The effects of water table draw-down
on the hydrology of a patterned fen peatland near Quebec City, Quebec, Canada

by

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AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

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Abstract

Hydrological response to climate change may alter the biogeochemical role that peatlands play in the global climate system, so an understanding of the nature and magnitude of this response is important. Simple hydrological models have predicted the effects of climate change on the hydrology of these systems, and estimated a ~20 cm water table draw down. This draw down amount was modeled to estimate the changing role that wetlands may play in global biogeochemical cycling, but failed to account for modifications of the peatland structure, which has profound implications for the hydrology of these systems. Volume change in compressible soils occurs as the result of different processes, mainly compression and oxidation. Compression occurs instantaneously as a change in water pressure (e.g., from water table draw down) occurs and the peat matrix is unable to withstand the increased pressures and subsides. Oxidation is the long term chemical breakdown of the peat under aerobic conditions.

Consequently, in 2002 the water table in a fen peatland near Quebec City was lowered by ~20 cm (Experimental site), and the hydrological response was measured compared to a Control (no manipulation) and Drained site (previously drained c. 1994).

As a result of the draw-down, the surface in the Experimental pool decreased 5, 15 and 20 cm in the ridge, lawn and mat topographic locations, respectively resulting in an increased bulk density of ~60% in the Experimental lawn. Hydraulic conductivity (K) generally decreased with depth and from Control (25 to 125 cm) 10^{-1} to 10^{-5} cm s^{-1} to Experimental (25 to 125 cm) 10^{-2} to 10^{-7} cm s^{-1} and to Drained (25 to 75 cm) 10^{-2} to 10^{-6} cm s^{-1}. In similar topographic locations (ridge, lawn, mat), K trended Control>Experimental>Drained, usually by an order of magnitude.

Water table fluctuations in the Drained site were, on average, twice that of the Control site, whereas water table fluctuations within sites trended ridge>lawn>mat. The water table in the Control lawn was able to remain at a stable depth relative to the surface (~ -1 cm) because the lawn peat floats with changes in water table position. However, because of the denser, degraded peat, the Drained lawn peat was more rigid, forcing the water to fluctuate relative to the surface, further enhancing peat decay and densification.

While climatic change will not occur instantaneously the limitations of the experiment required an abrupt change in water table position (drainage). However, regardless of how volume change occurs in the peat (compression or oxidation) the direction of change to the hydraulic properties is the same (increased bulk density, decreased hydraulic conductivity) which affects the hydrology of these systems (increase water table fluctuations and decreases surface movement). Thus, valuable information can be obtained regarding the changing role of peatlands in global biogeochemical cycling processes.

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1. Introduction

1.1. Context

Wetlands represent nearly 3% of the worlds land surface (Tarnocai, 1998) and are estimated to contribute approximately 12% of annual global methane emissions (Hansen *et al.*, 1989), and hence are a significant component of the global carbon cycle (Moore *et al.*, 1998). Over 14% of Canada's land area is wetland, representing 25% of the world's wetlands (Tarnocai, 1998). It is well established that hydrology is one of the most important overall controls on the carbon budget of wetlands (Moore *et al.*, 1998).

By their nature, the hydrology of wetlands (which are predominantly found in northern latitudes (Roulet *et al.*, 1992)) is sensitive to changes in climate because of the delicate balance between evaporation and precipitation (Clair, 1998). Many global circulation models predict that northern latitudes will be subject to the greatest changes in temperature and precipitation under climate change conditions (Mitchell, 1989). Therefore, an understanding of the hydrological changes that may occur under a warming scenario is paramount in being able to understand the role wetlands play in global biogeochemical cycling.

Roulet *et al.* (1992) modeled the hydrological response of a 2 x CO_2 climate scenario (increase in temperature and precipitation of 3 C° and 1 mm d^{-1}, respectively (Mitchell, 1989)) and predicted a ~14 – 22 cm draw-down in the water table. This was then applied to a subarctic/northern boreal wetland system (Moore *et al.*, 1990) to evaluate the role climate change may play in carbon gas (particularly methane) dynamics. Some studies suggest that under warmer conditions wetlands will act as a source of CO_2 and a sink for CH_4 (Blodau and Moore, 2003; Waddington and Price, 2000); a reversal of their current role. However, Roulet *et al.'s* (1992) approach was simplistic because modifications of the wetland structure, and the consequent hydrological response were not considered. Therefore, an evaluation of the nature and magnitude of hydraulic change is needed, as are the implications on the hydrological regime of a wetland system.

In Canada, wetlands are defined as land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment (National Wetlands Working Group, 1997). Wetlands are subdivided into two broad categories: organic and mineral wetlands (National Wetlands Working Group, 1997). Organic wetlands (commonly called peatlands) represent over 90% of the wetlands in Canada (Tarnocai, 1998). The focus of this study is a peatland system. Peatlands are subdivided into fens, bogs and some swamps (swamps will not be addressed in this thesis). Bogs are ombrogenous (generally only receiving water inputs through precipitation), whereas fens can receive some surface and subsurface water input (National Wetlands Working Group, 1997). Fens (which are the primary focus of this thesis) are further classified into 19 different types (National Wetlands Working Group, 1997); one of particular interest is the String Fen. String fens are a type of patterned ground which is a prominent landform in boreal and subarctic regions (Foster and King, 1984; Price and Maloney, 1994; Quinton and Roulet, 1998). Despite the prominence of patterned peatlands, relatively little is know about both the origin and hydrology of these systems, especially how they may respond to climate change.

The Kyoto protocol is an extension to the commitment of the United Nations Framework Convention on Climate Change (UNFCCC) and calls for a decrease in greenhouse gas emissions and an accounting of sources and sinks of carbon as a direct result of anthropogenic land use change (limited to afforestation, reforestation, and deforestation). Despite Kyoto's bias towards anthropogenic land use changes, Roulet (2000) states that if the objective of the UNFCCC is taken literally, then all sources and sinks, regardless of origin, should be accounted for. Because a substantial portion of the world's wetlands are located in Canada, (which are known sources and sinks of atmospheric carbon), understanding how these systems will respond in warming climates becomes increasingly important.

By studying the affects of water table draw-down in fen peatlands, a better understanding of the hydrological changes that may occur under a warming scenario will be attained, which is paramount in being able to understand peatlands' future role in global biogeochemical cycling and carbon storage.

1.2. Patterned Peatlands: Formation and Function

1.2.1. Formation

Peatlands represent a long-term sink for carbon – the accumulated remains of incompletely decomposed plant materials in the wet anoxic environment (Clymo, 1983). In some circumstances peatlands evolve with a distinct pattern of alternating pools and ridges (Foster and King, 1984). The formation of patterned peatlands is complex. Foster *et al.* (1983) propose a hypothesis whereby drainage is impeded at the base of a gentle slope. This impediment could be from an ice push ridge that prevented flow into the lake, accented by melt water from the deeper snow found on the lee side of trees (which grow on the ice push ridges) found along the shoreline, creating waterlogged conditions (Foster and King, 1984; Foster *et al.*, 1983). In these wet areas peat forming vegetation, such as *Magnocaricetum,* may begin to colonize (Foster and Fritz, 1987). As the peat develops it helps create a more homogenous surface which favours sheet flow (opposed to channelled flow) (Foster *et al.*, 1983). The newly formed peat tends to have a lower hydraulic conductivity (K) (Foster *et al.*, 1983) which further helps to impede drainage. Hydraulic conductivity governs the rate at which a liquid (e.g., water) can flow through a porous medium (e.g., peat) for a given energy gradient (Freeze and Cherry, 1979). Water that collects in any topographically low surface areas creates small ponds. The vegetation (e.g., *Carex exilis*, *Scirpus cespitosus*, and *Sphagnum*) that borders these small ponds creates a hummock and hollow microtopography (Foster and King, 1984; Foster *et al.*, 1983). The hollows, because they are inundated, have poor peat producing vegetation, thus the contrast in elevation between hummock (with greater peat accumulation) and hollow becomes larger and the pools deepen and become more defined. Once the pools are able to maintain significant standing water, decomposition of the pool bottom will begin, further deepening the pool bottom (Foster *et al.*, 1983). During wet periods the depressions (or pools) may begin to coalesce laterally (along a contour), creating larger, but narrow pools perpendicular to the slope. Price and Maloney (1994) found that pools in a patterned fen were typically roughly oblong in shape, 25-50 m long and 5-7 m wide, with ridges 0.1 to 0.4 m high. As a ridge continues to grow, it will impede drainage from upslope, allowing the process to repeat itself.

This process of turning land into wetland is called paludification. Foster and King (1984) and Foster and Fritz (1987) conducted similar experiments in Leech Lake Peatland, Labrador, Canada and in patterned fens in Dalarna, Sweden. In both Sweden and Labrador, the ages (confirmed with radio carbon dating) of the pools decreased with increasing elevation, supporting the theory that the initial pools were formed at the base of the slopes (Foster and Fritz, 1987; Foster and King, 1984; Foster *et al.*, 1988) and that paludification is important. Price and Maloney (1994) also found that dominant flow paths ran perpendicular to the alignment of pool/ridge topography.

1.2.2. Hydrology

Despite the attention that has been given to understanding the formation of patterned peatlands (Foster and Fritz, 1987; Foster and King, 1984; Foster *et al.*, 1983; Foster *et al.*, 1988) relatively few studies have tried to understand and quantify the hydrology of patterned peatlands (Price and Maloney, 1994; Quinton and Roulet, 1998). Fortunately, the hydrology of any wetland system can be described using the water balance concept, which is essentially an accounting system where water is the currency (Ingram, 1983). A typical water balance equation for a peatland is;

$$P + SW_I - E_t - Q - Q_{ss} = \Delta S + \xi \quad , \qquad \text{Equation 1.1}$$

where P, is precipitation, SW_I is surface water inflow, E_t evapotranspiration, Q is the surface discharge, Q_{ss} is the subsurface discharge, ΔS is the change in storage and, ξ, is the residual term (Equation 1.1 modified from Price and Maloney, 1994). The dimension of the previous terms is length [L], usually expressed as a depth in mm.

1.2.2.1. Physical Properties and Structure of Peatlands

The topographical features (hummocks/ridges and hollows) that result in patterned peatland formation are also the same features that control the current day hydrological interaction between and within pools, and the subsequent carbon cycling (Belyea and Clymo, 2001). The presence of alternating layers of variably degraded peat, and sequences of vegetation within the vertical profile of most peatlands (Siegel, 1983), is evidence that this process is part of the normal evolution of peat systems. Ingram (1978) identified two distinct layers within a peatland, called the acrotelm and the catotelm. The upper, acrotelm, is the variably saturated layer composed of living, dead and poorly decomposed mosses (Price *et al.*, 2003) and its thickness is defined by the depth from surface to lowest water table position (Ingram, 1978), usually between 0 and 50 cm (Price *et al.*, 2003). In the acrotelm the peat is generally of lower bulk density (mass of solids/total volume, typically <0.07 g cm^{-3} (Van Seters and Price, 2002)), higher porosity (volume of voids/total volume, typically >90% (Baird and Waldron, 2003)) and higher hydraulic conductivity (typically $>10^{-3}$ cm s^{-1} (Rycroft *et al.*, 1975)). Consequently, the volumetric moisture content (volume of water/total volume) is lower (however, it can be up to 95%). Volumetric moisture content rises quickly during precipitation events but drains relatively quickly too. Hydraulic conductivity in the acrotelm decreases with depth by more than 4 orders of magnitude over 50 cm (Hoag and Price, 1995). It is this difference in hydraulic conductivity that can regulate the amount of sub/surface and surface water outflow and thus infiltration of water into the catotelm (Rycroft *et al.*, 1975). The lower, catotelm layer is saturated, has a higher bulk density (typically > 0.1 g cm^{-3} (Van Seters and Price, 2002)), lower porosity and lower hydraulic conductivity (typically $<10^{-4}$ cm s^{-1} (Rycroft *et al.*, 1975)) (Ingram, 1978).

Because of saturated conditions, the pore spaces are generally filled with water, therefore volumetric moisture content will equal porosity (with the exception of biogenic gas bubble formation (see Baird *et al.*, 2004a; Beckwith and Baird, 2001; Kellner *et al.*, 2005)). The hydraulic parameters noted above control the timing and magnitude of water fluxes and stores for given climate inputs.

1.2.2.2. Surface and Subsurface Flow in Patterned Peatlands

Surface flow in patterned peatlands is strongly influenced by the antecedent conditions (Quinton and Roulet, 1998). Quinton and Roulet (1998) note two distinct hydrological phases: 1) when water supply exceeds the depression storage and 2) when seepage and evaporation exceed inputs and the pools become isolated. (This is similar to the lateral coalescence process mentioned earlier during larger pool development.) When the conditions are saturated (directly following spring melt) surface flow (SW_I and Q) between pools occurs through the acrotelm across ridges and around ridge flanks. Price and Maloney (1994) found that the pool-ridge sequence of a patterned fen has a very large depression storage as the pools will be able to fill with water after precipitation events when there were dry antecedent conditions.

Subsurface flow is often considered negligible for a few reasons. As noted previously, the slope in these systems is generally quite low; for instance, Quinton and Roulet (1998) found a slope of 0.004 and Price and Maloney (1994) found a water table gradient of 0.006, this, combined with a lower hydraulic conductivity in the catotelm, will result in minimal subsurface flow (according to Darcy's Law). Price and Maloney (1994) found subsurface flow to be about 3% of daily total runoff. Another reason that Q_{ss} is considered negligible is that patterned peatlands can only form when drainage is impeded and water pools. If the deeper subsurface (catotelm) was of a high enough hydraulic conductivity to permit significant flow, patterned peatlands would not form under the paludification hypothesis discussed earlier.

Not all water movement in peatlands is horizontal. In fact, the vertical processes in boreal peatlands can dominate the water balance during summer (Price, 1996). The location of the water table within the acrotelm has profound implications for both storage changes, as well as carbon cycling. Hoag and Price (1995) note that because of fluctuations in water table position, the acrotelm experiences much greater changes in storage than the catotelm, which experiences no water table variation, and thus experiences very little change in storage. Specific yield, S_y, is the ratio of the volume of water yielded by gravity drainage to the volume of the block of soil (Price *et al.*, 2003). Storage changes, ΔS, are controlled by the magnitude of water table change, Δh, and the specific yield ($\Delta S = \Delta h * S_y$) (Hoag and Price, 1995). However, the acrotelm tends to have a very high specific yield (typically increasing from 0.2 to 0.6 near the surface) because of the higher porosity of the acrotelm, whereas the catotelm has a lower specific yield (typically 0.2 to <0.06) (Price, 1996) and thus higher water retention capacity (Schlotzhauer and Price, 1999). This implies that in the acrotelm a large amount of water must be removed to lower the water table. Branfireun and Roulet (1998) found significant increases in water table position, yet minimal increases in discharge when there were dry antecedent conditions with a low water table, however, with wet antecedent conditions (and a high water table) discharge increased rapidly. As discussed earlier, the lower hydraulic conductivity of the catotelm prevents significant subsurface seepage. Also, during dry antecedent conditions the pools are isolated, which means that the dominate water loss must be due to evapotranspiration (equation 1.1). Typically wet conditions are only found following significant precipitation events and during spring snow melt.

1.2.2.3. Evapotranspiration

Evapotranspiration (E_t) combines evaporation (from open water – pools) and transpiration (from vegetation – lawns, ridges/hummocks). Thus, it is largely dependant on the proportion of open water bodies within the peatland and the vegetation type (after overhead climatological conditions are considered). Evapotranspiration is the dominant outflow component of the water balance (e, quation 1.1), outside of the snowmelt period (when SW_O and Q can dominate). For instance, Price and Maloney (1994) found that, post snow melt, evapotranspiration accounted for 126 mm in a Labrador fen (when precipitation only totalled 120 mm) over a six week period.

A common method of estimating evapotranspiration is the Priestley-Taylor combination model, which has been commonly adopted by wetland scientists for the estimation of evapotranspiration as it requires less intensive field instrumentation than other methods. The alpha, α, value (see Methods section 3.1) is a proportionality constant (parameter) that is the ratio of actual evapotranspiration (E_a) (determined empirically using lysimeters for *in situ* estimates) to equilibrium evapotranspiration (E_{eq}) (the amount of water that could be evaporated into an atmosphere with no vapour pressure deficit (VPD)). Determination of the alpha value requires independent estimation of E_a for similar surfaces. This can be achieved with lysimeters. Lysimeters are soil cores placed in buckets which are then placed into the hole left from the soil core. Lysimeters actually yield discharge measurements, which can then be used to estimate evapotranspiration (Kelemen and Ingram, 1999). Because VPD commonly occur in a peatland, the alpha value is often greater than 1.0. Price and Maloney (1994) found alpha values of 1.55 and 1.27 for a fen pool and ridge, respectively. In a similar location (north eastern Quebec/Labrador, Canada) Quinton and Roulet (1998) found comparable alpha values of 1.6 and 1.34 for pool and non-pool surfaces. Price (1997) found alpha to be 1.21 for a bog in south central Quebec, Canada. The use of lysimeters is inherently problematic, however, as matching the internal (inside the lysimeter bucket) and external (the soil surrounding the bucket) moisture condition is difficult (Kelemen and Ingram, 1999). Further, weighing errors can be large, and errors in estimating precipitation must be incorporated.

1.2.2.4. Intra-pool Hydrology

Little research has been conducted that specifically looks at the local (pool – ridge) scale hydrology. Price and Maloney (1994) found that there were evaporative differences between ridges and pools (0.5 mm d^{-1}) and significant differences between fens and bogs, mainly as a result of depth to water table, as fen ridges tended to be lower and wetter than bog ridges. The ability of a system to sustain a water table that replicates the topographic profile is a function of the hydraulic conductivity for a given set of water inputs (Ingram, 1982). Microtopography (hummock/ridge and hollow) with sufficiently low K, can result in ground water ridges or mounds that can control the lateral flow direction (e.g., Price and Maloney, 1994). However, as noted previously (see Section 1.2.1 and 1.2.2.1) hydraulic conductivity is very important to the creation of patterned peatlands, and is in a 'symbiotic' relationship with plant growth (as the plants grow in wetter, lower K areas, and subsequently decay, they are creating an increasing lower K). Kellner and Halldin (2002) state that different moisture content dynamics in acrotelm peat, between ridges, hummocks and hollows, is dependant on the water retention properties of the peat in those topographic features. (While hummock and hollow topography is limited to bogs, lawns and mats in fens would subject to similar dependencies). Ridge species tend to be smaller and more densely packed, and subsequently are able to retain and transport water more effectively (in the acrotelm, as a result of a lower specific yield). Kellner and Halldin (2002) found that the thickness of the unsaturated zone (i.e., depth to water table) varied the most in the ridges. During drying periods, the response of groundwater levels in ridges and hollows was similar, however, the hollows responded greater to precipitation events (Kellner and Halldin, 2002). Despite this, water flow from hollow to hummock was small.

While considerable research could be conducted examining the water balance of patterned peatlands and the subsequent hydrological processes, all could be significantly inaccurate unless the non-rigid nature of peat is considered.

1.3. Peat volume change

Peat is not a rigid soil because of its high water content (Price and Schlotzhauer, 1999) and large compressibility, thus changes in water table position (seasonally or long term change) can alter the storativity of peat (Price, 2003; Price and Schlotzhauer, 1999; Schlotzhauer and Price, 1999). The seasonal effect has been termed 'mooratmung' (German for 'mire breathing'), which describes the vertical movement of the peat surface (Ingram, 1983).

