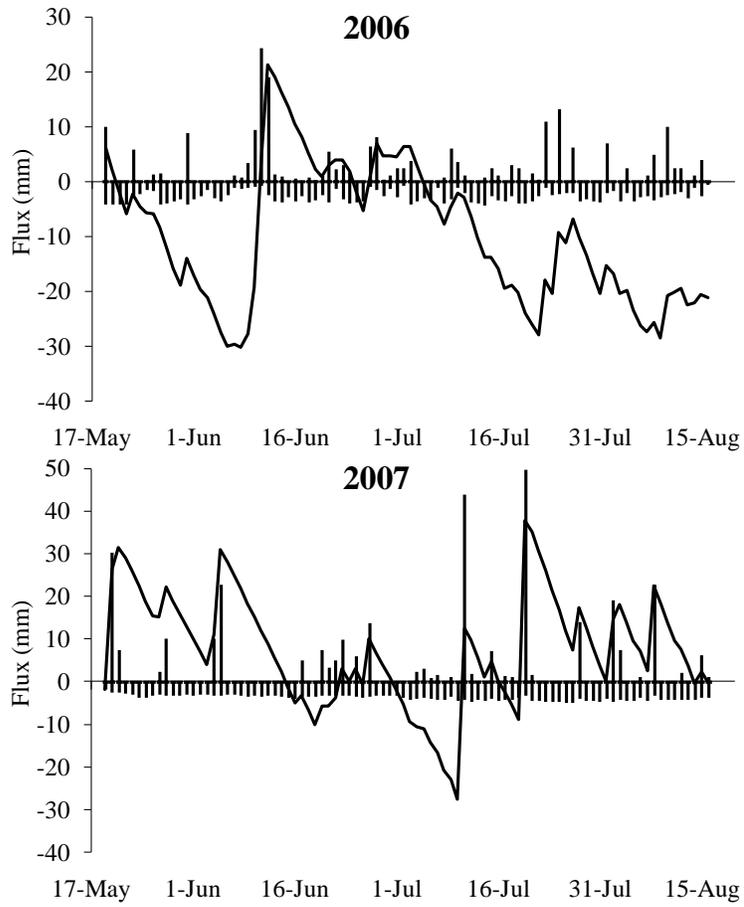


Figure 5-2 Precipitation (P, bars > 0), evapotranspiration (ET, bars < 0) and cumulative P – ET (line) for the Cacouna bog

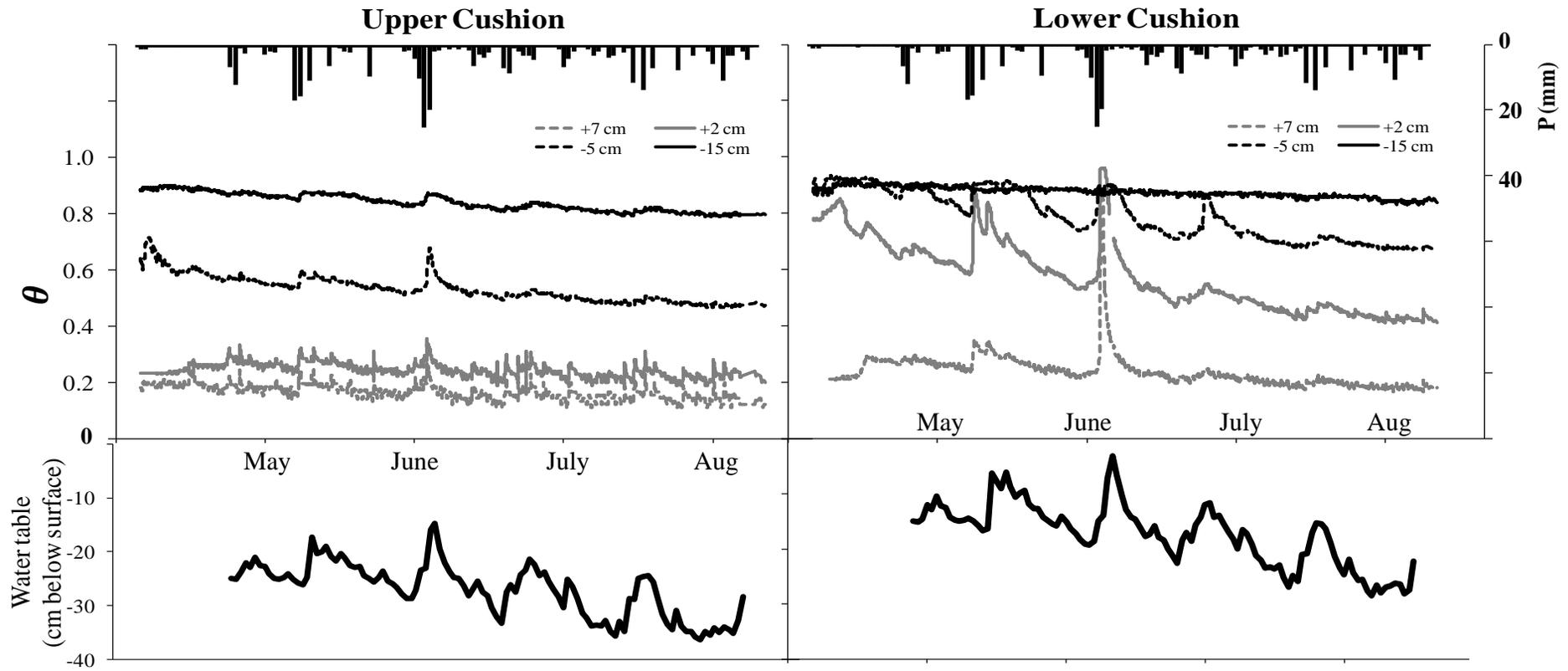


Figure 5-3 θ , water table and precipitation (P) at the upper (drier; left graph) and lower (wetter; right graph) moss cushions during the 2006 study period

Moisture dynamics within *Sphagnum* cushions

Data from the 2006 study period (19-May to 16-Aug) demonstrate that water table variations produced a more distinct response in θ at the lower cushion (higher average water table) than at the upper cushion (lower average water table) (Figure 5-3). θ decreased upwards into the moss cushion, further from the water table. The average (\pm range) water table position relative to the interface at the upper cushion was -28 ± 5 cm, compared to -18 ± 5 cm at the lower cushion (Table 5-1), which resulted in higher and more variable θ at all depths at the lower cushion (Figure 5-4). θ variability was greatest at the base of the lower cushion (θ_{+2}), indicated by the large standard deviation in Figure 5-4, as the lower cushion was influenced more strongly by variations in the position of the shallower water table.

