HYDROLOGICAL PROCESSES
Hydrol. Process. **13**, 2591–2601 (1999)

Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland

Jonathan S. Price* and Susanne M. Schlotzhauer
Wetlands Research Centre and Department of Geography, University of Waterloo, Waterloo, ON, Canada, N2L 3G1

Abstract:

This study examines changes in peat volume in a mined peatland near Lac St Jean, Quebec, during the spring and summer of 1995 and 1996, and the implication for water storage changes. Lowering of the water table caused drainage above the water table, but the specific yield (S_y) of the peat was relatively small (0·48), and did not adequately describe the water storage change. Lowering of the water table also caused surface subsidence, which was shown to be partly due to shrinkage above the water table ($<3{\cdot}6$ cm), and partly due to compression of the saturated peat (about 6 cm). Measured total surface subsidence ranged from 6·5 to 10 cm. The change in peat volume occurred over the entire depth of the peat deposit (b), and so the storativity due to peat compression (bS_s), estimated to be 0·13, was more important than specific yield in determining water storage changes. Total storativity (S_{tot}) was best estimated as the sum $S_y + bS_s$.

Changes in peat volume in the 0–3 cm layer were evident in the temporally variable bulk density (83–101 kg m^{-3}). Its relationship with volumetric moisture content was highly hysteretic, reflecting the complexity of the process in the unsaturated zone. However, there was a linear relationship with water tension, suggesting a more direct causal relationship. Changes in peat volume were also recorded below the water table, as the volumetric water content of the saturated peat decreased by 3·5% over the season. Since this applied to a relatively thick layer of peat, its total effect was greater than shrinkage in the zone above the water table. It was concluded that most peatland water balances should make account of storage changes associated with peat volume changes, and that peat volume changes may increase the water limitations to plants when the water table drops below the surface. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS peat; subsidence; compression; shrinkage; storage change; storativity

INTRODUCTION

Peat is very compressible on account of its high water content. The engineering consequences of this have been understood for some time (McFarlane, 1969), but the hydrological significance is scarcely recognized. The highly deformable peat matrix can (partially) accommodate storage changes by expansion and compaction, a seasonal effect known in Germany as *Mooratmung* ('mire breathing') (Ingram, 1983). Consequently, the water table may reside closer to the surface than it would otherwise. This may result in higher rates of groundwater flow (Price, 1992), evapotranspiration rates (Lafleur, 1990), and methane flux (Moore *et al.*, 1990). Furthermore, soil hydraulic parameters related to pore size volume, including water retention, hydraulic conductivity and specific yield, are affected (Chow *et al.*, 1992).

Soil scientists have studied the process of peat compression, primarily to determine its mechanical properties for engineering purposes (Hobbs, 1986). The most significant portion of volume changes in peat is

---

* Correspondence to: Dr J. S. Price, Wetlands Research Centre and Department of Geography, University of Waterloo, Waterloo, ON, Canada, N2L 3G1. E-mail: jsprice@watserv1.uwaterloo.ca

CCC 0885–6087/99/162591–11$17·50

Received 9 July 1998
Accepted 26 May 1999

due to ‘normal compression’ (McLay *et al.*, 1992; Pyatt and John, 1998), in which volume changes equal the volume of water lost from soil pores (McGarry and Malafant, 1987). Volume changes due to ‘residual shrinkage’ (McGarry and Malafant, 1987), which occurs when air enters the soil, are significantly smaller than for ‘normal shrinkage’ (McLay *et al.*, 1992). This process is related to contraction of the matrix resulting from the water tension within the soil (Hobbs, 1986). (Schothorst, 1977 ascribed 10% of the volume change of a Dutch peatland, which occurred over a period of six years, to shrinkage above the water table; 35% was by compression below the water table; 55% due to peat oxidation above the water table.) Over the long term, oxidation causes a general lowering of the surface. However, compression and shrinkage are at least partly reversible. Therefore, water gained or lost by volume changes of peat need to be considered when evaluating water storage changes.