Volume change in peat may occur by three processes related to a change in water table position: 1) compression, 2) shrinkage and 3) oxidation. Compression occurs as the weight of material overlaying a point in a peat matrix is transferred from the fluid to the soil structure, which happens when the water pressure decreases (e.g., with a water table decline). When the water table is lowered, the peat structure becomes unable to support the overlying material and the pore structure collapses, resulting in compression of the peat matrix and a lowering of the surface. The force of the overlaying material (total stress, σ_T) is a product of the depth, h, and the total density, ρ_T, of the material overlaying it, and the acceleration due to gravity, g;

$$\sigma_T = \rho_T g h \quad . \qquad \text{Equation 1.2}$$

Fluid pressure (or pore water pressure, ψ) provides a buoyant forces against the total stress. Thus effective stress, σ_e, is the stress placed on the structure of the peat not borne by the fluid. Thus;

$$\sigma_e = \sigma_T - \psi \quad . \qquad \text{Equation 1.3}$$

Changes in effective stress can help explain the amount of compression that occurs in peat (Price, 2003). Shrinkage occurs above the water table. Shrinkage is the contraction of the peat matrix resulting from the water tension within the soil pulling the peat together (Price and Schlotzhauer, 1999). Price and Schlotzhauer (1999) note that normal compression and shrinkage are at least partly reversible. Kennedy and Price (2004) found in cutover peat that shrinkage was nearly 60% of seasonal volume change, compression nearly 40% and the remainder was due to oxidation.

Oxidation can lower the surface by breaking down (oxidizing) the peat soil in the (primarily) aerobic zone (the zone above the water table) reducing pore spaces. The reduction in pore space comes from the release of carbon (e.g., carbon dioxide gas, methane gas, dissolved organic carbon runoff) and the remaining smaller particles becoming more tightly packed, which reduces the pore space and increases bulk density. Volume change due to oxidation is irreversible. Rates of oxidation in peatlands are not well understood, especially long term rates (Waddington and McNeill, 2002). Waddington and McNeill (2002), found that the long term and intermediate oxidation rates in a disturbed/cutover site were similar at 5.7 and 6.2 mm yr^{-1}, respectively, and the contemporary rate was 4.8 mm yr^{-1}. Waddington and McNeill (2002) conclude that hydrology (Price, 1997) and peat structure (Price, 2003; Price and Schlotzhauer, 1999; Schlotzhauer and Price, 1999) are the main controls on the long term oxidation rate (as they control the water table position).

1.4. Effect of peat volume change on hydrological parameters

Compression affects the main hydraulic parameters (see section 1.6) including: porosity, n, bulk density, ρ_d, hydraulic conductivity, K, specific yield, S_y, and volumetric moisture content, θ_{VMC}. As the water table drops, compression causes the porosity to decrease as the larger pores collapse first (Chow *et al.*, 1992). As the porosity decreases, bulk density must increase assuming the particle density ρ_s, remains constant, porosity is given as;

$$n = 1 - \frac{\rho_d}{\rho_s} \quad . \qquad \text{Equation 1.4}$$

The hydraulic conductivity also decreases with the collapsing of larger pores since the large pores conduct most of the flow (Chow *et al.*, 1992). Specific yield will decrease as the more tightly packed particles retain a greater amount of capillary water in the smaller pore spaces (Price, 2003). The volume change processes in peat are a response to changes in the water table position, caused by climate variability or other anthropogenic causes. Considerable hydrological research has been conducted in cut-over peatlands (e.g., Kennedy and Price, 2004; Kennedy and Price, 2005; LaRose *et al.*, 1997; Price, 1996; Price, 1997; Price, 2003; Price *et al.*, 2002; Price and Whitehead, 2001; Price and Whitehead, 2004; Schlotzhauer and Price, 1999; Van Seters and Price, 2002; Waddington and McNeill, 2002; Waddington *et al.*, 2002) from which a great deal of insight can be gained regarding the nature and magnitude of drainage and peat volume change.

Chow *et al.* (1992) found that porosity decreased by 7% (from 92 to 85%) when compressed, resulting in a increase in bulk density of nearly 100% (0.124 to 0.240 g cm^{-3}) (equation 4). Schlotzhauer and Price (1999) found that bulk density of cutover peat changed seasonally from 0.11 to 0.16 g cm^{-3} with changes in peat volume. With oxidation, Van Seters and Price (2002) found, over the longer term (~30 years), that bulk density increased 0.07 to 0.13 g cm^{-3} in a harvested site when compared to a nearby natural site. With compression, Price (2003) found decreases in hydraulic conductivity by up to 3 orders of magnitude with change in water table of ~40 cm, whereas Van Seters and Price (2002) found longer term changes of half an order of magnitude with oxidation. Van Seters and Price (2002) found specific yield declined by 50% as a result of volume change. Depending on how much compression has occurred, during periods of precipitation the peat can swell and experience an increase in volume, thus the changes to the hydrological parameters mentioned previously can reverse, although compression is not always fully reversible (Price, 2003).

Kellner and Halldin (2002) found that 40% of storage changes in a Swedish bog could be explained by seasonal swelling and shrinking (“mooratmung”), while Price and

Schlotzhauer (1999) found it was about 70% in a partly restored cutover Quebec bog. Therefore, volume change directly affects the water flows and stores within the soil (Price, 2003), and hence geochemical exchanges from and within the peatland, as well as other biogeochemical processes (Strack *et al.*, 2004).

The understanding of peatlands' response to various stressors is beginning to emerge, and models that integrate the complex array of processes (e.g., Kennedy and Price, 2005) can be used to provide better management planning for disturbed peatlands (Price *et al.*, 2003), and to incorporate the important feedback mechanisms like those needed in global climate models (Letts *et al.*, 2000). However, more field study is required to quantify the nature, direction and magnitude of peat soil hydraulic changes, particularly in response to water table lowering, and their implications on the hydrological regime. Consequently, the water table in a fen peatland near Quebec City was manipulated in 2002, and the hydrological response was measured.

The objectives of this study are to determine how water table drawdown affects hydrological parameters and water exchanges in a patterned fen and bog. Specifically, the objectives are to determine 1) the effect of water table drawdown on the main hydrological parameters (n, ρ_d, S_y, θ_{VMC}); 2) specifically how water table drawdown affects hydraulic conductivity between mat, lawn and ridge topography; 3) how changes in these hydrological parameters affect water table position and variability in pool, mat, lawn and ridge topography; and 4) the implications for water flow and storage within and across pool systems. Finally, the implications of these changes will be considered from a climate change perspective.

2. Study Site

2.1. Overview

The study area) is located 20 km east of Quebec City, near Saint-Charles-de-Bellechasse (46°75'N, 70°98'W), Quebec, Canada (Figure 2.1). The site is a string fen (National Wetlands Working Group, 1997) remnant, surrounded by two actively vacuum harvested fields (north-east and south-east margins, an abandoned harvested field (north-west) and an access road (south-west margin). The remnant is approximately 120 by 220 m. Located within the fen are a series of pool systems which include the pool itself and the surrounding mat, lawn and ridge areas that were the focus of this study. Three pool systems were the focus of this study and are identified the Control, Experimental and Drained sites (Figure 2.2). The Control site water level was not manipulated, whereas the Experimental site was drained by approximately 20 cm on 11 June 2002 by a shallow hand-dug ditch connecting it to a pre-existing peripheral drainage canal. The Drained site was drained circa 1994 (approximately 8 years prior to the drainage of the Experimental site) by the landowners in preparation for peat harvesting (but subsequently was never harvested) (Strack *et al.*, 2004). It was assumed that, pre-disturbances, all three pools were similar hydrologically.

At the fen the dominant shrubs are *Chamaedaphne calyculata*, *Kalmia angustifolia*, *Vaccinium angustifolia* and *Andromeda glaucophylla*. The dominant sedges at the fen are *Carex oligasperma, Carex limosa, Rhyncospora alba, Eriophorum virginicum and Scirpus subterminalis* (in the pools). The mosses at the fen include: Hummocks: *Sphagnum rubellum, S. papillosum, S. magellanicum; Lawns: S. magellanicum, S. fallax.* Hollows: *S.*

majus, S. cuspidatum and also bare peat or a cover of liverworts (*Cladopodiella fluitans* and *Gymnocolea inflata*).The Drained site is similar but the hummocks have more bare peat and *Polytrichum strictum* moss.

The general flow direction in the remnant is from Control → Experimental → Drained. The ridge in the Control site is ~25 cm higher than the ridge in the Experimental site, which is ~15 cm higher than the ridge of the Drained site. Within sites, the ridges were approximately 13, 28 and 20 cm higher than the lawns in the Control, Experimental and Drained sites, respectively. The Control site pond is the largest, followed by Drained and Experimental site ponds (~800, 200, and 100 m^2, respectively). All three sites are underlain by a clay layer, which is 80, 110, and 130 cm below the surface in the mat areas in the Drained, Experimental and Control sites, respectively.

The climate for Quebec City (18 km north west of the site) is classified as a Moist Mid-Latitude Climate with Cold Winters (Koppen classification: Dfb). The average annual temperature for Quebec City is 4.0°C with average January and July temperatures of -12.8 and 19.2 °C, respectively (Environment Canada, 2005). Mean annual precipitation is 1230 mm with 26% falling as snow.

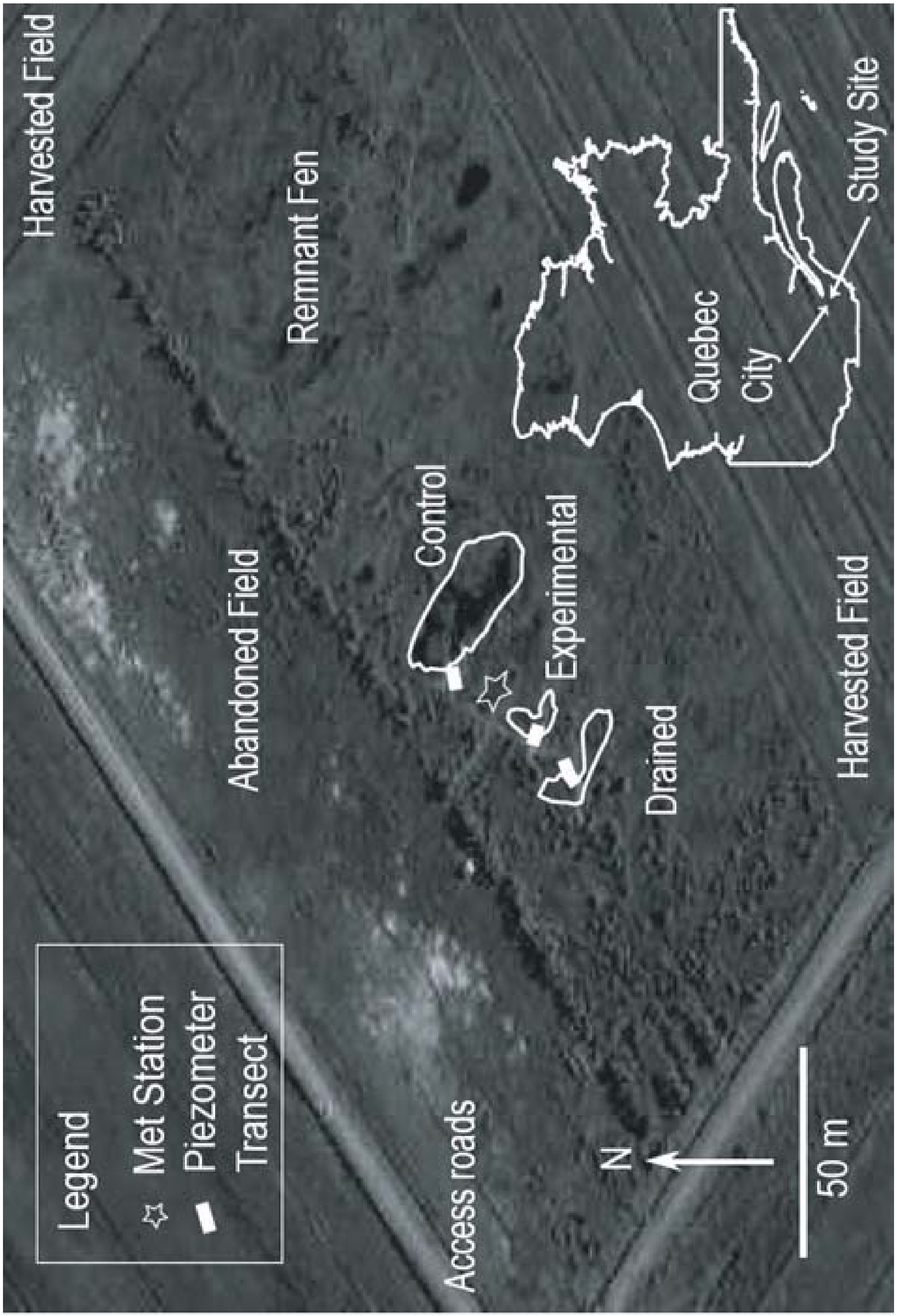


Figure 2.1 Ariel view of the Fen study site

Figure 2.2 Site photos taken June 8, 2004 of the Control (top), Experimental (middle) and Drained (bottom) sites.

2.2. Nomenclature

The site was studied from May to September 2002–2004. The pools in the Fen will be called Control, Experimental and Drained with the initials C, E, and D, respectively. This thesis was part of a PERG (Peatland Ecology Research Group) project involving McMaster University (primarily concerned with gas fluxes), Universite Laval (ecology and plant succession), Environment Canada (Dissolved Organic Carbon), and the University of Waterloo (hydrology). Thus, while some idiosyncrasies (which will become apparent) exist in naming conventions of instrumentation, the 'actual' site names have been used in efforts to make this thesis usable by others involved with this PERG project.

The author of this thesis was present for the 2003 and 2004 field seasons.

3. Methods

Instruments marked with an asterisk (*) were connected to a Campbell Scientific Data Logger (either CR10, CR10x, 21x or 23x) and logged at 60 second intervals with outputs (e.g., average, total) every 20 minutes. The reader is directed to Figure 3.1.

3.1. Micro meteorological instrumentation

A meteorological station was installed between the Control and Experimental pools. Instrumentation at this site was replicated from 2002-2004, except were noted. Air temperature was recorded by using a copper-constantan thermocouple* located approximately 100 cm from the ground surface in a Styrofoam cup covered in aluminium foil. A soil temperature profile also used copper-constantan thermocouples* located at 0, 2, 5, 10, 20, 30, 50, and 70 cm below the surface. A tipping bucket rain gauge* was used to automatically record precipitation events. A manual rain gauge was located beside the tipping bucket and used as a data check. A photosynthetically active radiation (PAR) sensor*, and a net radiometer* were installed. In 2004, a second net radiometer* was installed over the Control pool. Two ground flux heat plates* were installed in the 2004 season. Evapotranspiration estimates were made using the Priestley and Taylor (1972) combination formula. Where

$$E = \alpha\left(\frac{s}{s-q}\right)\left(\frac{86400\left(Q^{*}-Q_{G}\right)}{L\rho}\right)*10^{3} \quad , \qquad \textbf{Equation 3.1}$$

and where s is the slope of the saturation vapour pressure – temperature curve (kPa $^{o}C^{-1}$);

$$s = \frac{4098 * Es}{(237.3 + T)^2} \quad . \qquad \textbf{Equation 3.2}$$

Es is the saturation vapour pressure (kPa);

$$Es = \frac{6.11^{\left(\frac{17.3}{T+237.3}\right)}}{10} \quad , \qquad \textbf{Equation 3.3}$$

where *L* is the latent heat of vaporization (J kg^{-1});

$$L = (2.501 - 0.002361 * T) * 1000 \quad , \qquad \textbf{Equation 3.4}$$

q is the psychrometric constant (assumed to be 0.0662 kPa $^oC^{-1}$), *T* is temperature in ^oC, α, is the ratio of actual and equilibrium evapotranspiration, Q^* and Q_G are the net radiation and net ground heat flux (J day^{-1}), respectively, and, *ρ,* is the density of water (assumed to be 1000 kg m^{-3}). The α coefficient, which represents the slope of the actual versus equilibrium evaporation relationship, was estimated using plastic lysimeters (see next section).

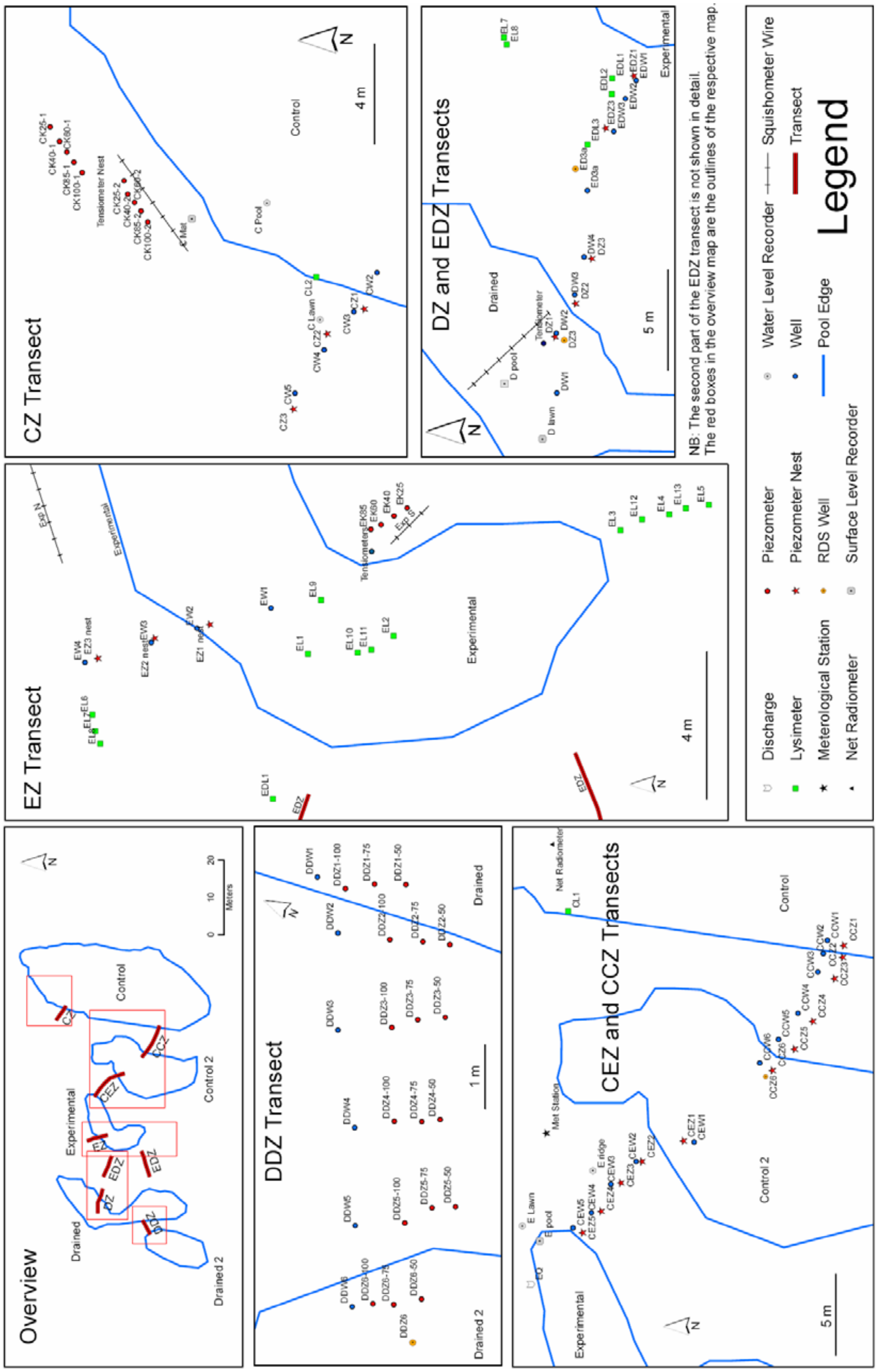


Figure 3.1 Site map of instrumentation

3.2. Lysimeters

Lysimeters were used to estimate evaporative losses on the basis of mass changes due to precipitation/evapotranspiration, to and from, the peat (Kelemen and Ingram, 1999; Van Seters and Price, 2002). The lysimeters were constructed from plastic containers, either circular 20 litre paint buckets or rectangular Rubbermaid buckets. A bucket was perforated at the bottom, and placed into another, non perforated bucket of identical dimensions. Peat monoliths were placed into the perforated container. The perforated bottom allowed water to drain through the sample so that water content characteristics could be manipulated to match the conditions outside the lysimeter, and drainage into the non-perforated bucket could be subsequently measured. Lysimeters were weighed twice a week in 2003, and approximately five times a week in 2004. At the time of each weighing a qualitative inspection was completed to assess the needs of water content manipulation (removing water if soil surrounding looked drier – by emptying the non-perforated bucket, or adding water if surrounding soil appeared saturated). Approximately once a week in 2004 a Hydrosense was used, as a quantitative check, to compare volumetric water content (VWC) between the surrounding soil and within the container.