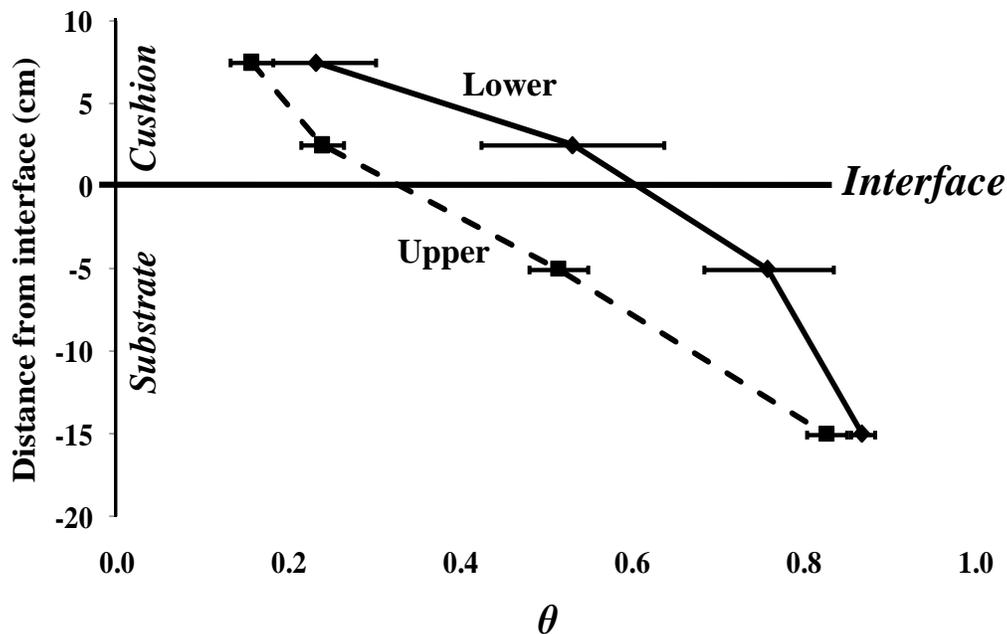


Figure 5-4 Seasonal θ at the upper (dashed line) and lower (solid line) cushions in 2006 (error bars represent the standard deviation)

Both the upper and lower cushion θ responded to precipitation events and the accompanying water table fluctuations. The largest precipitation event of the 2006 study period occurred from 9-June to 19-June, totalling 61 mm of rain, with as much as 40 mm in 24 hours (11-June). θ_{+7} at the lower cushion increased by 0.65, while θ_{+2} increased by 0.45 and reached

saturation as the cushion became partially inundated by the rising water table (Figure 5-5B). The maximum water table depth beneath the upper cushion during the event was -11 cm, resulting in a less drastic increase in moss cushion θ (at θ_{+2}) of 0.1, while the substrate θ increased by over 0.15 at θ_{-5} (Figure 5-5A). The top and bottom portion of both the upper and lower cushions remained well-connected throughout the 2006 study period, as indicated by the strong positive relationships ($R^2 \geq 0.95$) between θ_{+2} and θ_{-7} within both cushions (Figure 5-6).

Connectivity between Sphagnum cushions and the remnant peat substrate

Sphagnum cushions were generally well-connected to the moisture regime of the cutover peat substrate when the water table was close to the surface (Figure 5-7). The lower cushion was influenced more strongly by the relatively high water table position (slope of relationship is greater) compared to the drier upper cushion. The threshold water table below which θ was less responsive was -20 and -30 cm for lower and upper cushions, respectively. In the unsaturated zone below the lower cushions, where the water table was generally closer to the surface, the vertical hydraulic gradients (Figure 5-7 inset) were consistently upward, and increased during periods of higher water table (A). Hydraulic gradients below the upper cushion were much smaller, also upwards during wetter periods when the water table was higher (C), but turned downwards during dry periods when the water table was low (D).

Table 5-1 Seasonal average θ , ψ (2006 only) and water table (2006 and 2007) at the upper and lower moss cushions. Values in brackets represent the standard deviation. Note: no θ or ψ data is shown for 2007 due to the perpetually inundated state of the cushions following site rewetting

Location		Depth (cm relative to cushion–substrate interface)	θ	ψ (mb)	Seasonal Average Water Table (cm relative to cushion - substrate interface)	
					2006	2007
Upper Cushion	Moss	+7	0.16 (± 0.03)		-28 (± 5)	+12 (± 2)
		+2	0.24 (± 0.02)			
	Substrate	-5	0.53 (± 0.05)	-10		
		-15	0.84 (± 0.03)	-1		
Lower Cushion	Moss	+7	0.24 (± 0.06)		-18 (± 5)	+58 (± 2)
		+2	0.58 (± 0.13)			
	Substrate	-5	0.79 (± 0.09)	-8		
		-15	0.88 (± 0.02)	+13		