Water storage changes manifest by fluctuating surface elevation have been reported by (Almendinger *et al.*, 1986; Nuttle and Hemond, 1988; Roulet, 1991; Price, 1994). The changes are relatively small in consolidated or highly mineralized peat. For example, changes in surface elevation in response to semi-diurnal tidal inundation of a salt marsh (Nuttle and Hemond, 1988) were less than 0·8 cm. By contrast, ‘floating’ or ‘quaking’ peatlands, which have a very high water content, may experience changes up to 2 to 4 cm d^{-1} (Roulet, 1991). Other studies have recorded seasonal changes of 10 cm (Almendinger *et al.*, 1986), 12 cm (Price, 1994), and even up to 50 cm (Buell and Buell, 1941; in Roulet, 1991). Schlotzhauer and Price (in press) noted settlement of the surface in the range of 11 and 23% of the lowering of the water table in a mined peatland. Nevertheless, estimates of water storage changes in peatlands typically neglect this mechanism, but rather, relate water table changes to storage changes through the specific yield (S_y) parameter (Bay, 1968; Bavina, 1975; Owen, 1995; Price, 1996). However, water table changes equivalent to the surface elevation change e.g. (Roulet, 1991) would result in an estimate of no storage change by this drainage alone, since the water table remains at the (adjusting) surface.

Water storage changes in an aquifer are governed by its storativity (S_{tot}), defined as the volume of water released from an aquifer per unit surface area per unit decline in head. In an unconfined aquifer, this is typically accomplished when air enters the pores above the water table as the water table declines, and the storativity is equivalent to the specific yield (S_y). Where storage changes occur solely by compression of an aquifer of thickness (b), the storativity is equivalent to bS_s, where S_s is the specific storage, given by

$$S_s = \rho_w g(\alpha + n\beta) \tag{1}$$

where ρ_w is density of water, g is gravitational acceleration, α is the compressibility of the matrix, n is porosity, and β is the compressibility of water. Water is not significantly compressible under the range of pressures encountered in shallow systems, so

$$S_s = \rho_w g\alpha. \tag{2}$$

From Equation (2), we see that specific storage is a function primarily of the compressibility of the aquifer. Since volume change (i.e. compression) in a horizontally extensive soil is manifest entirely by a decrease in its thickness, its surface elevation (∂z) per unit decline in head (∂h), can be expressed

$$bS_s = \frac{\partial z}{\partial h}. \tag{3}$$

The total storativity of the aquifer (S_{tot}) is therefore a function of both specific yield, and the specific storage, such that

$$S_{tot} = S_y + bS_s. \tag{4}$$

In the saturated part of an aquifer there is no free drainage of pore water, so the first term on the right hand side of Equation (4) is zero. In most unconfined aquifers, S_s is small and considered negligible relative to the effect of S_y. However, because peat is highly compressible, both processes may operate. Estimates of S_y reported for peat range from 0·09 to 0·45 (Vorob'ev, 1963), 0·08 to 0·84 (Boelter, 1964), 0·1 to 0·55 (Price, 1992), and 0·048 to 0·55 (Price, 1996). Lower values are for decomposed peat, and higher values are for undecomposed or living mosses. Estimates of bS_s derived from the literature range from 0·024 (Nuttle *et al.*, 1990), 0·17 (Koerselman, 1989), and even up to 1·0 for the 'floating fens' reported by Roulet (1991). Note that the elevation change is a function of peat thickness (b), and that thicker peat typically undergoes more surface adjustment (Almendinger *et al.*, 1986).

