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A conceptual model of volume-change controls on the hydrology of cutover peats

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Abstract

Modeling hydrological processes in certain peats requires a detailed understanding of short-term changes in soil volume and it's influence on the system's hydraulic properties. A study of cutover sites abandoned for 7-years (H92) and 2-years (H97), and an undisturbed section of the Lac Saint-Jean (LSJ) cutover bog was conducted to characterize peat volume changes and its associated hydrological behaviour. Shrinkage and compression accounted for 96–97% of seasonal volume change. Saturated hydraulic conductivity (K_S) varied linearly with peat compression; a 1 cm decrease in peat thickness causing a 5.2 cm d^{-1} decrease in K_S at H92, and a 1.4 cm d^{-1} decrease in K_S at H97. A 2–6% seasonal decrease in saturated volumetric moisture content (θ_S) at the cutover sites was partly due to soil compression, although the development of CH_4 bubbles possibly affected moisture content. In the unsaturated zone moisture retentivity (θ–Ψ) was seasonally transient due to the shifting soil structure.

The greater volumetric response to a change in water storage of the more porous and less decomposed peat at H97 indicates a long-term decreasing trend in peat compressibility due to irreversible losses in pore volume. Deterioration of high water storage and low water retention properties at H92 suggests that cutover sites abandoned for longer periods will become increasingly hostile to *Sphagnum* recolonization despite the blockage of drainage ditches.

Keywords: Peat; Hydrology; Compression; Subsidence; Volume-change; Restoration; Model

1. Introduction

The hydrological functioning of cutover peats is strongly controlled by the structure and deformable character of the peat matrix (Price, 2003; Price and Schlotzhauer, 1999; Van Seters and Price, 2001). Peat volume changes occur at the time-scale of water-table change (Lang, 2002), significantly affecting hydraulic properties related to peat pore structure (Chow et al., 1992; Lang, 2002; Price, 2003). This phenomenon is unique to highly deformable peats since the structural composition of mineral soils, with the exception of swelling clays, is typically stable over time periods considered in most hydrologic analyses (Dingman, 1994). It follows that simulation of the hydrology of cutover peats using conventional flow models will yield inaccurate prediction of peatland hydrological

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response because these models fail to consider important linkages between peat deformation and water storage and flow processes (Schlotzhauer, 1998). Thus, modeling hydrological processes in cutover peats requires a detailed understanding of the dynamics of seasonal peat volume change and its effect on the system's hydraulic behaviour. Modeling the hydrological and volume change behaviour of cutover peats has important implications with respect to the restoration of these ecosystems, since water storage and soil water pressure are crucial to the re-establishment of *Sphagnum* mosses (Price and Whitehead, 2001). Therefore, the objectives of this study were to: (1) determine the spatial, seasonal and inter-annual characteristics of peat volume change and its hydrological consequences, and (2) develop a conceptual model of the hydrological functioning of the cutover peat system.

1.1. Volume change theory

Volume change mechanisms in peatlands are commonly identified as shrinkage, compression, and oxidation (Eggelsmann, 1976; Schothorst, 1977). Peat oxidation consists of irreversible subsidence due to mineralization of carbon to water and CO_2. Compression is attributed to changes in effective stress (σ') on peat layers below the water-table due to water-table fluctuations and snow loads, and comprises primary consolidation (δ_p) and secondary compression (δ_s) components (Lang, 2002). Primary consolidation can be described by classical 1D consolidation theory (Terzaghi, 1943) whereby peat volume changes are due to an equivalent change in pore-water volume. The change in void ratio can be predicted by

$$\Delta e = -m_v \, \Delta\sigma'(1 + e_0), \tag{1}$$

where Δe is the change in void ratio, m_v is the coefficient of volume compressibility ($m^2\ kN^{-1}$), $\Delta\sigma'$ is the change in effective stress (kPa), and e_0 is the initial void ratio. According to the effective normal stress concept developed by Terzaghi (1943), σ' is estimated as the pore-water pressure subtracted from the total normal stress

$$\sigma' = \sigma - u, \tag{2}$$

where σ is the total normal (intergranular) stress and u is the pore-water pressure. Note that in Eq. (2) when the pore-water pressure (u) is negative (i.e. in the unsaturated zone), u is added to σ, increasing the effective stress to a value greater than the total stress. At σ' less than the material's pre-consolidation pressure (P_c), volume changes are reversible and peat compressibility can be estimated as the slope of the recompression curve (m_r), whereas at effective stresses greater than the material's P_c, irreversible structural changes occur, and peat compressibility can be estimated as the slope of the virgin consolidation curve (m_v) (Fig. 1).

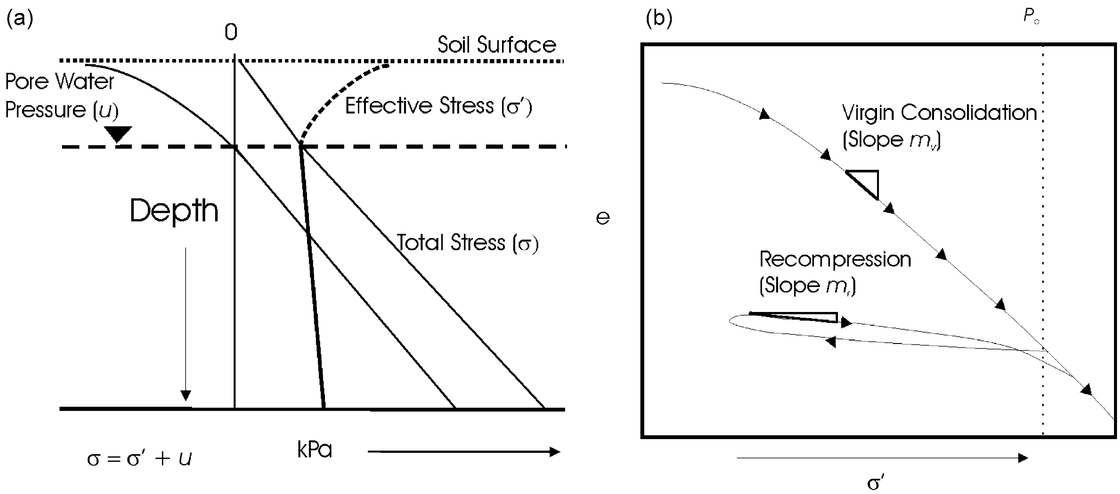

Fig. 1. (a) Effective stress concept, and (b) theoretical consolidation plot.

Secondary compression, which is attributed to the gradual re-arrangement of the saturated peat matrix under load into a more stable configuration, is a time-dependent relation expressed by

$$\delta_s = C_{sec} \log \frac{t_f}{t_0} z, \tag{3}$$

where δ_s is secondary compression (cm), t_0 and t_f are the initial and final times, respectively (d), C_{sec} is the secondary compression constant, and z is the peat thickness (cm).