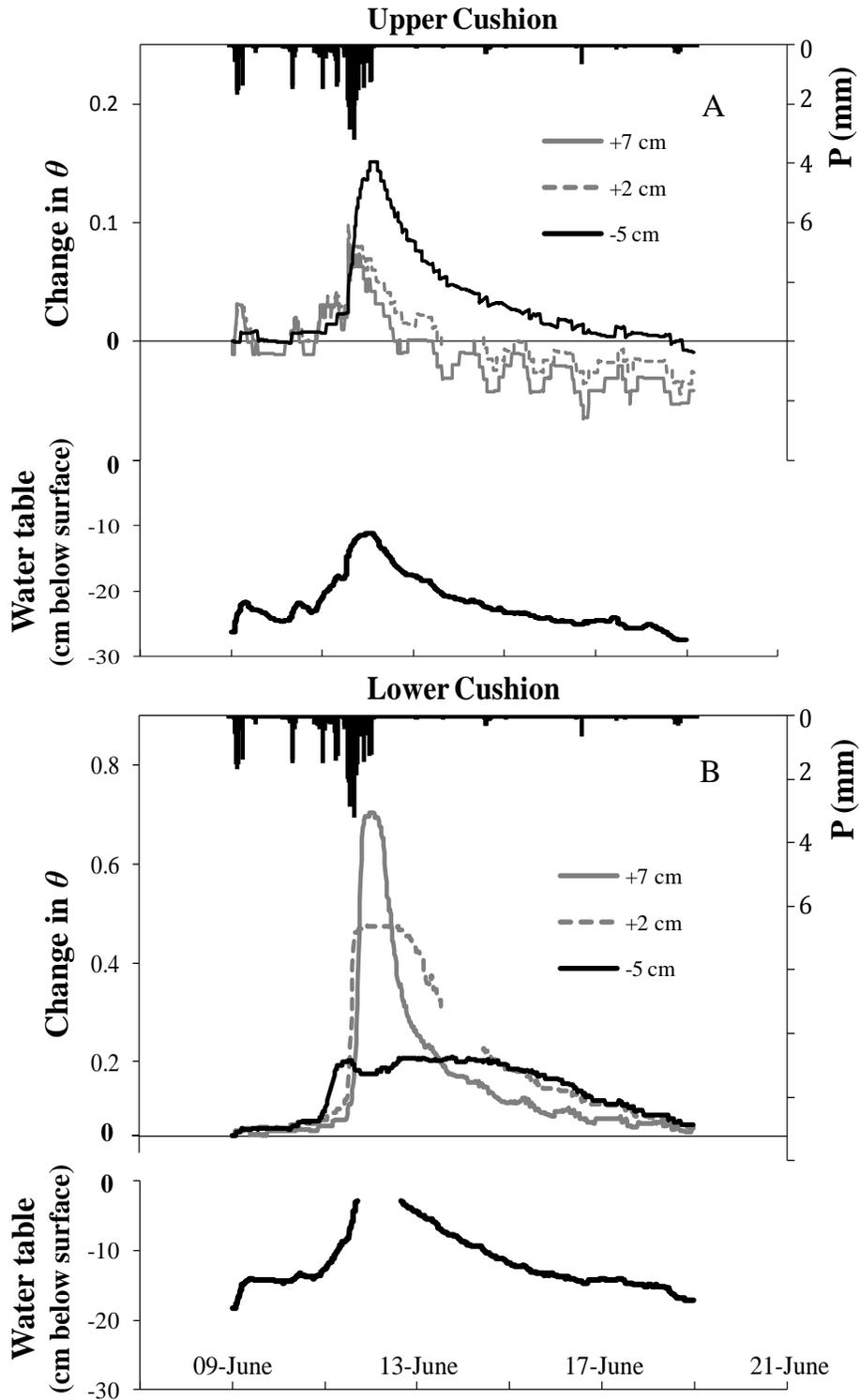


Figure 5-5 Water table and θ during a 61 mm precipitation event during the 2006 study period at A) the upper cushion and B) the lower cushion (bars represent precipitation). Note the different scale for change in θ on the upper and lower cushion plots. $\theta = 0$ represents pre-event conditions

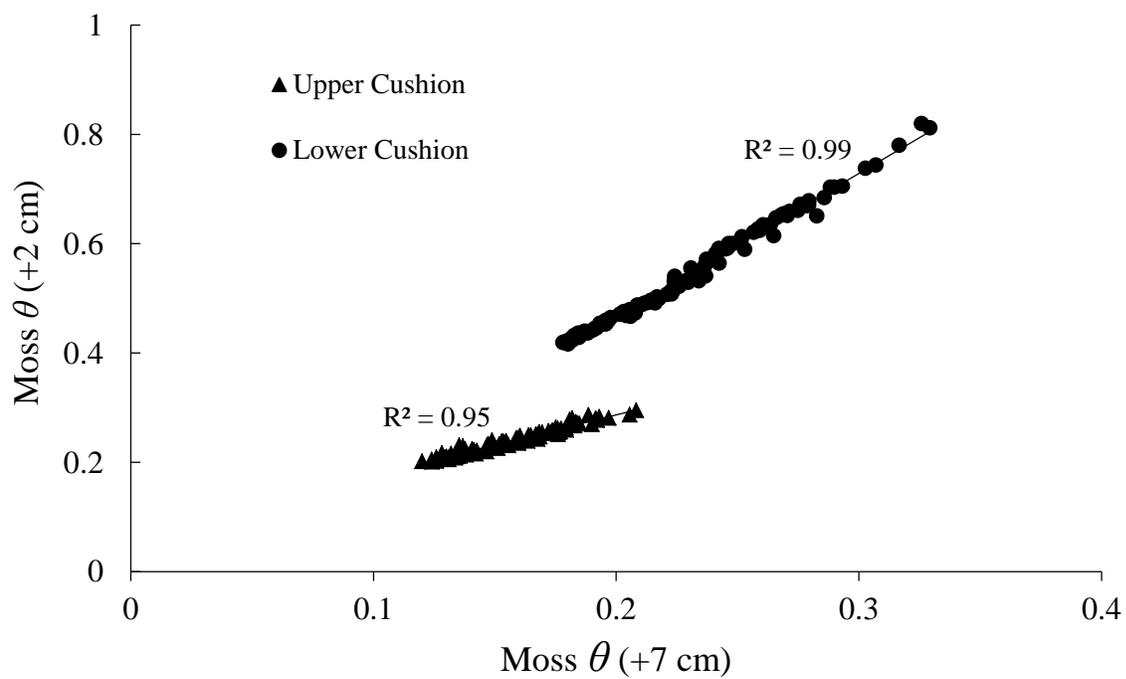


Figure 5-6 The relationship between θ at the bottom of the moss cushion (i.e., θ_{+2}) and θ at the top of the moss cushion (i.e., θ_{+7}) for both the upper and lower *Sphagnum* moss cushions in the study trench at the Cacouna bog (2006)