In 2002 three lysimeters were installed in the lawn area of the Experimental pool. In 2003 two lysimeters were installed in the mat and three installed in the ridge of the Experimental pool. In 2004 three nests of three lysimeters were installed in the mat, lawn and ridge of the Experimental pool. Two lysimeters were installed in the mat of the Control Pool. All lysimeters remained in the ground throughout the winter and were re-used the subsequent season.

3.3. Drainage

A small ditch was constructed in June 2002 to facilitate drainage of the Experimental pool. This ditch extended from the drainage network of the abandoned peat field (north margin) to 3 m from the northern tip of the Experimental pool. A 3 m long, 10 cm diameter PVC (polyvinylchloride) tube connected the final 3 m from the ditch to the Experimental pool. The middle of the tube was buried approximately 15 cm below the original peat surface (leaving the two ends exposed). The pipe allowed the Experimental pool site's water level to drain, and be maintained at ~20 cm below the antecedent level.

3.4. Cores

In August 2002 a Wardenaar corer was used to extract 3 cores in the lawn area of each site (Control, Experimental, and Drained). The cores were cut into approximately 4 equal sections (of roughly 15 cm in length) with depths centered at 15, 30, 45 cm, and, where possible, 60 cm. Standard methods (e.g., Freeze and Cherry, 1979) were used to calculate bulk density (ρ_d) and specific yield (S_y).

3.5. Soil Moisture Content

In 2004 Campbell Scientific Water Content probes* (CS 615) were in the mat/lawn areas of Control, Experimental and Drained sites at four depths (10, 20, 30 and 40 cm, respectively).

3.6. Squishometers

Lines of elevation sensor rods (Price, 2003), henceforth known as squishometers, were installed in 4 locations in the 2002 season. At each of the pools, a sight wire (to provide a stable point of reference) was strung between two rebar poles (approximately 3-5 m apart) driven into the clay substrate below. The rebar poles were surrounded by PVC tubing to reduce the binding of peat onto the rebar (which could influence peat movement). The sight wires ran parallel with the edge of the pool (to sample similar topography and surface type). Squishometers were installed adjacent to the wire at various depths using two different anchoring techniques. For shallower squishometers (installed at less than 25 cm), a drywall screw was affixed to the end of a wooden doweling (with a diameter of 0.48 cm) (Figure 3.2). For deeper squishometers, spring loaded toggle bolts were affixed to the end of the doweling using a shrink-wrap tube. The squishometers were installed so that the doweling that protruded from the ground was very close to the site wire. Attached to this section of doweling was a small length of measuring tape (c. 20 cm). To determine vertical movement of the peat, the markings on the measuring tape were read against the sight wire. It was thought, *a priori*, that the most significant peat volume change would occur in the lawn areas, thus this is where the squishometers were installed. Thus, while this represents only a small portion of the site (~5%) it is the most important (arguably) for ridge – pool water exchanges. At the Control pool, squishometers were installed to depths of 130, 100, 70, 50, 30, 20, 10 and 5 cm. Two sight wire lines were installed in the Experimental pool (called Experimental North and South (see Figure 3.2)) with squishometers in the North installed at 135, 100, 70, 50, 30, 20, 10, and 5 cm and in the South at 115, 70, 50, 30, 20, 10, and 5 cm. Squishometers installed at the Drained site were at 85, 50, 30, 20, 10, and 5 cm. The squishometers were read approximately twice a week in 2002 and 2003, and approximately five times a week in 2004.

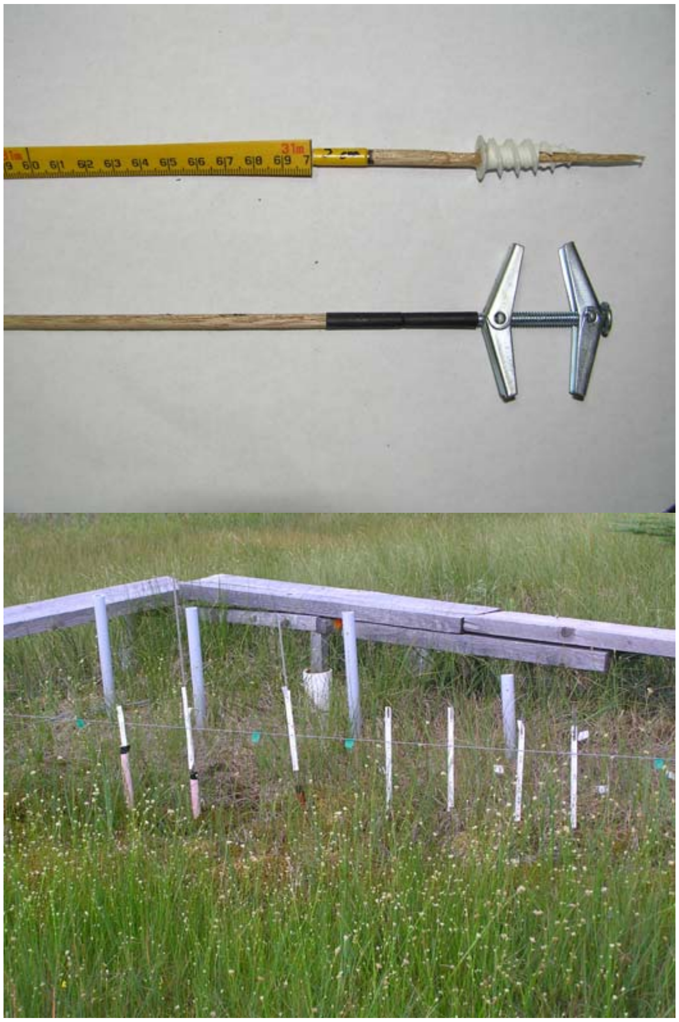


Figure 3.2 Top: Shallower (5 cm) squishometer (upper) and deeper squishometer (lower) prior to installation; Bottom: Squishometers installed at the Experimental South site (note use of white measuring tape, opposed to yellow).

3.7. Piezometer Installations and Locations

All piezometers were made of polyvinylchloride (PVC) pipes. The radii and length of slotted intakes for all the piezometers can be found in Appendix A. Water level measurements were taken manually one to two times a week in 2002 and 2004, and two to three times a week in 2003.

Figure 3.1 shows the locations of all piezometer nests and wells at the Fen site. In addition to the three fen pools already mentioned, two further pools were also studied. Control 2 is located between Control and Experimental and the water table was not directly altered. Drained 2 is located south of the Drained pool, and was also not directly altered. The Drained to Drained 2 (DDZ) transect inset map shows individual piezometers, and because the piezometers within a nest are located relatively close together (10s of cm), it was not necessary to repeat this scale in the other inset maps. Nest topography, installation year and pipe depths are summarized in Table 3.1.

In 2002 three, three nest transects were installed perpendicular to the pool edge in the Control, Experimental and Drained sites (depths of slotted intakes shown in Table 3.1) encompassing mat, lawn, and ridge topography. In addition to the nomenclature previously mentioned (see Nomenclature page 20) Z stands for pie‘Z’ometer. Thus EZ1 – 25 would read Experimental Piezometer nest 1 depth 25 cm. In addition to every nest always containing a well (W = well), these transects also had a fourth well installed in a pool topographic location.

In 2003 a five-nest piezometer transect connecting Control 2 (another un-manipulated pool close by) to Experimental (CEZ) was installed. CEZ1 was located on the Control side, whereas CEZ5 was on the Experimental side. Another transect was installed between the Experimental and Drained pools. EDZ1 and EDZ3 (there was no EDZ2) were in one transect connecting the two pools, and EDZ4, EDZ6, and EDZ8 (there was no EDZ5 or EDZ7) were in another. Again, wells were installed within each transect, as well as between nests (EDW 2, EDW3a, EDW5, and EDW 7). EDW3a was installed after EDW3 and EDW4 was installed and labelled (hence the a).

In 2004 a 6 nest, 3 piezometer transect was installed between the Control pool and Control 2. CCZ1 was located in the original Control pool. A similar transect was installed between the Drained pool and a neighbouring pool (one that contained more water and looked similar to the Experimental pool) called Drained 2. DDZ1 (Drained to Drained 2) was located within the original Drained pool.

In 2002, in addition to the piezometers listed above, piezometers were installed parallel to the lines of squishometers (see section 3.6; not shown in Table 3.1; 4 piezometers can be seen in Figure 3.2 behind the squishometers). The piezometers were installed so that the slotted intakes were at similar depths to the squishometers: Control: 25, 40, 60, 85, and 100 cm. Experimental North (not shown in Figure 2) front row: 25, 40, 60, 85, and 100 cm, back row: 60, 85, 100, 25, and 40. Experimental South (not shown in figure 2): 25, 40, 60, and 85 cm. Drained (not shown): 60, 40, and 25 cm.

	Topography	2004 K test schedule	Year	Depths (cm)
EZ1	Mat	1 2 3	2002	25, 50, 75, 100
EZ2	Lawn	1 2 3		25, 50, 75, 100, 125
EZ3	Ridge	1		
DZ1	Mat	1 2 3	2002	25, 50, 75
DZ2	Lawn	1		
DZ3	Ridge	1		
CZ1	Mat	1 2 3	2002	25, 50, 75, 100, 125
CZ2	Lawn	1 2 3		
CZ3	Ridge	1		
CEZ1	Mat	1 2 3	2003	50, 75, 100
CEZ2	Lawn	1		
CEZ3	Ridge	1		
CEZ4	Lawn	1		
CEZ5	Mat	1 2 3		
EDZ1	Lawn	1 2 3		
EDZ3	Ridge	1		
EDZ4	Lawn	1 2 3		
EDZ6	Ridge	1		
EDZ8	Lawn	1 2 3		
CCZ1	Mat	1 2 3	2004	
CCZ2	Lawn	1		
CCZ3	Ridge	1		
CCZ4	Ridge	1		
CCZ5	Lawn	1		
CCZ6	Mat	1 2 3		
DDZ1	Mat	1		
DDZ2	Lawn	1		
DDZ3	Ridge	1		
DDZ4	Ridge	1		
DDZ5	Lawn	1		
DDZ6	Mat	1 2 3		

Table 3.1 Piezometer nest details and 2004 K test schedule, where 1, 2 and 3 refer to weeks 1, 2 and 3, respectively

3.8. Hydraulic Conductivity (K)

Bail tests (Hvorslev, 1951) were used to determine K for each piezometer. The values of K were caculated as outlined in Freeze and Cherry (1979) based on Hvorslev (1951):

$$K = \frac{r^2 \ln(L/R)}{2LT_0} \qquad \text{Equation 3.5}$$

where, *r,* and, *R,* are the internal and external radii of the piezometer, *L,* is the length of the slotted intake, and T_0, is the basic lag time parameter, which is calculated from the head recovery curve of the bail or slug test. In 2002 and 2004 water was drawn out of the pipe using a flexible rubber tube. Changes in initial head ranged from 10 to 50 cm. In 2003 a pump was used to ensure a consistent change in head (10 cm). The rate of head recovery was then measured. In 2002 each squishometer piezometer (e.g., CZK, DZK, EZK) had weekly tests conducted on them. In 2003 each pool piezometer (excluding those piezometers next to the squishometers) had one K test conducted on it between June and August. In 2004, K tests were preformed on a three-week cycle which was repeated five times (to total 15 weeks), as indicated in Table 3.1. Week 1 all piezometers at the Fen were tested (excluding the squishometer piezometers). Week 2 most mat and lawn nests, as well as the squishometer piezometers were tested. Week 3 the mat and lawn piezometers, as well as the squishometers piezometers were tested. The mat and lawn nests were tested weekly to assess a K dependence on water table depth (e.g., to assess if a seasonal drying trend affects K). All other piezometers were tested at least 5 times.

3.9. Surface and Water Level Recorders

Pool water levels were recorded with electrical potentiometer devices* attached to a float-pulley system anchored to the sediment. Ground surface elevation changes were recorded with a similar device but with counter-weights instead of floats. Manual measurements of the distance from the centre of the wheel to the water level or surface level, respectively, were taken weekly. Where non-pool water table locations are reported, a 10 cm diameter PVC well or metallic stove pipe was used (Figure 3.3). The locations of all water/surface level recorders is shown in Table 3.2.

Figure 3.3 Float-pulley system measuring the Control lawn water table.

RDS (Remote Data System) wells were used in 2004. The RDS well was programmed to log every 20 minutes and were data downloaded weekly. 5 RDS (Remote Data Systems) wells were installed in the: ridge between Experimental and Drained near well EDZ3; lawn near DZ1; DDZ6 pool; ridge near CZ3; and CCZ6 pool; respectively.

Category	Short Name	Year(s) used
Surface Level Recorders	C sur lawn	all
	D sur lawn	all
	E sur lawn	all
Water level recorders	E water ridge	all
	E water lawn	2002, 2003
	C water lawn	all
	D water ridge	all
	C water ridge	all
	DZ1 water lawn	2004
Pool water level recorders	C pool	all
	D pool	all
	E pool	all
	CCZ6 pool	2004
	DDZ6 pool	2004

Table 3.2 Water and surface level recorder locations and years used. (sur = surface)

4. Results

The results of this thesis are divided into three sections: 1) Meteorological, 2) Hydrological Parameters, and 3) Hydrology. The rationale is an attempt to keep the reader focused on a specific theme or set of processes. The Discussion section will integrate all of the Result sections.

4.1. Meteorological

Meteorological conditions were monitored from JD 131, 129 and 129 to 301, 268 and 233 for 2002, 2003 and 2004, respectively. The meteorological conditions for the field seasons were different, as indicated by the monthly average, maximum and minimum temperature values (Table 4.1). The 2004 field season was the warmest season with only June below the 30 year mean. Both 2002 and 2003 saw below normal average temperatures for all months. With the exception of June, July and August 2002, all monthly averages were within ± 2 C° of the 30 year mean.

		Temperature			Precipitation	
		Average	Max	Min		Total
2002	May	10.8	33.8	-3.6	112.7	
	June	9.9	28.1	-10.9	80.2	
	July	16.1	33.2	-1.4	122.6	
	August	15.3	31.0	-3.3	18.3	334.0
2003	May	10.0	30.7	-4.9	40.1	
	June	16.0	34.7	-4.3	84.8	
	July	17.2	34.3	0.8	95.3	
	August	16.9	31.1	1.6	128.6	348.5
2004	May	12.4	32.0	-1.1	83.1	
	June	15.8	34.0	-1.5	117.1	
	July	20.0	36.3	6.8	177.1	
	August	18.8	35.2	5.5	66.6	443.7
30 year*	May	11.2			105.5	
	June	16.5			114.2	
	July	19.2			127.8	
	August	17.9			116.7	464.8

Table 4.1 Average, minimum and maximum temperature values and precipitation totals per month for 2002 to 2004 seasons as well as the 30 year running average (*Environment Canada, 2005 at Quebec Lesage International Airport. Located 20 km west of the study site)

Total precipitation for the recorded study period between May and August for 2002, 2003, and 2004 were 334, 349, and 444 mm, respectively (Figure 4.1), which were all less than the 30 year mean of 464.8 mm (Table 4.1). There were 10, 10, and 15 precipitation events greater than 10 mm that accounted for 66, 64 and 74% of the total rainfall for 2002, 2003 and 2004, respectively.

The 2002 and 2003 field seasons were similar in that they both had a number of relatively long (> 1 week) dry periods, whereas 2004 saw very few, long dry periods (Figure 4.1). The frequency of dry periods was determined by finding the length of time (in hours) between rain events (ignoring precipitation events of less than 0.5 mm) (Figure 4.2).

Average daily evaporation loss (E_a) measured with the lysimeters were 2.8, 3.1 and 3.5 mm day^{-1} for 2002, 2003 and 2004 respectively (Table 4.2, Figure 4.1) at the Experimental site. Equilibrium evaporation (E_{eq}) was calculated with the Priestley and Taylor (1972) model for identical periods (some lysimeter data were rejected when heavy rain flooded lysimeters), and the ratio was used to estimate daily evaporation (E_a) thus $\alpha = E_a/E_{eq}$. The water deficit (P – E) was calculated to be 10, 7 and 72 mm for 2002, 2003, and 2004, respectively.

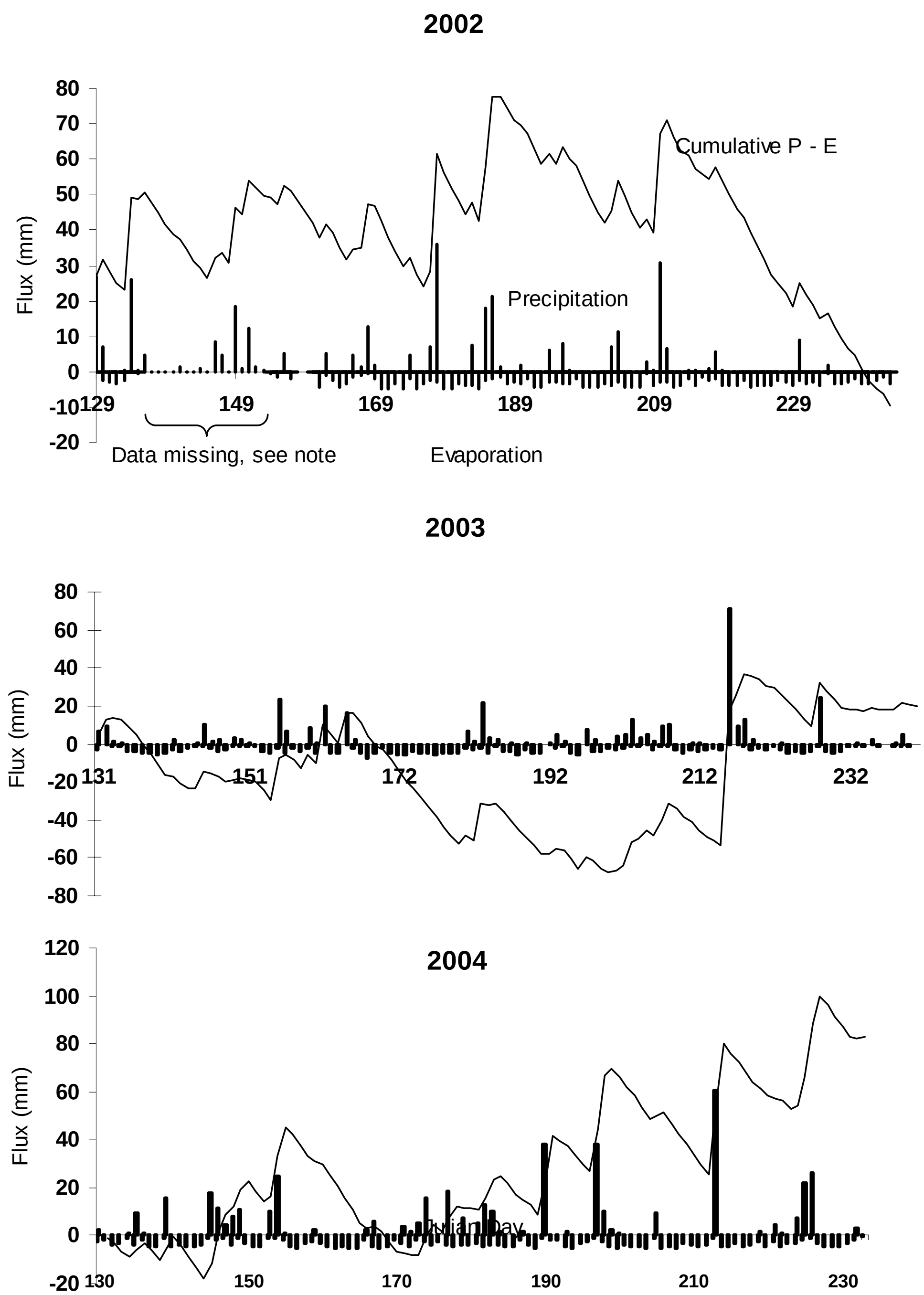


Figure 4.1 Daily precipitation (positive black bars) and evaporation (negative black bars) for 2002 to 2004 with cumulative flux (P-E) (line). Evaporative data (meteorological station) was missing from JD 136-153 in 2002 and thus the average daily loss was added to the cumulative line. Note different scale in negative direction for 2003

Year	E_a (mm day^{-1})	E_{eq} (mm day^{-1})	Total Rainfall (mm)	Total Evaporation (mm)	Alpha	Water deficit (mm)
2002	2.85	2.91	334	324	0.98	10
2003	3.11	3.18	349	342	0.97	7
2004	3.5	3.8	444	372	0.93	72

Table 4.2 Actual (E_a) and Equilibrium (E_q) evaporation rates, and water deficit (P – E) for 2002 to 2004.