Where water table fluctuations are large, such as in mined peatlands; where specific storage is large, such as in 'quaking' or 'floating' peatlands; or where peat is especially thick, the potential for incorrectly assessing storage change is higher. Therefore, the objectives of this study are to:

1. quantify the rate and amount of peat volume changes above and below the water table, and its nature;
2. explore the effect of peat volume changes on estimating water storage changes; and
3. determine the implications for management of peatland restoration

STUDY AREA

The study area is in the Lac Saint-Jean area of Québec, Canada (48°47′N, 72°10′W). The average annual temperature is 1·7 °C, with average January and July temperatures of −17·1 and 17·3 °C, respectively (Environment Canada, 1982). Mean annual total precipitation is 906 mm (32% falling as snow). Mean annual runoff in the nearby Mistassini River, which is indicative of the difference between precipitation and evaporation, is 623 mm (Environment Canada, 1992).

The peatland is located over a terrace of deltaic sands in the Lac Saint-Jean lowland (Morin, 1981), and is part of a 4315 ha bog-poor fen complex which has been classified as Plateau Bog (NWWG, 1987). The peat deposit has developed over permeable sands because the presence of a well developed iron pan limits seepage losses (Price, 1996). Residual peat thickness ranges from 1·2–1·8 m, and has suffered oxidation and compression due to drainage and mining activities. This study examined a cutover portion of the peatland. Drainage operations began in 1990. The upper 0·35 to 0·6 m was removed by block-cutting with heavy machinery in 1991, then the ditches were blocked with peat dams in the fall of 1992. The cutover surface is generally flat.

METHODS

The study examines May to September data from 1995 and 1996. Water table elevation was measured daily in seven 25 mm i.d. pvc wells secured 1·1 m below the surface, along a transect perpendicular to a blocked ditch, at distances of 0·5, 1, 2·5, 5, 7·5, 10 and 15 m from the ditch edge. Distance to the surface was measured each time a water level was determined. Water tension was measured with tensiometers set 1, 3, 7, 10, 20, 30, 40 and 50 cm below the surface in 1995, and 2, 10, 20, 30 and 50 cm in 1996. Soil moisture was measured gravimetrically in 1995 and 1996. For the gravimetric analysis three soil samples were collected from the cutover peat surface, 3 cm thick, each sample day, and lumped for analysis. Moisture content and soil bulk density were determined from the same samples. In 1996 soil moisture was also measured with TDR at the same depths as the tensiometers. The TDR was calibrated for this soil.

Rain was measured in a tipping bucket rain gauge. Evaporation was estimated with the Priestley and Taylor (1972) model. For this, net radiation was measured at 3 m with a REBS net radiometer, soil heat flux with 2 REBS heat flux plates, and air temperature at 1 m with a shielded thermocouple. The model was calibrated with evaporation measured in 1993 and 1994, using the Bowen ratio energy balance method (Price, 1996). Further details on the use of this model at this site can be found in Price (1997).

RESULTS AND DISCUSSION

Following inundation and saturation of the site by snowmelt, the water table and soil moisture (Figure 1) decreased in response to evaporation and drainage. The physical properties of the soil are not static, as shown by bulk density variations (Figure 1). During this period, there is a general decrease in the surface elevation, ranging from 6·5 to 10 cm (Figure 2). As noted earlier, the decline in surface elevation in peatlands can be attributed to changes in soil volume both above and below the water table.

Soil volume changes above the water table

Soil moisture and bulk density data representing only the upper 3 cm of peat, were plotted against each other (Figure 3). Four phases in the regime of bulk density change were identified: (1) During the period 7 June