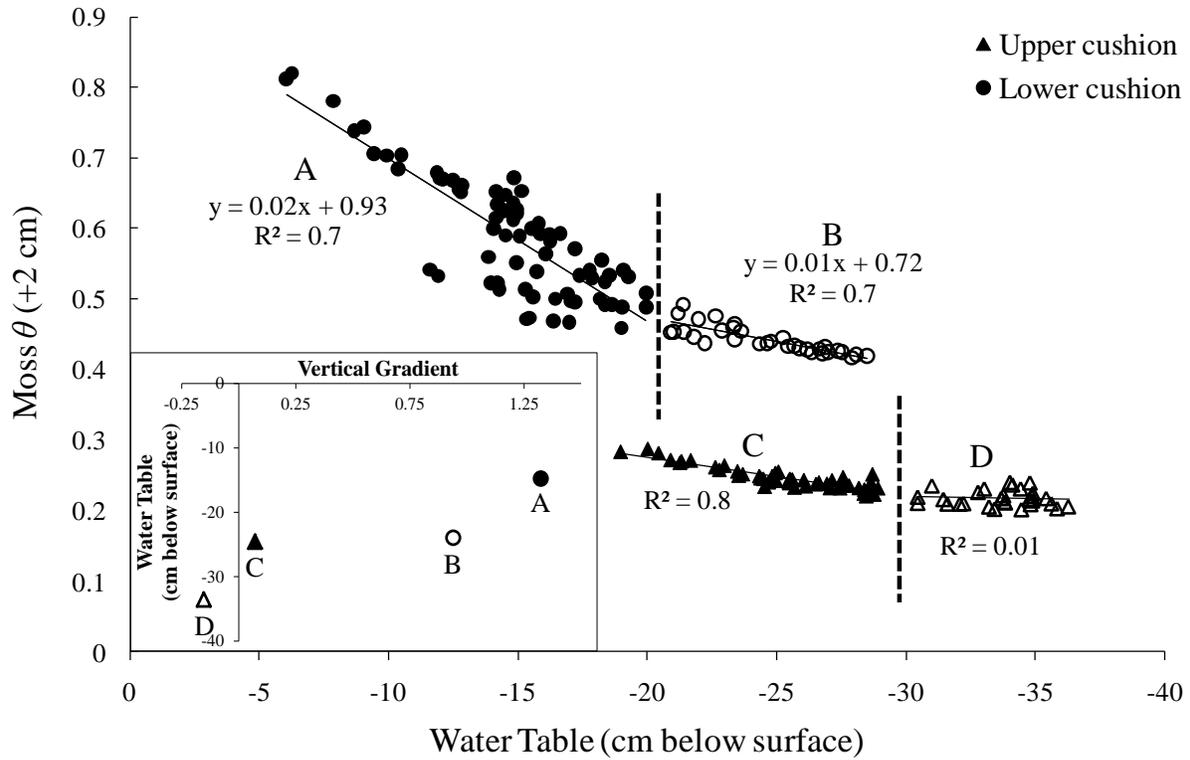


Figure 5-7 The relationship between water table and θ_{+2} (within the cushion) at the upper and lower cushions. Open symbols represent θ when it becomes less dependent upon the position of the water table (B and D, for the lower and upper cushions, respectively) and solid symbols represent conditions when θ is responsive to changes in water table (A and C for the lower and upper cushions, respectively). Dashed vertical lines distinguish between these trends. The inset figure illustrates the average vertical hydraulic gradients measured beneath the cushions under the corresponding average water table position. Positive values indicate upwards gradients (i.e., from the substrate to the cushion)

Ecohydrological impact of restoration (rewetting)

Blocking the drainage network at the Cacouna bog resulted in flooding of much of the lower lying portions of the site (i.e., trenches), where most of the *Sphagnum* mosses had spontaneously recolonized prior to rewetting. Inundation killed many of the established moss cushions, including the upper and lower cushions from this study. However, the smaller cushions that had recolonized drier areas further upslope within the study trench were also being monitored in 2006 and 2007. At these cushions, the water table was higher in 2007 than 2006, and its depth below the surface depended on the cushions' topographic position within the trench. θ , ψ and water table position were comparable beneath two selected cushions prior to rewetting (Table 5-2); however the cushion that was situated in a topographically lower position within the study trench (the 'wet' cushion) was impacted more by the rewetting than the cushion located further upslope in the trench (the 'dry' cushion) (Figure 5-8). The average seasonal water table position at the 'wet' cushion increased by 34 cm, while the water table increased by 7 cm at the 'dry' cushion. Accordingly, both ψ and θ increased proportionately more at the 'wet' cushion compared to at the 'dry' cushion (see Table 5-2 and Figure 5-8).

Table 5-2 ψ , θ (averaged over 0 to -12 cm) and water table at two *Sphagnum* moss cushions within the study trench at the Cacouna bog

		Wet Cushion Diameter = ~33 cm Height = ~16 cm		Dry Cushion Diameter = ~25 cm Height = ~22 cm		Change	
		2006	2007	2006	2007	Wet Cushion	Dry Cushion
ψ (mb)	-5 cm	-28	7	-26	-18	+ 35	+ 8
	-12 cm	-24	12	-22	-12	+ 36	+ 10
$\theta_{0-12\text{ cm}}$		0.23	0.58	0.25	0.39	+ 0.35	+ 0.14
Water Table		-42	-8	-43	-36	+ 34	+ 7

