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Soil water flow dynamics in a managed cutover peat field, Quebec: Field and laboratory investigations

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Abstract. In this paper concerned with soil water dynamics in a managed cutover peat field, the microscale hydrological processes and parameters governing water flow and storage through variably saturated peat are investigated. An open water ditch-reservoir enhanced wetting of adjacent cutover peat, maintaining the water table depth above 43 cm during the summer, surface soil moisture above 45%, and water tension in the surface layer above −45 mbar. Desaturation of pores was noted in the −2 and −10 cm depths, but at −30 and −50 cm a decrease in moisture content of several percent was associated with compression of the peat as the water table dropped. Air entry occurred only at pressures below −15 mbar. Seasonal subsidence resulted in cumulative vertical displacement in excess of 10 cm during the study period. Typical settlements in the peat ranged between 11 and 23% of the lowering of the water table. Considerable hysteresis was observed, and vertical displacement was 5 times greater in response to water loss, compared to rewetting. The specific storage (S_s) in the 180 cm thick deposit averaged 9.4×10^{-4} cm^{-1} during drying periods but averaged only 2.6×10^{-4} cm^{-1} on rewetting. S_s was more important than specific yield (S_y) in the overall aquifer storativity. Transient hydraulic properties resulted from the shifting soil structure. The increase in peat bulk density caused by drying increased the water retention capacity and decreased hydraulic conductivity. Mean saturated hydraulic conductivity was 15 cm d^{-1} and decreased 2 orders of magnitude as the degree of saturation dropped from 1 to 0.4. The horizontal/vertical anisotropy ratio was 4. The changing surface elevation in response to seasonal subsidence had a profound influence on the nature of the storage changes and hydraulic parameters of the peat soil.

1. Introduction

Exploitation of peatlands for horticultural peat and peat fiber is an important industry in Canada [*Keys*, 1992]. Unfortunately, harvesting operations alter the hydrological conditions necessary for reestablishment of *Sphagnum* mosses, the primary peat forming vegetation, on abandoned cutover peat fields [*Price et al*., 1998]. In an intact bog the high water-storage capacity of the surface layer (acrotelm), and its ability to shrink and swell, gives it a regulatory function which minimizes water table fluctuations and maintains a water table close to the surface [*Ingram*, 1983]. Drainage and extraction, however, irreversibly transform the structure of peat, exposing the older, more decomposed layer (catotelm) to the surface and consequently changing the manner in which water storage occurs [*Price*, 1997]. The denser soil and smaller pore sizes characteristic of cutover peat cause exaggerated variability in water table depth, lower saturated moisture content, and greater soil matric suction [*Price*, 1996]. The low permeability and high water retention capacity of cutover peat is magnified by shrinkage and compression of the medium at desorption [*Heiskanen*, 1995]. This creates a hostile environment for recolonizing *Sphagnum* mosses, which are unable to generate the critical capillary suction to draw water from the soil in all but the wettest conditions.

For successful *Sphagnum* regeneration, *Schouwenaars* [1988] suggests that the water table should be maintained within 40 cm of the cutover peat surface during the summer water deficit season. Drying out of the surface is, however, only partly controlled by the depth to the water table. When the rate of evaporation exceeds the transport of capillary water to the surface, the top layer of peat dries out; a water table response does not necessarily occur [*Price*, 1997]. Thus knowledge of the soil-water-atmosphere relations during the summer season is more relevant to the viability of *Sphagnum* regeneration than simply the water table position.

Because of its high water content, peat is highly compressible [*Hobbs*, 1986]. Forced loading with odometric cells [*Lefebvre et al*., 1984] demonstrate that consolidation of peat is distinct from mineral soils, both in magnitude and character. Volume change in peat can be 10 times greater than in swelling clay soils [*Hobbs*, 1986], which profoundly changes the values of standard hydraulic parameters and relationships (i.e., porosity, storativity, hydraulic conductivity, pressure-moisture relationships, and the degree and direction of anisotropy).

Practical methods used in peatland restoration have been met with some success [*Price et al*., 1998; *Quinty and Rochefort*, 1996]. One strategy used to improve soil moisture conditions at the cutover peat surface is the creation of open water ditch-reservoirs (i.e., blocked ditches cut perpendicular to the regional flow direction) [*LaRose et al*., 1997]. Open water increases the mesoscale water storage capacity (i.e., "bulk" specific yield) by lateral seepage, limiting the degree of water table fluctuations and improving moisture conditions at the surface [*LaRose et al*., 1997]. Although open water ditch-

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reservoirs have a significant effect on the local-scale storage capacity within cutover peat fields, the microscale hydraulic processes generating these changes are not well understood.

From a management perspective it is necessary to predict the subsurface flow regime under various rewetting strategies, since this controls the efficacy of drainage and water availability for plants. The ability to reasonably predict the transient response of a peat-ditch system to evaporative demands is necessary to determine critical hydrological thresholds for living *Sphagnum* diaspores. This research was designed to better understand the microscale and mesoscale hydrological processes associated with mined peatlands and their restoration. The objectives are to (1) quantify the efficacy of an open water ditch-reservoir recharge system to replenish moisture lost from an evaporating cutover peat surface, (2) document the nature and magnitude of water storage changes above and below the water table, and (3) quantify the hydraulic parameters needed to model the hydrological behavior of the system.