Shrinkage refers to the contraction of peat layers above the water-table due to the development of negative pore-water pressures as the peat dries, and is typically described by the empirical soil shrinkage characteristic (SSC), which relates void ratio (e = volume of voids/volume of solids) to moisture ratio (ν = volume of water/volume of solids). In very dry conditions, peat can undergo a permanent material change, causing moisture, and hence volume losses to only partially recover upon re-wetting (Pyatt and Craven, 1979; Hobbs, 1986; Pyatt and John, 1989; Wösten et al., 1997). The theory describing the stress-strain dynamics of saturated peat can be extended to the unsaturated zone, such that below some critical stress (P_c), peat shrinkage is reversible. The effective stress concept cannot be directly applied to partially saturated soils, however, because pore-water pressure (u) is only partly convertible to mechanical stress. Bishop and Blight (1963) proposed an empirical parameter (χ) to permit the evaluation of effective stress in the unsaturated zone according to Terzaghi (1943) effective stress concept

$$\sigma' = \sigma - \chi u, \tag{4}$$

where χ varies as an empirical function of the degree saturation (S) from 0 at $S=0$ to 1 at $S=1$. The nature of χ is not very well understood (Brutsaert and El-Kadi, 1984), especially as it applies to fibric materials such as peat.

2. Study area

A field study, following a similar setup as reported by Price (2003) for 1998, was performed from May 7th to August 13th of 1999 near Sainte-Marguerite-Marie, in the Lac-Saint-Jean (LSJ) region of Quebec, Canada (48°47′N, 72°10′W) (Fig. 2). Field studies at LSJ were also performed in 1995 (Price, 1996) and 1996 (Price and Schlotzhauer, 1999). The climate is humid continental with a mean annual temperature of 2.2 °C, and average January and July temperatures of −17.1 and +17.3 °C, respectively (Environment Canada, 1992a). Mean annual precipitation is 908.5 mm (36% falling as snow) and mean annual runoff in the nearby Mistassini River is 623 mm (Environment Canada, 1992b). The study area is part of a 4315 ha bog-poor fen complex, classified as ombrogeneous Plateau-Bog (NWWG, 1997), which has developed over a terrace of permeable deltaic sands in the Lac-Saint-Jean lowland due to the presence of an underlying iron-pan formation that limits seepage losses (Price, 1997).

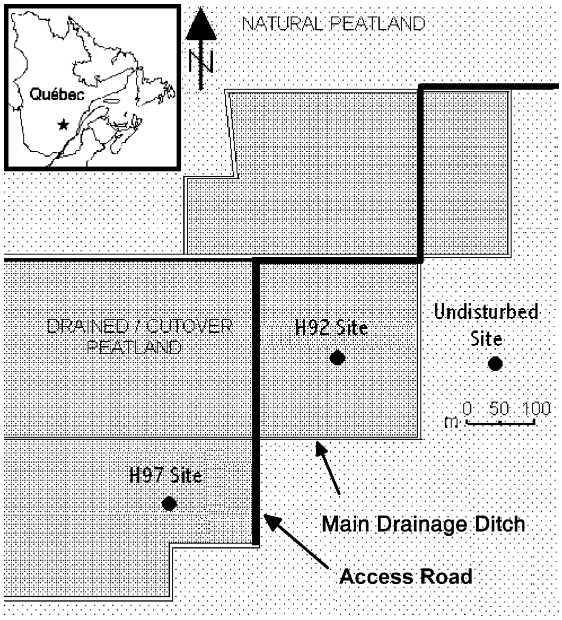

Fig. 2. Schematic of the LSJ study site showing locations of H92, H97, and UNDISTURBED sites.

Data were collected at two cutover and one undisturbed site (Fig. 2). At the H92 site, drainage and extraction operations commenced in 1990 and drainage ditches were blocked in 1992, whereas at H97 drainage ditches were excavated in 1995 and blocked in 1997. Details are given in Kennedy (2002) or Price (2003). The residual peat deposit, which has undergone oxidation and compression due to drainage and extraction activities, consisted of moderately decomposed peat (von Post ≤ 4) with a mean dry bulk density of approximately 0.109 g cm^{-3} at the H92 site and a mean dry bulk density of 0.084 g cm^{-3} at H97 (Price, 1997). Comparatively, the mean dry bulk density of peat at the UNDISTURBED site was only 0.052 g cm^{-3}. Peat thickness ranged from 2.60 to 2.90, 1.80 to 1.95 and 1.66 to 1.70 m at the UNDISTURBED, H97 and H92 sites, respectively. The portions of the bog that have been drained and extracted are essentially devoid of vegetation.

3. Methods

Water-table, soil moisture, and meteorological data were measured every minute, then recorded as average hourly values using Campbell Scientific™ CR10 data loggers at all three sites. Water-table position was recorded using a float-potentiometer device, and soil moisture was logged using an array of Campbell Scientific™ CSI615 reflectometer probes at depths −5, −20, and −100 cm. A laboratory calibration revealed that the probes did not share a common calibration for well-saturated peat, exhibiting a similar slope but variable intercept. The probes were therefore calibrated in the lab by matching the saturated volumetric water content (θ_S) of a destructively sampled peat core (0.85) to the intercepts of the sensor output. The error associated with the actual volumetric soil moisture values could be ±5%, however, the error associated with the change in moisture content is expected to be within ±0.5%. A meteorological station installed at the H92 site measured daily precipitation (P) using a manual rain gauge, and net radiation, ground heat flux, and air temperature so that evaporation (ET) could be determined using the Priestley and Taylor (1972) combination model. See Price (1996, 2003) for details.

At the two cutover sites, pressure head (Ψ) was measured at depths −2, −5, −10, −20, and −50 cm with tensiometers. The upper three tensiometers consisted of a 1 cm o.d. tubes fitted with a porous ceramic cup, connected to a partially water filled L-shaped tube, installed horizontally into a (backfilled) pit wall with the top of the L-shaped tube protruding above the peat surface. The −20 and −50 cm tensiometers consisted of 2.5 cm o.d. straight tubes fitted with a porous ceramic cup, inserted vertically into predrilled holes. Two tensiometers nests were installed at H92 and one nest was installed at H97. Pressure head, measured with a Tensimeter™ (Soil Measurement Systems, Tucson, USA) pressure transducer accurate to 1 mb, was adjusted to account for the height of the water column above the ceramic cup, and was expressed in cm of water (1 cm ≅ 1 mb).

A set of PVC (2.5 cm i.d.) piezometers, slotted along the bottom 20 cm and covered with a 250 μm geotextile screen, was inserted at depths −50, −60, −70, −80, −90, and −120 cm at each of the three sites, spaced approximately 50 cm apart. At the cutover sites, the piezometers nests were positioned parallel to the blocked drainage ditches, at distances of 3 and 13 m from adjacent ditches at H92 and H97, respectively, whereas at UNDISTURBED, the piezometers were installed along a straight transect in a lawn section of the site. The relative elevation of piezometers and tensiometers within a nest was determined by measuring the pipe elevation above a level datum.