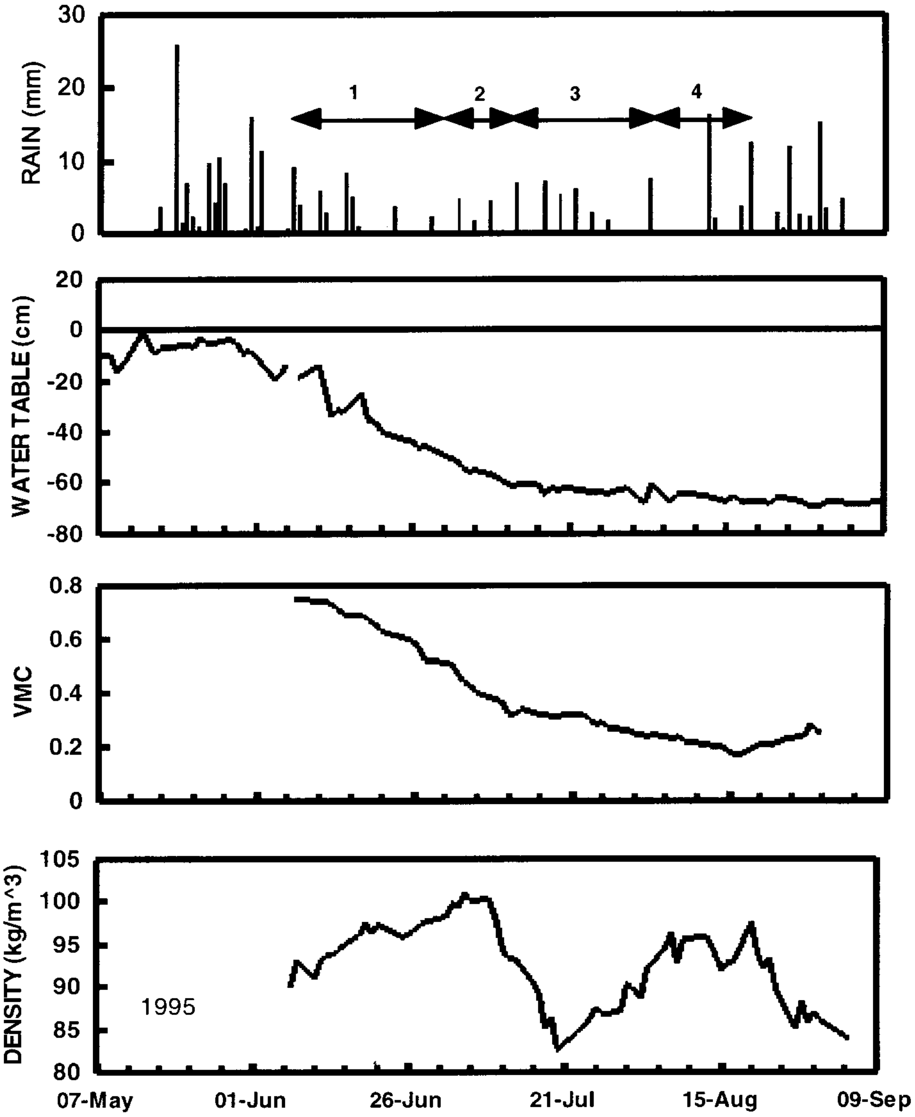

Figure 1. a) Rainfall, b) water table depth, c) 7-day moving average of volumetric soil moisture of the 0–3 cm layer, and d) 7-day moving average of bulk density of the 0–3 cm layer. Numbers 1 to 4 in a) relate to similar numbers in Figure 3

