

The influence of peat volume change and vegetation on the hydrology of a kettle-hole wetland in Southern Ontario, Canada

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SUMMARY

Links between local hydrology and vegetation type exist in wetlands, yet it is unclear what role peat volume change plays in these interactions. We measured peat volume change and hydraulic conductivity (K_{field}) at three contrasting sites located on the quaking vegetation mat of a kettle-hole peatland in southern Ontario. The three sites had visibly different plant communities and were named, according to their dominant vegetation, Sedge (*Carex* spp.), Typha (*Typha angustifolia*) and Carr (*Cornus stolonifera*). Peat was also collected for laboratory studies of peat volume change, vertical (K_v) and horizontal (K_h) hydraulic conductivity and the effect of compression on hydraulic conductivity (K_c).

In the field, the water table rose throughout the study period, resulting in swelling of the peat. Peat volume change above the -100 cm layer was 11.2%, 6.0% and 3.8% at the Sedge, Typha, and Carr sites respectively. In laboratory samples, a falling water table caused compression of the peat below the structured surface mat, and relative peat volume change between the sites followed the same pattern as in the field. K_{field} , K_v and K_h generally decreased with depth from *ca.* 10^{-2} to 10^{-6} cm s⁻¹. In the surface layers (0 to -50cm) K trended Carr>Typha>Sedge, whereas the reverse trend was observed in deeper peat. Artificial compression affected K only in the uppermost layers (0 to -15cm). The decline in K_c with compression also trended Sedge>Typha>Carr. Differences in peat volume change and K are probably related to differences in vegetation and soil structure, and may be important for maintaining suitable growing conditions within each community.

KEY WORDS: hydraulic conductivity, kettle-hole peatland, quaking mire, strain, subsidence.

INTRODUCTION

Kettle-hole wetlands, developed in depressions (basins) formed by residual ice blocks (Warner *et al.* 1989), are widespread in glaciated landscapes. In Southern Ontario these ecosystems provide important habitat for species that are typical of more northerly landscapes (e.g. Tiner 2003). Buoyant peat-vegetation mats and quaking mire are common features of these wetlands (Kratz & DeWitt 1986, Bunting & Warner 1998), so that peat volume change is likely to be important in maintaining suitable growing conditions for the vegetation.

Development of the vegetation in kettle-hole wetlands occurs by hydrosere succession, which has been well described by paleoecological studies (e.g. Bunting & Warner 1998). The process is driven by internal (autogenic) factors such as the accumulation of organic matter, and by external (allogenic) factors such as climate. Thus, conditions within the wetland result from the interaction between vegetation, soil formation and hydrology.

The succession results in a vegetation gradient between the edge and centre of the basin. Hydrology and peat accumulation influence the arrangement of plant communities along this gradient; but because the vegetation provides the organic matter for peat accumulation, there is potential for feedback to local hydrological attributes such as compressibility and hydraulic conductivity. Whilst the importance of local hydrology in controlling soil aeration, nutrient mineralisation and vegetation productivity has been investigated (e.g. Laiho *et al.* 2003), the interaction between plant community and local hydrology remains unclear.

Given that volume change in organic soil (peat) can be ten times greater than in clay soil (Hobbs 1986), soil volume change is an important consideration for peatland hydrology (Kellner & Halldin 2002, Price 2003, Kennedy & Price 2005). Changes in peat volume related to natural water table fluctuations and drainage can affect soil water storage (Price & Schlotzhauer 1999, Kellner & Halldin 2002), bulk density (Silins & Rothwell

1998, Whittington & Price 2006), pore size and structure (Kennedy & Price 2005) and hydraulic conductivity (Chow *et al.* 1992, Price 2003, Whittington & Price 2006). These interactions are important not only for peatland hydrology (e.g. Hogan *et al.* 2006); but also for peatland ecology and biogeochemistry, which are linked to water table position and water movement (e.g. Bubier 1995, Waddington & Roulet 1997).

Volume change in peat is related to the movement of the water table and the consequent changes in pore water pressure (Price 2003). During periods of static water table, the force acting downwards at a given point in the peat, known as the total stress (σ_T), is equal to the product of the mean density (ρ_T) of the overlying material (water, soil and air), the gravitational constant, g , and the depth, h , to that particular point (Terzaghi 1943), i.e.

$$\sigma_T = \rho_T gh \quad [1]$$

Since air has little mass compared to the water and organic material in the overlying peat,

$$\rho_T = (M_s + M_w)/V \quad [2]$$

where M_s and M_w are the mass of soil and water respectively within a given volume (V) of the soil column. M_w is equivalent to the product of gravimetric water content (θ_g) and M_s , therefore:

$$\rho_T = M_s/V + \theta_g M_s/V. \quad [3]$$

Since dry bulk density (ρ_b) is equal to M_s/V , Equation 3 can be written:

$$\rho_T = \rho_b(1 + \theta_g). \quad [4]$$

Thus, total stress can be expressed as:

$$\sigma_T = \rho_b(1 + \theta_g)gh. \quad [5]$$

σ_T is offset by the upward force of pore water pressure (ψ), so that the force or effective stress (σ_e) that the peat structure must bear is given by

$$\sigma_e = \sigma_T - \psi. \quad [6]$$

At a fixed location in the peat column, ψ and θ_g are reduced if the water table (as measured against a stable datum, hereafter referred to as absolute water table WT_{abs}), is lowered. The reduction in θ_g results in a decline in σ_T , but this is exceeded by the reduction in ψ so that σ_e increases. If the increase in σ_e exceeds the ability of the peat structure to

withstand it, compression (shrinkage/subsidence) will occur. Conversely, a rise in water table will increase ψ , reducing σ_e and resulting in swelling/expansion. As the water table rises and falls, the profile typical of a kettle hole wetland system swells and subsides by various amounts at different depths (Haraguchi 1992). This uneven swelling and subsidence is referred to as peat volume change (Price 2003). The percentage change in thickness of a given peat layer is defined as strain (ε), with positive strain indicating expansion and negative strain compression (Figure 1a).

Because changes in WT_{abs} can result in peat volume change, the surface level (relative to a stable datum, SL_{abs}) also changes through time. This means that shifts in water table position relative to the surface (WT_{rel} , Figure 1a) are smaller than the changes in WT_{abs} , leading to more stable moisture conditions at the peat surface than would be observed in a rigid soil (Price & Schlotzhauer 1999). In this study we measured the altitudes of the surface, water table and peat layers against reference stakes driven into the stable clay layer beneath the peatland (Figure 1a). All altitudes, in both the field and the laboratory, are expressed relative to an arbitrary datum set at the initial altitude of the surface; positive values of SL_{abs} indicate expansion of the peat and negative values compression.