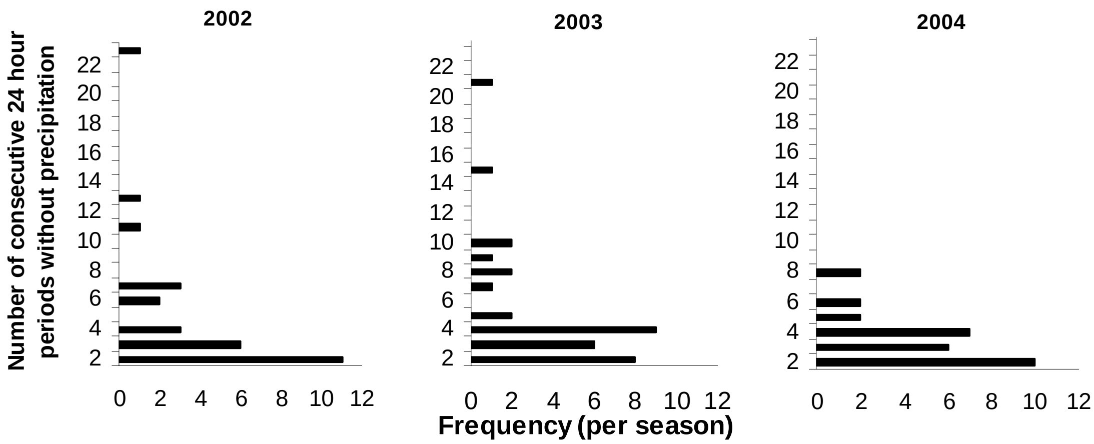


Figure 4.2 Frequency of '24 hour precipitation free' periods for 2002 to 2004 field seasons. (In efforts to conserve the scale of < 24 hours (i.e., 1 on the y axis) is omitted because there are many (> 200) short time periods between rain events.)

4.2. Hydrological Parameters

4.2.1. Drainage

Drainage of the Experimental pool by 20 cm lowered the mat, lawn and ridge surfaces 25.5, 13.3 and 6.8 cm, respectively, over the 2002 field season (Figure 4.3, Figure 4.4). This can be observed visually (Figure 4.3) as yellow electrical tape was affixed to the piezometer at the pre-drainage surface level. Water levels dropped ~20 cm in the mat and lawn immediately (~4 hours) following drainage, whereas the ridge water table took considerably longer to decrease (~14 days, Figure 4.4).

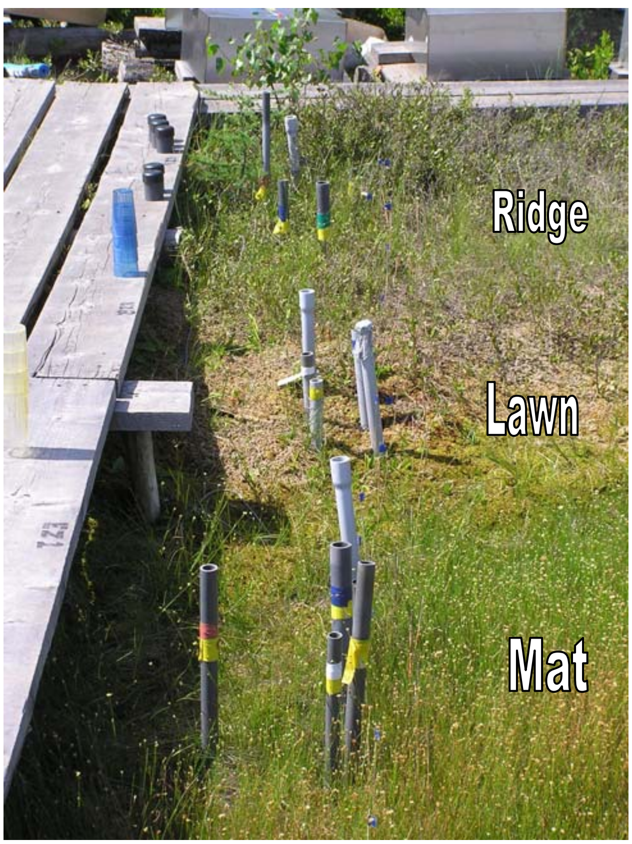
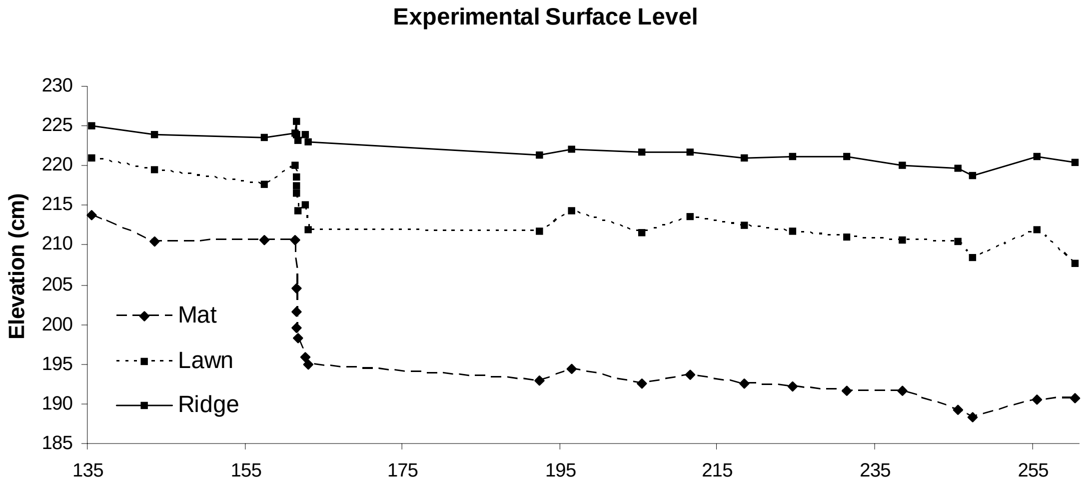


Figure 4.3 Surface subsidence along the Experimental transect. Yellow tape indicates the pre-drainage surface level with respect to the side of the piezometer.



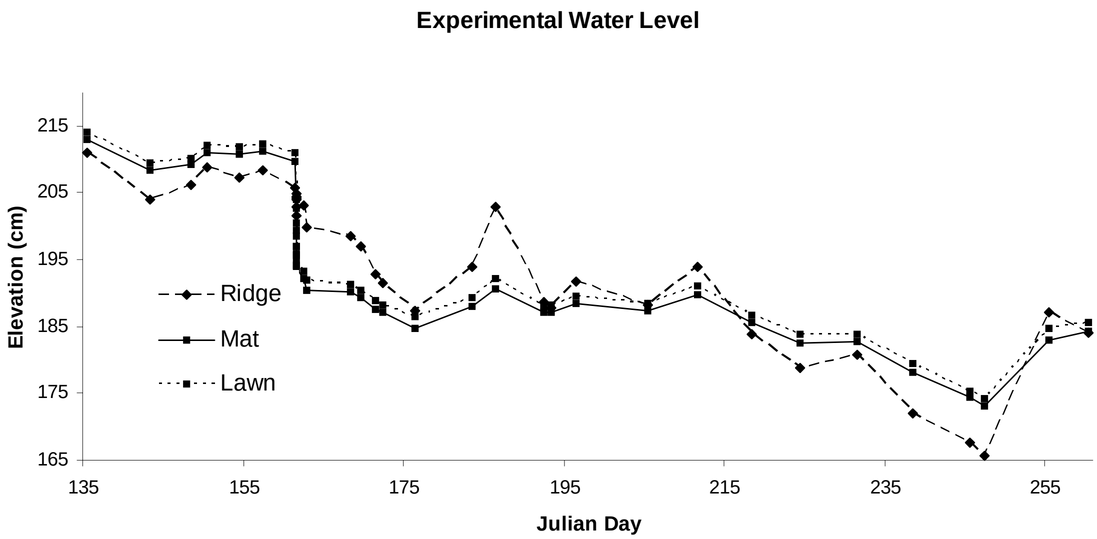


Figure 4.4 Top: Surface subsidence measured manually relative to piezometer top for the Experimental pool, 2002. Bottom: Water table drawdown measurement manually relative to top of piezometer. Note: Drainage occurred on JD 161.

4.2.2. Hydraulic Parameters

At equivalent depths, bulk density trended Drained>Experimental>Control. Bulk density (Figure 4.5a) increased with depth in all three cores, whereas Experimental ≈ Drained in the upper layer (15 cm). Average bulk density for Control, Drained and Experimental site peat was 0.083, 0.144, and 0.147 g cm^{-3}, respectively.

Specific yield (Figure 4.5b) was 0.211, 0.233, and 0.070 at the 15 cm depth in the Control, Experimental and Drained sites, respectively. At depths 30 cm and below specific yield was similar between sites.

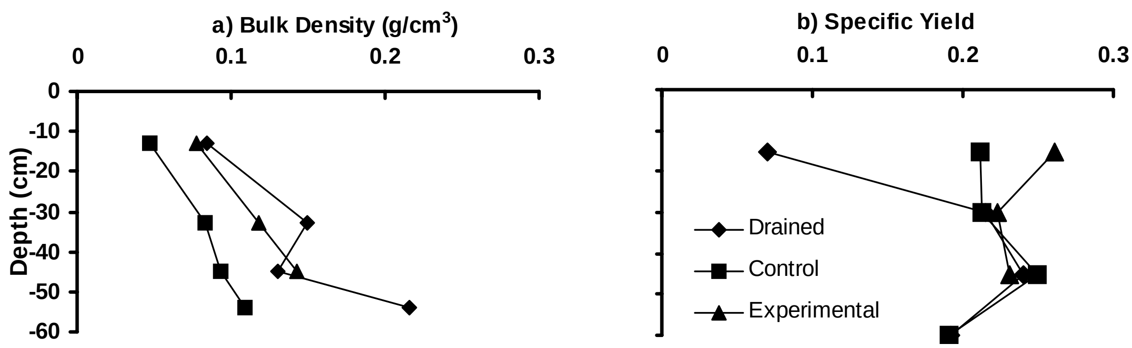


Figure 4.5 Bulk density (a) and specific Yield (b) in the Drained, Control, and Experimental lawns

4.2.3. Water Content

The CS 615 water content probes proved to be problematic at reporting realistic water contents (some started, and maintained water contents of > 1.0 (i.e., >100%)), however they did seem to be able to detect changes in water content, and thus comments on trends can be made. The values from the probes were calibrated by assuming that, upon installation, the soil was 100% saturated (following spring melt). Therefore moisture content would equal porosity. Porosity values were calculated using equation 1.4, assuming particle density was 1.55 g cm^{-3} (Price, 2003).

In all pools at all depths (Figure 4.6) moisture contents declined over the course of the 2004 season to ~JD (Julian Day) 170, but continued to decline for the remainder of the summer, with the exception of a few slight increases, even though water tables increased thereafter, (the Drained 10 cm probe reported a constant value for the entire season and thus was assumed to be malfunctioning and not shown). Moisture contents changed slightly with changes in water table locations, albeit with subdued responses. (Regressions of water table and moisture contents yielded R^2 values of >.08 for Control and Drained and between 0.1 and 0.5 for Experimental (not shown).)

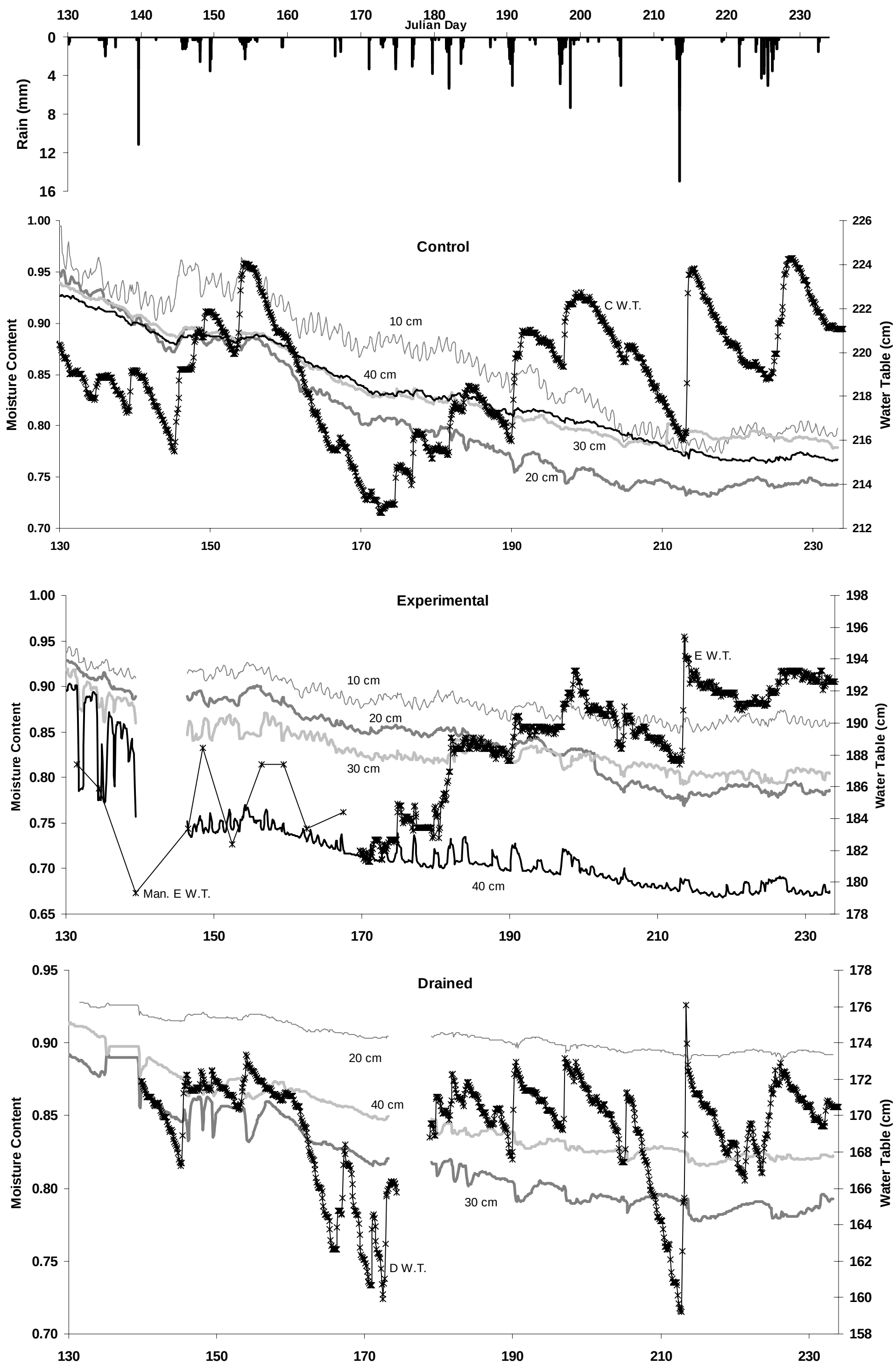


Figure 4.6 Soil Moisture Content (expressed as a proportion of total soil volume) for 2004. Depths of probes are indicated above/below the line. Water tables (W.T.) are indicated by C, E, or D W.T. For the first part of 2003, manual Experimental water tables are used (Man. E W.T.)

4.3. Squishometers

The strain (or relative change in layer thickness) (Figure 4.7) that occurred in peat layers between sensors was determined as the difference in position of the sensor relative to its starting position. Thus, each subsequent day the 'current' distance between sensors was divided by the 'original' distance. Thus, values <1 represent subsidence, and >1 represent swelling. Because of the number of squishometers and similar strain ranges, only the upper, middle and lower layers are shown (Figure 4.7). However, summary values for all layers can be found in Table 4.3. In the Drained and Experimental South sites, the upper layer (the layer between the 5 and 10 cm squishometer) experienced the greatest range in strain, 18 and 24%, respectively over the 2004 season. At the Experimental North site, the greatest range in strain occurred in the 20 to 30 cm layer, however, similar ranges where observed towards the upper most layer (10 to 6 %). Generally, the range of strain decreased with depth at the Drained and two Experimental sites. The Control site, however, experienced increasing strain with depth, with the most strain occurring in the 100 to 130 cm layer and the least in the upper 5 to 20 cm layer (the 10 cm squishometer was missing). The 5 to 10 cm layer at the Experimental South site appeared to be the only layer that swelled, and maintained a larger volume throughout the entire season.