2. Mechanisms of Water Storage Changes in Peat Soils

Subsidence of peat soils occurs mainly through decreasing volume by shrinkage and oxidation above the water table and by compression below [*Schothorst*, 1977]. When the hydraulic head within a saturated peat formation decreases, the fibrous peat matrix compresses because the weight of the overlying material is transferred from the liquid to the peat fibers (i.e., increase in effective stress), concomitantly increasing bulk density and expelling water from storage [*Fetter*, 1994]. The process of consolidation is associated with the compression of water-saturated peat, where volume loss in the soil is equal to the volume of water expelled from the pores but where saturation is sustained [*McLay et al*., 1992]. Upon further drying, air enters pores; capillary suction and the gradual desiccation of peat above the water table then cause shrinkage and further settlement of the peat surface [*Hobbs*, 1986]. However, volume decreases in the shrinkage phase do not necessarily equal moisture losses [*Bronswijk*, 1988]. If loss of water results in significant peat shrinkage, then loss of pore volume occurs instead of air entry into the sediment [*Nuttle et al*., 1990]. It is therefore incorrect to assume that water loss from cutover peat requires an equal volume of air to enter the pores.

The significance of storage changes caused by peat compressibility has typically been ignored in studies involving peatland hydrology. The volume of water released from storage by compression of the peat matrix is characterized by a parameter called specific storage S_s, a property normally associated with confined aquifers [*Freeze and Cherry*, 1979]. For confined units, aquifer storativity S (defined as the volume of water expelled from storage per unit surface area per unit change in head) is the integral of S_s throughout the aquifer of thickness b [*Fetter*, 1994].

In unconfined aquifers, where pore water drainage results in air entry, the release of water from storage is typically characterized by the specific yield S_y, which relates a change in water storage (Δs) to a change in hydraulic head (Δh). Since S_y is normally so much larger than S_s in unconfined units, S_s is often ignored in the overall aquifer storativity, where $S = S_y + bS_s$; and thus the coefficient of storage approximates the specific yield [*Ward and Robinson*, 1990]. In peat, however, this may not be the case because of its high compressibility. In cutover peat, with its low S_y and high water retention, changes in storage due to desaturation of the pores are small relative to the change in head. *Price and Schlotzhauer* [1999] found S_s in cutover peat was 67 to 170% larger than S_y and that changes in storage were evaluated correctly only when S_s and S_y were used together to characterize aquifer storativity. Over the longer term, *Schothorst* [1977] estimated that 65% of long-term subsidence in Dutch polders was caused by shrinkage above the water table, and 35% was caused by compression below. However, over 85% of the observed shrinkage was due to irreversible peat oxidation over the long term (6 years). The proportion of shrinkage versus compression at shorter timescales, and its reversibility, is not well known. *Price and Schlotzhauer* [1999] estimated seasonal shrinkage of cutover peat above the water table to be 3.6 cm, whereas compression of saturated peat below the water table was 6 cm.

3. Materials and Method

3.1. Experimental Site

The study was conducted within an abandoned section of an exploited peatland, licensed by Toubière Fafard, near Sainte-Margeurite-Marie, in the Lac Saint-Jean region of Quebec, Canada (48°47′N, 72°10′W). The climate is humid continental with a mean annual total precipitation of 820 mm (25% falling as snow) and an average July temperature of 17.3°C [*Environment Canada*, 1993]. Mean annual runoff in the nearby Mistassini River is 623 mm [*Environment Canada*, 1992].

The peatland, classified as an ombrogenous plateau bog [*National Wetland Working Group*, 1986], is part of a 4315 ha bog–poor fen complex situated on a terrace of deltaic sands [*Price*, 1997]. The bog is hydrologically isolated from the regional aquifer by a well-developed iron pan above the mineral substrate [*Price*, 1996]. *Sphagnum fuscum*, *S. angustifolium*, *S. magellanicum*, and *S. capillifolium* form the dominant natural surface cover. A large portion of the bog has been drained, exploited for peat extraction, and subsequently abandoned.

The study site, located at the core of an abandoned cutover peat field, was drained in 1990 by a network of ditches spaced 30 m apart. The upper 45 to 60 cm (acrotelm) of the peat deposit was harvested in 1991 by block cutting with heavy machinery, leaving a residual peat thickness of approximately 185 cm [*LaRose et al*., 1997]. The surface is essentially devoid of vegetation. The residual peat has an average bulk density of 0.109 g cm^{-3} and an average specific yield of 0.048, which is fairly constant with depth [*Price*, 1996].

In 1993 the main drainage ditches were dammed with residual peat but not backfilled. A section of the site was rewetted in 1994 by excavating a series of 20 m long parallel water-holding ditches (1 m × 1 m) cut perpendicular to the regional flow direction [*LaRose et al*., 1997]. An experimental plot was established between two parallel ditch reservoirs spaced 5 m apart (Figure 1). To ensure symmetry (i.e., common water level) within the peat balk, the ditches were hydraulically connected in May 1996 with a 10 cm diameter pipe. Core samples of the cutover peat were obtained at the site in July of 1996, then sealed and refrigerated for further analysis in the laboratory to determine soil physical properties, including porosity, water content, bulk density, hydraulic conductivity, and unsaturated soil moisture relationships with pressure and conductivity. Each peat core was carefully cut from the bog using surgical scissors and a scalpel, progressively sliding a cylindrical brass sampler (5.4 cm diameter by 6 cm length) over the sample to ensure a tight fit, with minimal sample compression.