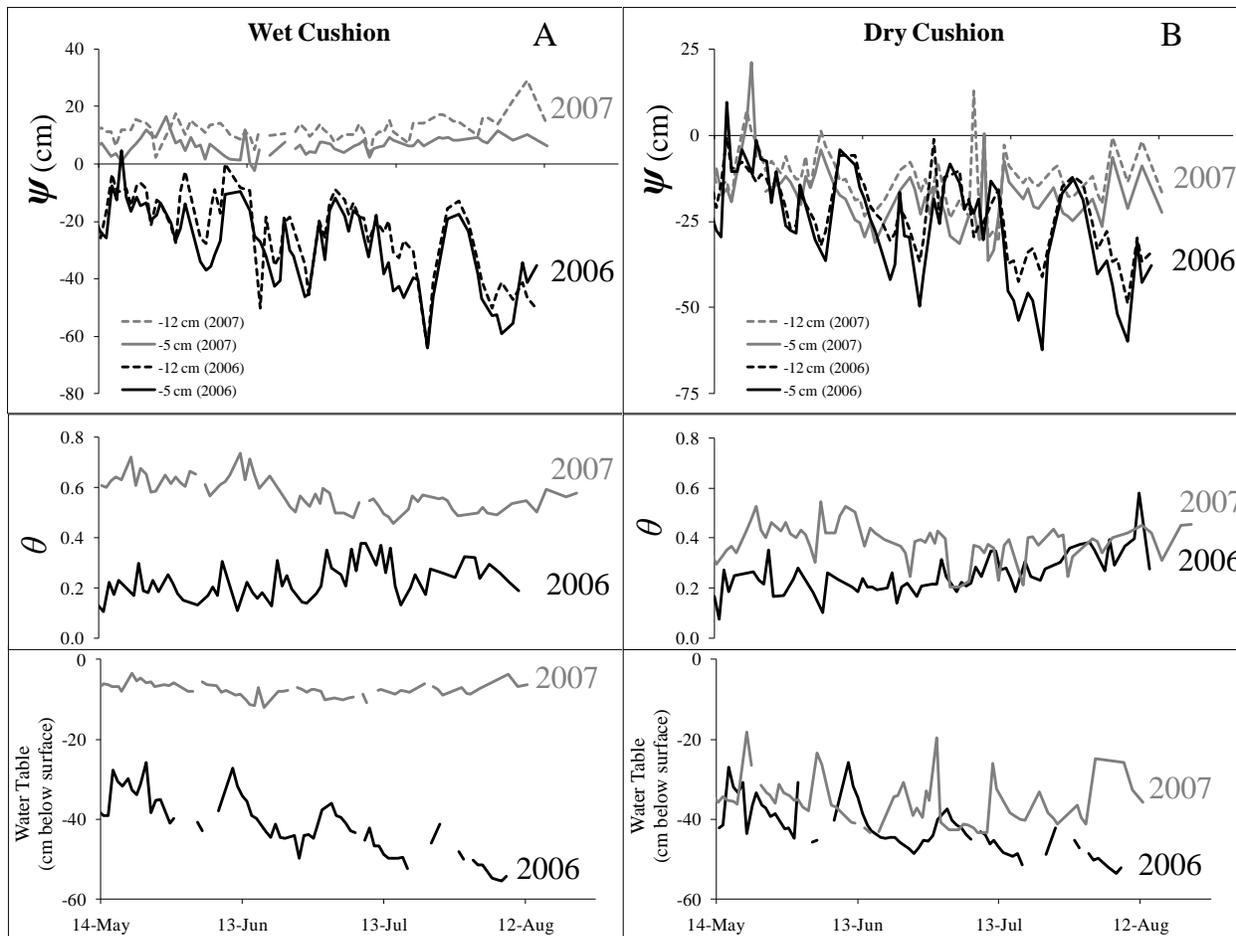


Figure 5-8 θ , ψ and water table position at two *Sphagnum* moss cushions in the study trench prior to (2006) and following (2007) rewetting. The wet cushion (A) was situated in a topographically lower position within the study trench compared to the dry cushion (B)

5.6 Discussion

Water inputs from precipitation were shed rapidly from both upper and lower cushions; however, the upper cushion returned to pre-event moisture conditions much more rapidly (within ~2-3 days) than the lower cushion (~7 days; Figure 5-5). Although some of this effect is caused by the overall site drainage (i.e., lower areas drain later), the rapid stabilization of θ within both the upper and lower moss cushions indicates that rain events provide water that persists in the mosses for only about a week. Despite that, θ_{+7} at both moss cushions was sustained during extended dry periods with low water table and infrequent precipitation (Figure 5-3) and was sufficient for critical physiological processes at the photosynthesizing capitula (judging from the moist-to-touch surface and healthy appearance of the mosses).

Numerical simulations of water flow between the moss cushion and the cutover peat substrate were not possible because reliable estimates of unsaturated hydraulic conductivity were not available. However, the direction and magnitude of vertical pressure gradients measured beneath the cushions indicates that water fluxes were occurring from the substrate to the mosses at the lower cushion (Figure 5-7 inset). Water fluxes remained in the upwards direction even under conditions of relatively deep water table at the lower cushion, albeit reduced gradients indicate smaller magnitude fluxes of water, which is in agreement with the concurrent reduced dependency of cushion θ on water table position (Figure 5-7). At the upper cushion, however, downwards gradients indicate some movement of water from the cushion to the substrate when conditions are very dry (deep water table). Nonetheless, given the strong connectivity within both cushions (Figure 5-6) and considering the relatively stable θ_{+7} and θ_{+2} at the upper cushion (Figure 5-4), it seems that upwards capillary transport of water within the cushion and water retention near the moss capitula is sufficient to withhold water against the tensions observed within the substrate in this study.

Water balance of Sphagnum cushions

Time-series θ data within the cushions permits calculations of one dimensional (vertical) water flux dynamics using mass balance based on the volumetric water content changes in a moss layer of known volume (cf. Yazaki et al., 2006). This requires the assumption that the sample volume remains constant, which is not necessarily true for *Sphagnum* mosses. However, the volume change is assumed to be small given the small moisture fluctuations in cushions (Yazaki et al., 2006). Also, lateral fluxes of water within the cushions were ignored, since they are minimal considering the flat center areas within the *Sphagnum* cushions (Yazaki et al., 2006).

An estimation of the seasonal (19-May to 16-August 2006) water budget was determined for each cushion, where

$$P - ET + q + \varepsilon = \Delta S_{cushion}$$

Equation 5-2

where q is the net water flux between the moss cushion and the substrate and $\Delta S_{cushion}$ is the water storage change within the moss cushion. $\Delta S_{cushion}$ was calculated daily as the summation of the change in θ_{+2} and θ_{+7} multiplied by the thickness of the moss layer (0-5 cm for