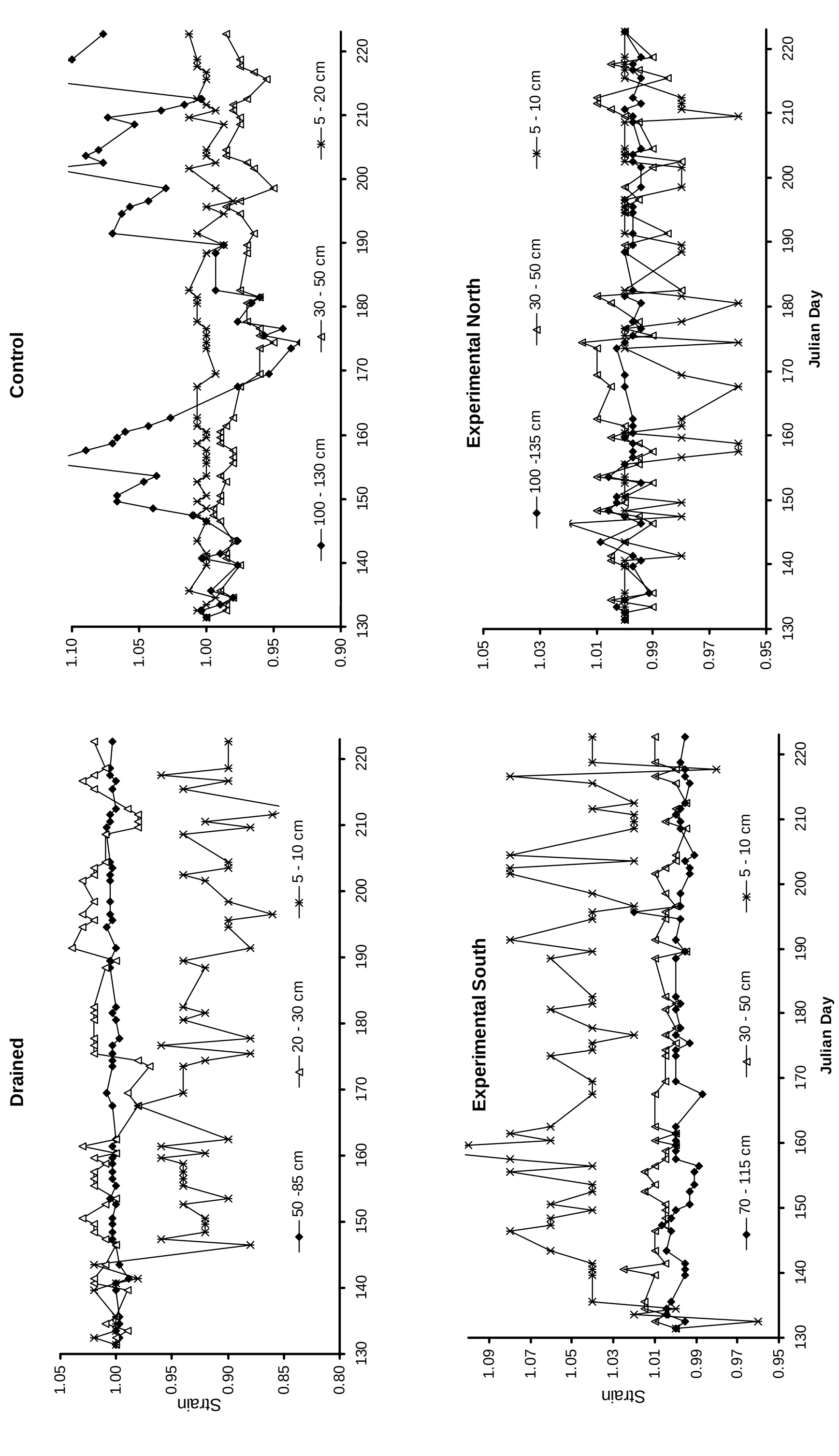


Figure 4.7 Strain for squishometers 2004. Not all layers are shown as strain values are similar in magnitude. Note different vertical scales for all sites so that more detail could be shown.

		Average	Min	Max	Range	St Dev
Drained	50 -85 cm	1.00	0.99	1.01	0.02	0.004
	30 - 50 cm	1.01	0.98	1.02	0.04	0.009
	20 - 30 cm	1.01	0.97	1.04	0.07	0.016
	10 - 20 cm	0.99	0.94	1.02	0.08	0.015
	5 - 10 cm	0.93	0.84	1.02	0.18	0.043
E South	70 - 115 cm	1.00	0.99	1.02	0.03	0.005
	50 - 70 cm	1.01	1.00	1.03	0.03	0.006
	30 - 50 cm	1.01	1.00	1.03	0.03	0.006
	20 - 30 cm	0.99	0.97	1.00	0.03	0.009
	10 - 20 cm	0.99	0.98	1.01	0.03	0.007
	5 - 10 cm	1.05	0.96	1.12	0.16	0.028
E North	100 -135 cm	1.00	0.99	1.01	0.02	0.003
	70 - 100 cm	0.99	0.98	1.00	0.02	0.005
	50 - 70 cm	1.00	0.99	1.02	0.03	0.007
	30 - 50 cm	1.00	0.98	1.02	0.04	0.008
	20 - 30 cm	1.00	0.97	1.02	0.05	0.012
	10 - 20 cm	0.99	0.97	1.00	0.03	0.008
	5 - 10 cm	0.99	0.96	1.02	0.06	0.014
Control	100 - 130 cm	1.03	0.93	1.13	0.20	0.053
	50 - 100 cm	1.01	1.00	1.09	0.10	0.013
	30 - 50 cm	0.98	0.95	1.00	0.05	0.012
	20 - 30 cm	0.98	0.96	1.02	0.06	0.013
	5 - 20 cm	1.00	0.98	1.01	0.03	0.007

Table 4.3 Squishometer strain summary by layer. Values greater than 1 indicate swelling, and less than 1 compression.

4.3.1. Hydraulic Conductivity

4.3.1.1. Test Summary

A small number of piezometers (10 of 129) could not be tested (detailed below). In total, 221, 56, and 938 K tests were completed during the 2002, 2003, and 2004 field seasons, respectively, totalling 1215 tests. The following piezometers have no reported K value because the head recovery was too quick for manual measurement techniques: CCZ1-50, CCZ6-50, and CZ1-25 to 100. At the following piezometers the water table fell below the intake: EZ1-25, EZ2-25, EZ3-25, and EZK3 - 25.

4.3.1.2. Intra-Pool Transects

Hydraulic conductivity (K) generally decreased with depth from Control: 10^{-1} to 10^{-5} cm s^{-1}; Experimental 10^{-2} to 10^{-7} cm s^{-1}; to Drained 10^{-2} to 10^{-6} cm s^{-1} (Figure 4.8a, b, and c, respectively). At the Control site (Figure 4.8a) K decreased, by an order of magnitude on average, between topographic locales in the order $K_{mat}>K_{lawn}>K_{ridge}$. At the Experimental site (Figure 4.8b) K also trended $K_{mat}>K_{lawn}>K_{ridge}$. In the Drained site (Figure 4.8c), $K_{mat}\approx K_{lawn}\approx K_{ridge}$ at the 50 and 75 cm layers (10^{-5} and 10^{-6} cm s^{-1}). Furthermore, for each topographic location (mat, lawn and ridge) the trend was $K_{Control}>K_{Experimental}>K_{Drained}$ (Figure 4.8 d, e, f)

4.3.1.3. Inter-Pool Transects

The CCZ (Control to Control 2) and CEZ (Control 2 to Experimental) transects were combined to produce Figure 4.9 because both transects share the Control 2 pool. Throughout the entire transect, *K* generally decreased with depth. Within the first 4 nests of the CCZ transect (mat, lawn, ridge and ridge) *K* generally decreased through the topographic profile so that $K_{mat}>K_{lawn}>K_{ridge}$. The remaining lawn and mat nests in Control 2 of the CCZ transect had a general increase in K, with the exception of K_{100cm} that remained low (~10^{-6} cm s^{-1}). The CEZ transect had reverse trends in *K* compared to the CCZ where *K* increased through the topographic profile so that $K_{mat}<K_{lawn}<K_{ridge}$.

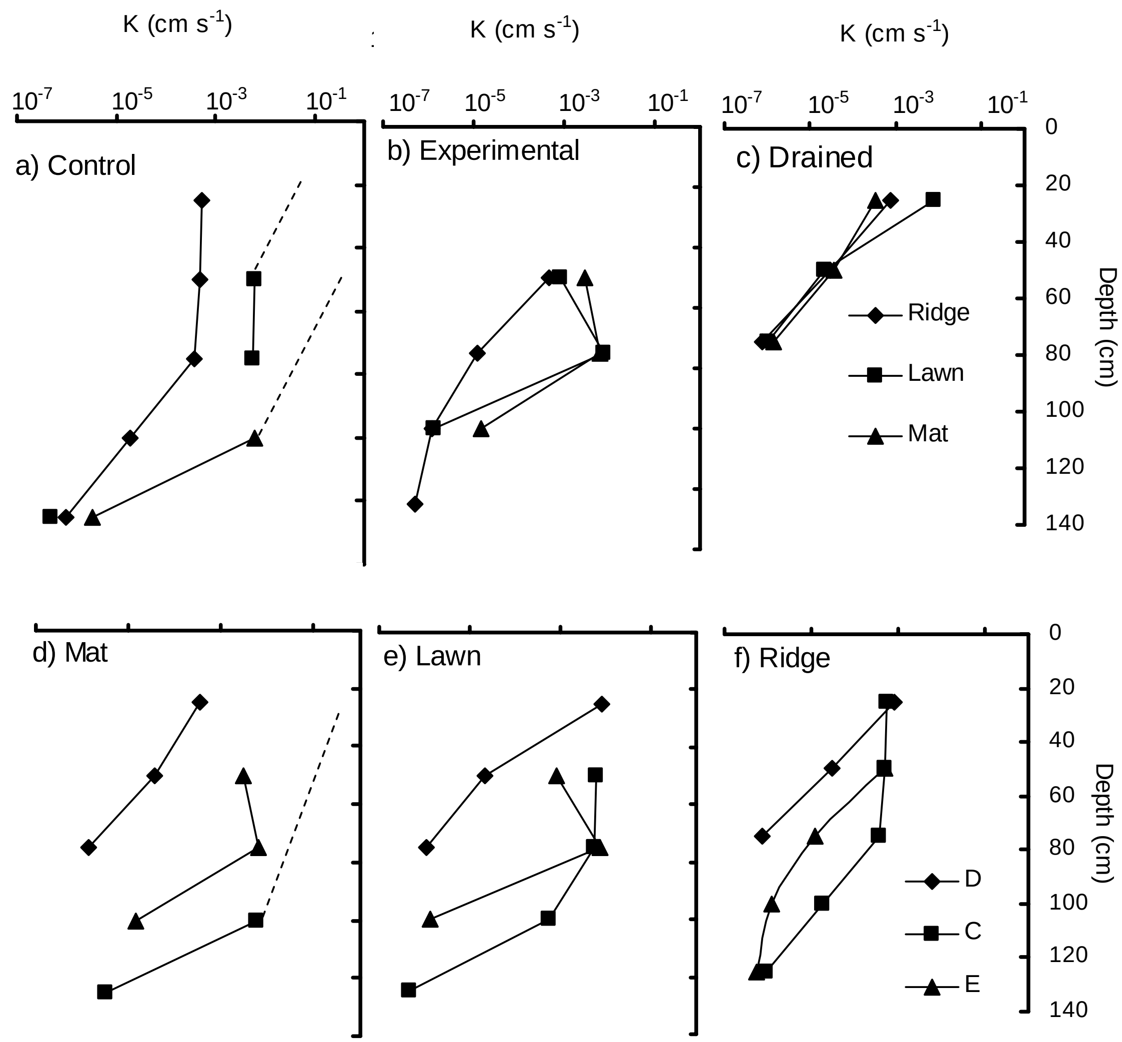


Figure 4.8 Hydraulic Conductivity by topographic location within sites (a-c) and between sites (d-f). The dotted lines for Control in Figures a) and d) indicate that those K responses were too quick for manual measurement

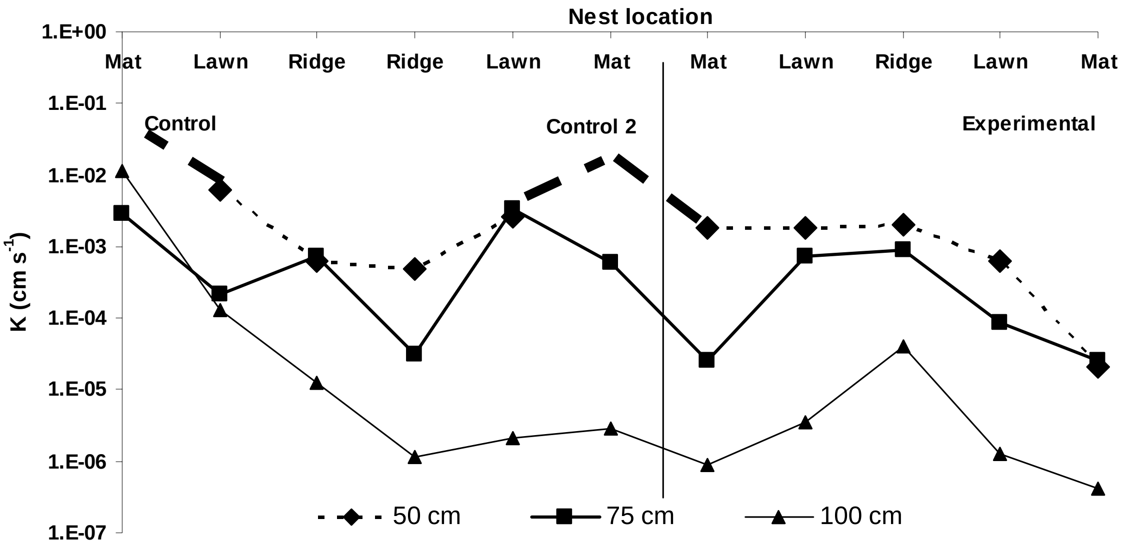


Figure 4.9 Hydraulic Conductivity through the CCZ and CEZ transects. The vertical line denotes the change between the CCZ and CEZ transects. The heavy dashed lines indicates that head recovery was too quick for manual measurement (50 cm).

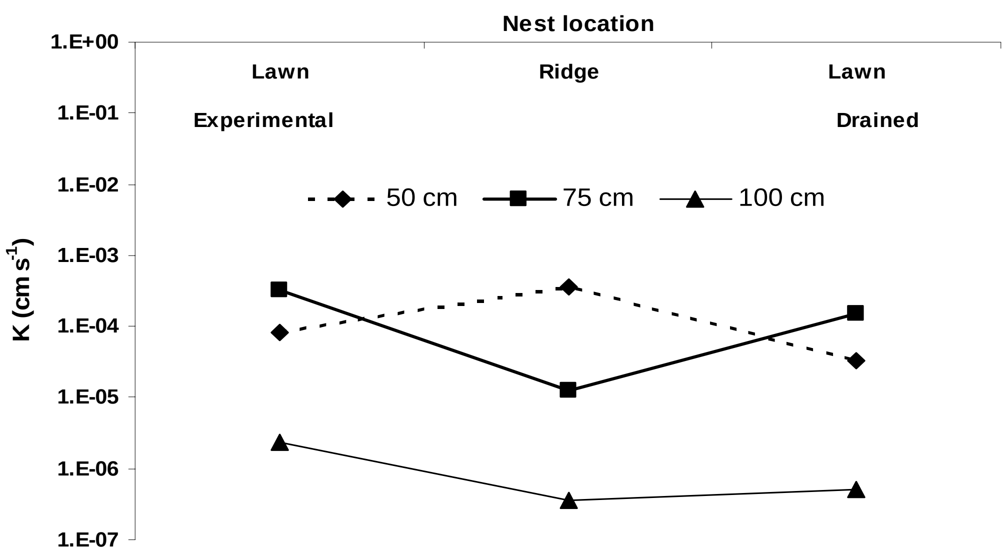


Figure 4.10 Hydraulic Conductivity through the EDZ transect

Figure 4.11 shows the average 2004 K values for the DDZ (Drained to Drained 2) transect. Throughout this transect the deeper, 100 cm, layer changes only slightly with topographic features, remaining around 10^{-6} cm s^{-1}. In the 50 and 75 cm layers K is lower in the mat location than the lawn and ridge on the Drained side (DDZ1), but then increases $K_{ridge}<K_{lawn}<K_{mat}$ on the Drained 2 side (DDZ6).

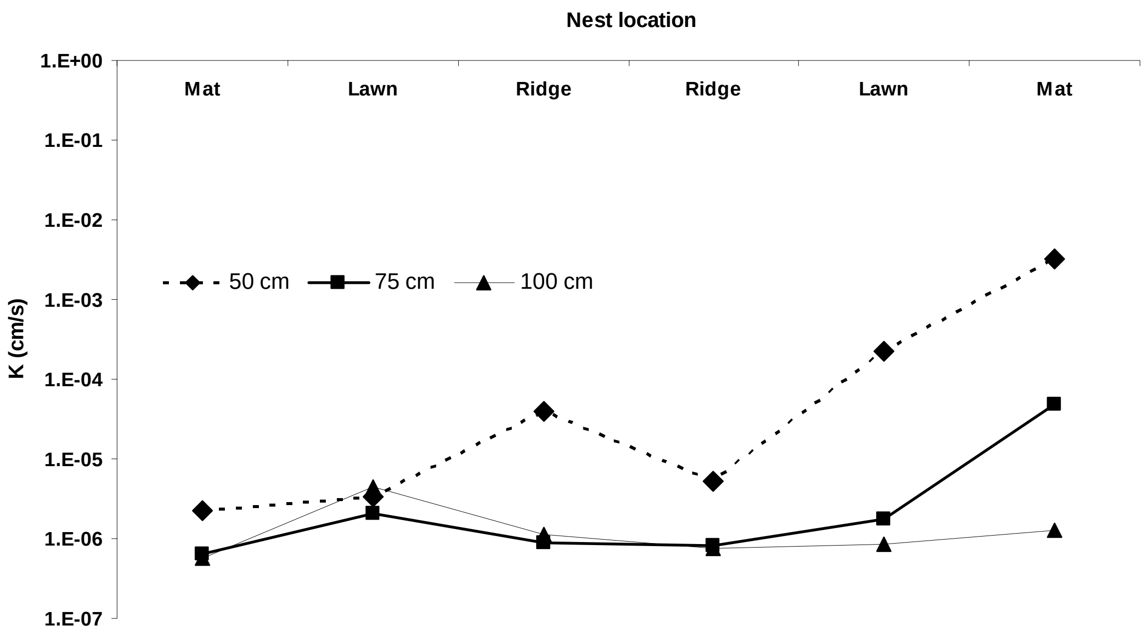


Figure 4.11 Hydraulic Conductivity through the DDZ transect

4.3.1.4. Seasonal Time Series Trend in K

Some mat and lawn piezometers were tested weekly (in 2004) to determine if a seasonal trend in K could be observed. The two mat nests of the CEZ (Control to Experimental) transect show little variation (Figure 4.12), all staying within a range of an order of magnitude, with the exception of CEZ5-50 that increased from ~5.0 x 10^{-6} cm s^{-1} to 3.0 10^{-5} cm s^{-1}.

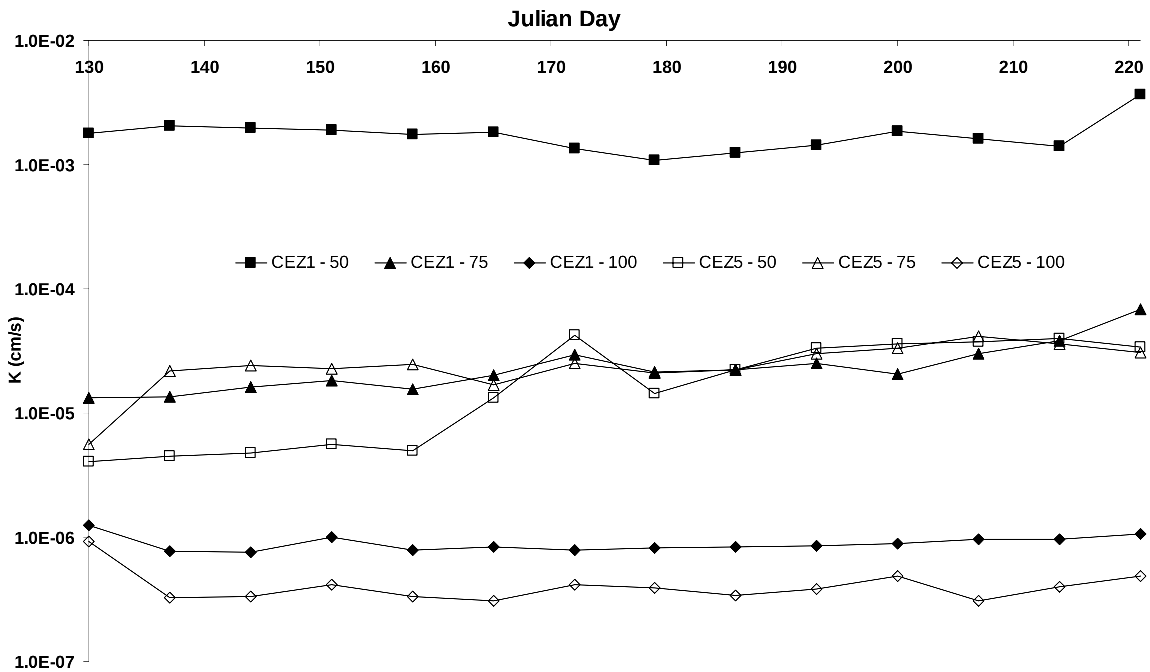


Figure 4.12 Weekly K values for the mat nests of the CEZ transect. (Julian day is the date of the Monday for the week the test was completed.)