The magnitude of peat volume change in response to a given hydrological perturbation varies within and between peatlands (Kellner & Halldin 2002, Price 2003, Whittington & Price 2006). The magnitude of ε for a given change in σ_e is defined as the compressibility C_v of the soil (Price *et al.* 2005). Variation of C_v across a peatland will result in variation of factors such as dry bulk density, hydraulic conductivity and aeration of the peat with consequent effects on water movement, nutrient mineralisation rate and vegetation productivity. The variability in C_v is not well explained by readily measured peat properties such as bulk density, degree of humification or fibre content (Price *et al.* 2005), indicating that additional factors are involved. Weiss *et al.* (1998) improved their models of soil water retention in peat by taking into account vegetative composition, and it is likely that vegetation also plays a role in governing other hydrophysical properties of peat. Given that quaking mats and vegetation gradients are common in kettle-hole peatlands (Kratz & DeWitt 1986, Bunting & Warner 1998), it is important to understand the interactions between vegetation, peat volume change and hydrology in order to improve our ability to describe the ecohydrology of these systems.

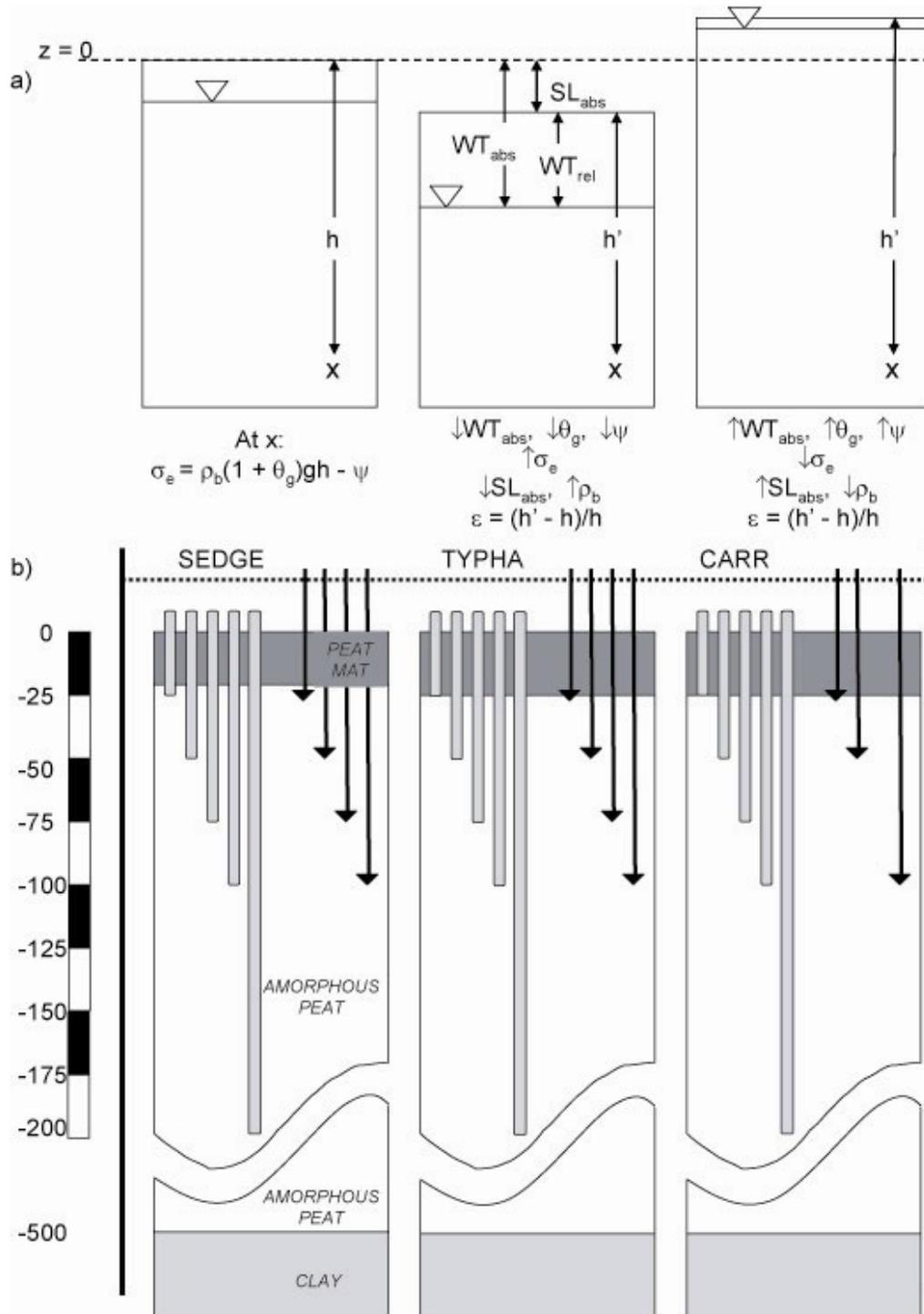


Figure 1. (a) Conceptual diagram showing the relationship between absolute water table position (WT_{abs}), gravimetric water content (θ_g), pore water pressure (ψ), effective stress (σ_e), absolute surface level position (SL_{abs}), dry bulk density and strain (ε). X is a point of interest within the peat and h and h' are the heights of the mire surface above X initially and after a shift in WT_{abs} . Water table position expressed relative to the surface ($WT_{abs} - SL_{abs}$) is shown as WT_{rel} . All altitudes given in the text are expressed relative to an arbitrary stable datum set equal to zero at the surface of the peat on the first measurement date of the study (in either the field or the laboratory). Thus, positive changes in SL_{abs} indicate expansion of the peat column and negative values compression. (b) Diagram showing the positions of piezometers (■), peat altitude sensors (↓) and the fibric peat mat for each field location. Absolute altitudes were measured relative to a stable sighting wire (dotted line) supported by reference stakes (■) driven into the underlying clay.

The goal of this paper is to examine the nature and magnitude of peat volume change in a kettle-hole peatland and its relationship to hydrology and vegetation. The specific objectives of the work reported were to investigate, through field and laboratory studies:

- 1) how peat volume change varies between sites with different plant communities;
- 2) how hydraulic conductivity (K) differs between plant communities; and
- 3) the relationship between peat volume change and hydrology.

METHODS

Study site

Spongy Lake peatland lies approximately 14 km west of Waterloo, Ontario at 43° 25' N, 80° 37' W. It

formed in a kettle-hole depression and has an area of approximately 30 hectares. Steep slopes 15–20 metres in length are present along the eastern and western sides of the depression, and a peatland has developed at its centre. A buoyant (quaking) peat-vegetation mat covers a substantial portion of the peatland, but shallow water is often present over unvegetated peat (muck) at its centre (Figure 2). Beneath Spongy Lake, 5 m of highly decomposed peat is underlain by a clay layer of undetermined thickness (Karrow 1993).