These rings held the samples during transport and testing in the laboratory. Field monitoring of site hydrological conditions made it possible to compare laboratory parameters with observed field behavior.

3.2. Field Instrumentation

Meteorological data were collected at a meteorological station located 100 m from the experimental site. Detailed meteorological data were previously reported [*Price*, 1996] and are representative of bare peat conditions. Precipitation P was measured with a tipping bucket gauge. Daily evaporation E was estimated with the combination model of *Priestley and Taylor* [1972]. The surface water flux was calculated as P-E in cm d^{-1}. Field instrumentation and calculations are described in detail by *Price* [1996].

Frost table depth was monitored daily using a graduated metal rod until the ground was completely thawed. Water table fluctuations in the reservoir ditch and peat balk were monitored daily using a transect of wells installed perpendicularly from the ditch to the midpoint of the balk. PVC pipes (2.5 cm ID), with 75 cm slotted intakes covered with 250 μm geotextile screen, were inserted approximately 100 cm into the peat at 20, 40, 50, 100, 150, 200, and 250 cm from the ditch edge. A similar well was installed in the center of the ditch adjacent to an iron rod inserted down through the mineral substrate. Well elevations were referenced to a common datum on July 16 using standard surveying techniques. Water table and surface elevations were calculated from daily measurements of distance from pipe tip to water level and ground surface, respectively.

Field estimates of saturated hydraulic conductivity K_s were conducted during mid-July with bail tests, using the hydrostatic time-lag method of *Hvorslev* [1951]. Values of K_s reflect the average permeability of the saturated peat layers down to a depth of 100 cm (maximum depth penetration of the seven wells) under the prevailing water table conditions. We recognize the potential for error in field determination of hydraulic conductivity, because of the effect of soil compression and gas bubble formation in the pores around the well screen [see *Baird and Gaffney*, 1994]. *Hemond and Goldman* [1985] point out that evaluating hydraulic conductivity in peat soils remains "an extremely difficult problem." Nevertheless, *Rycroft et al.* [1975] noted that reasonable estimates of K can be derived from head recovery in piezometers in poorly decomposed fibric peat. The peat in this study was fibric and poorly to moderately decomposed. While it is not possible to determine the magnitude of error, laboratory tests were done for comparison. *Rycroft et al.* [1975] and *Hemond and Goldman* [1985] provide interesting discussion on the applicability of Darcy's law in peat.

Volumetric soil moisture content (θ) and dry bulk density (ρ_B) were determined gravimetrically using weekly triplicate field samples of the top 3 cm of peat sampled along the center line of the balk, at least 2 m away from the transect of wells. Vertical profiles of soil moisture content and pressure head (ψ) were monitored daily throughout the 1996 summer field season (May 4 to August 29) using time domain reflectometry (TDR) probes and tensiometers installed on the center line of the 5 m experimental balk. Installation of TDR probes and tensiometers at the 30 and 50 cm depth increments were delayed until the peat at these levels had thawed. In situ moisture characteristic curves were established for each peat layer monitored (i.e., -2, -10, -30, and -50 cm), coupling water content and tensiometry. On the basis of the assumption that saturated moisture content reflects field porosity, vertical profiles of pressure versus degree saturation were estimated to reflect equivalent pore size distributions [*Danielson and Sutherland*, 1986]. The profiles were used to show a shifting peat structure over time and its effect on the system's ability to retain water.

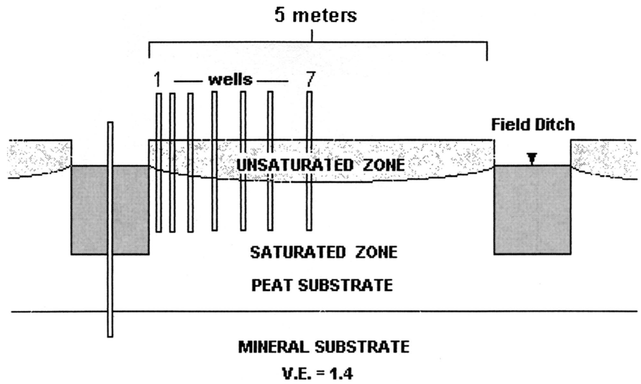

Figure 1. Schematic diagram of experimental site. The instrumented peat balk was the center balk situated between four adjacent open water ditch-reservoirs. Only the two center ditches are shown here. The ends of the two ditches were connected with a 10 cm diameter pipe to equilibrate their water levels. The water table shown here is a generalized representation of dry conditions with recharge from the ditches.

3.3. Laboratory Analysis

To determine the degree of hydraulic anisotropy, eight samples of cutover peat (six surface samples and two at the 30 cm depth profile) were cut in both horizontal and vertical orientations, immersed in distilled water, covered, and subjected to a slow saturation (minimum 3 weeks) from below. To obtain their respective permeabilities, the constant-head method described by *Freeze and Cherry* [1979] was used. The same samples were used to determine unsaturated hydraulic conductivity. The method used is similar to that described by *Hsieh and Enfield* [1974], who proposed to measure the steady state water potential distribution $\psi(x)$ and water flux (q) in an evaporating soil column. Minitensiometers were used to measure the potential gradient of water in the soil column. The water flux was measured using a calibrated water supply. Further details of the experimental design and procedure for both saturated and unsaturated hydraulic conductivity tests were described by *Schlotzhauer* [1998].