θ_{+2} and 5-12 cm for θ_{+7}). ε is the residual term, which incorporates much smaller probable sources of water such as dewfall, distillation and vapour transport, as well as measurement error. Since P , ET and $\Delta S_{cushion}$ were quantifiable, the water budget equation can be rearranged to calculate the net water flux, q , where

$$q + \varepsilon = P - ET \pm \Delta S_{cushion} \quad \text{Equation 5-3}$$

ET rates from moss-covered surfaces (3.0 mm d^{-1}) were higher than the average daily P and resulted in a water deficit ($P - ET$) of -52 mm (Figure 5-9). In response to this there was a change (decrease) in soil water storage ($\Delta S_{cushion}$) of -8 and -24 mm over the season within the upper and lower cushions, respectively (Figure 5-9), based on a decrease in average volumetric water content, θ , of 0.13 and 0.43 , respectively (Figure 5-3). Consequently, water fluxes (q) of 44 and 28 mm to the upper and lower cushion, respectively, are required to satisfy the water budget (Table 5-3). Considering the predominance of upward pressure gradients in the substrate (Figure 5-7), it is hypothesized that some of this flux is satisfied by upward water movement from the unsaturated cutover peat. However, based on Darcy's law using literature values of unsaturated hydraulic conductivity of cutover bog peat (at zero matric potential) of 0.03 m s^{-1} (Schlotzhauer and Price, 1999), and hydraulic gradients observed here, the measured water deficit is at least an order of magnitude larger than the calculated Darcy flux at the upper cushion. This suggests the mosses are relying upon additional sources of water (see below) coupled with passive water conservation mechanisms to maintain the relatively stable θ observed near the cushion surface (Figures 5-3 and 5-4).

Table 5-3 Components of the *Sphagnum* moss cushion water budget, seasonal average vertical hydraulic gradient and the estimated minimum unsaturated hydraulic conductivity necessary ($K(\psi)_{MIN}$) in order to meet the water demand at the surface of the moss cushions (in the absence of other water sources and passive water conservation mechanisms)

Cushion	P-ET	$\Delta S_{cushion}$	q		Average Vertical Gradient	$K(\psi)_{MIN}$
	mm	mm	mm	mm d^{-1}		m s^{-1}
Upper	-52	-8	44	0.5	0.006	0.94
Lower	-52	-24	28	0.3	1.17	0.003

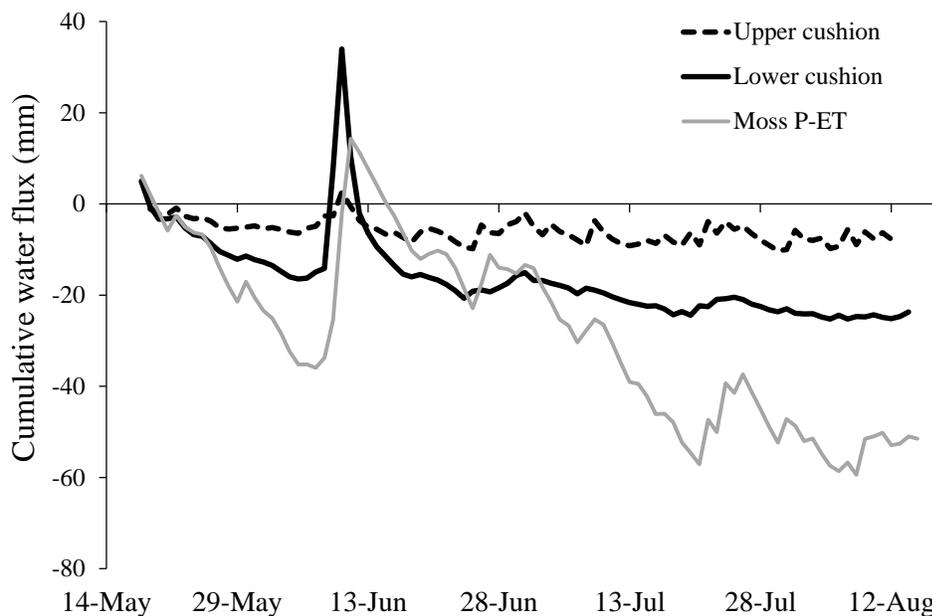


Figure 5-9 Cumulative water storage at the upper and lower cushions and the net water flux at the moss surface (P-ET) in 2006. Negative water fluxes indicate loss of water storage from the cushions

The potential role of small-scale water sources on moss cushion moisture dynamics

The methodology of a parallel experiment (not reported here) involved removing the ericaceous shrubs from several *Sphagnum* moss cushions within the Cacouna bog. These mosses quickly desiccated and whitened, becoming dry and brittle to the touch; a phenomenon previously observed by McNeil and Waddington (2003). However, field observations during the 2007 study period indicate that these cushions regained colour and elasticity and were moist to the touch in the early morning hours (and following precipitation events); returning to their desiccated state typically before noon. It is hypothesized that overnight dewfall is, under the right meteorological conditions, partially responsible for this rejuvenation of mosses; although this occurrence was still observed on mornings following nights when atmospheric conditions (relative humidity and temperature) were not conducive to dewfall. It stands to reason that a similar flux occurred to the cushions reported here.

In a previous study by Carleton and Dunham (2003), nocturnal mass (water) gains were observed in feathermosses on a boreal forest floor. This overnight delivery of water was driven by thermal gradients; where an overnight temperature profile inversion (i.e. temperature at the surface of the moss < temperature at depth within the mosses) within the feathermoss cover

resulted in the upwards transport and subsequent condensation of vapour (distillation) within the mosses, thereby hydrating the uppermost parts of the mosses. Similarly, nocturnal temperature inversions were observed in the current study within *Sphagnum* moss cushions (in 2007; data not shown), which could result in a similar upwards transport and subsequent condensation of water vapour within the mosses, delivering small amounts of water to the moss capitula. It is, however, controlled by the vapour flux, which Price et al. (2009) suggest is only ~1% of the total water flux, but which may be critical physiologically when moisture availability is limited. Though small, these water sources (dewfall and distillation) could represent a physiologically critical supply of water to the capitula, especially during a period of water deficit.