Spongy Lake lies above the regional water table. Its water sources include agricultural runoff (mainly during snowmelt), groundwater recharge from a perched aquifer in the south-east corner, and direct precipitation (Dempster *et al.* 2006). The 1971–2000 mean annual precipitation is 908 mm and the average January and July temperatures are -7.1 and 19.8 °C respectively (Environment Canada 2007).

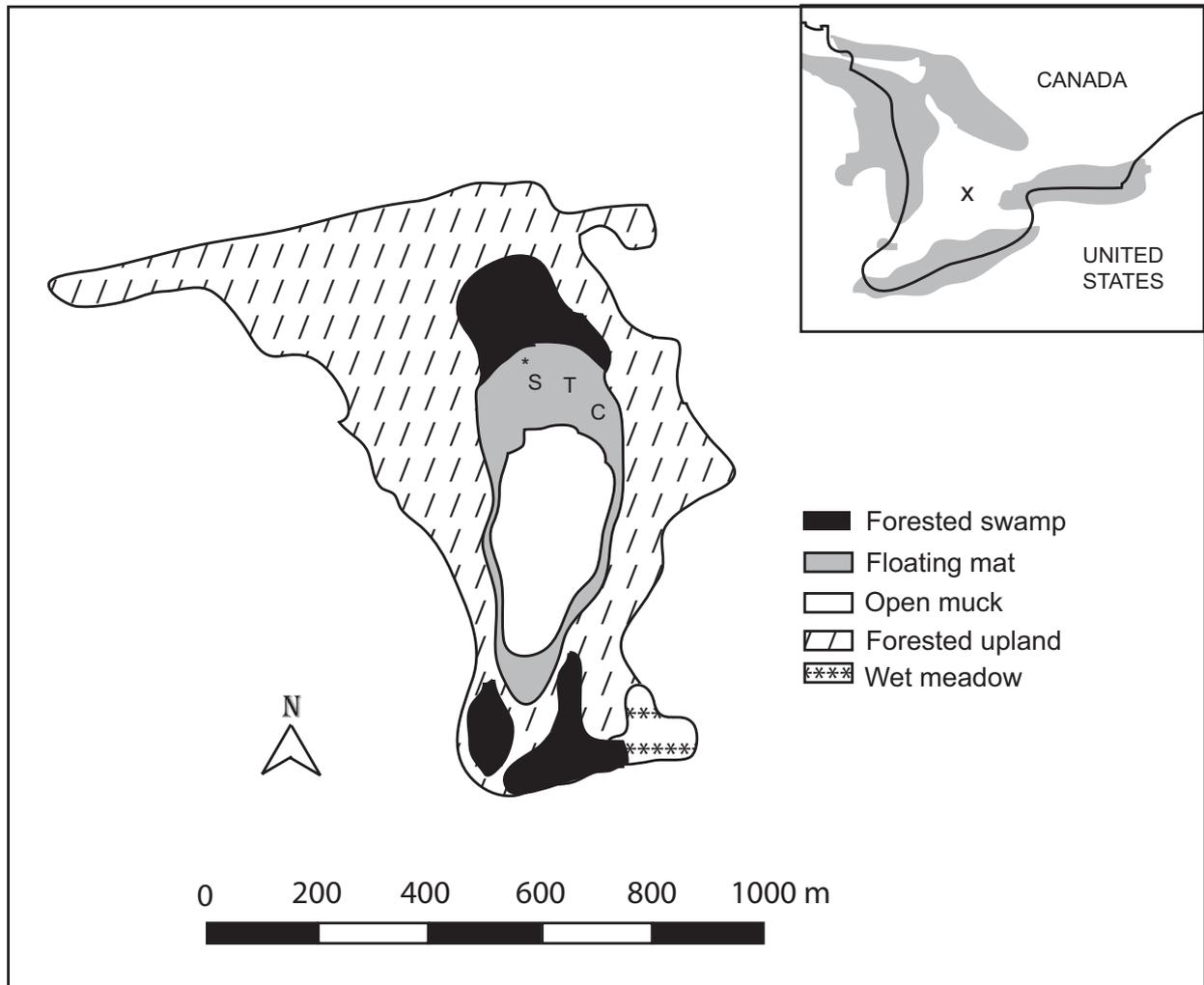


Figure 2. Map of the Spongy Lake basin showing the locations of the micrometeorological station (*) and the three sampling sites Sedge (S), Typha (T) and Carr (C). The inset map shows the location (X) of Spongy Lake (in Southern Ontario, Canada) in relation to Lakes Huron (upper left), Erie (bottom centre) and Ontario (right), which are represented by grey shading.

The vegetation was described by Bloemen *et al.* (1979) and authorities for all identified species are given according to Scoggan (1978). According to Bloemen *et al.* (1979) the vegetation of the lower hillslope and quaking mire areas consists of cattails (*Typha angustifolia* L.), sedges (*Cyperaceae* in particular *Carex* spp.), grasses (family *Poaceae*), mosses (*Sphagnum* spp.), cut-leaf water horehound (*Lycopus americanus* Muhl. ex W. Bart.), marsh cinquefoil (*Potentilla palustris* (L.) Scop.), leatherleaf (*Chamaedaphne calyculata* (L.) Moench) and dogwood (*Cornus stolonifera* Michx.). To the north and south there is cedar swamp dominated by *Thuja occidentalis* L. The side slopes of the depression are covered by mixed hardwood forest which includes red maple (*Acer rubrum* L.), tamarack (*Larix laricina* (Du Roi) Koch), and chokeberry (*Pyrus arbutifolia* (L.) L.f.).

Three sites, denoted Sedge, Typha and Carr (Figure 2), were monitored for peat volume changes and hydrology from 15 October 2003 to 03 December 2003 (day of year (d) 288–337). The sites, which lie within 150 m of one another, were chosen because they are visually distinct and represent the dominant plant communities of the quaking mire. The Sedge site is dominated by *Carex* spp. with a mat of sedge leaves and rhizomes 15–20 cm thick. The Typha site is dominated by *Typha angustifolia* and has a 25 cm mat of *Typha* leaves and large, fleshy rhizomes. The Carr site is dominated by red osier dogwood (*Cornus stolonifera*) with a 25 cm mat composed of leaves and woody debris. At all sites - and indeed throughout the wetland - there is a layer of amorphous, highly decomposed gyttja-like peat beneath the fibric mat; nowhere did we find a lens of water. While the surface at the Sedge and Typha sites is highly quaking, the Carr site is closer to the mineral margin and firmer. Instrumentation (described below) was placed at representative points within each community.

Micrometeorology

Precipitation, air temperature, water table and surface altitude were recorded adjacent to the Sedge site at 30 minute intervals from d 309 to d 337, using a Campbell Scientific CR10 data logger. Water table and surface altitude were measured, with respect to a stable datum post anchored in the clay substrate, using counter-balanced pulley mechanisms attached to calibrated potentiometers. Precipitation was recorded with a tipping bucket raingauge and air temperature with a thermocouple.