Soil moisture characteristic curves were established from six field samples retained in a cylinder 5.4 cm ID by 3 cm in length. Retention experiments were run at desorption (0 down to -1000 mbar) using an applied air pressure and volumetric water content outflow technique with single sample Tempe™ pressure cell. Dry bulk density ρ_B (g cm^{-3}) and saturated volumetric water content θ_s were determined for each sample based upon total sample volume at saturation. It was assumed that the volumetric water content at saturation represents the total porosity of the peat sample. Shrinkage of the medium during desorption was not measured.

4. Results and Discussion

4.1. Surface Water Exchanges

During the period May 4 to August 31, 1996, total precipitation recorded at the meteorological station was 40.2 cm,

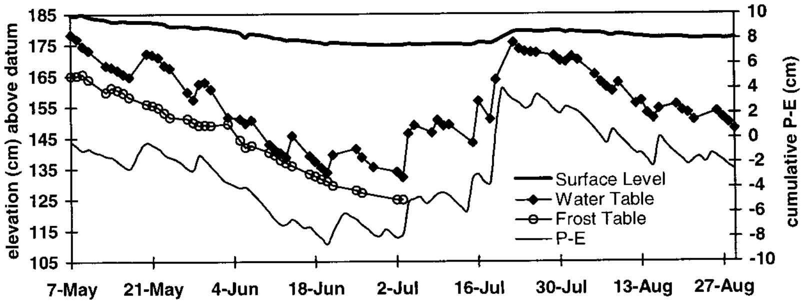

Figure 2. Average surface level, water table, and frost table elevations May 7 to August 29, 1996, in response to water flux at the cutover peat surface (P-E).

close to the 30 year normal value of 39.5 cm (May 1–August 31) [*Environment Canada*, 1993]. On a monthly basis, July received a significant water surplus of +9.9 cm, whereas May, June, and August had a net water deficit of −3.1, −5.0, and −4.0 cm, respectively. During the 1996 field season, 52% of the total rainfall occurred within the month of July, 22% above the normal for this month. Evaporation from the bare peat surface ranged from 0.06 to 0.61 cm d^{-1}, with an overall daily average of 0.35 (±0.14 cm d^{-1}), for a total of 42.5 cm over the study period. The combination of precipitation and evaporation resulted in a net water deficit of −2.3 cm from May to August (Figure 2).

4.2. Subsurface Water Exchanges

Summer water table and surface elevation changes closely followed the net water flux at the peat surface (Figure 2). The maximum water table depth below the surface (−42.7 cm) was reached on July 3, corresponding to the disappearance of the frost table. The frost table elevation was always below that of the water table and receded at an average rate of 0.53 cm d^{-1}. Significant rainfall events during July recharged the soil moisture, raising the water table for the duration of the month. Compared to unmanaged cutover sites [*Price*, 1997], the ditch recharge system maintained a relatively high water table with limited fluctuations. Over the study period the water level was within 40 cm of the peat surface 95% of the time, with an average (± standard deviation) depth of 22 (±10.5) cm. This was due, in part, to the unusually wet conditions during July but also was due, in part, to the stabilizing influence of the ditch-reservoir system.

Typical configurations of the water table and surface profiles perpendicular to the ditch from the midpoint of the balk are shown in Figure 3. The shape of the water table profile under wetting and drying events was influenced by the presence of the open water reservoir. When there was a net water deficit as a result of evaporation (May 27 to July 3), the water level in the peat fell faster than the water level in the ditch because of differences in their storage properties, for example, S_y. This set up a hydraulic gradient that caused water to move laterally from the ditch toward the peat balk. As a consequence, water from the ditch recharged some of the water lost from storage in the peat, effectively minimizing the degree of water table fluctuations observed in the balk. During precipitation events (May 29 to July 4), however, the water level rise in the peat was greater than in the ditch. This resulted in lateral drainage from the peat to the ditch and the development of a typical groundwater mound (i.e., a water table that slopes toward the ditch). The horizontal gradients generated during precipitation events are exaggerated since the rate of rainfall with respect to lateral flow in the balk is greater than the low steady rate of evaporation.

Throughout the season the surface elevation moved with the water table, indicating that the peat system shrank and swelled continuously in close relation with changes in moisture content (Figure 2). Decreases in peat thickness and head corresponded with periods of net losses of water by evaporation. Periods of rainfall corresponded to periods of swelling of the peat and increased hydraulic head. For example, from May 9 to July 3 a net water deficit (P-E) of −7.1 cm produced a water table drawdown of 42.5 cm with respect to a fixed reference datum and a corresponding surface displacement of 10.1 cm. This resulted in a net change in head with respect to the surface of 32.4 cm. Thus the distribution of head within the system was the net result of storage losses because of desaturation of the pores and surface subsidence.