4.3.1.5. Affect of Drainage on K in Squishometer Piezometers

The squishometer piezometers (those installed parallel to the squishometers) were the only piezometers that were tested in both 2002 and 2004 (Figure 4.13 a – c). Recall that in the Experimental pool there were two lines of squishometers, North (N) and South (S), and that the North site had two lines of piezometers, Front (F) and Back (B) (see section 3.6). In the ENF (Figure 4.13 a) line drainage of the Experimental pool lowered K in the 100 cm layer by ~1.5 orders of magnitude and half an order of magnitude in the 40 cm layer. The 60 cm layer appears unaffected by drainage (Figure 4.13 a). Following drainage the 25 cm layer became dry and untestable (as well as in ENB, Figure 4.13 b), whereas the 85 cm layer (not shown) was not tested in 2002 (recall the author was present for the 2003 and 2004 seasons). In ENB (Figure 4.13 b) the 40 cm layer decreased similarly to ENF (half an order of magnitude). The 60 cm layer also trended similarly to ENB by decreasing only very slightly. The 100 cm layer had only one test preformed on it pre-drainage and yielded a very low *K* (~.5 $x10^{-6}$ cm s^{-1}); yet following drainage increased nearly 3 orders of magnitude before continuously declining for the remainder of the season. In the ES (Figure 4.13 c) line *K* decreased (slightly) in the 40 and 60 cm layers, and again, the 25 cm layer (not shown) dried up. Like ENB – 100, a very low pre-drainage K value was also found for ES – 85 which increases once more after drainage, and fell slowly until rebounding at the end of the 2002 season.

4.3.1.6. Squishometer Piezometers: 2002 to 2004

In ENF (Figure 4.13 a) the 60 cm layer varied little between 2002 and 2004, whereas the 100 cm layer increased to pre-drainage levels. The 40 cm layer was ~ 1 order of magnitude lower in 2004 then 2002. In the ENB line (Figure 4.13 b) the 60 and 85 cm layers increased, whereas the 100 cm layer continued to decrease. Both the 40 and 60 cm layers remained close to the last 2002 *K* test. In ES (Figure 4.13 c) the 40 and 60 cm layer remained similar, whereas the 85 cm layer dropped to pre-drainage levels.

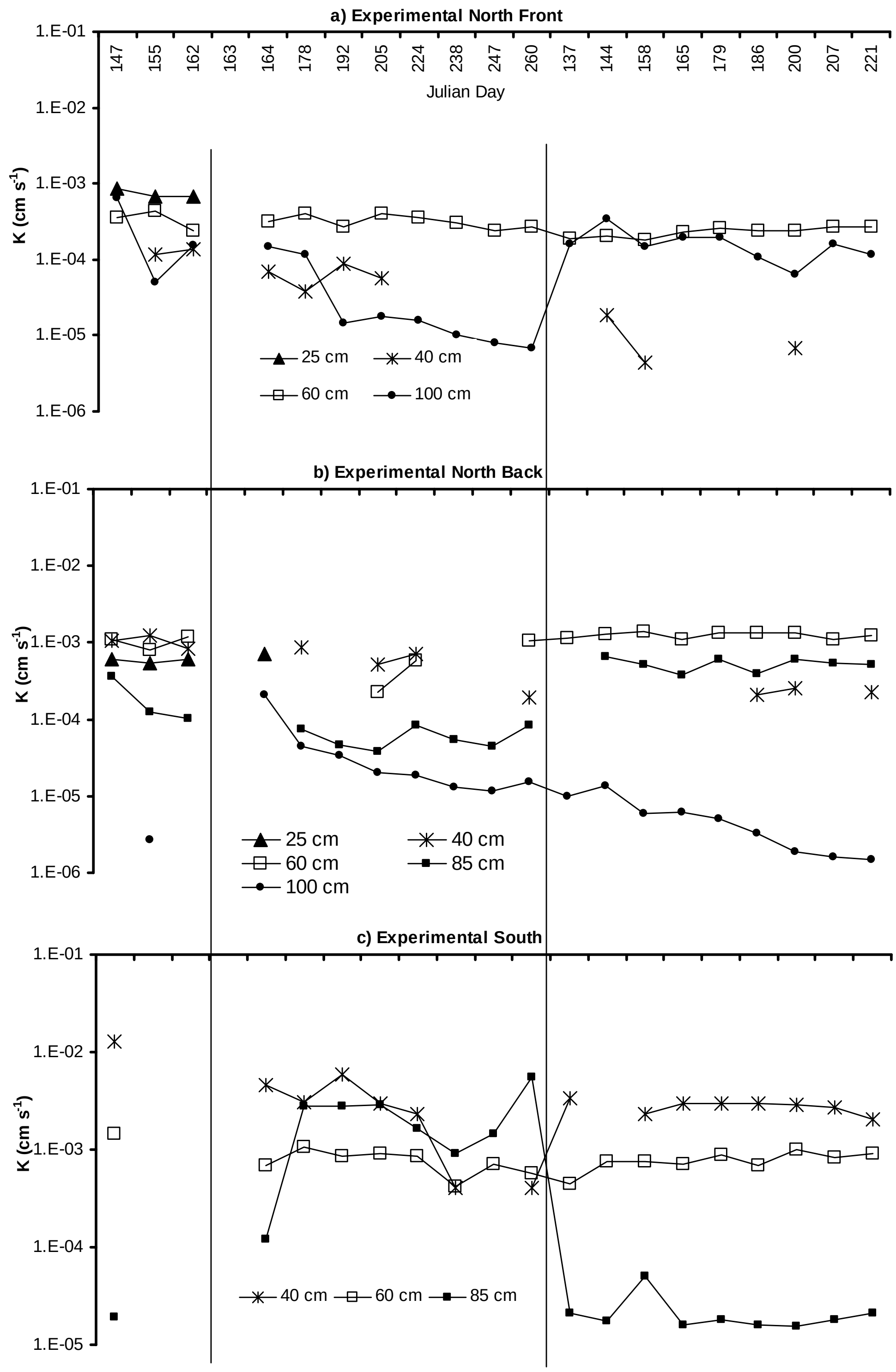


Figure 4.13 Hydraulic conductivity for the squishometer piezometers in 2002 and 2004. Note: vertical lines separate pre-drainage, 2002 and 2004.

4.4. Hydrology

4.4.1. Water Table Position

The distinct water level elevation differences between pools in this fen are evident (Figure 4.14, Figure 4.15), cascading from Control→Experimental→Drained. The Experimental pool, whose water level decreased ~20 cm by drainage in 2002, had a water table elevation notably below the Control pool, but only slightly above the Drained pool (Figure 4.14). During wet periods the water tables were close or above the surface (within ~5 cm) in the pool and mat locations, with the exception of the Drained site which was ~ -10 cm (Figure 4.14 in 2002 and 2004). During dry periods water tables in the Control site still maintained similar water table positions (relative to the surface) but dropped in the ridge and lawn. However, in the Drained site water tables fell >15 cm from the surface in the pool bottom and mat locations. The dry period water tables between 2002 and 2004 were quite different with 2002 (dry year) having particularly low dry-period water table levels as opposed to the higher 2004 levels. At the Experimental site water tables did remain close to the surface in the pool locations, but dropped considerably in the lawn and ridge locations.

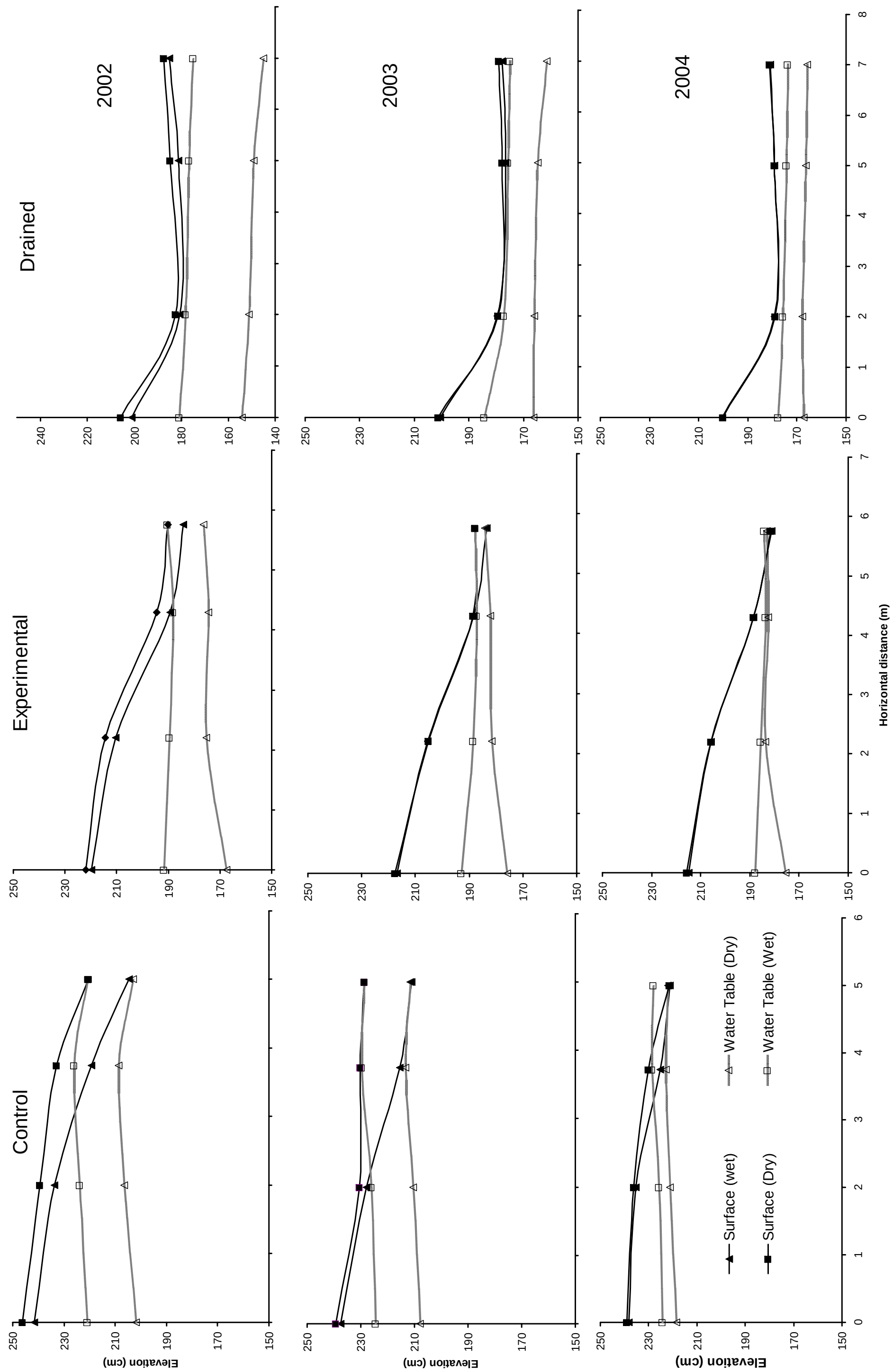


Figure 4.14 Water table location for wet and dry periods between pools for all years. Note: Dry and Wet are relative terms for each specific year. The four points along the X-axis represent, from left to right, ridge, lawn, mat, and pool locations. Note that the surface elevation changes decreases from Control to Drained. Surface is the peat surface in the ridge, lawn, mat and pool topographic location, at a 'dry' and 'wet' time, respectively. Water table is the water table in the ridge, lawn, mat and pool topographic location, at a 'dry' and 'wet' time, respectively.

4.4.2. Surface Level and Water Table Fluctuations

Recall that the potentiometers were used to measure both surface and water table level fluctuations. In non-pool locations (Table 4.4 group 2) where water tables are reported, either an RDS well was used, or an open well casing (Figure 3.3). For 2003 and 2004 multiple storm events were selected so that water table responses could be determined (Table 4.4 and Figure 4.15). The response was calculated by subtracting the minimum water table/surface level value from the maximum value for the period before (~ 4 to 6 hours) and after (~ 4 to 6 hours) the storm event. It was assumed the minimum value would represent the pre-storm level and that the maximum value occurred during or just after the rain event.

4.4.2.1. Surface Level Fluctuations

In both 2003 and 2004 the lawn in the Control site responded the greatest (43 and 77% for 2003 and 2004 with n = 3 and 7, respectively). When the Control lawn did respond the greatest, it often responded more than 5 times greater than the Experimental mat or Drained lawn.

4.4.2.2.Non-pool Water Table Fluctuations

The Experimental ridge water table in 2003 was more variable than the water level in the lawn area of the Experimental pool. This pattern continued in 2004 with the Drained ridge water table being the most variable of the ridge and lawn water tables (Table 4.4 section 2). The Experimental ridge water table fluctuations were also always greater than in the Control ridge.

4.4.2.3. Pool Water Table Fluctuations

The water table fluctuations in the pools of the Control and Experimental sites were similar in magnitude (Figure 4.15, Table 4.4 section 3) and were smaller than at the Drained site. In the Drained site pool the water did not persist above the surface, and its water table was more responsive to wetting and drying events than at the Experimental site. The water table response of the Drained pool to precipitations events was greater than that in the Control and Experimental pools, for the majority of the storms selected in both 2003 (71%, n=5) and 2004 (66%, n=6).

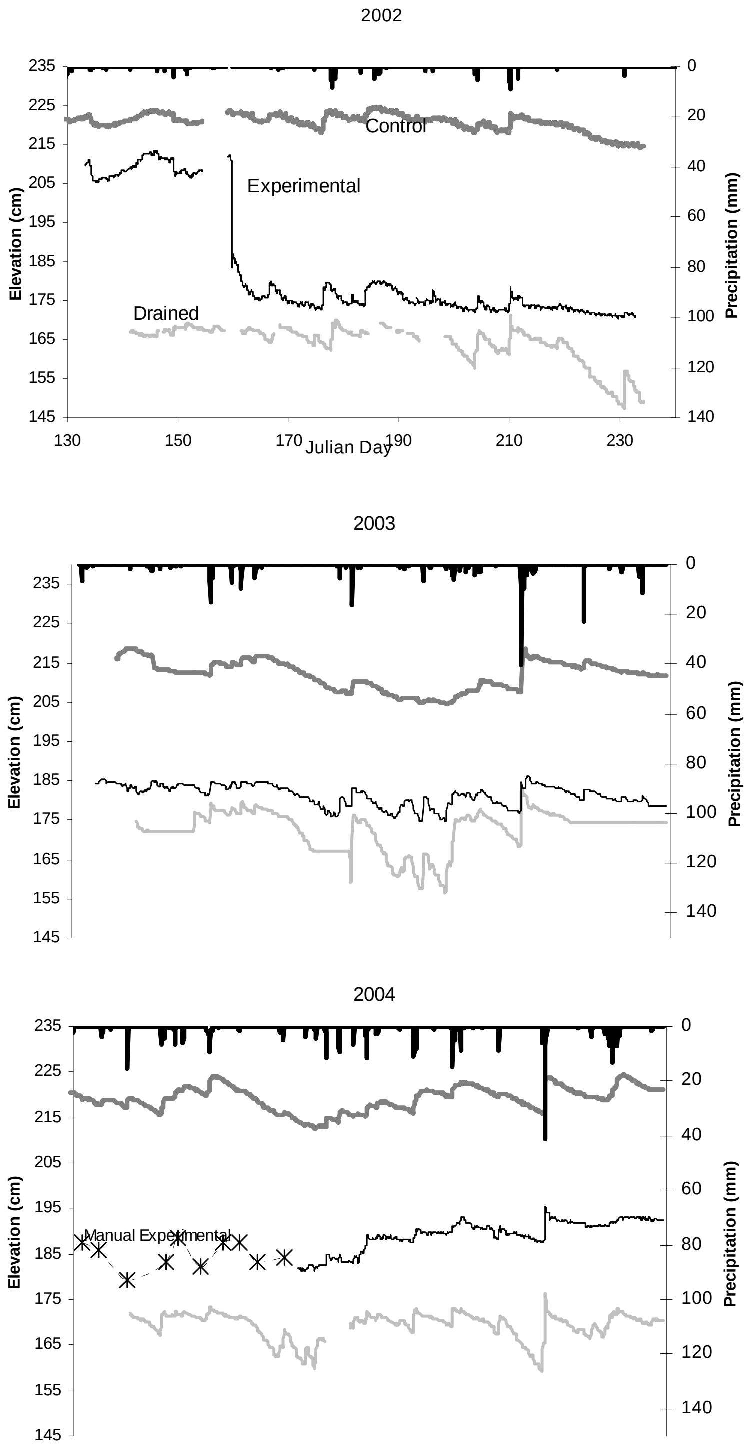


Figure 4.15 Bi-hourly total precipitation and average water table elevation above a common datum, in pools. The large and rapid decline in the Experimental pool in 2002 (top) was the drainage of the Experimental pool

2003	**^Julian Day**	216	156	183	162	160	197	181
	Precip. mm	48.8	29.7	23.9	20.3	7.4	7.4	6.4
1	C sur lawn	**7.0**	**1.4**	0.0	**1.7**	0.0	0.0	0.0
	D sur lawn	0.6	0.5	**0.7**	0.4	0.0	0.0	0.0
	E sur mat	0.0	0.0	0.4	0.0	**2.0**	**0.4**	**0.1**
2	E W.T. ridge	**21.8**	**12.3**	**15.6**	**8.1**	**5.1**	**5.5**	**5.7**
	E W.T. lawn	13.7	4.6	6.1	3.1	1.5	3.6	3.1
3	C pool	8.9	3.7	2.9	2.1	1.2	0.7	0.6
	D pool	**18.9**	**5.6**	**17.3**	**3.0**	1.4	**8.6**	0.0
	E pool	11.4	3.4	4.7	1.9	**1.8**	5.9	**4.6**

2004	**^Julian Day**	213	197	190	154	177	174	205	173	171
	Precip. mm	60.7	40.1	37.8	34.5	18.3	15.5	9.4	7.1	3.8
1	C sur lawn	**5.8**	**3.6**	**4.8**	**2.7**	**1.2**	0.7	0.5	**1.0**	**0.5**
	D sur lawn	1.4	0.5	0.3	0.3	0.0	**9.5**	**1.0**	0.7	0.2
	E sur mat	0.4	0.2	0.4	0.4	0.4	1.5	0.2	0.4	0.4
2	C W.T. lawn	4.3	1.4	5.0	2.9	1.1	0.4	0.4	1.1	0.4
	E W.T. ridge	17.2	**9.1**	13.9	6.3	11.0	10.0	3.9	6.4	3.7
	C W.T. ridge	13.7	7.6	9.9	6.1	7.9	7.4		3.8	2.8
	D W.T. ridge	**36.3**		**23.9**	**18.3**	**14.5**	**12.7**	**7.4**	7.4	4.1
	DZ1 W.T. lawn	18.0		6.9	3.8	5.3	6.6	5.3	**9.1**	**6.4**
3	C pool	8.0	3.1	4.8	4.1	2.6	2.0	1.1	0.6	0.4
	D pool	**18.0**	4.8	5.7	3.0	0.0	0.7	**3.9**	**6.4**	**3.9**
	E pool	8.5	2.1	2.8	0.7	2.1	3.5	2.8	1.4	1.4
	CCZ6 pool	11.9	**7.6**	7.6	5.6	3.8	2.8	1.8	1.3	1.3
	DDZ6 pool	12.2		**8.9**	**5.8**	**4.6**	**4.6**	2.0	3.3	2.5

Table 4.4 Surface elevation and water table elevation movements for 2003 and 2004. 1: Surface level recorders, 2: Water table recorders in topographic location, 3: Pool water table position (for Drained, the middle of the pool). Bold values represent the largest change within that category for a particular storm event. All values in cm except precipitation (mm).