Weekly field determinations of saturated hydraulic conductivity (K_S) were conducted in each of the piezometers using a Levelogger™ (pressure transducer, Model 3001, Solinst Canada, Georgetown, CA). The transducer was inserted into a piezometer for a sufficient amount of time to measure 90% head recovery following a known volumetric displacement caused by the transducer device (67.78 cm^3). The deeper piezometers at the H92 and UNDISTURBED sites exhibited a very slow rate of head recovery, precluding them from weekly determinations of K_S. The hydrostatic time-lag method of Hvorslev (1951) for piezometer slug tests was employed to derive horizontal K_S values (see Freeze and Cherry, 1979).

Peat elevation changes were measured at all three sites by recording the weekly displacement of aluminum rods inserted at depths of −5, −10, −20, −30, −50, −100, and −150 cm (Fig. 3). The rods were anchored at the three upper depths using 2.5 cm long plastic drywall screw ‘grommets’ into which the rods were fixed. To provide stability for the rod installed at 5 cm depth, the rod protruded 5 cm below the peat anchor. The four deepest anchors consisted of a 5 cm section of flighted aluminum augur.

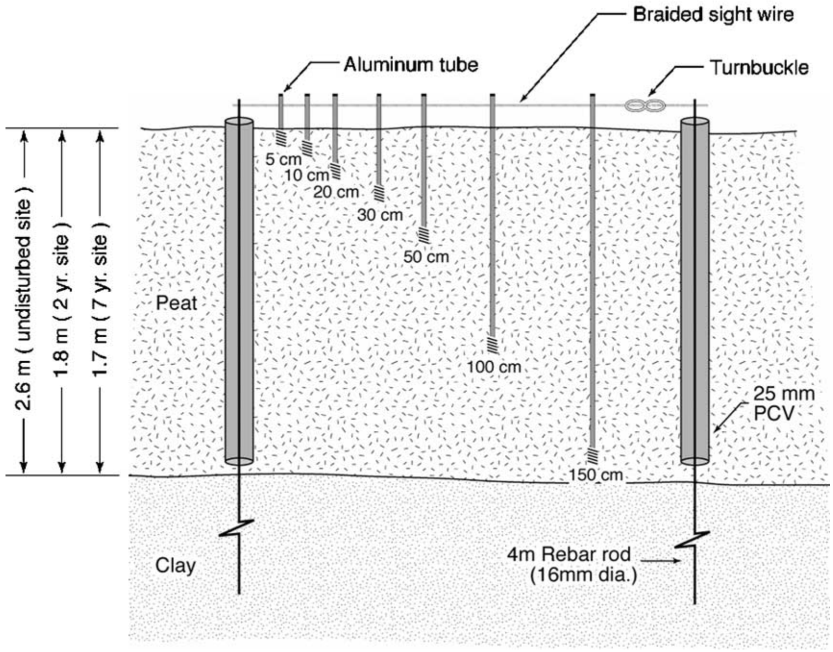

Fig. 3. Diagram of the peat elevation change measurement apparatus.

The anchors were augured into place with a removable hollow shaft, and were spaced 30 cm apart. Rods from all of the anchors extended approximately 30 cm above the peat surface, and were positioned adjacent to a ‘sight wire’ stretched tightly between two 4 m long, 1.6 cm steel rebar posts. The posts were set in the underlying mineral substrate, spaced approximately 10 m apart, and were pushed through 2.5 cm i.d. PVC tubes that extended to within 50 cm of the mineral substrate. The PVC tubing minimized friction between the immobile rod and the shrinking and expanding peat, and the wide spacing of the posts ensured that any such friction was well removed from the measurement rods. The ‘sight wire’ was kept in a relaxed state between each series of readings.

Displacement values were recorded by viewing elevation changes of each graduated rod through binoculars resting on a fixed post, relative to a stable datum (sight wire). Values were expressed relative to the initial measurement (JD 133). Since the change in elevation of a particular rod integrates all elevation changes below the layer of interest, changes below this layer were deducted for each time interval to derive the change in thickness of each individual soil layer. Peat volume changes were assumed to be entirely manifest as vertical surface displacements since vertical cracks were generally not evident. Compression was estimated as the change in elevation of the uppermost rod below the water-table over each measurement interval. Shrinkage was calculated by subtracting compression from the total change in elevation (-5 cm rod), and thus represents peat volume change above the water-table. Compression may be slightly underestimated since the uppermost sensor in the saturated zone varied between 0 and 20 cm below the water-table. Peat subsidence due to oxidation was estimated using 1999 LSJ modeled carbon flux values (Waddington et al., 2002) at H92 and H97 and converted into a decrease in peat thickness by assuming that the peat material was 50% carbon by dry mass with a constant dry bulk density of 0.1 g cm^{-3}. Millette and Broughton (1984) found that soil oxidation rates were greatest in the upper 1–3 cm of the peat profile, and thus it was assumed that all oxidative volume changes occurred above the -5 cm rod.

3.1. Peat compressibility

The change in water storage in peat due to a change in bulk volume is known as specific, or dilation storage (Nuttle et al., 1990). Specific storage (S_s) can be estimated from the change in peat thickness (db), per unit change in head (dh), per unit aquifer thickness (b) (see Price and Schlotzhauer, 1999):

$$S_s = \frac{db}{dh}\frac{1}{b} \tag{5}$$

The dilation coefficient (S_d) is the change in thickness of the peat deposit per unit change in head (db/dh), and hence provides a depth-integrated estimate of the peat volumetric response to a change in water-table, and thus a measure of peat compressibility:

$$S_d = bS_s \tag{6}$$

3.2. Soil shrinkage characteristic

Peat shrinkage was characterized through measurement of the soil shrinkage characteristic (SSC), obtained from laboratory drying of resin coated peat blocks sampled from the H92, H97, and UNDISTURBED sites. Core samples were collected in July of 1996 and October of 2000 using a rectangular sampler (12 cm×16 cm), and then sealed and frozen. Laboratory shrinkage tests were performed according to the methods described by Brasher et al. (1966), whereby peat samples are coated with a Saran resin (Dow Chemical Company, Midland, Michigan). To estimate the dry mass of the peat it was necessary to correct for the mass and volume of the Saran coating. Following oven-drying of the sample at 70 °C to stable mass, the coating was cut away and scraped clean, and then its mass deducted from the total mass. Since some shrinkage occurred during the coating process and could not be measured directly, this portion of the curve was extrapolated to the sample's initial void ratio and saturated volumetric moisture content:

$$e_0 = \frac{(M_w - M_d)/\rho_w}{M_s/\rho_s}, \tag{7}$$

$$\theta_{S(0)} = \frac{(M_w - M_d)/\rho_w}{(M_w - M_d)/\rho_w + (M_s/\rho_s)}, \tag{8}$$

where e_0 is the initial void ratio, $\theta_{S(0)}$ is the initial saturated volumetric moisture content (assumed to be equivalent to soil porosity so that $e_0 = \nu_0$), M_w is the mass of the sample at saturation (g), M_d is the dry mass of the sample (g), ρ_w is the density of water (1 g cm^{-3}), and ρ_s is the particle density (g cm^{-3}). The particle density of the LSJ peat averaged 1.45 g cm^{-3} (Lang, 2002).