4.3. Changes in Storage

The seasonal soil moisture regime and distribution of pressure head in the upper 2 cm of peat ranged between 78 and

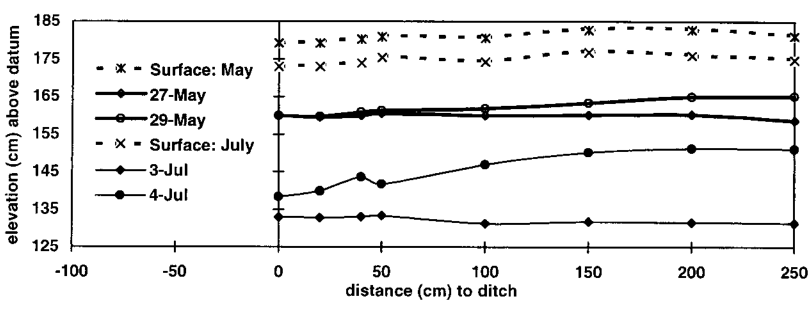

Figure 3. Typical water table profiles under precipitation (May 29 and July 4) and evaporation (May 27 and July 3) events. Note the 6 cm drop in surface elevation between May and July in 1996.

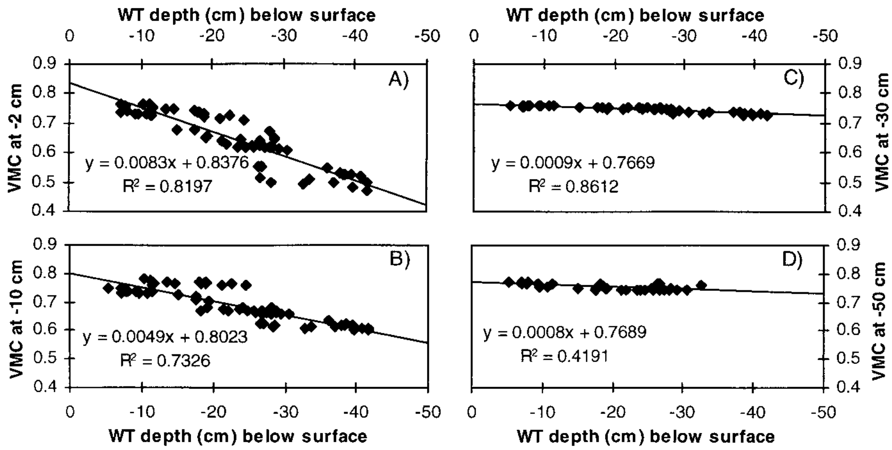

Figure 4. Volumetric moisture content (vmc) versus water table depth below the surface at −2, −10, −30, and −50 cm (A to D, respectively), May 7 to August 29, 1996. The peat at 30 and 50 cm depth profiles remained saturated during the study. The change in vmc is due to compression.

40% and >0 and −45 mbar, respectively. The average volumetric soil moisture content and pressure head in the underlying peat was greater than at the surface because of the proximity of the water table and evaporation from the peat surface. Soil moisture conditions at the surface followed a seasonal trend similar to that of the water table and surface elevation. Partial drainage of the pores at the 2 and 10 cm depth profiles occurred as the water table declined (Figure 4). A decrease in volumetric moisture content also occurred at 30 and 50 cm below the peat surface, even though these layers remained at saturation over the duration of the study. The gentle but definite slope of the volumetric moisture—water table relationship at −30 and −50 cm represents the dewatering of the peat matrix as the soil was compressed by the increased effective stress associated with a lower water table. Subsidence of the upper layer by compression can be assumed to have occurred in a similar fashion. However, because of the water tension associated with air entry into the upper layer, additional surface lowering probably occurred. Evidence for this can be found in the changes in bulk density of the surface layer (Figure 5). Bulk density, at field wetness, averaged 0.126 g cm^{-3} ±0.016. Peaks in bulk density tended to correspond to drier periods when the greater matric suction resulted in a decrease in pore volume (i.e., shrinkage). The opposite was generally true during rehydration, although a sudden increase in bulk density was observed on July 31, following a series of major storm events. It appears that the load imposed on the peat because of the heavy inundation caused a collapse in the peat structure, consequently decreasing its pore volume. The proportion of shrinkage versus compression was not measured here. However, it should be noted that shrinkage is restricted to a relatively thin layer (top 30 cm or less), whereas compression occurred throughout the peat thickness of about 180 cm.

Assuming the total surface elevation change by shrinkage in the upper 0–30 cm layer is much less than compression of the entire peat deposit, the total change in storage due to bulk volume changes in the peat is represented by the slope of the thickness versus head relation, that is, dilation coefficient [*Nuttle et al.*, 1990]. In this case the volume of water lost by dilation storage per unit sediment thickness is equal to the measured decrease in surface elevation, and the dilation coefficient divided by the initial peat thickness is an estimate of the depth-averaged specific storage S_s [*Nuttle et al.*, 1990]. Figure 6 shows a significant change in peat thickness versus head relation over time; associated estimates of S_s are 12.5×10^{-4} cm^{-1}, 2.6×10^{-4} cm^{-1}, and 6.2×10^{-4} cm^{-1} for curves A, B, and C, respectively, yielding a seasonal average of 9.6×10^{-4} cm^{-1}. In general, wetting and drying measures of S_s were not comparable; for example, curves A and C represent predominant drying events, while curve B represents the S_s of the sediment upon resaturation (i.e., net influx of water into the system). The coefficients indicate that peat compressibility in expansion was much less than in compression (a ratio of 5:1). Furthermore, S_s of the sediment at the end of the season was