Peat volume change

The strain (ϵ) that occurred because of changes in

pore water pressure was determined manually at the Sedge, Typha and Carr sites using altitude sensors similar to the 'elevation sensor rods' described by Price (2003). Each sensor consisted of a length of 5 mm diameter wooden dowelling (the rod) with a spring-loaded metal anchor affixed to one end and a measuring tape at the other end. A narrow hole was augered into the peat to a depth a few centimetres shallower than the desired anchoring depth, and a 2 cm diameter plastic tube was installed. The sensor was inserted into the tube with the anchor retracted and pushed beneath the bottom of the plastic tube. As the anchor was pushed out of the tube, it sprang open and anchored the rod into the peat at that depth. The plastic tube reduced friction of the peat against the rod so that the peat above the anchor could expand and contract freely. Volume change was determined by reading the measuring tape against a sight wire strung between stable metal posts anchored into the clay substrate. Because of the thickness of the sight wire and human error in reading the measuring tape, precision was ± 0.2 cm.

Manually read sensors were anchored at depths of -25, -50, -75 and -100 cm relative to the surface at the Sedge and Typha sites, and at -25, -50 and -100 cm at the Carr site (Figure 1b). Their initial altitudes were recorded immediately after installation. On each subsequent measurement date, the new altitude of each sensor was recorded and referred to the initial position; and the thickness of each layer (e.g. -25 to -50 cm depth) was computed from the changes in altitude of the sensors at the top and bottom of the layer. Strain was calculated as the change in the thickness of the layer since the initial measurement, divided by its initial thickness (25 cm in most cases). The manual sensors were read weekly from d 288 to d 337. An additional -100 cm altitude sensor was installed at the Sedge site and monitored with a pulley-potentiometer device, as for the surface altitude and water table measurements outlined above (see Micrometeorology).

Peat was extracted from each site for laboratory strain experiments. Each sample was obtained using a 20 litre plastic bucket with the bottom removed. This was inserted into the peat until the top of the bucket was flush with the peat surface. During insertion, a saw was used to cut down into the peat to reduce compaction/damage to the sample. The lid of the bucket was then affixed and sealed to create suction for removal, and the bucket was lifted out of the ground whilst supporting the sample from below. After lifting, the sample was allowed to slide into an intact bucket of the same size. The bottom of the second bucket was pre-fitted with a flexible manometer tube to allow water level manipulation; it already contained 2.5 cm of sand to facilitate

drainage and approximately 3 litres of water to ensure that the sample had adequate buoyancy to minimise compression during transport to the laboratory.

The movements of the surface and of two altitude sensors, anchored within and beneath the fibric mat respectively, were used to determine peat volume change under manual water table drawdown. As the thickness of the fibric mat differed between sites, the rods were anchored at -15 and -25 cm in the Carr and Typha sample buckets, and at -10 and -25 cm in the Sedge sample bucket. The tops of the buckets were covered loosely with plastic film to prevent water loss by evapotranspiration. The water level was drawn down in increments of -1 to -2 cm by lowering the outflow/manometer tube, and the altitude sensors were read 24 hours after each change. Strain in each layer was calculated as for the field measurements.

Hydraulic conductivity

At each of the three sites, five piezometers were installed on a transect (25 cm horizontal spacing) at -25, -50, -75, -100, and -200 cm depth. Each piezometer was constructed from 2.54 cm i.d. PVC tubing and provided with a 20 cm perforated intake centred at the measurement depth. At equilibrium, the water level in each piezometer indicated the water pressure at the measurement depth. *In situ* hydraulic conductivity (K_{field}) at the five measurement depths was determined using simultaneous bail tests (Hvorslev 1951), which involved removing water from the tubes then monitoring the recovery of the water level towards its initial (equilibrium) position through time. For each tube, K was calculated from the slope of the recovery curve using shape factors derived according to Freeze & Cherry (1979).

A WardenaarTM corer was used to collect peat cores (cross section *ca.* 10 cm x 13 cm) from all three sites for laboratory determination of vertical and horizontal hydraulic conductivity (K_v and K_h). Due to the non-rigid nature of the peat below the fibric mat, the cores were limited to 40 cm depth at the Sedge and Typha sites and 60 cm at the Carr site. The cores were divided into visually homogeneous sub-samples which were then cut smaller and sealed with paraffin wax into 10.2 cm i.d. PVC tubes (Hoag & Price 1997). Profiles of K_v were determined by removing the wax from the tops and bottoms of the subsamples and placing them on a constant head permeameter with water movement in the upward direction. After a steady flux of water was achieved, K_v was determined using Darcy's law. K_h was determined on the same sub-samples by removing them from their wax casings, rotating

them through 90 degrees, re-sealing, and measuring K_h using the same method as for K_v .

The effect of compression on hydraulic conductivity (K_c) was investigated on separate 15 cm long peat samples taken from three depths at the Sedge, Typha, and Carr sites. Each sample was collected in a graphite coated 10.2 cm i.d. PVC tube inserted into the peat with the assistance of a saw. The graphite coating allowed the peat to slide freely along the tube when compression was applied in the laboratory. The samples, still inside their tubes, were then sealed into water-filled plastic bags to prevent compression during transport.

Vertical hydraulic conductivity at various stages of compression (K_c) was determined using a constant head permeameter without sealing the cores in wax. Mechanical compression was applied using a plunger with a perforated steel disk set at the top of the sample. Compression was achieved by tightening wing nuts causing the steel disk to press down on the peat sample until a displacement of 0.2 cm was achieved. The sample was allowed to equilibrate for 30 minutes before K_c was determined. Compression was increased sequentially until a total compression of 1 cm was achieved. This provided a level of strain comparable to that recorded in the field.

RESULTS

During the 29-day period of logger records (d 309–337), precipitation occurred on 17 days and the total precipitation input was 94 mm (Figure 3a). A snowfall event during the latter part of the period was not measured by the tipping bucket raingauge.

WT_{abs} at the Sedge site rose by about 22 cm during this period (Figure 3b). Precipitation caused the water table to rise but it stabilised and/or declined within 0.5 hours of each precipitation event (not shown by the daily averages in Figure 3b). The accumulation of *ca.* 5 cm of snow, not recorded in the precipitation totals, had a direct impact on pore water pressure and caused the water table to rise sharply after d 330.

The peat surface and the -100 cm sensor rose with the water table (Figures 3b, 3c). The rate of rise was similar to that of the water table until d 319, after which the peat fell behind the water table so that inundation of the site eventually resulted. At the end of the study period, WT_{rel} was 16 cm. The change in surface level from d 309 to d 337 was 6.6 cm, and the change in the altitude of the -100 cm sensor was 5.5 cm over the same period (Figure 3c). This indicates a strain of 1.1% in the upper 100 cm during this period.