4. Results

4.1. Hydrology

Mean monthly air temperatures were +3.1, +1.2, and +0.2 °C relative to the normal 30-year means of May, June, and July, respectively (Environment Canada, 1992a). Evapotranspiration over the 1999 study period totaled 376 mm, and precipitation (P) totaled 354 mm, representing approximately 140% of the 30-year precipitation normal for this period (1961–1990) (Environment Canada, 1992a). The sites remained relatively wet throughout the 1999 season and did not experience any prolonged periods of drought. Consequently, water-table (WT) remained high and relatively stable throughout the 1999 study season (Fig. 4a). Fluctuations in WT position were greatest at the two cutover sites, ranging from −54 to −8 cm at H92 and from −38 to −3 cm at H97, whereas the water-table position at the UNDISTURBED site experienced considerably less seasonal variability, ranging from −28 to −2 cm. Volumetric moisture content (θ) at 5 cm depth exhibited a similar seasonal trend as water-table (Fig. 4b). Variability in θ decreased according to UNDISTURBED > H92 > H97 (see also Price, 1996). Pressure head (Ψ) at 2 cm depth also followed a similar seasonal trend as water-table, ranging from −39 to +3 cm at H92 and from −34 to +2 cm at H97.

In the upper 50 cm of the peat profile (−2 to −50 cm) a mean upward vertical hydraulic gradient of 0.96±0.10 at H92 and 0.93±0.14 at H97 was estimated from multi-level tensiometer measurements (n=9 sets of measurements over study season). Comparatively, in the saturated zone, a mean downward vertical hydraulic gradient of −0.27±0.12 at H92 and −0.09±0.05 at H97 was estimated from piezometers at 50 and 120 cm depth (n=12).

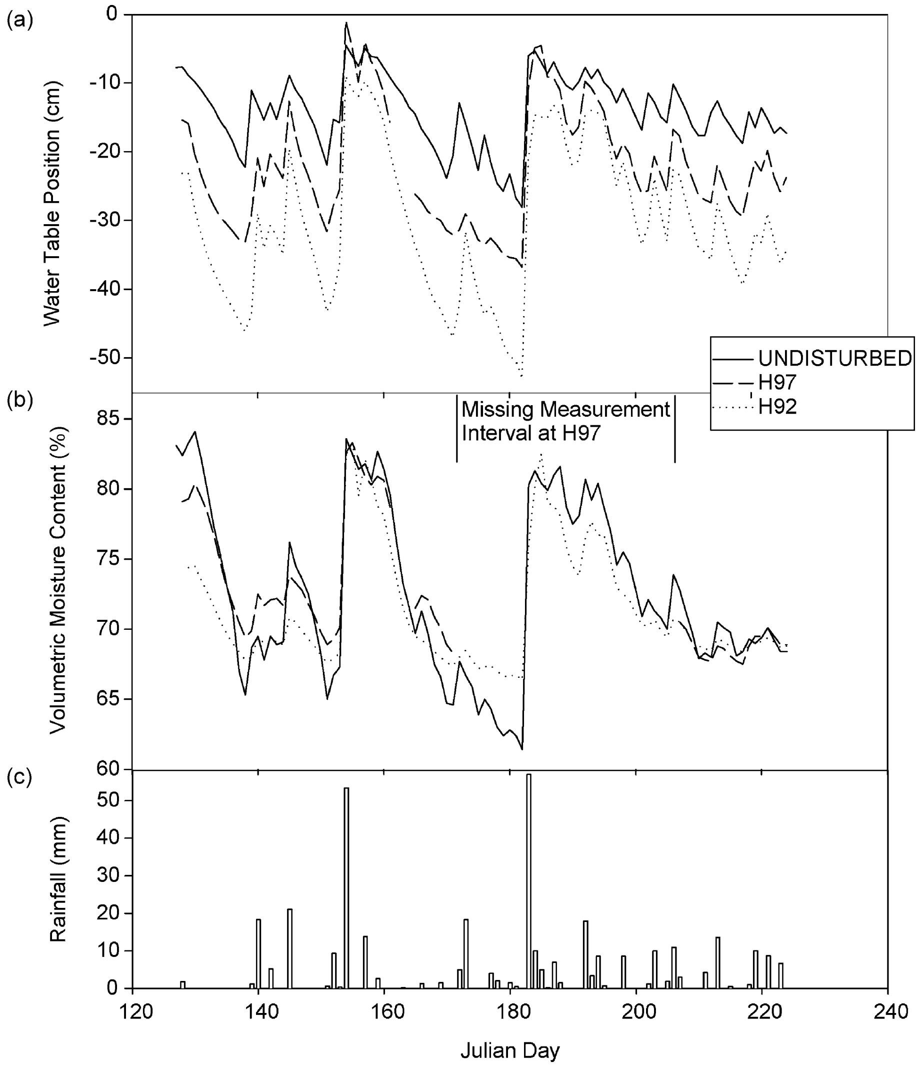

Fig. 4. (a) Water table, (b) volumetric moisture content at H92, H97, and UNDISTURBED sites and (c) daily precipitation.

Previous research at the H92 site has reported horizontal gradients toward (0.0020) and away (0.0027) from blocked ditches during dry and wet periods, respectively (Price, 1996). Comparatively, the horizontal hydraulic gradient at the UNDISTURBED site was measured to be 0.0007 (Price, 1996). Saturated hydraulic conductivity (K_S) ranged from approximately 10^{-5} to 10^{-7} cm s^{-1} at H92, from 10^{-4} to 10^{-6} cm s^{-1} at H97, and from 10^{-4} to 10^{-7} at the UNDISTURBED site. The slow rate of head recovery, and hence low saturated hydraulic conductivity at the H92 and UNDISTURBED site (at depth) impeded weekly determinations of K_S using the Levelogger™ device. As a result, a complete seasonal trend in K_S was obtained only for the -50 cm piezometer at these sites.