4.4.2.4.Ratio of Change:Rain

By taking the change in the hydrograph (from pre-precipitation to peak) and dividing it by the precipitation input, a unit water table response can be calculated (Figure 4.16), thus a value of 1 would imply that the water table or surface elevation rose in a 1:1 ratio with the amount of precipitation that fell (recall some potentiometers were used to measure surface elevation changes, as opposed to water table changes). The greatest changes generally occurred in the ridges, with Drained (6.9) >Experimental (5.1) >Control (3.3) (Figure 4.16, 2004). Unit water table responses also trended Drained>Experimental>Control for pool locations for both years with 3.4, 1.7, 1.1, and 4.0, 3.4 and 1.3 for Drained, Experimental and Control for 2003 and 2004, respectively. While the lawn and mat surface elevations had much smaller unit surface level responses than the unit water table responses, it trended opposite of ridge and pool water tables where Control (0.9) > Drained (0.5) > Experimental (.4) in 2004. In 2003 surface changes trended Experimental (0.5) > Control (0.4) > Drained (.1).

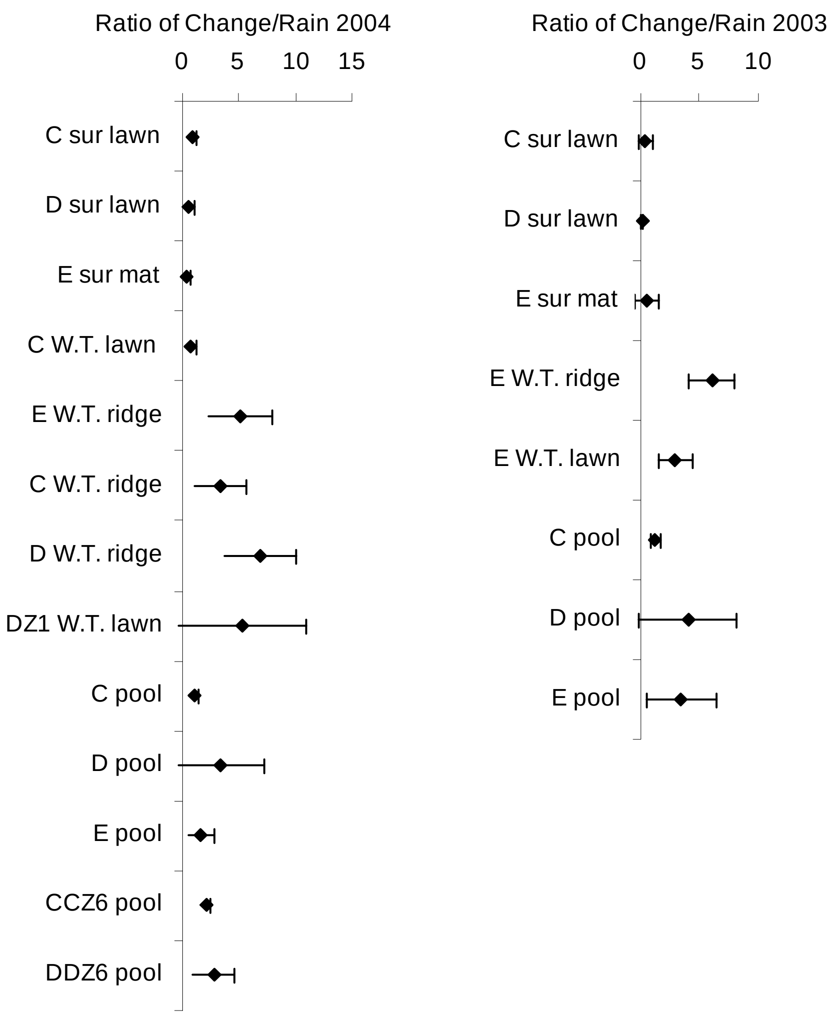


Figure 4.16 Average ratio of change of hydrograph (mm) to precipitation (mm) input for 2003 (right) and 2004 (left). Bars are +/- standard deviation.

4.4.3. Mooratmung

Changes in water table elevation did not necessarily correspond to changes in water table depth because of surface elevation changes. For example, at the Control lawn site, water table changes were closely matched by surface elevation changes (Figure 4.17a), so that the water table remained close (~ -1 cm) to the surface (Figure 4.17c). In contrast, Drained lawn (Figure 4.17a) and all ridge sites (Figure 4.17b) experienced much less surface elevation change, so their water tables were deeper with respect to their surface (Figure 4.17c and d).

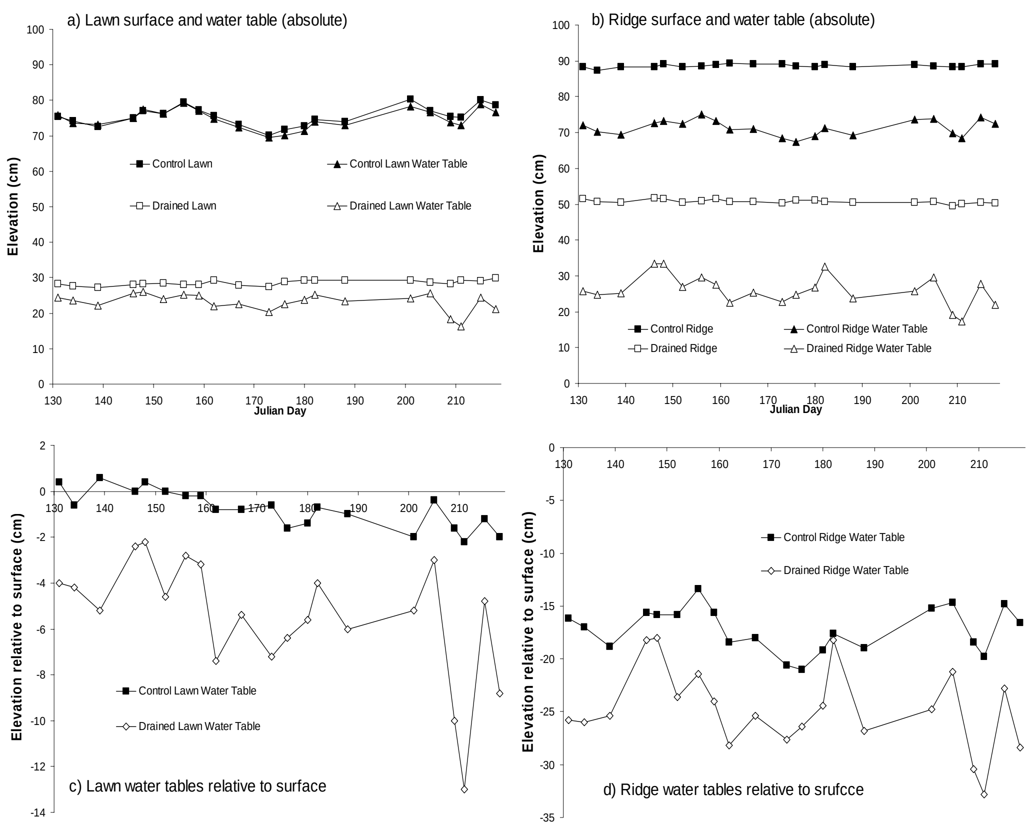


Figure 4.17 Lawn and Ridge (a and b) surface and water table elevations for the Control and Drained sites, 2004. Lawn and ridge (c and d) water table fluctuations, relative to the surface for the Drained and Control sites. (Note different vertical scales for c and d.)

5. Discussion

The study site is a small remnant patterned fen system, surrounded by a previously or currently drained and harvested peatland. Consequently, the study site cannot be considered truly undisturbed. However, water table profiles across the remnant (Findlay, 2004) indicated notable water table lowering 3 m from the bordering ditches, but no water table effect at or beyond 8 m. Thus the Control site was relatively undisturbed, compared to the recently drained (Experimental) and previously drained (Drained) fen pool systems. This provides insight into the seasonal hydrological responses of pool systems that have undergone a sequence of change that represents some aspects of a shift to drier conditions. The short-term response is characterized by differences between the Control and Experimental (2-years drained) pool systems, whereas longer-term changes are represented by the hydrological response of the Drained (10-years drained relative to this year of study) pool system. Thus in this fen the spatial location of the three pool systems is an analog for temporal change. To a certain degree, this is a surrogate for a warming climate that is expected to lower the water table (Roulet *et al.*, 1992). This will be discussed later. A discussion on error can be found in Appendix B.

5.1. Meterological

The meteorological conditions between field seasons were different. The 2002 and 2003 seasons had similar amounts of rainfall, well below (>100mm) the 30 year average. In 2004, however, it was much wetter than the 2002 and 2003 seasons, and was very close to the 30 year average. The 2004 season was also generally much warmer than the 2002 and 2003 seasons, with air temperature in all but June above the 30 year average. These differences (temperature and precipitation) can also provide insight into how these peatland systems respond under various weather conditions.

Evaporation losses of 2.9, 3.11 and 3.5 mm d^{-1} for 2002, 2003 and 2004, respectively, are in the upper range of values reported in other studies of local disturbed peatlands. For example, in a restored vacuum harvested peatland near Riviere-du-Loup, Quebec, Petrone *et al.* (2004) found average daily evaporation (mid-May to end of August) to be 2.7 and 3.5 mm d^{-1} in year 2000 and 2001, respectively. Near that location Van Seters and Price (2002) found average daily evaporation in a revegetated cutover bog and in an undisturbed bog to be 2.9 mm d^{-1}, from mid-May to mid-August 1998. For the current study, the site is a small remnant fen surrounded by relatively dry vacuum harvested or abandoned harvested peat fields, thus likely experienced an oasis effect (Findlay, 2004) which boosts the available energy for evaporation (Oke, 1987). However, the α values of 0.98, 0.97 and 0.93 do not imply a large advective effect. Given the rainfall, the net flux (P – E) over the study periods were 10, 7 and 72 mm for 2003 and 2004, respectively (see Figure 4.1 and Table 4.2).

However, Price and Maloney (1994) did find α to be 1.00 for a bog ridge, stating that the ridge was drier in this location. The Experimental site, because of the draw down, would have a much lower water table than found typically in other fen systems. Almost all of the lysimeters used were located within the Experimental site, and subsequently could have predicted lower alpha values as a result.

5.2. The Hydrology of Water Table Draw Down

The water table response to rain and evaporation exhibit features unique to each site. These can be explained in terms of their respective hydraulic parameters (n, ρ_d, S_y, K, θ_{VMC}), which themselves have undergone a transition due to the disturbance (i.e., at the Experimental and Drained pool systems). Before assessing the hydrological behaviour of individual sites, it is necessary to discuss the processes by which these parameters have undergone change. The conceptual diagram (Figure 5.1) shows how these various parameters and processes are interrelated and acts as an outline for the first part of the Discussion section. Figure 5.1 will be referenced in the text with the corresponding 'box' number succeeding the 5.1 (e.g., Figure 5.1 4.1 would be referencing the Porosity box).

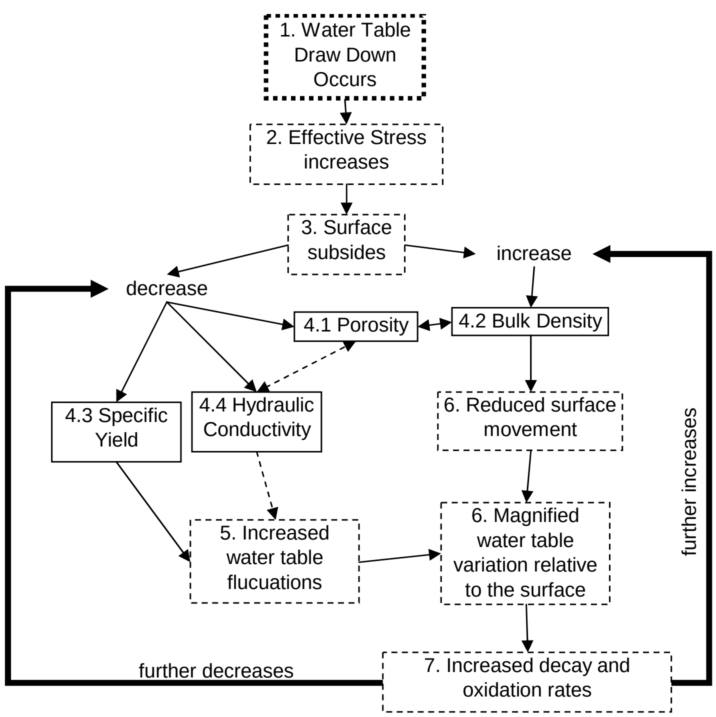


Figure 5.1 Conceptual diagram of water table draw down and subsequent volume change. Solid lines indicate direct relationships, whereas dashed lines are inferred or indirect associations. Solid boxes are hydrological parameters, whereas dashed are processes or actions.

5.2.1. Long Term Water Table Change

Seasonal fluctuations and longer-term changes in the peat-matrix volume caused by changes in water pressure (i.e., water table) and decomposition can significantly affect the hydraulic parameters. Subsidence caused by 1-dimensional consolidation (compression) of the peat due to a reduction in pore-water pressure (Hobbs, 1986) or densification by decomposition (Boelter, 1969), can decrease the hydraulic conductivity by several orders of magnitude (Price, 2003), and increase the water retention capacity of the peat soil (Chow *et al.*, 1992; Kennedy and Price, 2004). Changes in water pressure do occur both seasonally due to wetting and drying events, and have occurred over the longer term with drainage at the Experimental and Drained sites. Changes in peat volume caused by decomposition (oxidation) are generally a longer-term phenomenon.

In the Drained and Experimental sites, the water table was lowered by anthropogenic drainage, pore water pressure decreased, resulting in an increase in effective stress (Equation 1.3, Figure 5.1 1 and 2) (Price, 2003). The increase in effective stress resulted in compression (Figure 5.1 3). This was observed by the decrease in surface elevation relative to the piezometers in the EZ transect (Figure 4.3 and Figure 4.4). However, the decrease in surface elevation was not constant among topographic features. Subsidence increased, not surprisingly, from ridge to mat. The denser ridge peat, (necessary for patterned peatland formation), was less susceptible to consolidation than the more buoyant, less dense, mat peat.

5.2.2. Hydrological Parameters

Larger pores in the peat structure are the first to collapse as effective stress increases, as they are the least supported. Equation 1.4 relates porosity and bulk density and because bulk density trended Control<Experimental<Drained (Figure 4.5 a), porosity must trend Control>Experimental>Drained (Figure 5.1 4.1 and 4.2). The further decrease in bulk density at the Drained site is likely due to oxidation (peat volume change process) further decaying and breaking down the peat (Figure 5.1 7). Specific yield was notably lower in the upper layer (Figure 4.5 b) for the same reasons discussed above (peat decomposition and decrease in pore size).

The squishometer behaviour was distinctly different between sites. At the Control site the upper layers did not experience much change in thickness but their position (elevation) changed due to swelling and shrinking of the lower layer on which they rest. This is contrary to the behaviour expected on the basis of consolidation theory (Terzaghi, 1943) in which the upper (more compressible) layer should experience the most strain. Moreover, the upper layers are the first layers to dissipate excess pore-water upon loading (i.e., they are closer to the water table).

Strack *et al.* (2004) observed a build-up of methane gas within the peat in the Control and Drained lawns at this site. Methane (CH_4) concentrations in the Control site at 40 and 65 cm depths were 5 – 6 mg l^{-1} more than the Drained site. Also, the Control site generally increased in CH_4 concentration with depth to 90 cm, before decreasing to 100 cm, whereas the Drained site decreased with depth. Thus, it seems likely that the upper peat layers were buoyant, responding in unison to changes in gas pressure, both of which would cause the observed behaviour. The steady decline in soil moisture (Figure 4.6), despite an increase in water table, most notably at the Control site, can be explained by an increasing presence of biogenic gasses in the peat (Kellner *et al.*, in press; Price, 2003; Strack *et al.*, 2004).

Hydraulic conductivity was also greatly affected by volume change (Figure 4.8 shows the differences in K between Control, Experimental, and Drained, which are surrogates for different volume change amounts). Larger pores are responsible for transmitting most flow (Baird, 1997), thus consolidation of peat, which preferentially collapses larger pores (Chow et al., 1992), will affect hydraulic conductivity (*K*) (Figure 5.1 4.4). Peat at the Control site had the highest *K*, which decreased in the Experimental site, and further in the Drained site (Figure 4.8 d-f) as the peat became progressively more compressed and decayed (oxidized). Interestingly, at the Drained site, the expected $K_{ridge}<K_{lawn}<K_{mat}$ trend found at the Control site, is replaced with $K_{ridge}\approx K_{lawn}\approx K_{mat}$. This implies that 10 years post drainage, compression and oxidation results in *K* homogeneity between mat, lawn, and ridge topography (Figure 4.8 c), the initially more compressible mat and lawn peat having undergone the greatest change in K. The Experimental pool also seems to be changing in this direction as at the upper 50 cm layer, $K_{ridge}\approx K_{lawn}\approx K_{mat}$ and at the 75 cm layer $K_{lawn}\approx K_{mat}$ (Figure 4.8 b).

Similar trends are also observed in the other transects (CCZ, CEZ, and DDZ), supporting the above hypothesis. In the CCZ transect, on the Control side in the mat and lawn locations (left side of Figure 4.9) *K* decreased with depth and trended $K_{ridge}<K_{lawn}<K_{mat}$. However, on the Experimental side of the CEZ transect (right side Figure 4.9) *K* trended $K_{ridge}>K_{lawn}>K_{mat}$ (the complete opposite), implying that the more compressible mat and lawn peat underwent greater change. The spatial homogeneity between mat, lawn and ridge found in the DZ transect (Figure 4.8 c) is also observed in the DDZ transect (left side Figure 4.11).

5.2.3. Seasonal Water Table and Surface Level Fluctuations

Specific yield controls water table fluctuations as it relates a change in head to a change in storage. Therefore, a lower specific yield will result in increased water table fluctuations (Figure 5.1 4.3 and 5). On average, the Drained site, for a given topographic feature (ridge or pool), always had the largest water table fluctuations (Figure 4.16), because of the lower specific yield found there (Figure 4.5). Within pools, on average, water table variations trended Ridge>Lawn or Mat, likely because of the denser peat with tightly packed pores (Kellner and Halldin, 2002) resulting in a lower specific yield.

Surface level fluctuations (swelling and subsiding) trended Control>Experimental>Drained (Figure 4.16), which follows from the bulk density and porosity discussion above. Because the Experimental and Drained peat have been compressed, they have lower porosity and are subsequently less susceptible to changes in water table position (Figure 4.17 a) and have reduced surface movement (Figure 5.1 6). The lower strain (Figure 4.7) found in the Control site in the upper layers also supports the surface movements.