It is, however, unlikely that these small fluxes can account for sufficient water to sustain the level of saturation observed in the moss cushions. Although the absence of unsaturated hydraulic conductivity estimates prevents direct calculation of water fluxes between the moss cushion and the cutover peat substrate, evaporation dominates the cushion water budget and likely has a larger amount of associated uncertainty. *Sphagnum* has passive mechanisms for water conservation that are an intrinsic component of the hydrologic structure of the moss. For example, the wide range of unsaturated hydraulic conductivities demonstrated by *Sphagnum* mosses at variable moisture levels (Price et al., 2008) produces an equally variable ability to satisfy evaporative demands at the surface of the moss (Price and Whittington, 2010). The most restricted upward movement of water thus coincides with the driest cushion condition. Accordingly, reduced evaporation losses help to relieve the cushion water imbalance (Table 5-3), although it is unknown to what extent, as direct measurement of evaporation from each cushion surface was not available. Future studies should aim to characterize evaporation rates under varying moss moisture conditions to evaluate the extent of the reduction in moss surface evaporation rates, as it likely accounts for a substantial error term in the current study. Also, research with more replicate samples is required to characterize variability spatially as well as between *Sphagnum* species. Measurement error is also likely contributing to the calculated water imbalance. This is included in the ϵ term in Equation 5-3; however quantification of this error is not possible with the current dataset.

Capillarity and the role of Sphagnum species on moss moisture dynamics

Notable differences existed in the nature of the fluxes and stores of water within the two cushions in this study. These differences are likely a function of the different moss species that

comprise each cushion and the resultant variations in structural arrangement of the community of individual moss plants. The upper moss cushion is dominated by *S. rubellum*, which is a hummock species characterized by small pore sizes formed by a tightly packed communal arrangement (Gunnarsson and Rydin, 2000) that imparts a high water retention capacity (Luken, 1985). The lower cushion is dominated by the more loosely packed *S. capillifolium* (with some *S. magellanicum*) which has a less dense community arrangement, resulting in a cushion with larger pores. Moisture was more evenly distributed within the upper cushion as compared to the lower cushion (Figure 5-4), which could be attributed to greater capillarity within the small pores of the upper cushion. In addition, the species composition (i.e., cushion pore diameter) might have influenced the water storage dynamics within each cushion. Restricted water storage losses from the upper cushion (Figure 5-9) resulted in a fairly constant θ throughout the study period (Figure 5-3), indicating that the water storage within the cushion is becoming only slightly depleted between rain events and throughout the summer months (Table 5-3), which experienced a water deficit in 2006 (Figure 5-2). The lower cushion, however, displays a more prominent trend of decreasing θ throughout the season (Figure 5-9), especially at θ_{+2} (Figure 5-3), indicating a greater loss of internal water from cushion storage (Table 5-3). Here, water losses from the cushion exceed the rate of replenishment from atmospheric sources and upward conductance from the substrate, which is likely attributable to the more loose community arrangement of the individual mosses limiting water retention and constraining water redistribution within the cushion.

Rewetting and moss survival

The presence of cushions in the southern portion of the trench suggests conditions were already inherently suitable for moss recolonization prior to rewetting. Raising the water table by ditch-blocking increased ψ and θ within the remnant peat (Figure 5-8). The degree to which ψ and θ within the substrate are affected depends on surface topography and the level of peat decomposition, which affects pore-size distribution, hence water retention and capillary rise. Regardless, the higher water table caused an increase in ψ and θ in the substrate beneath the moss cushions (Figure 5-8), which creates favourable conditions for photosynthesis (as long as they are not inundated). Given the weak connectivity between the mosses and the underlying substrate at low water tables (Figure 5-7), rewetting must raise the water table within the remnant peat to within 30 cm of the cutover peat surface re-establish a good capillary connection that

favours water fluxes to *Sphagnum* cushions. The connection strength between the remnant peat deposit and the new mosses is in part a function of the characteristics of the cutover peat (e.g. bulk density, pore-size distribution, botanical composition) as well as the *Sphagnum* species. As previously noted, species with tighter structure (thus smaller average pore diameter) are able to impart a stronger capillary force and more effectively withhold water from (reduce water loss to) the cutover substrate.

5.7 Conclusions

The position of the water table exhibited a strong control on the moisture regime of the *Sphagnum* moss cushions; however this relationship weakened when ψ and θ in the peat substrate beneath the cushion decreased as the water table dropped. Specifically, cushion θ was no longer influenced by the moisture regime within the cutover peat substrate at water table positions that exceeded -30 cm. Under these dry conditions often found in cutover peatlands, the newly formed *Sphagnum* mosses are likely relying upon atmospheric (rain, dew) and internal (capillary transport, distillation) water inputs over the water table within the remnant peat deposit as a source of water for critical physiological functions. However, precipitation waters are poorly retained within the cushions, indicating that rain event water can only be relied upon by the mosses for a short period of time following precipitation events. Soil-water storage characteristics appeared to be influenced by the cushion community architecture, which can be affected by the species composition of the *Sphagnum* moss cushion, with more tightly arranged mosses exhibiting a more uniform and less variable moisture profile and diminished water losses from storage. Future studies with replication are required to characterize different moisture regimes between *Sphagnum* moss species and the implications for the relation between moss moisture variability and the conditions in the underlying substrate. Nocturnal temperature inversions create conditions favourable for the condensation (distillation) of upwardly transported water vapour, which could provide a small yet critical source of water at the moss capitula. Additionally, observations indicated that dewfall was capable of rejuvenating desiccated moss cushions, justifying the consideration of dew as a potentially important source of water for the mosses as well. Further quantification of these small-scale water fluxes is required.

Intense field-based measurements coupled with parameterization of the unsaturated hydraulic properties of the mosses and cutover peat should facilitate future modelling of water

fluxes within spontaneously regenerated *Sphagnum* mosses in cutover peatland ecosystems. Restoration (rewetting) efforts created conditions more favourable for *Sphagnum* survival through increased soil moisture and soil-water pressure; however future rewetting efforts should strive to obtain a more uniform impact throughout the peatland. Water table fluctuations should be constrained within the upper 30 cm of the cutover peat surface to ensure sufficient water fluxes to *Sphagnum* cushions.

6.0 Conclusion and future direction

Under dry conditions often found in cutover peatlands, the newly formed *Sphagnum* mosses are more reliant upon atmospheric (rain, dew) and internal (capillary transport, distillation) water than water within the remnant peat deposit. Nonetheless, upward hydraulic gradients in the unsaturated zone below moss cushions indicate that the mosses are receiving some inward fluxes of water from the remnant peat deposit, although it is unlikely that this is sufficient to balance the cushion water budget. Only slight depletion of moss cushion moisture contents during the summer indicated that moss water retention and soil-water storage are likely important, despite poor retention of precipitation water. Characterization of capitula density for a range of *Sphagnum* moss species and the relation of species to capillarity could aid explaining the moss water retention and soil-water storage variability observed in this study. Additionally, intense field-based measurements with more replicate samples, coupled with parameterization of the unsaturated hydraulic properties of the mosses and cutover peat, should facilitate future modelling of water fluxes within spontaneously regenerated *Sphagnum* mosses in cutover peatland ecosystems.