4.2. Peat volume changes

Seasonal trends in shrinkage, compression and oxidation at the H92 and H97 sites are shown (Fig. 5) in relation to changes in water-table position, with Δz representing the sum of all three components. Estimates of shrinkage, compression and oxidation

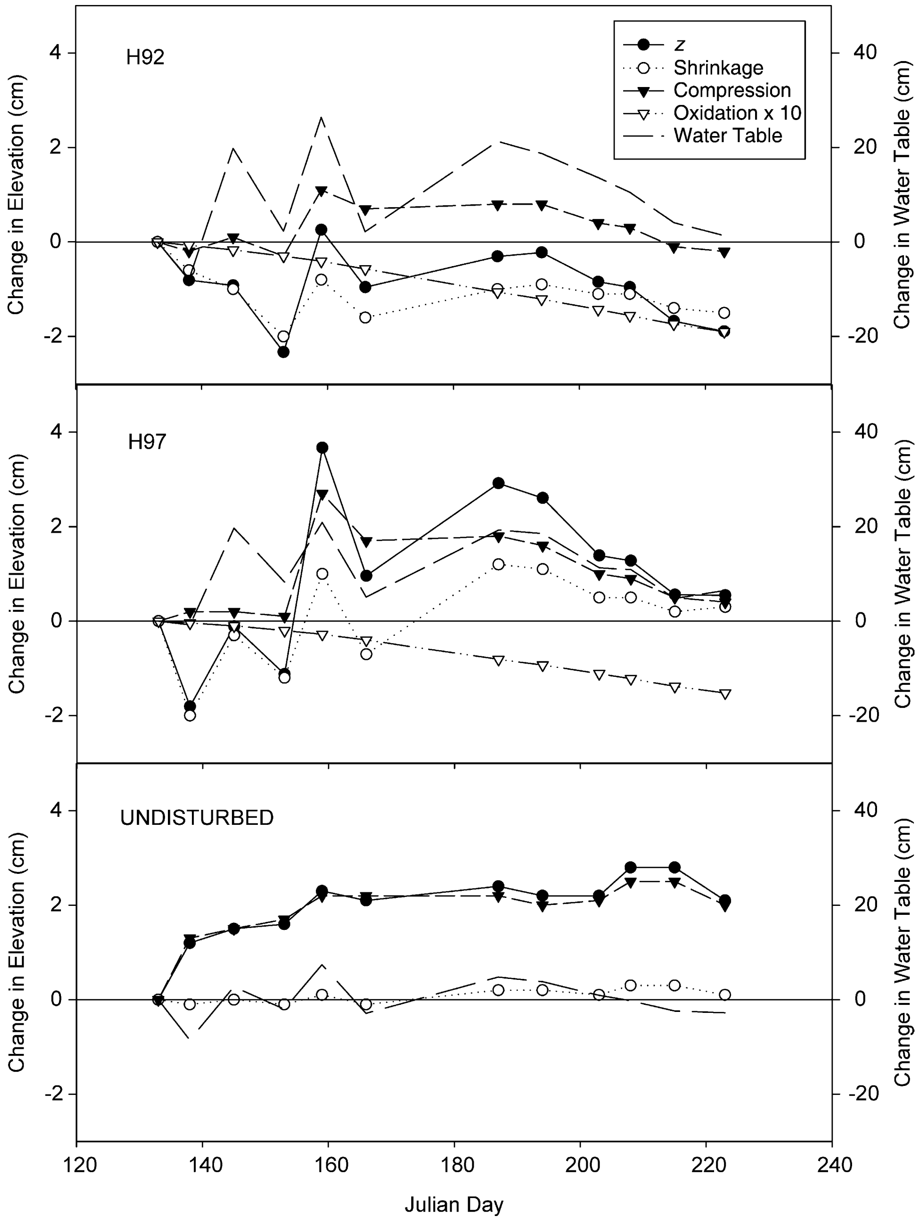

Fig. 5. Components of volume change at H92, H97, and UNDISTURBED sites.

were also expressed as a proportion of the total change in elevation occurring over each measurement interval and averaged seasonally. Shrinkage accounted for 55 and 59% of seasonal soil volume changes at H92 and H97, respectively, whereas compression accounted for 41 and 38%, and oxidation represented 4 and 3% of soil volume changes, respectively. Seasonal trends in shrinkage and compression are also presented for the UNDISTURBED site. Soil volume changes due to oxidation could not be determined because CO_2 emissions were not measured at this site in 1999 (Waddington et al., 2002). Oxidation at the UNDISTURBED site, however, is expected to be small due to the wet conditions over the study season and because CO_2 emissions at the cutover sites were significantly higher (260–290%) in previous years (Waddington et al., 2002).

Peat elevation (Δz) increased at both the H97 (+0.7 cm) and the UNDISTURBED sites (+2.1 cm) over the 1999 season, whereas a small decrease in elevation was observed at H92 (−1.7 cm). Of the two cutover sites, H97 exhibited the greatest variability in elevation, with a seasonal range of 5.5 cm being observed, compared to a seasonal range of 2.6 cm at the H92 site. Seasonal trends in elevation were less dynamic at the UNDISTURBED site (Fig. 5), with the peat gradually expanding a maximum of 2.8 cm over the study period. Volume changes at the cutover sites followed patterns of water-table and θ whereas volume changes at the UNDISTURBED site did not correspond very well to changes in WT and θ.

The soil shrinkage characteristic (SSC) curve (Fig. 6) can be divided into three phases: normal shrinkage (slope ∼1) between ν_0 and ν_1, residual shrinkage (slope <1) between ν_1 and ν_2 as air enters the peat, and a 0 shrinkage phase (slope→0) after the samples had lost 30–40% of their initial moisture content, where $\nu < \nu_2$. An exponential equation (Fig. 6) describes the shape of the SSC exhibited by each of the three peat samples.

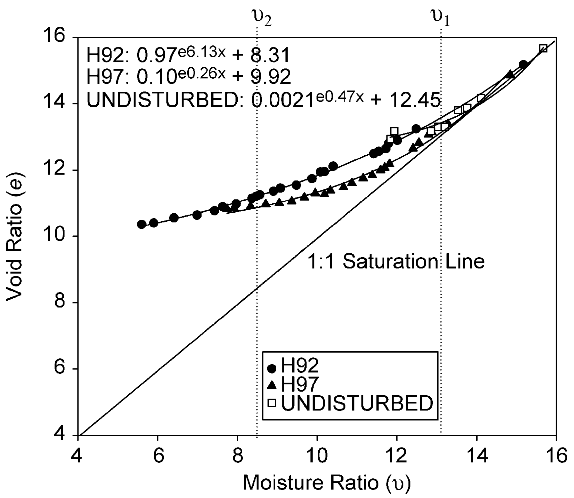

Fig. 6. The soil shrinkage characteristic at H92, H97, and UNDISTURBED sites.