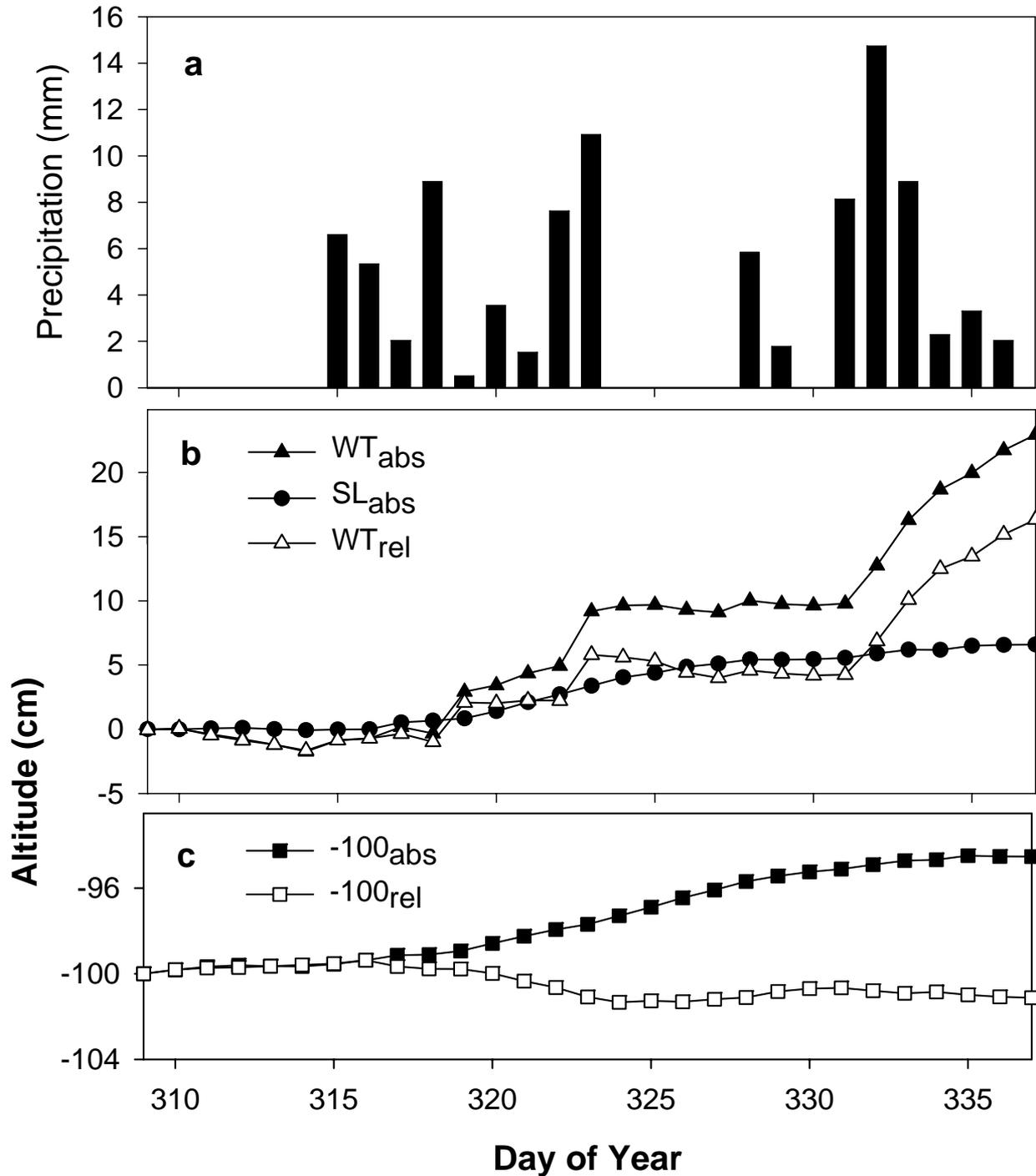


Figure 3. (a) Precipitation, (b) absolute surface level (SL_{abs}), absolute and relative water table (WT_{abs} , WT_{rel}), and (c) absolute and relative altitude of the logged (-100 cm) sensor at the Sedge site. Absolute altitudes are given relative to the initial surface level (on d 309), and relative altitudes are given relative to the surface level on the date of measurement.

Peat volume change

In the field, peat volume change below -25 cm was greatest at the Sedge site and least at the Carr site. The total increase in altitude of the -25 cm sensor was 7.9, 6.3 and 4.6 cm at the Sedge, Typha and

Carr sites respectively. All sites showed similar increases in volume until d 309, after which peat expansion at the Carr site was less than that at the Sedge and Typha sites (Figure 4). These volume increases coincided with a rise in water table

(Figure 3b). At all sites, the peat layer immediately above the -100 cm sensor exhibited the greatest strain (ϵ), which amounted to 11.2%, 6.0% and 3.8% at the Sedge, Typha and Carr sites respectively. The strain in each layer varied with time (Figure 5). In several cases, expansion of the upper layers led to compression of deeper layers; for example on d 309 at the Typha site and on d 323 at both the Sedge and the Typha sites (Figure 5).

In the laboratory, the surfaces of all peat samples subsided as the water table was lowered. When the water table was at *ca.* -20 cm, ϵ in the layer beneath

the fibric mat was -15.2%, -8.0% and -7.2% at the Sedge, Typha and Carr sites respectively. Strain was much lower within the mat. Sedge experienced volume loss (-0.8%), whereas Typha and Carr expanded by 2.4% and 0.8% respectively. Because precision of the peat altitude sensors was 0.1–0.2 cm, changes in volume of less than 1.6% of the 25 cm mat were within this error and likely to be negligible. Thus, there was little change in volume of the mat in any of the laboratory determinations; the majority of the strain occurred in the peat below -25 cm.