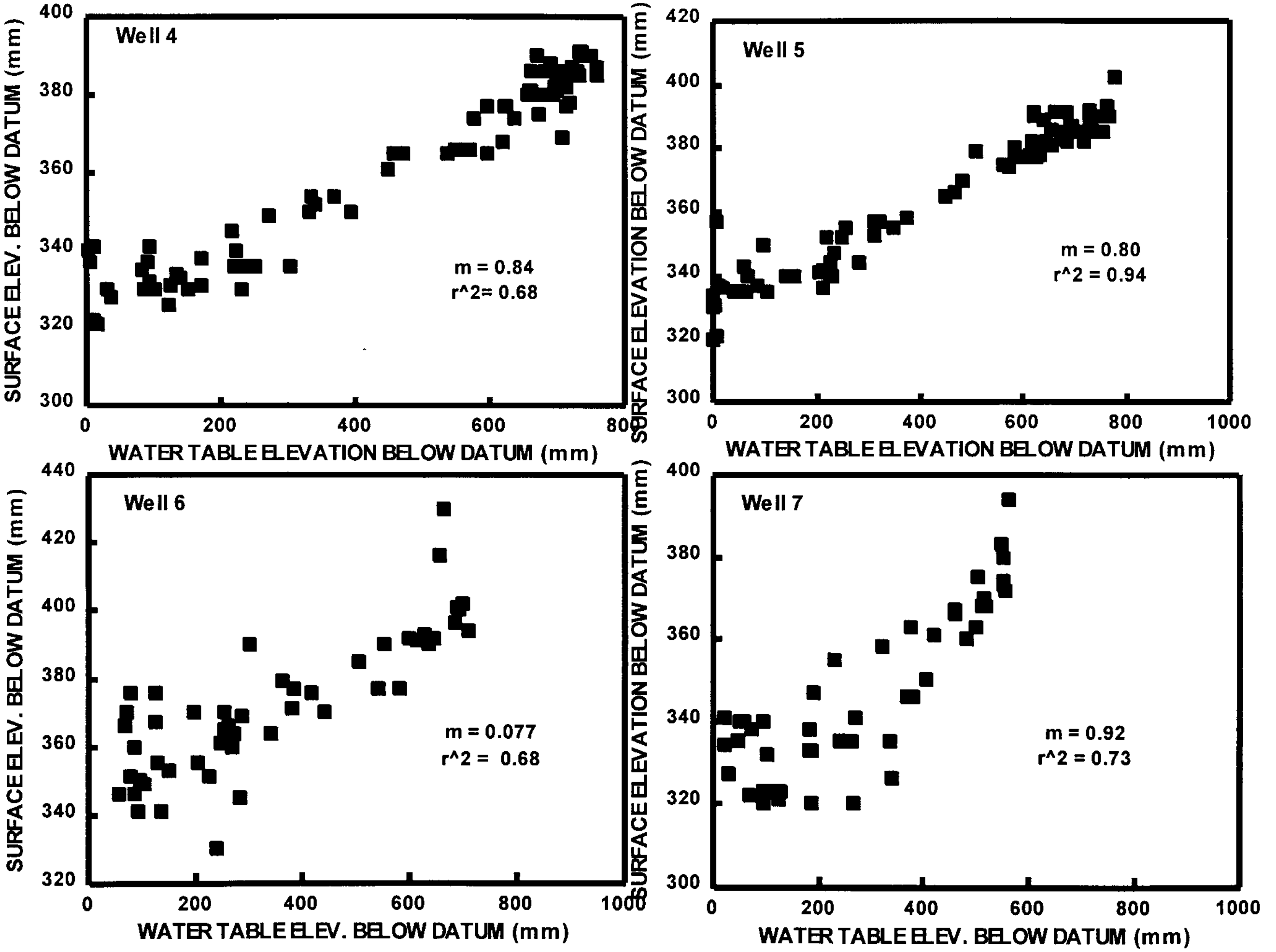

Figure 2. Surface elevation versus water table elevation for wells 4, 5, 6 and 7, located respectively at 5, 7·5, 10 and 15 m from the blocked drainage ditch, 1995

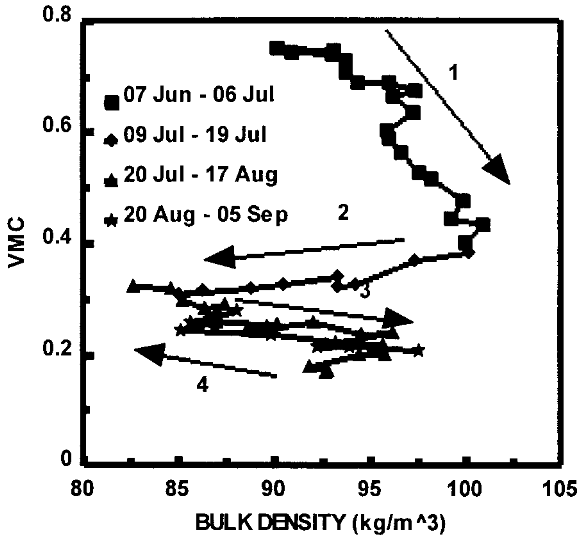

Figure 3. Volumetric moisture content and bulk density of the 0–3 cm layer (1995), all 7-day moving averages. Numbers 1 to 4 relate to Figure 1. The arrows show the temporal progression of each point