4.3. Temporal variability in hydraulic properties and peat compressibility

Saturated volumetric moisture content (θ_S) at 100 cm depth decreased from 83 to 81%, and from 84 to 78% at H92 and H97, respectively. Saturated hydraulic conductivity (K_S) varied directly with change in elevation at both the H92 and H97 sites (Fig. 7). K_S (at 50 cm depth) ranged from 0.3 to 7.4 cm d^{-1} at H92 over the study season in response to an elevation change (−50 cm rod) of 1.2 cm ($r^2=0.81$, $P=0.0058$), so that each 1 cm change in elevation was associated with a 5.2 cm d^{-1} change in K_S. Comparatively, at the H97 site, K_S ranged from 1.0 to 3.5 cm d^{-1} in response to an elevation change of 1.5 cm ($r^2=0.76$, $P=0.0005$), so that each 1 cm change in elevation was associated with a 1.4 cm d^{-1} change in K_S. K_S could not be correlated with elevation change at the UNDISTURBED site.

The field θ–Ψ relationship at H92 was seasonally variable. Despite exhibiting a virtually identical moisture profile from 0 to −20 cm depth, pressure head values obtained on August 10th were 1.5 to 3 times less than on June 1st, differing by as much as −15 cm at 2 cm depth. The shift towards lower pressure heads indicates an increase in water retentivity. Water-table position was −36 cm on both dates. The dilation coefficient (S_d) was also transient. At H92 (the only site with long-term data), a seasonal decreasing trend in S_d was observed (Table 1). The inter-annual S_d data shows decreasing seasonal variability and decreasing early season compressibility over time. Except for 1995, where a relatively continuous decline in water-table was observed over the study period, the initial water-table levels associated with early and late season date ranges shown in Table 1 were comparable (±6 cm).

5. Discussion

The results provide insight into seasonal and longer-term changes to the character of peat following extraction operations, and their influence on peatland hydrological behaviour. Measuring and understanding these changes is necessary to develop a model of cutover peat systems that will assist in management

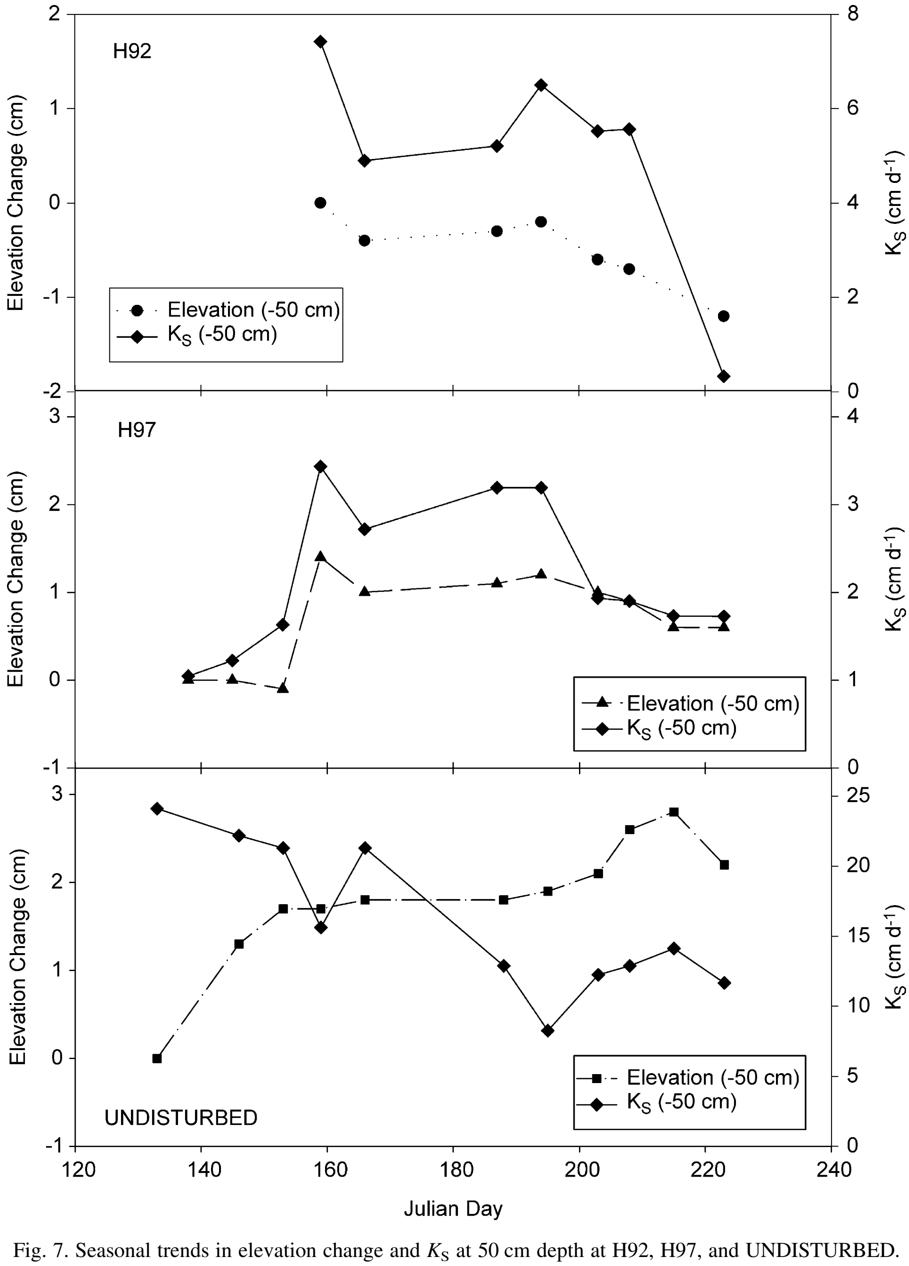

Fig. 7. Seasonal trends in elevation change and K_S at 50 cm depth at H92, H97, and UNDISTURBED.

decisions regarding site restoration. Longer-term changes can be deduced from spatial differences between UNDISTURBED, H97 and H92 because these sites represent a sequence of increasing time since disturbance. Hydrological responses are reported in detail for 1999, and are supplemented by data from 1995 to 1998.

5.1. Hydrological sensitivity to peat type

The comparison of hydrological behaviour at H92, H97, and UNDISTURBED sites illustrates the importance of peat type. The low S_y ($\sim$0.05) characteristic of the more compacted and humified peat (smaller pores, higher bulk density) of H92

Table 1
Seasonal and inter-annual trends in S_d at the H92 site

Year	Date range	Water table change: dh (cm)	Elevation change: db (cm)	S_d
1995	June 14th–July 4th	−17.8	−3.0	**0.17**
	July 4th–August 29th	−17.8	−0.7	0.04
1996	May 8th–June 6th	−38.1	−5.3	**0.14**
	July 26th–August 15th	−35.9	−2.6	0.07
1998	May 13th–May 28th	−20.4	−2.5	**0.12**
	July 29th–August 10th	−27.5	−1.3	0.05
1999	May 25th–June 2nd	−17.5	−1.4	**0.08**
	July 22nd–August 11th	−12.6	−1.0	0.08

resulted in the greatest range (±46 cm) of water-table fluctuation (Fig. 4a). High S_y (∼0.2–0.5) at the UNDISTURBED site (Price, 1996) moderated the range of WT fluctuation (±26 cm). Similarly, a decreasing trend in θ variability from undisturbed to cutover sites (UNDISTURBED > H97 > H92) was observed because retentivity is inversely related to average pore size diameter; the smaller pores at H92 retaining more water upon drainage (see also Boelter, 1965; Okruszko, 1995). The influence of altered pore structure is evident at H92, which had lower K_S (10^{-5}–10^{-7} cm s^{-1}) and more variable Ψ (range = 42 cm) at 2 cm depth compared to H97 (10^{-4}–10^{-6} cm s^{-1} and 36 cm, respectively). The reduced water flow to drying surface layers and more variable Ψ at H92 presents a more hostile environment for the re-establishment of *Sphagnum* than H97.