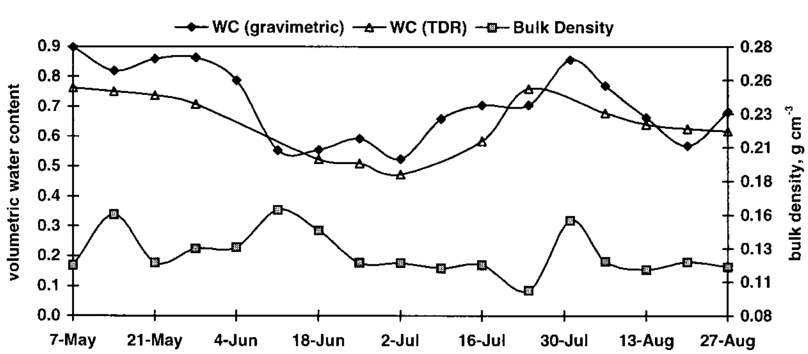

Figure 5. Average volumetric soil moisture (WC) and bulk density measured from weekly triplicate samples in the top 3 cm of peat versus time domain reflectometry (TDR) measurements at −2 cm depth profile.

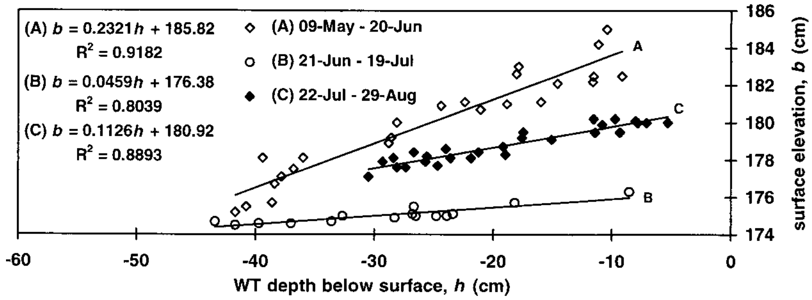

Figure 6. Slopes inferred from the thickness versus head relation observed from May 9 to August 29, 1996, are estimates of storage changes associated with the mechanism of dilation storage. The slope divided by the intercept is an estimate of the depth-averaged specific storage. The net water flux at the peat surface (P-E) was -7.9 cm, $+9.1$ cm, and -6.1 cm for curves A, B, and C, respectively.

only half that measured from its initial state, indicating that bulk volume changes may be governed to some extent by the degree of saturation [*Lefebvre et al.*, 1984] and dependent on the previous loading history [*Freeze and Cherry*, 1979]. Typical settlements of the cutover peat surface ranged from 11 to 23% of the lowering of the groundwater table.

4.4. Changes in Water Retention Properties

The soil water retention capacity of the cutover peat controls, in part, the degree of water table fluctuation in the system. The water content-pressure relationship of four horizons, based on field measurements, is shown in Figure 7. The analytical model of *van Genuchten et al.* [1991] found in the RETC (Retention Curve) computer code was used to graphically describe the observed soil water retention relationships (solid lines). *Weiss et al.* [1998] found the van Genuchten model to be suitable to empirically describe moisture retention curves in peat soils, but it works best at higher moisture contents. This is apparent in Figure 7. Soil moisture was related to soil water tension in a nonlinear fashion, typical of these relationships. The data show that the cutover peat underwent a change in its retention capacity both over time and with depth. For example, during the initial period of study (solid symbols) the surface layers (0–10 cm) had a higher moisture content at a given suction than the soil at 30 cm depth, which is subject to greater overburden pressures. By August, however, the volumetric moisture content of the surface layers at a specified pressure (open symbols) decreased from its initial state, even after substantial rewetting had occurred during July. The surface peat in May was able to retain more water at lower suctions than in August, indicating hysteresis in the pressure-saturation relationship. As a result, two distinct moisture characteristic curves were generated for the surface peat during the first and latter part of the season. An infinite variety of curves can lie inside the main drying curves, depending on the sequence of wetting and drying events in the soil.

In Figure 8, pressure head is plotted against degree saturation (S_w), where $S_w = \theta/\theta_s$, based on field data (Figure 8a) and laboratory desorption experiments (Figure 8b). The alternate x axis is plotted as equivalent pore diameter, $2r$, where in simplified form, $2r \cong 3000/\psi$ (where ψ is expressed in centimeters of water) [*McLay et al.*, 1992]. In theory, the volume of water withdrawn from the soil by increasing the suction reflects the volume of pores having radii between the sizes corresponding to those suctions. Thus, if we treat the peat pore system as a bundle of capillaries with different radii, then an equivalent pore size distribution may be used to explain the soil's moisture retention characteristics. Since the soil pores are not capillary bundles, the pore throat is actually the effective diameter that governs drainage. Nevertheless, the approach of *Danielson and Sutherland* [1986] and *McLay et al.* [1992] provides a useful way of conceptualizing the process and facilitates comparison of pore behavior at different times and pressures and the comparison of field data with laboratory results. Associated physical properties of the six laboratory samples are presented in Table 1. In both May and August, approximately 16% of the total pore water is associated with pore spaces $\geq$120 μm (Figure 8a). Between May 15 and June 10, lowering of the water table (by 24 cm) is associated with a 3% reduction in pore