This reduction in surface movement in the Drained site reduces the 'mooratmung' (see section 4.4.3) effect found in the Control site which maintains a water table at, or near, the surface in the lawn (Figure 4.17 c) unlike the increased water table fluctuations relative to the surface in the Drained site (Figure 5.1 6). Price (2003) states that shrinkage and swelling that occurs seasonally (or even daily) could be an important self preservation mechanism to maintain higher moisture contents.

5.2.4. The Positive Feedback Loop

Biogeochemical processes that rely on oxidation-reduction reactions are strongly influenced by water table variability (Belyea and Malmer, 2004; Strack *et al.*, 2004). Therefore water table variations relative to the surface are more important than variations in absolute elevation. Belyea and Malmer (2004) state that areas of water table variation have the greatest peat decay rates. The Drained site had large water table fluctuations because of the lower specific yield and denser, less buoyant peat, resulting in increased peat oxidation, creating a positive feedback loop (Figure 5.1 7). However, this loop does not appear to continue indefinitely. A model by Gilmer *et al.* (1998) predicted that oxidation rates decrease after 10 to 15 years post-drainage, as a result of a decrease in labile carbon with time (this study was conducted in cutover peatlands, and thus no new peat was being created). This helps to explain the K homogeneity at the Drained site. If oxidation rates continued at similar rates (i.e., the carbon supply was limitless), then $K_{mat}>K_{lawn}>K_{ridge}$ (as is present in the Control site) would continue throughout time and not become $K_{ridge}≈K_{lawn}≈K_{mat}$. Also, if oxidation rates continued, then $K_{Drained}$ would be <<< $K_{Experimental}$ and $K_{Control}$ but instead is only 1 and 2 orders of magnitude, at similar depths and topographic locations, respectively (Figure 4.8 d, e and f).

Few studies have attempted to quantify long term oxidation rates (Waddington and McNeill, 2002) but if it is assumed that the Drained site labile carbon is diminishing, then the differences in hydraulic parameters between Control and Drained can be utilized for modeling purposes. The Experimental site, however, has only undergone compression, and possibly some oxidation. Fortunately, Schothorst (1977) estimated that 55% of long term subsidence in Dutch polders was caused by oxidation, and 35% by compression (the remainder being shrinkage). Using this information, the percentage of volume change by process (oxidation, compression, and shrinkage) could be compared to the Drained (primarily oxidation) and Experimental (primarily compression) in relation to Control (no change). Therefore, it is not surprising that $K_{Experimental}$ is ~1 order of magnitude higher than Drained and lower than Control (Figure 4.8 d, e and f), because at present (2004) only approximately 45%, (35% compression + 10% shrinkage (Schothorst, 1977)) of the potential volume change has occurred to the Experimental site, whereas the Drained site appears to have reached ~100% of its potential volume change (if the supply of labile carbon is diminished). (i.e., If it is assumed that the 2 order of magnitude decrease between Control and Drained represents 100% of the volume change, then the Experimental pool should have experienced a ~50% (45% compression and shrinkage, +5% of the oxidation for the 2003 season (55% oxidation divided by ~10 years ≈ 5% per year, assuming a linear decrease)) or 1 order of magnitude decrease in *K*, which was observed.)

5.2.5. As a surrogate for climate change?

Water tables are expected to decline under climate warning scenarios. The anthropogenic water table draw down of the Experimental site, thus, can replicate some important aspects of climate change. The hydraulic differences between the Control and Drained sites represent the succession of these systems as may occur with a shift to a drier climate. So while the volume change that occurred at the Experimental site was primarily compression, the Drained site was able to experience oxidation and compression so that different volume change processes on varying time scales (Experimental versus Drained) could be observed. Regardless of how the volume change occurs, the direction of change to the hydrological parameters will still be the same (Figure 5.1) (i.e., increased bulk density and decreased specific yield and hydraulic conductivity) which would affect the hydrology (water table position, fluctuation and lateral water fluxes) similarly. Therefore, within the confines of this study, some important aspects of climate change were replicated.

5.3. Local Scale Hydrology of Patterned Peatlands

Unfortunately, the representativeness of the remnant fen for larger scale patterned peatlands is lacking, as it is hydrologically disconnected from the other wetland systems in the area (i.e., surrounded by vacuum harvested fields). Despite this, and the climate change overtone of this thesis, considerable insight can be gained about the local scale hydrological processes in patterned peatlands, of which extensive literature is lacking.

5.3.1. Inter-pool Water Flow

Water exchanges between the Control, Experimental and Drained sites (through the ridges) is small, which is why pools in sloping patterned peatlands can exist at all (e.g., Foster and King, 1984). Darcy's Law can be used to calculate discharge rates through the ridges as

$$q = \frac{Q}{A} = K \frac{dh}{dl} \,, \qquad \textbf{Equation 5.1}$$

where q, is specific discharge, Q is discharge and $dh\ dl^{-1}$ is the hydraulic gradient (change in hydraulic head over length), and A, is the cross sectional area of flow. By using average K_{ridge} values (Figure 4.8) and water table heights (Figure 4.14) flow rates between Control and Experimental and Experimental and Drained can be made (Table 5.1). Patterned peatlands typically have very small gradients (Price and Maloney, 1994; Quinton and Roulet, 1998) and thus small flow rates. Quinton and Roulet (1998) found that the specific groundwater flux (which is comparable to specific discharge, above) during the isolated phase (see section 1.2.2.2) was .188 cm day^{-1}, which is a lot higher than the Control to Experimental flow rate (3.7 x 10^{-7} cm day^{-1}), and Experimental to Drained (1.1 x 10^{-6}) cm day^{-1}). Flow between the Experimental and Drained pools was very small and, when compared to evaporative fluxes are negligible.

	Elevation (cm)	Average K (cm s^{-1})	Length (cm)	Area (cm^2)	q (cm day^{-1})
Control to	225	1.E-04	2100	440000	3.7E-07
Experimental	185			(44 m x 1.1 m)	
Experimental to	185	1.E-05	1000	16000	1.1E-06
Drained	165			(20 m x .8 m)	

Table 5.1 Average discharge rates between pools based on average water table elevations and K values

5.3.2. Intra-pool Water Flow

Perhaps of more interest hydrologically are the flow rates and directions between ridge and pool during dry and wet periods. The Control and Experimental sites had similar amounts of flow between ridge and lawn at about 10^{-6} cm day^{-1} (in either the pool or ridge direction). This supports that vertical flow processes are dominant (Price, 1996) as this represents negligible volumes when compared to evaporative fluxes. The Control ridge acted primarily as a discharge location as the gradients indicated pool to ridge flow (Figure 4.14 and Table 5.2) which also helps to explain the more stable water table found there (Table 4.4). However, during wet periods the Experimental pool reversed flow direction and the ridge discharged into the pool. The Drained pool had a negligible quantity of flow (10^{-8} cm day^{-1}), likely as a result of the much lower K and relatively flat water table.

		h_{ridge} (cm)	h_{pool} (cm)	dl (cm)	K (cm s^{-1})	Area (cm^2)	q (cm day^{-1})
Control							
2002	**Wet**	220.8	220.6	540	6.1E-03	1.8E+06	1.1E-07
	Dry	201.9	203.1	540	6.1E-03	1.8E+06	-6.5E-07
2003	**Wet**	224.5	228.7	540	6.1E-03	1.8E+06	-2.3E-06
	Dry	207.9	211.5	540	6.1E-03	1.8E+06	-1.9E-06
2004	**Wet**	224.3	228.1	540	6.1E-03	1.8E+06	-2.0E-06
	Dry	218.5	222.1	540	6.1E-03	1.8E+06	-1.9E-06
Experimental							
2002	**Wet**	191.8	190.3	610	4.3E-03	4.4E+05	2.1E-06
	Dry	167.6	176.3	610	4.3E-03	4.4E+05	-1.2E-05
2003	**Wet**	192.9	187.7	610	4.3E-03	4.4E+05	7.2E-06
	Dry	176.0	184.3	610	4.3E-03	4.4E+05	-1.2E-05
2004	**Wet**	187.9	184.3	610	4.3E-03	4.4E+05	5.0E-06
	Dry	175.5	183.1	610	4.3E-03	4.4E+05	-1.1E-05
Drained							
2002	**Wet**	180.9	175.0	700	1.1E-05	6.4E+05	1.3E-08
	Dry	154.3	144.9	700	1.1E-05	6.4E+05	2.1E-08
2003	**Wet**	184.5	175.1	700	1.1E-05	6.4E+05	2.1E-08
	Dry	166.3	161.5	700	1.1E-05	6.4E+05	1.1E-08
2004	**Wet**	177.7	173.9	700	1.1E-05	6.4E+05	8.3E-09
	Dry	167.3	165.9	700	1.1E-05	6.4E+05	3.1E-09

Table 5.2 Summary of specific discharge (q) for the average of K_{50cm} lawn and K_{75cm} lawn (Figure 4.8) and water table heights for wet and dry periods for 2002 to 2004 (based on Figure 4.13). dl is the linear distance between wells. Positive specific discharges indicate ridge to pool flow, whereas negative specific discharges represent pool to ridge flow. Areas were determined by multiplying the approximate perimeter distance by average peat depth. Perimeters were estimated to be 120, 40 and 80 m in C, E, and D, respectively, with peat depths of 1.4, 1.1, and .8 m, in C, E, and D, respectively.

6. Conclusion

In this experiment artificially induced changes (drainage) to parts of a patterned fen system, caused changes in the hydraulic parameters that govern water relations within and between pool systems. Drainage of the Experimental pool site caused abrupt subsidence of the peat surface. The surface lowering was associated with peat-volume change due to compression. Based on a comparison with the Control pool site, the bulk density increased, while specific yield and hydraulic conductivity decreased. A similar pool system that had been drained, 10 years previous to this study, presumably underwent a similar change following its drainage by the peat harvesting company. However, since that time additional changes occurred because of peat oxidation, and thus bulk density, specific yield and hydraulic conductivity changed even more.

As a direct result of drainage, loss of the normal buoyancy of the peat, notably in the mat and lawn areas, altered the primary mechanism of water storage from peat volume change, to soil drainage (i.e., water table fluctuation). The greatest change occurred in the most compressible parts of the system (mat and lawn), whose hydraulic properties (hydraulic conductivity) became less distinct from one another.

The implications of these changes are that lateral water exchanges between pool systems was reduced (lower K), and the deeper and more variable water table depth during summer have the potential to alter the biogeochemical function. The relative rigidity of the peat increased water table fluctuations, enhancing peat oxidation and decay, further modifying the hydraulic parameters.

The exacerbated oxidation and decay reduces the storage capacity of the peat, and thus, during spring melt and times of heavy rain (i.e., the connected phase) greater runoff ratios would be present as less storage would be possible (with dry antecedent conditions).

This experiment replicates some of the changes that a patterned fen system may experience due to the anticipated climate change. Under a climate-driven drying scenario, peat compression will occur slowly, and changes to peat structure are likely to be more attributable to decay. Nevertheless, the effect on hydraulic parameters should be similar – higher bulk density, lower specific yield and lower hydraulic conductivity. A change to these parameter conditions exacerbates the water table variability, which provides a positive feedback loop that could intensify the degradation of the peat and further change the governing parameters.

Appendix A

Pie - Fen	Radius (m)	Length (m)	Pie - Fen	Radius (m)	Length (m)
CZ1-25	0.0103	0.0	EDZ1-50	0.0103	0.2
CZ1-50	0.0103	0.2	EDZ1-75	0.0127	0.2
CZ1-75	0.0103	0.2	EDZ1-100	0.0127	0.2
CZ1-100	0.0127	0.2	EDZ3-50	0.0103	0.2
CZ1-125	0.0175	0.3	EDZ3-75	0.0127	0.2
CZ2-25	0.0127	0.0	EDZ3-100	0.0127	0.2
CZ2-50	0.0127	0.2	EDZ4-50	0.0127	0.2
CZ2-75	0.0127	0.2	EDZ4-75	0.0127	0.2
CZ2-100	0.0127	0.2	EDZ4-100	0.0127	0.2
CZ2-125	0.0127	0.3	EDZ6-50	0.0127	0.2
CZ3-25	0.0103	0.0	EDZ6-75	0.0103	0.2
CZ3-50	0.0103	0.2	EDZ6-100	0.0127	0.2
CZ3-75	0.0103	0.2	EDZ8-50	0.0103	0.2
CZ3-100	0.0127	0.2	EDZ8-75	0.0127	0.2
CZ3-125	0.0175	0.3	EDZ8-100	0.0127	0.2
EZ1-25	0.0103	0.04	DDZ1-50	0.0127	0.2
EZ1-50	0.0127	0.2	DDZ1-75	0.0127	0.2
EZ1-75	0.0127	0.2	DDZ1-100	0.0127	0.2
EZ1-100	0.0175	0.2	DDZ2-50	0.0127	0.2
EZ2-25	0.0127	0.04	DDZ2-75	0.0127	0.2
EZ2-50	0.0127	0.2	DDZ2-100	0.0127	0.2
EZ2-75	0.0127	0.2	DDZ3-50	0.0127	0.2
EZ2-100	0.0127	0.3	DDZ3-75	0.0127	0.2
EZ3-25	0.0103	0.04	DDZ3-100	0.0127	0.2
EZ3-50	0.0103	0.2	DDZ4-50	0.0127	0.2
EZ3-75	0.0103	0.2	DDZ4-75	0.0127	0.2
EZ3-100	0.0127	0.2	DDZ4-100	0.0127	0.2
EZ3-125	0.0175	0.3	DDZ5-50	0.0127	0.2
DZ1-25	0.0103	0.04	DDZ5-75	0.0127	0.2
DZ1-50	0.0175	0.2	DDZ5-100	0.0127	0.2
DZ1-75	0.0175	0.3	DDZ6-50	0.0127	0.2
DZ2-25	0.0103	0.04	DDZ6-75	0.0127	0.2
DZ2-50	0.0175	0.2	DDZ6-100	0.0127	0.2
DZ2-75	0.0175	0.3	CCZ1-50	0.0127	0.2
DZ3-25	0.0103	0.04	CCZ1-75	0.0127	0.2
DZ3-50	0.0103	0.2	CCZ1-100	0.0127	0.2
DZ3-75	0.0127	0.3	CCZ2-50	0.0127	0.2
CEZ1-50	0.0103	0.2	CCZ2-75	0.0127	0.2
CEZ1-75	0.0103	0.2	CCZ2-100	0.0127	0.2
CEZ1-100	0.0127	0.2	CCZ3-50	0.0127	0.2
CEZ2-50	0.0103	0.2	CCZ3-75	0.0127	0.2
CEZ2-75	0.0127	0.2	CCZ3-100	0.0127	0.2
CEZ2-100	0.0127	0.2	CCZ4-50	0.0127	0.2
CEZ3-50	0.0103	0.2	CCZ4-75	0.0127	0.2
CEZ3-75	0.0127	0.2	CCZ4-100	0.0127	0.2
CEZ3-100	0.0127	0.2	CCZ5-50	0.0127	0.2
CEZ4-50	0.0103	0.2	CCZ5-75	0.0127	0.2
CEZ4-75	0.0103	0.2	CCZ5-100	0.0127	0.2
CEZ4-100	0.0127	0.2	CCZ6-50	0.0127	0.2
CEZ5-50	0.0103	0.2	CCZ6-75	0.0127	0.2
CEZ5-75	0.0127	0.2	CCZ6-100	0.0127	0.2
CEZ5-100	0.0127	0.2			

Appendix B

Sources and estimations of error

Lysimeters proved to the most problematic and error prone. The scale was a fish scale which weighed in 100 gram increments and was subject to swaying. As the majority of the lysimeters were between 5 and 10 kg ± 100 g yield a measurement error of 1 – 2%. The size of the lysimeters was, on average, about 400 cm^2 and thus an evaporate loss rate of ~3 mm day^{-1} would be 120 grams, i.e., within the measurement accuracy of the scale. The precision of the lysimeters is questionable, as matching internal and external moisture contents is difficult. It is likely that the lysimeter measurements were ±25%, though the author offers no quantitative proof. Stewart and Rouse (1976) note that the Priestley and Taylor (1972) method is accurate, under ideal conditions, to ±15%.

All water table measurements made in wells or piezometers were made with a blow stick and were within ± 2 mm. The pipes were surveyed each year to provide reliable pipe top elevations using an electronic theodolite.

The Wardeener corer did a relatively good job with denser soils, but is problematic for peat, especially in the upper layers. Care was taken by pre-cutting guidance pathways for the corer to go through, until it reached denser peat. Measurements of bulk density were made with an electronic scale with a precision of ± .1g, whereas the volume was calculated using the brass soil ring. The difficult part was making sure that the peat sample filled the brass ring, especially with the upper layers. Values were likely ± 10%. Specific yield, however, is much more difficult because of swelling. As the peat is allowed to soak, it can swell to volumes larger than the brass ring, and thus can yield more water upon drainage (i.e., specific yield values > 1.0). Errors in specific yield could be as high as 25%, with small sample volumes, though the author offers no quantitative assessment of this.

Care was taken with the measurement of the squishometers. As the value on the squishometer was read against the site wire, changes in 'researcher' elevation would affect the angle of the sight wire against the squishometer. Thus all measurements were taken from a fixed point, and for >%90 of the measurements, taken by the author. Readings were ± 1 mm and as some sensors moved 5+ cm and others <0.5 cm seasonally, errors could range from 2 to 20%, but were likely closer to 5%. This precludes using minute daily changes for discussion, but longer term (drying), or significant daily changes (i.e., major rain storms).

Hydraulic conductivity tests were preformed with a blow stick and stop watch. As mentioned previously, the blow stick is ±2 mm and when an initial head difference is >10 cm, error becomes very small (<2%). The time of the blow stick measurement was recorded to the closest quarter minute unless the piezometer was known to recovery within 10 minutes, then the nearest second was used; regardless, the error associated with measurement time was <1%. The accuracy of the test procedures, however, is more questionable. Hvorslev (1951) discussed many potential sources of error in the determination of groundwater levels and pressures. One such error is erosion and development of the soil surrounding the piezometer intake. When a piezometer is inserted into peat soil, it is typical to first auger a hole, to prevent compression and destruction of the peat when the piezometer is installed. During this process fine particles of soil can be trapped into the peat matrix surrounding the piezometer, reducing the ability of the water to flow into the pipe, increasing the lag time (or the rate of head recovery) (Hvorslev, 1951). Inducing strong inflows into the pipe (called development) to remove this material can help to achieve a 'true' value of K. However, too frequent, or too large inflows can erode the material surrounding the pipe causing preferential pathways to develop (Hvorslev, 1951). All piezometers were developed prior to the first test of a season, and after installation. Baird *et al.* (2004b) assessed the differences between bail and slug tests and found that bail tests provided quicker, and more replicable estimations of hydraulic conductivity, and thus bail tests were used. They hypothesized that any peat particles in the piezometer might be forced out of the pipe and differentially block pore spaces in subsequent tests, slowing head recovery during a slug test. Baird and Gaffney (1994) assessed the calculation methods of K for compressible soils, such as peat. They determined that when head recovers were non-linear (or exhibited compressible soil theory), estimations of K, based of Hvorslev (1951) could yield differences in K values by 2 orders of magnitude. Where non-linear trends were observed for this thesis, the basic lag time parameter associated with the test (Freeze and Cherry (1979) page 340) was determined by taking the slope of the shallower, tailing part of the curve, rather than the initial, steeper part (Hvorslev, 1951). It was assumed, that as long as test procedures were consistent, that any systematic error in measurement would be constant for all tests, and as the trends and relations to other piezometers were more important than the actual values, confidence can be placed in the results.

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