to 6 July, the peat dried rapidly, and bulk density increased. The start of this period was rainy, and the system wet from residual snowmelt water. The peat had high soil moisture, but underwent its greatest decrease. Toward the end of this period there was little rain, and surface drying occurred. (2) From 9 to 19 July the bulk density decreased. This period was rainier than the last week of the previous period, and resaturation of the surface evidently caused peat to expand. Water tension measurement (at 2 cm depth) are available for this period, and averaged −98·0 mb. (3) Bulk density again increased between 20 July and 17 August. Note that at the end of this period conditions are quite dry, because of low rain and high evaporation. Average soil water tension climbed to −183 mb. (4) The bulk density dropped sharply at the end of the summer (20 August to 5 September), when average rainfall increased substantially. After 23 August the average soil water tension dropped to −99·0 mb. The additional rain and lower tensions allowed the peat to expand.

The changes in bulk density exhibited extreme hysteresis with respect to soil moisture. Drying conditions during phase 1 decreased the peat volume, and lowered the volumetric soil moisture. The increase in peat volume during phase 2 was in response to slightly wetter conditions. However, this was not sufficient to increase the calculated volumetric soil moisture content (because the new volume was larger). Instead, the moisture content remained relatively steady (Figures 1 and 3). The additional moisture was held in a larger volume of peat, nullifying any increase in volumetric moisture content. During the third phase (drying) the bulk density again increased (peat volume decreased), minimizing the decrease in volumetric soil moisture. The fourth phase (rewetting) occurred during a notably wetter period and peat expansion and soil moisture change reversed the previous drying trend. The change in peat volume observed here was greatest early in the summer, when the peat was closest to saturation. Dilation (expansion) did not occur at the same rate during rewetting; it was considerably less. Hysteresis reported by Schlotzhauer and Price (in press) noted that vertical displacement during periods of water loss was five times greater than during periods of water gain.

Given the range in average bulk density (83–101 kg m^{-3}), the maximum volume decrease of peat within the top 3 cm layer was about 18%. Presumably the average volume decrease in the whole unsaturated zone was somewhat less than this, since it did not dry to the same extent (Price, 1997). For example, the average moisture content calculated in 1996 (average of daily 10, 30, and 50 cm TDR measurements) was 0·71. Data on volume changes in this zone are not available for 1996.