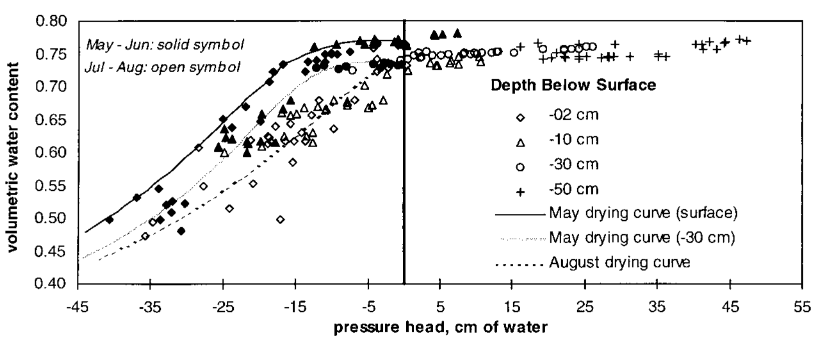

Figure 7. In situ pressure-saturation relationships at 2, 10, 30, and 50 cm below the peat surface. The observed soil water retention data were fit to an analytical soil water retention function using the RETC (retention curve) computer code. The solid curves describe the unsaturated soil retention properties during prevailing drying events in May and August.

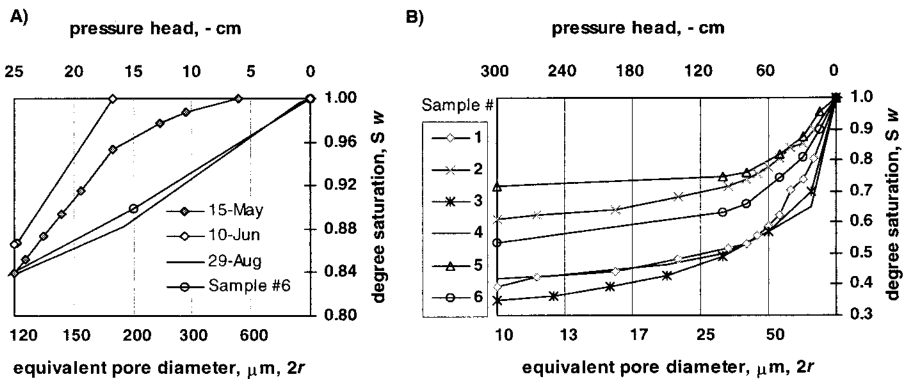

Figure 8. Moisture retention characteristics based on (a) field data and (b) laboratory experiments. In Figure 8a, porosity (θ_s) was determined as 0.77, 0.73, and 0.74 for May, June, and August, respectively. In Figure 8b, θ_s was calculated based on the initial wet sample volume (see Table 1). Owing to shrinkage of the samples at desorption, their water retention would increase slightly if expressed per volume of shrunk medium.

volume, subsequently increasing water retention in the upper peat layers. The flatter curve observed in August indicates a more even pore size distribution. Compared to May and June, August shows a 4% increase in the proportion of larger pores (200–600 μm) and an equivalent decrease in the proportion of pores between 120 and 200 μm. The change in pore size distribution in the upper peat layers, together with the hysteresis effect, explains the observed reduction in the peat's ability to retain water over time.

Within the range of pressure potentials observed in the field, that is, 0 to −40 cm, the pore size distribution of the laboratory samples (Figure 8b) was not significantly different from the field data described in Figure 8a; for example, see sample 6 in Figure 8a. The laboratory samples provided additional information on the nature of the pressure-saturation relationship at greater matric potentials. At −100 cm pressure head, for example, the peat samples retained, on average (± standard deviation), 60% (±11%) of their total pore water, indicating that 40% of the total pore volume was associated with pores larger than 30 μm. In living *Sphagnum* carpets, however, 90% of all the water is associated with pore spaces with a mean diameter ≥30 μm [*Hayward and Clymo*, 1982], compared to 30% in well-decomposed peat [*Boelter*, 1968].

4.5. Hydraulic Conductivity

Saturated hydraulic conductivity K_s measured in the field was 15.0 (±8.1) cm d^{-1} (geometric mean is 12.9 cm d^{-1}), ranging from 4.4 to 33.0 cm d^{-1}. Water table levels were relatively low during the period of measurement, averaging 25.6 cm below the surface. Thus the measured values represent the average conductivity between the phreatic level and depth penetration of the wells, for example, between 25 and 100 cm below the peat surface. The measured hydraulic conductivities are similar to the mean K_s value of 16 (±14) cm d^{-1} observed by *LaRose* [1996], whose measurements spanned the entire 1994 summer season at this site, encompassing a full range of water table conditions. In this study, lower K_s values tended to correspond with greater depths to the water table. For example, on July 9 the average water table position within the balk was 24.9 cm below the peat surface with a mean K_s of 14.9 cm d^{-1}. On July 10 an increase in the average depth to the water table by 1.5 cm subsequently decreased the average hydraulic conductivity of water through the system to 12.1 cm d^{-1}. A decrease in hydraulic conductivity was observed in five of seven wells, but the difference was not statistically significant at the 0.1 level.