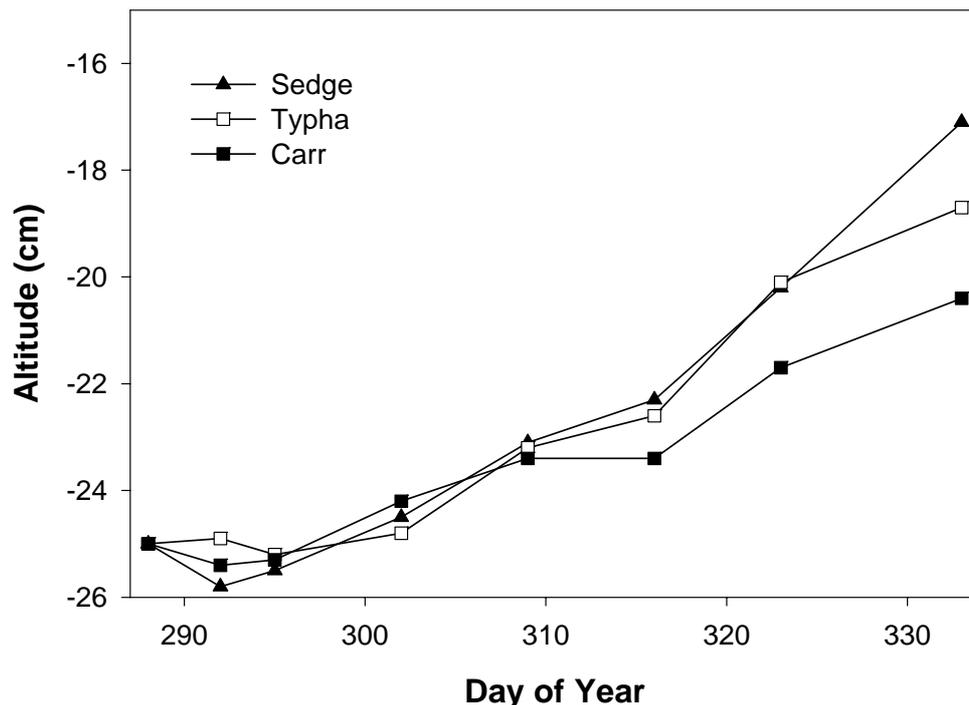


Figure 4. Changes in positions of the -25 cm altitude sensors in the field at Sedge, Typha and Carr sites.

Hydraulic conductivity

Field measurements of hydraulic conductivity (K_{field}) (Figure 6), ranged from 10^{-2} to 10^{-6} cm s^{-1} ($n = 14$). Hydraulic conductivity in the fibric mat generally decreased with depth. The deepest piezometer (-200 cm) consistently had the lowest K_{field} , and K_{field} declined by an order of magnitude between -50 cm and -75 cm at both Typha and Sedge. Three piezometers (Carr -200 cm, Sedge -50 cm and -200 cm) recovered by less than 50% during the sampling period, whereas recovery at the -25 cm Carr piezometer was too fast for our manual instruments to record. At -50 cm and above, Carr had the highest K_{field} followed by Typha and Sedge, whereas at -75 and -100 cm the pattern was reversed. K_{field} was similar at -200 cm for all sites.

In the laboratory, K_v declined with depth at all sites except Sedge, where K_v reached a maximum in the -8 to -17 cm layer. However, this pattern was not observed in a second core taken from the same site (Table 1). K_v varied between 9.5×10^{-2} and 4.5×10^{-3} cm s^{-1} for the Sedge sample and between 2.7×10^{-3} and 7.5×10^{-5} cm s^{-1} for the Carr sample, and was 1.2×10^{-2} cm s^{-1} at the two measurement depths in the Typha sample. Values of horizontal hydraulic conductivity (K_h) exceeded 10^{-2} cm s^{-1} everywhere except in the -38 to -52 cm sample from the Carr site (10^{-4} cm s^{-1} ; Table 1). For Sedge and Typha, K_h patterns were similar to those observed for K_v . K_h was generally greater than or equal to K_v , values for the majority of the samples being 1.18–1.98 times the associated K_v measurements.

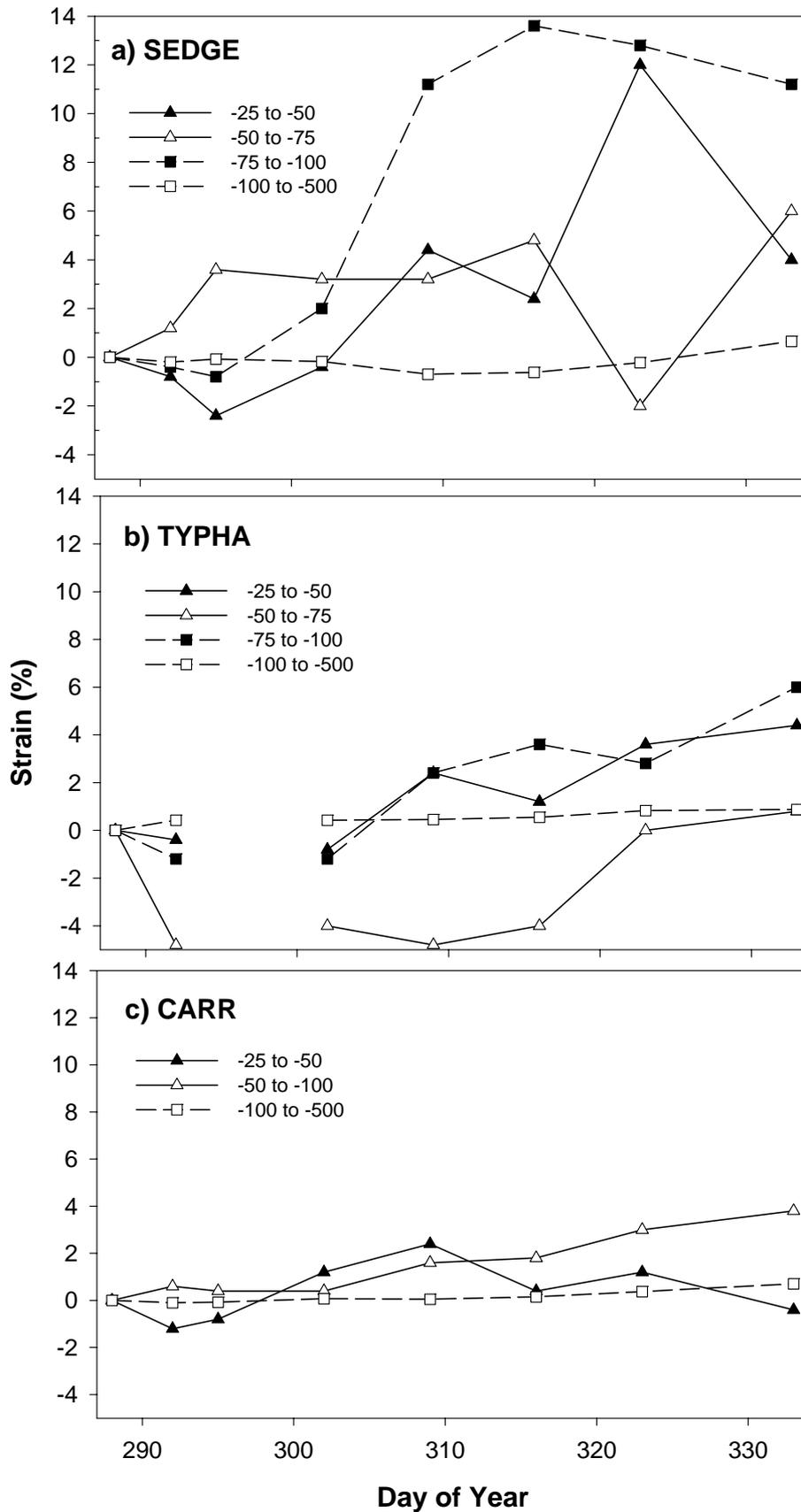


Figure 5. Variation of strain (compression) through time in different peat layers at (a) Sedge, (b) Typha and (c) Carr, derived from manual altitude sensor readings in the field. For each site, the depth ranges (in cm) of the layers that were tested are indicated.