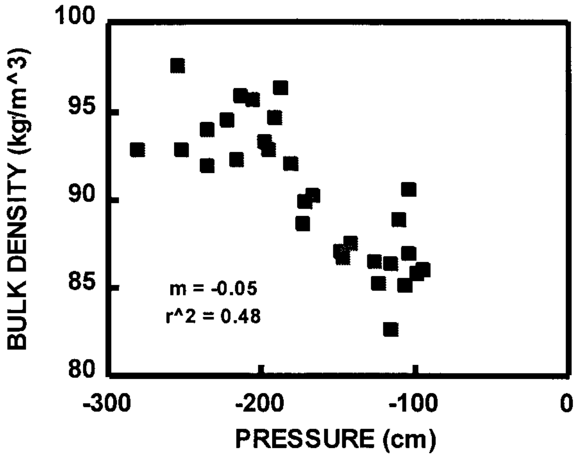

Figure 4. Bulk density versus pressure (1995), all 7-day moving averages

While the relationship between volumetric soil moisture and bulk density was hysteretic, there was a more direct relationship between bulk density and soil water tension (Figure 4), since shrinkage is caused by the suction generated within the pores (Hobbs, 1986). While there is some scatter in the relationship ($r^2 = 0{\cdot}48$), this is to be expected given the spatial variability of soil samples, which were retrieved at the same site as the tensiometers, but necessarily at some distance from it, and at a different location each time (i.e. destructive sampling). The scatter in Figure 4 is random, unlike that in Figure 3. The maximum water tension in 1995 occurred on 22 August. Based on tensiometers positioned at 10, 20, 30, 40 and 50 cm below the peat surface (see Price, 1997), the depth-averaged tension was $-106{\cdot}4$ cm. Therefore, the total change in bulk density was estimated from the change in tension from zero following the snowmelt period, to 106·4 kg m^{-3} (the average tension). From Figure 4 this can be seen to equal approximately 5·3 kg m^{-3}. Assuming the average bulk density in the profile was less than or equal to that at the surface (92·1 kg m^{-3}), the maximum volume decrease was about 6% of the peat in the zone above the water table. Furthermore, assuming all displacement is in the vertical axis, and since the maximum thickness of this zone was 0·6 m (Figure 1), a lowering of the peat surface of up to 3·6 cm was calculated for the zone above the water table (0·6 m * 0·06).

Soil volume changes below the water table

In 1996 volume changes in the peat below the water table were evident from the decrease in volumetric moisture content there, as the water table above it was lowered (Figure 5). It suggests that lowering of the water table resulted in compression of the peat, as the total stress caused by the weight of the overlying material (peat and water) increased. The decrease was only 3·5% of the total peat volume (i.e. extrapolating from a water table depth of zero following snowmelt). However, since this 3·5% decrease in volume occurred over the entire saturated thickness (1·7 m), the total vertical displacement due to compression alone was estimated to be about 6 cm (i.e. 1·7 m * 0·035). Since the total decrease in surface elevation ranged from 6·5 to 10 cm (Figure 2), compression below the water table likely contributed more significantly to peat volume changes than shrinkage above the water table.

Determining changes in water storage

It was shown earlier that water storage changes could be associated with changes in peat volume by determining the total storativity as $bS_s = \partial z/\partial h$. Therefore, from $\partial z/\partial h$ in Figure 2, the average ± s.d. of bS_s in 1995 was $0{\cdot}083 \pm 0{\cdot}006$. In 1996 the equivalent value was $0{\cdot}081 \pm 0{\cdot}016$. It seems likely, however, that the specific storage for this site was underestimated by this method, because the datum against which surface elevations were measured was only 1·1 m below the peat surface in a deposit approximately 1·75 m thick.

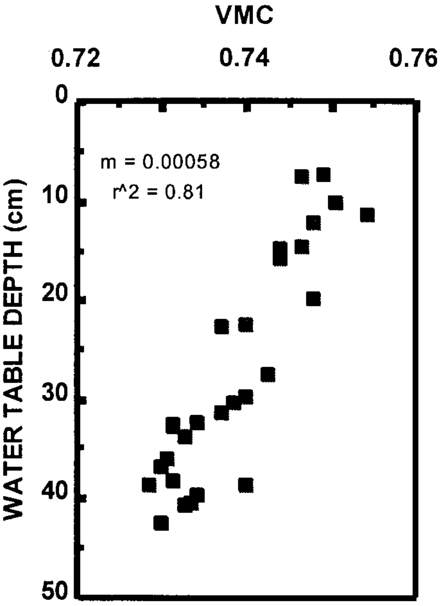

Figure 5. Water table depth below the surface versus volumetric moisture content (1996)

Thus compression of peat below this point was not included in the measurement of total surface elevation change. Based on the ratio 1·75/1·1, the actual surface elevation change was estimated to be about 60% greater than the measured change. On this basis, the storativity due to specific storage is estimated to be 0·13. This represents an important component of the total storativity ($S_{tot} = S_y + bS_s$) of the peat, given that the average specific yield for this peat is 0·048 (Price, 1996). Storage changes due to changes in peat volume, as described by specific storage over the depth of peat, therefore, are about two to three times as important as changes due to drainage by gravity.