While comparison of the H92 and H97 sites illustrated long-term changes to cutover peat structure, short-term transience in hydraulic properties as a consequence of peat volume change was also observed. The decrease in θ_S at 100 cm depth was partly attributed to peat compression. A 2–4% decrease in the peat's θ_S profile (−20 to −100 cm) was observed from June 3rd to July 3rd, corresponding to approximately 1.3 cm of saturated soil compression at the H92 site, and 2.5 cm at H97. Similarly, Schlotzhauer (1998) attributed a 2% decrease in θ_S to compression of the saturated peat matrix. However, given an initial θ_S of 85% and a saturated peat thickness of 125 cm (z_s), 2.5 cm of peat compression would only result in a 0.3% decrease in θ_S. The higher observed change in θ_S may be due to methanogenesis, which has been shown (Beckwith and Baird, 2001) to reduce θ in saturated peat (see also Price, 2003).

K_S was related to elevation change at 50 cm depth (Fig. 7), reflecting a change in the average pore size diameter of saturated peat (see also Chow et al., 1992). Schlotzhauer (1998) attributed a decrease in K_S under conditions of declining head, and hence increased load, to a reduction in the volume and continuity of macropores. However, this may be confounded by methane gas (Beckwith and Baird, 2001), which may partly explain the lack of correlation between elevation change at 50 cm depth and K_S at the UNDISTURBED site (Fig. 7). A decrease in the average pore size diameter of the peat due to consolidation also caused a shift in the field θ–Ψ relationship towards more negative pressure heads at a given θvalue (see also Schlotzhauer, 1998) between June 2nd and August 11th, since smaller pore sizes can exert more negative pore-water pressures.

5.2. Changes in peat compressibility over time

Peatland drainage and extraction activities resulted in changes to peat pore structure (Price, 1997), with the soil becoming more dense and humified with increasing duration of the post-extraction period. Seasonal volume changes were greater at H97 (2-year post-extraction) because this site had lower ρ_b, higher e_0, and greater changes in water storage in the unsaturated zone compared to H92 (7-year post-extraction). Peat compressibility has been generally found to increase with increasing initial void ratio (e_0) (Hough, 1957; Lefebvre et al., 1984) and decreasing bulk density (ρ_b) (von Ow et al., 1996). Thus, the dilation coefficient (S_d) measured at the H92 site was only 44% of the value obtained at H97 (Table 2).

Elevation changes (−5 cm post) at the cutover sites responded to changes in soil moisture and water-table, whereas the UNDISTURBED site had the lowest S_d (db/dh) despite having a higher predicted intrinsic compressibility than the cutover sites due to its greater thickness, lower ρ_b and more porous peat structure (higher e_0). Moreover, a small net increase in elevation occurred at H97 (+0.7 cm) and UNDISTURBED (+2.1 cm) despite experiencing a small

Table 2
Inter-site comparison of S_d

Site	Date range	Water table change: dh (cm)	Elevation change: db (cm)	S_d
H97	July 6th–August 11th	−12.8	−2.3	0.18
H92	July 6th–August 11th	−20.0	−1.5	0.08
UNDISTURBED	July 6th–August 11th	−10.4	−0.3	0.03

seasonal soil water deficit. Price (2003) speculated that a similar rise in peat elevation in 1998 (UNDISTURBED) was caused by the production of CH_4 gas in excess of equilibrium pore-water pressure, causing peat layers to swell despite losing water. The higher dilation coefficients, S_d (Table 1), observed towards the beginning of each season (1995–98) may be a consequence of soil freezing enlarging peat pore spaces (Viklander, 1998), and thereby increasing peat compressibility. Irreversible decreases in compressibility due to secondary compression, or loads in excess of the preconsolidation pressure (P_c), probably have a seasonal effect on S_d but these changes are more important over the longer term. The biochemical process of oxidation and consequent soil decomposition also reduces compressibility, although the long-term significance of oxidative wastage on pore structure is more pronounced (Schothorst, 1977; Wösten et al., 1997; Waddington et al., 2002). The inter-site differences in S_d (Table 2) reflect the expected longer-term changes in consolidation behaviour because H92 has been subjected to the various mechanisms of subsidence for a longer period of time, resulting in decreased peat compressibility.

5.3. Shrinkage, compression and oxidation

The relative importance of shrinkage and compression was determined from the profile of elevation change. Shallow peat layers, undergoing shrinkage, experienced a greater rate of strain than deeper peat layers due to relatively large changes in effective stress ($\Delta\sigma'$), resulting from pore-water pressures (Ψ) below equilibrium pressure, and large changes in water content (Price, 2003). In contrast to studies by Pyatt and John (1989) and McLay et al. (1992), the SSC of the cutover peat in this study exhibited residual shrinkage (Fig. 6), suggesting linear models of peat shrinkage cannot adequately describe the peat's volumetric response over mid to low water contents. Although the rate of volume change in the unsaturated zone was greatest, these layers represent a smaller proportion of the overall aquifer thickness, which explains why shrinkage (55–59%) and compression (38–41%) had similar importance (Fig. 5). Oxidation was relatively unimportant, accounting for only 3–4% of soil volume changes occurring in 1999 (1.5–1.9 mm). Comparatively, Waddington et al. (2002) attributed 7–8 mm of subsidence to oxidation at this site in 1998, which represented approximately 10% of the maximum surface displacement observed at H97 over that study season.

5.4. Conceptual model of the cutover peat system

A conceptual model of the LSJ cutover peat system was developed assuming a 1D flow system (Fig. 8), since vertical hydraulic gradients were almost two orders of magnitude greater than lateral gradients, favouring vertical flow in spite of an anisotropy ratio (K_x:K_z) at this site of 3.7 (Schlotzhauer and Price, 1999). Post-snowmelt runoff losses are low, comprising about 5% of precipitation input (Price, 1996), because drainage ditches are blocked and the peat has a high storage and infiltration capacity. Seepage losses to the underlying regional aquifer are restricted by an iron pan (Price, 1996). Water exchanges are therefore dominated by P and ET and are limited to the soil-atmosphere interface. The contribution of oxidation to seasonal volume change was relatively insignificant at LSJ, with peat volume change occurring mainly though shrinkage and compression (Fig. 5). Over the long-term, however, oxidation would be an important volume change mechanism since volume changes are irreversible. Soil shrinkage cracks were generally not evident at this site, indicating that the soil underwent mostly vertical deformation.