In the laboratory horizontal conductivity K_x at the surface was 4 times greater, on average, than at the 30 cm depth profile (Table 2). The decrease in hydraulic conductivity observed as the water table declined therefore can be explained by (1) the smaller pore size of peat that was compressed as the water table elevation decreased [*Chow et al.*, 1992] and (2) lower intrinsic permeability of the deeper peat. It should be noted that the mean hydraulic conductivity determined in the laboratory for the upper 30 cm of peat was 70.2 (±61) cm d^{-1}, almost 5 times greater than observed in the field. This may be due to the prolonged and careful saturation of laboratory samples. It was also notable that vertical conductivity K_z was 4 times less than the average horizontal conductivity, demonstrating anisotropy.

Unsaturated conductivity as a function of mean matric potential $K(\psi)$ and as a function of degree saturation $K_{rw}(S_w)$ is presented in Figures 9a and 9c, respectively. Hydraulic con-

Table 1. Physical Properties of Peat Samples Used in Soil Water Retention Experiments

Sample	Core Depth, cm	Total Porosity Volume, %	Bulk Density, g cm^{-3}
1	30	93.5	0.105
2	30	91.8	0.132
3	6	94.8	0.087
4	6	92.9	0.114
5	3	89.7	0.102
6	3	91.0	0.096
Average		92.3	0.106

Table 2. Laboratory Test Results of Saturated Hydraulic Conductivity K_s

Sample	K_z Surface	K_x Surface	K_x −30 cm
1	15.2	61.5	20.4
2	22.3	153.4	49.0
3	66.2	173.8	
Average	35	130	35

Values are given in cm d^{-1}. K_x denotes horizontal conductivity; K_z denotes vertical conductivity.

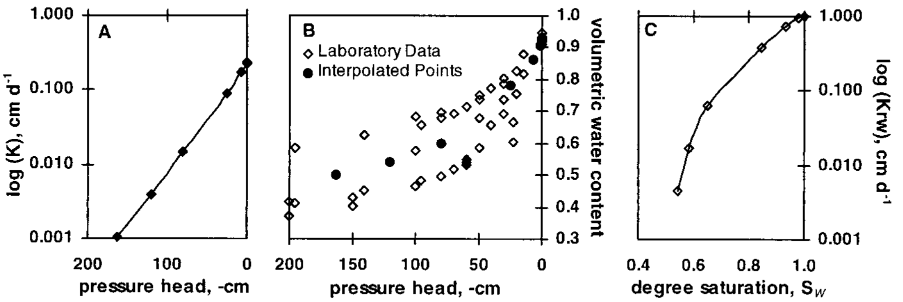

Figure 9. Estimated unsaturated hydraulic conductivity as a function of (a) matric suction and (c) degree saturation, based on (b) laboratory pressure-saturation relations. Relative permeability k_{rw} is defined as the ratio of $K(S_w)$ to K_s.

ductivity at zero matric potential was, on average, 0.23 cm d^{-1} and decreased with increasing matric suction in a logarithmic progression. In Figure 9c, degree saturation was estimated from the laboratory desorption experiments shown in Figure 9b. This is based on the calculated porosity at saturation. The variation in hydraulic conductivity with moisture content depends on the pore size distribution. In a deformable soil therefore hydraulic conductivity is not only a function of the moisture content θ but is also a function of porosity θ_s, which varies as the soil is compacted [*Bear and Veirujt*, 1987].

5. Conclusions

Over the 1996 study period, water exchanges between the open water reservoir and adjacent peat maintained a water table depth above 43 cm from the cutover peat surface. The seasonal water deficit produced a smaller water table drawdown at the managed site than observed at a nearby site without the influence of an open water ditch [*Price*, 1997]. This suggests that the peat-ditch system was effective at retaining water at the site, minimizing the degree of water table fluctuations and improving moisture conditions at the surface. The presence of open water reservoirs increased the bulk specific yield of the site thus improving water table stability. However, changes to the hydraulic properties of the peat associated with surface subsidence were also implicated.

Total surface subsidence was in excess of 10 cm over the study period. This was attributable to shrinking of the layers above the water table subject to internal capillary suction and compression of the underlying saturated layers subject to increased external loading. Volume changes due to shrinkage were a consequence of losing moisture because of drainage or upward capillary flows and therefore did not contribute to a further change in storage. Volume changes due to aquifer compression, however, resulted from an increase in effective stress and the concomitant expulsion of water from storage. The total amount of subsidence observed in the cutover peat deposit was therefore dependent on the thickness of the compressible units and their storage characteristics, as well as the suction imposed at the soil surface. Unfortunately, the experimental design in this study was not set up to measure the proportional contributions of shrinkage and compression to the total vertical displacement observed in the cutover peat.

Subsidence resulted in a shifting structure hence the water retention characteristic curve. Analysis of the pore size distribution of the cutover peat under field conditions indicated that shrinkage altered the distribution of pore spaces: As the water table was lowered, the volume of larger pore spaces decreased, consequently increasing the retention capacity of the soil. Marked shrinkage was also noted in the laboratory peat samples during the water desorption experiments. The increase in bulk density associated with the processes of shrinkage and compression had a negative effect on hydraulic conductivity, subsequently decreasing the conductance of water through the system as the water table descended through the peat profile.

Subsidence was important with respect to storage changes within the cutover peat through its effect on specific storage. Accurate prediction of the hydraulic response of the peat-ditch system to atmospheric demands can significantly aid in the understanding of the effect of storage changes on the soil moisture regime in cutover peat deposits. In the long run this should permit more control over the design of restoration strategies aimed at mitigating the limiting moisture conditions for the survival and growth of *Sphagnum* mosses.

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