Rewetting transformed the system hydrology and altered water relations within the Cacouna bog. Although it is beneficial to limit the ET losses from a restored site, since it is the dominant water loss each year, the most important impact of site rewetting on the system hydrology was the reduction in runoff efficiency following blockage of the drainage network. The restricted water losses via the site drainage network resulted in an increased water abundance following site management. Accordingly, soil moisture and soil-water pressure in the unsaturated zone increased. The new runoff regime was more dependent upon antecedent water table levels following rewetting; as the system responded rapidly once the site water holding capacity was exceeded and low-flow conditions dominated otherwise.

The higher water table following rewetting, coupled with the associated increased in soil moisture and soil-water pressure, created conditions generally well-suited for *Sphagnum* moss survival. The site topography and location of peat dams, however, caused the impact of rewetting to be highly spatially variable. Future rewetting efforts should strive to obtain a more uniform impact throughout the peatland, and water table fluctuations should be constrained to within the upper 30 cm of the cutover peat surface to ensure sufficient water fluxes to *Sphagnum* cushions. Flooded portions of the site are rapidly recolonizing with aquatic *Sphagnum* species, while more

time will be required for *Sphagnum* to colonize the cutover peat surface where moisture is more limited.

This study has focussed on aspects of peatland ecohydrology primarily at two different scales: 1) characterization of the movement and storage of water within *Sphagnum* moss cushions at the micro (moss) scale; and 2) quantifying the changes to the system hydrology caused by rewetting at the macro (site) scale. As such, this research is relevant to a broad audience. The findings should assist both with restoration efforts in other peatlands across North America and Europe that intend on blocking drainage networks to increase site wetness, as well as provide insight useful towards the eventual modelling of water fluxes within *Sphagnum* mosses. Although the focus of the micro (moss) scale water fluxes is on characterization over quantification, it provides an important segue into more in-depth quantification of water fluxes within *Sphagnum* mosses.

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Appendices

Appendix A: Time Domain Reflectometry (TDR)

Note: this appendix pertains to TDR probes, the theoretical basis for their use for measurement of soil moisture content and a calibration procedure. The Hydrosense probe and the CS615 soil moisture probes used in this thesis do not use the same TDR technology as described below. This appendix was left in this thesis to be a simple resource for future students.

Theory

TDR is a non-destructive method of obtaining on-site ‘real-time’ soil moisture measurements (Topp et al., 1980). Based on the properties of electromagnetic waves, the method consists of measuring transit time of waves along a probe in the soil (Ledieu et al., 1986). The fundamental principle of the method is based on determining the propagation velocity of electromagnetic waves, which is a function of the dielectric constant of the medium within which the wave is propagating, by actually measuring the transit time along a probe in the soil (Ledieu et al., 1986). Since water has a much higher dielectric constant than air and solid organic matter, the propagation velocity (and thus the dielectric constant) of the soil is largely dictated by the amount of water within the soil. For most soils, a general empirical relationship exists between the dielectric constant and the volumetric water content (VWC), independent of soil texture bulk density, and electrical conductivity (Topp et al., 1980). However, the dielectric constant of water varies with temperature and the transit time along the probe, which can be approximated by a simple correction factor (Ledieu et al., 1986). Variations in VWC can be accurately estimated from the dielectric constant by using an empirically determined calibration curve (Ledieu et al., 1986; Topp et al., 1980).

Measurement

To facilitate the measurement of the travel times of electromagnetic waves within the soil, De Clerck (as cited in Ledieu et al., 1986) developed the bifilary probe. This type of probe consists of two stainless-steel rods soldered to two diodes in opposition connected to a length of coaxial cable with a constant impedance (to prevent signal-weakening reflections). The diodes induce a reflection that allows the beginning of the rods to be marked through the creation of an artificial impedance discontinuity, giving a precise reference for transit time measurements (Ledieu et al., 1986). The stainless-steel rods serve as conductors, while the soil between and around the rods serve as the dielectric medium (Hillel, 1998). The time is measured from the

start of the electromagnetic wave pulse to the arrival of the wave reflection, varying directly with the dielectric constant of the soil.

Calibration

The calibration process is intended to establish the relationship between the transit time of the electromagnetic wave emitted along the TDR probe, a function of the dielectric constant (K), and the VWC of the soil (Ledieu et al., 1986). This can be determined empirically in a laboratory based setting using an undisturbed soil sample. A cylindrical sample of living and poorly decomposed *Sphagnum* moss (peat) was extracted from a trench adjacent to the ‘study trench’ and carefully placed at natural density in a bucket (12 566 cm³) for transport back to the laboratory. The sample was selected based on its similarity to the moss cushions equipped with TDR probes within the adjacent study trench. The water level was raised to and maintained at the surface of the moss until calibrations were performed, with the top of the bucket remaining open to the atmosphere to allow for natural evaporation and photosynthesis. Prior to calibration, the sample was drained to field capacity and weighed. A set of TDR probes used in the field (5, 10, 15 and 20 cm probe lengths) were inserted into the peat sample to determine the K. For the actual VWC measurements, the VWC of the sample was determined based on the volume of the cylindrical sample, the mass of the sample at the time of measurement and the mass of the organic peat material within the sample, as determined by oven drying the peat sample at 105°C until a constant mass was established. The VWC was estimated as

$$VWC = \frac{MASS_{sample} - MASS_{dry}}{VOLUME_{sample}} \quad \text{Equation A-1}$$

The sample was left to air dry (through the air-peat interface at the top of the sample) at room temperature for 24 hours, then closed at the top for a minimum of 8 hours to allow for uniform moisture distribution throughout the sample. The TDR probes were then measured and the sample weighed immediately afterwards. This process was repeated until a suitable number of points were collected to plot a curve of K versus VWC. An equation for estimating in-situ VWC using field K measurements was derived by applying a polynomial to the resultant calibration curve.