The hydrological functioning of the cutover peat system is conceptually illustrated under conditions of water surplus (P>ET) and water deficit (P<ET). When water inputs exceed outputs, water is added to the soil profile, raising the position of the water-table (ΔWT_1). The void ratio (e), and hence thickness of unsaturated peat layers (z_u), increases with increasing

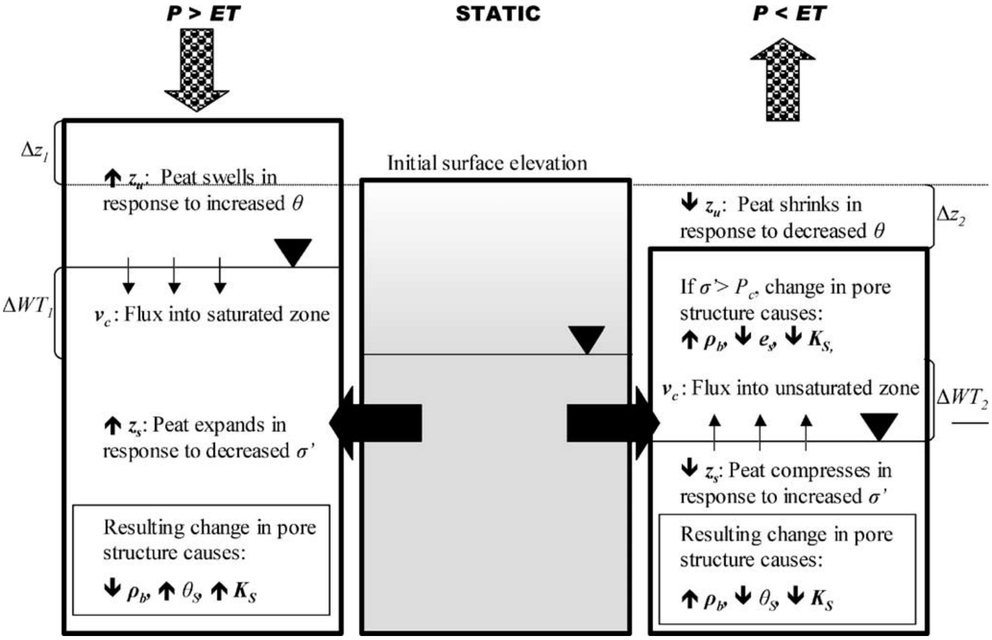

Fig. 8. Conceptual model of the LSJ cutover peat system illustrated under water surplus and water deficit scenarios.

θ according to the empirical soil shrinkage characteristic (SSC) (Fig. 6), whereas saturated peat layers (z_s) expand due to the decrease in effective stress (σ') associated with the rise in water-table (higher pore-water pressure—see Eq. (2)). A 1 cm increase in hydraulic head is approximately equivalent to a 0.1 kPa decrease in σ'. The magnitude of the increase in z_s per unit decrease in σ' is predicted by the peat's coefficient of volume compressibility (m_r), estimated as the slope of the recompression curve (Fig. 1). Expansion of saturated peat layers affects the soil's material and hydraulic properties, causing decreased bulk density (ρ_b), increased saturated volumetric moisture content (θ_S), and increased saturated hydraulic conductivity (K_S). A decrease in σ' is also associated with simultaneous downward flow into the saturated domain (v_c) as the pore-water pressure equilibrates to the static value governed by the new water-table position. The total increase in peat thickness (Δz_1) is expressed as the sum of shrinkage (z_u) and compression (z_s) components.

When the rate of evapotranspiration exceeds the rate of precipitation, water is withdrawn from the peat profile, decreasing θ and water-table elevation (ΔWT_2). The void ratio, and hence thickness of z_u decreases according to the SSC as a function of decreasing moisture content, whereas a *WT* decline increases the σ' on saturated peat layers, causing peat settlement by the processes of primary consolidation and secondary compression. Total peat settlement is expressed as Δz_2. The excess pore-water pressure generated in the saturated zone due to increased σ' is dissipated by upward flow of water into the unsaturated zone (v_c). It is assumed that primary consolidation is mostly reversible, since saturated peat layers have already experienced high effective stresses during drainage and extraction activities (Lang, 2002). Compression of saturated peat layers is associated with increased ρ_b, decreased θ_S, and decreased K_S. In the unsaturated zone, if the effective stress (estimated as $\sigma - \chi u$) exceeds the soil material's pre-consolidation pressure (P_c), an irreversible change in pore structure occurs, altering the soil's K_S, retention, and shrinkage characteristics. Decreased porosity and e therefore results in lower K_S and a shift in the θ–Ψ relationship towards more negative pressure heads at a specified moisture content.

The conceptual model does not explicitly consider the effect of CH_4 (g) accumulation on hydraulic variability because the sensitivity of the cutover peat's water storage and transmission characteristics to methane accumulation has not been quantified in the field. Methane gas accumulation within the peat profile may block pores, causing a confining layer (Romanowicz et al., 1995) that restricts flow and alters head gradients (Siegel, 1998).

6. Conclusions

Comparison of the hydrology and peat volume change at H92, H97, and UNDISTURBED sites illustrates the importance of pore structure in governing hydrological behaviour. Pore structure is variable in certain peats due to the changes in stress imparted by hydrological variability, and from oxidation of peat fibres. H92 experienced the greatest disturbance, and thus had a smaller characteristic pore size and consequently greater water retentivity and water-table fluctuation, the least variability in θ, and lower K and peat compressibility. Comparison of H92 (7-year post-extraction) and H97 (2-year post-extraction) results suggests a significant deterioration in the self-regulating capacity of the cutover bog over a relatively short time-scale (5 years). During this period there was oxidation and irreversible subsidence that reduced peat compressibility. The sensitivity of the system's hydrological functioning to pore architecture indicates that short-term temporal variability in pore structure has important hydrological consequences, which is evident from seasonal changes of θ–Ψ, K_S, and θ_S.

In conclusion, this study has shown that water inputs and outputs are dominated by P and ET (i.e. post-snowmelt runoff), volume changes are primarily attributed to shrinkage and compression in the vertical direction, and that volume changes result in transient hydraulic properties. These must be accounted for to predict the hydrological response of the system to seasonal weather patterns or water management activity. A 1D model of the cutover peat system can represent the important linkages between volume change and hydrological behaviour.

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