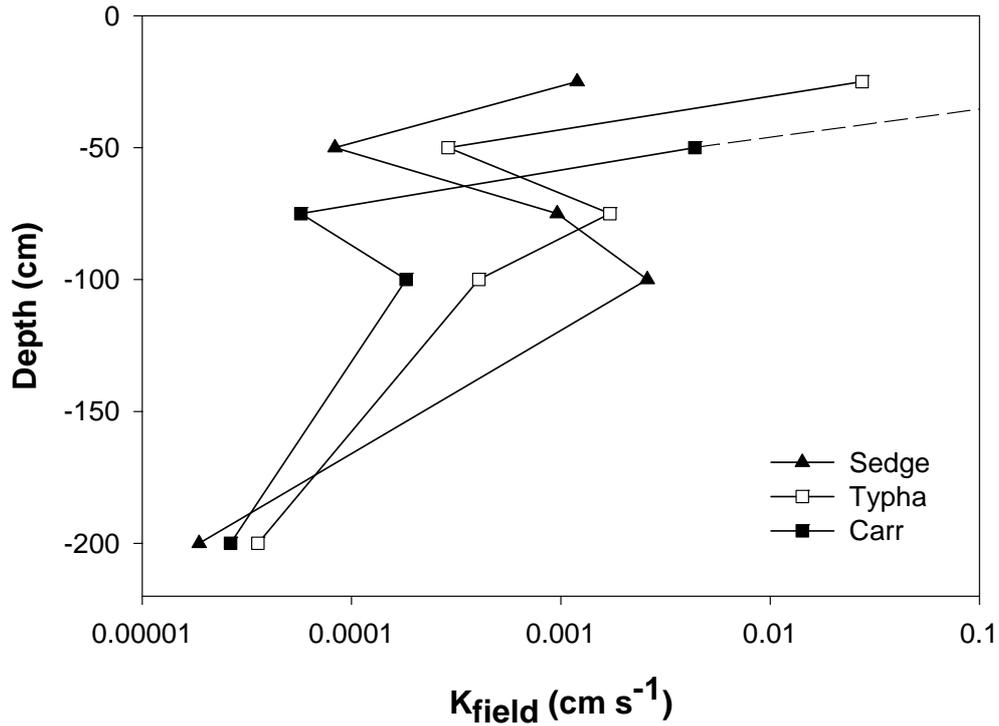


Figure 6. Depth profiles of K_{field} . The dashed line between -25 and -50 cm for Carr indicates that, even though the recovery was too fast to measure, the -25 cm value was greater here than at Sedge or Typha.

Table 1. Laboratory-determined K_v , K_h , and anisotropy.

Site	Depth (cm)	K_v ($cm s^{-1}$)	K_h ($cm s^{-1}$)	Anisotropy [$\log(K_h/K_v)$]
Sedge	0 to -8 ^a	3×10^{-2}	6×10^{-2}	0.28
	-8 to -17 ^a	9×10^{-2}	9×10^{-2}	0
	-17 to -28 ^a	1×10^{-2}	n.m.	n.c.
	-28 to -38 ^a	5×10^{-3}	n.m.	n.c.
	0 to -13 ^b	2×10^{-2}	2×10^{-3}	-0.88
	-13 to -24 ^b	1×10^{-3}	3×10^{-3}	0.42
Typha	0 to -18	1×10^{-2}	3×10^{-2}	0.35
	-18 to -30	1×10^{-2}	3×10^{-3}	-0.61
Carr	-15 to -25	3×10^{-3}	3×10^{-3}	0.10
	-25 to -38.5	8×10^{-4}	8×10^{-3}	1.02
	-38.5 to -52	7×10^{-5}	9×10^{-5}	0.08
	-52 to -64	8×10^{-5}	3×10^{-3}	1.63

Two Sedge cores were collected, and the superscripts ^{a,b} distinguish the two cores; n.m. = not measured; n.c. = not calculated.

Anisotropy was calculated as $\log_{10}(K_h/K_v)$ so that negative values indicate cases in which K_h was less than K_v . All values were positive except for peat from -18 to -30 cm at Typha and -13 to -24 cm at Sedge, where they were only slightly negative. The values obtained ranged from -0.6 to 1.6 (Table 1) with an arithmetic mean of 0.35. The average anisotropy was thus slightly lower than the values of

0.55 and 0.57 reported respectively by Beckwith *et al.* (2003) and Price & Schlotzhauer (1999).

Changes in hydraulic conductivity caused by compression (K_c) varied from 10^{-3} to 10^{-5} $cm s^{-1}$ (Figure 7). The values were consistent with the data from wax encased cores, indicating that preferential flow paths did not develop between the samples and the walls of the PVC tubes. The uncompressed

values for all samples supported the finding that hydraulic conductivity decreases with increasing depth. In general, this held true as compression was applied, although the surface layers at both Sedge and Typha were exceptions. K_c decreased with

increasing strain, although in a few cases large decreases in K_c were partly reversed when further compression was applied. K_c decreased by approximately half an order of magnitude over the -6% to -10% total range of strain applied.

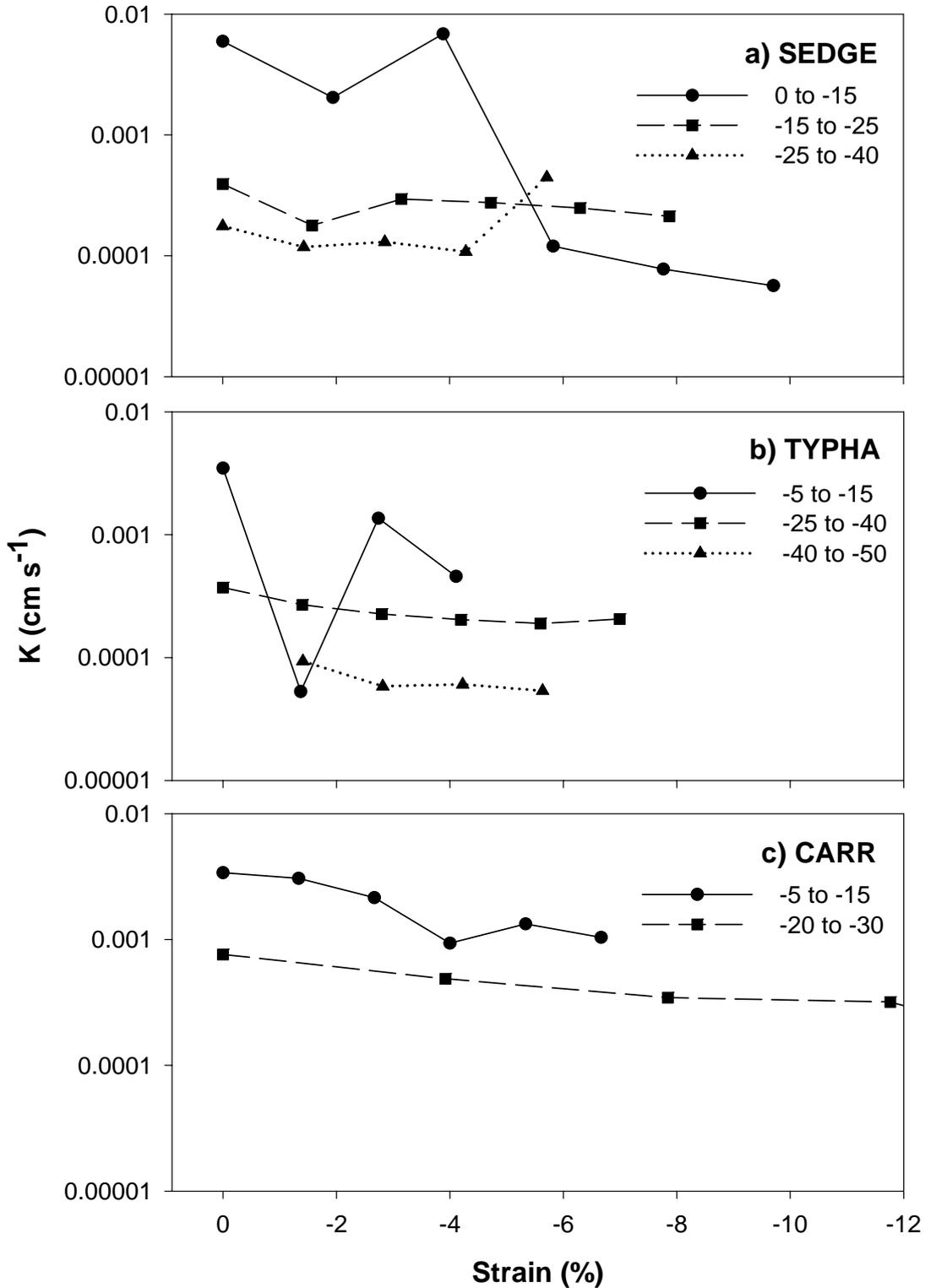


Figure 7. Variation of hydraulic conductivity (K_c) with strain (compression) in laboratory tests on peat collected from a) Sedge, b) Typha and c) Carr.

DISCUSSION

For a given change in water table position, peat volume change varies with depth and between vegetation types. Drawdown of the water table in the laboratory revealed that peat volume change near the surface (i.e. within the fibric mat) is limited, whilst the field studies indicated that most volume change occurs between -50 and -100 cm depth. In both cases Sedge peat exhibited the greatest strain, and Carr peat the least.

It is likely that these differences are related to differences in peat composition arising from the dominant vegetation at each site and its decay. At the Carr site, shrubs provide woody litter and roots which decompose slowly (Hobbie 1996) and have limited compressibility. Similarly, the large fleshy rhizomes of *Typha* impart a coarse structure to the mat and may limit compressibility. Such structure is absent from the Sedge site, but the leaf litter and extensive root systems here may limit strain within the mat to some degree. Deeper layers of the peat profile have been decomposing for longer than the surface layer, and much of the visible vegetation structure has been lost. It is also likely that the vegetation has changed over time with changes in climate and hydrological conditions (e.g. Belyea & Malmer 2004) so that peat at depth was not formed by the present plant community.

The low degree of decomposition near the surface means that large structures capable of limiting the amount of strain are present within the rooting zone. This was particularly apparent in the laboratory, where 20 cm lowering of the water table resulted in minimal compression of the material within the fibric mat. The high K values obtained for this zone in both the field and the laboratory can also be associated with the structure of the mat. The presence of woody roots and fleshy rhizomes at the Carr and *Typha* sites probably creates larger pores, resulting in higher K at -25 cm, than at the Sedge site. At all three sites, the peat below the mat lacks fibrous material such as roots and rhizomes to provide structure, yet our results indicate that hydraulic conductivity still exceeds 10^{-4} cm s⁻¹ above -100 cm. For compression (or expansion) to occur, pore water must be dissipated (or imbibed). The layer below the mat was the location of maximum strain, and this can be explained in terms of its physical proximity to the water sink (or source) (i.e. the surface), the lack of structures capable of resisting strain, and its relatively high hydraulic conductivity.

Below the mat, peat at the Sedge and *Typha* sites experienced greater volume change than Carr peat. This may be due to differences in depth of the

rooting zone or degree of decomposition between the sites; further investigation is required to determine specific controls. As the water table rose in the field, Sedge peat expanded the most. This would result in an increase in void ratio (volume of pore space per unit volume of solids, Price 2003), the expansion of pores leading to higher K . In contrast, lowered water table or increased effective stress would result in compression, smaller pore size and reduced K (Whittington & Price 2006). The K_c results indicate that this effect can be reproduced in the laboratory, but that it may be limited at depth. The outcome of lowering of the water table in the laboratory also supported the observation that, below the mat, Sedge peat was the most compressible as it exhibited the greatest strain.

On the basis of these results, the Sedge site should experience the greatest reduction in peat volume during periods of summer drought. This will tend to reduce drawdown of the water table relative to the surface and thus to maintain near-saturated conditions throughout the peat column. It will also reduce K . On the other hand, the peat at the Carr site is the least compressible so that it will exhibit less strain than that at the Sedge site when exposed to dry conditions, resulting in aeration of the upper soil layers and limited reduction of K . These differences may help to maintain the respective plant communities. Water table manipulation experiments have demonstrated an increase in shrub productivity under dry conditions (Weltzin *et al.* 2000). High K and limited peat volume change within the Carr mat will allow rapid drainage of precipitation inputs, promoting soil aeration which is likely to favour dominance of the shrub community. In contrast, the maintenance of saturated conditions at the Sedge site limits the growth of shrubs in this zone.

CONCLUSIONS

At Spongy Lake, peat volume change and hydraulic conductivity vary with depth and between plant communities. The 25 cm thick peat-vegetation mat shows limited volume change and highest K at all sites. Beneath the mat, peat volume change and K_{field} are highest at the Sedge site.

The presence at the *Typha* and Carr sites of more rigid vegetative components, such as rhizomes and woody litter, may help to limit compressibility at these locations. However, in order to understand better the specific controls on variability of peat volume change and K , further research is required on the scale of this variability and its relationship to the specific composition of the vegetation and to peat properties such as pore size distribution.

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