The actual water storage changes (∂S) during the summer of 1996 at this site are closely approximated by the difference between cumulative rainfall (P) and evaporation (E) (Price, 1996), since runoff is negligible during this period. The common practice of evaluating storage changes in unconfined aquifers by

$$\partial S = \partial h \cdot S_y \tag{5}$$

accounts only for gravitational drainage of water. Calculated storage using Equation (5) produces a value significantly less than Σ (P-E) (Figure 6). However, when the effect of surface subsidence is accounted for, by expanding the storage term to

$$\partial S = \partial h \cdot (S_y + bS_s), \tag{6}$$

a remarkably good fit is obtained, at least until mid-July (Figure 6). Notable deviation between the estimated storage and Σ (P-E) occurred following extreme rain events on 19 and 20 July, which added 70 mm of water. This event was associated with the devastating Saguenay River floods caused by storms that dumped 150–270 mm of water in nearby areas. This deviation can be explained by the loss of water to surface runoff following this event. Thereafter, the calculated rate of storage change was similar to the actual change, but offset by an amount approximately equivalent to the surface runoff loss. However, estimates of storage change in response to rewetting events did not generally follow Σ (P-E) as well as drying events. This may be attributed to hysteresis in the shrinkage/compression relationships (e.g. see Figure 3). It is evident from the shrinkage curves that decreases in volume are not readily reversed upon rewetting. The same is probably true

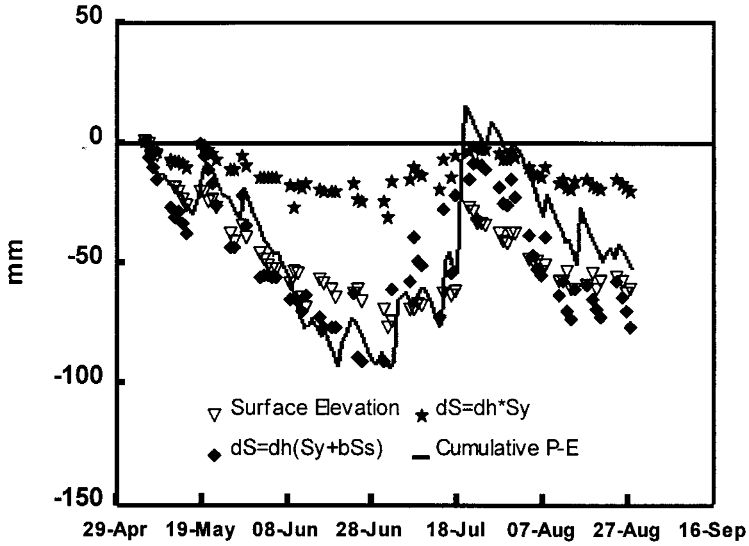

Figure 6. Changes in surface elevation (measured) and storage (1996) estimated by P-E, by specific yield, and by both specific yield and specific storage. The latter method of calculating storage matches the 'true' storage change estimated as P-E

for changes in peat volume below the water table by compression, since drainage resulted in a slow steady loss of pore water as the peat was squeezed. In contrast, episodic additions of (relatively) large quantities of water could not be so easily recharged throughout the peat profile.

LIMITATIONS

In this study, estimates of the specific storage were based on changes in surface elevation relative to water table changes. However, it was also shown that part of the surface elevation change was associated with shrinkage. The shrinkage that occurred was related to increased soil water tension in Figure 3, although at least part of that shrinkage was due to compression. Furthermore, the lack of a stable datum required the specific storage term (bS_s) be adjusted upward for the unmeasured portion of compression assumed to occur beneath the reference point. Further work is underway to refine the method. Nevertheless, even without this adjustment, the proportion of storage change attributable to bulk volume changes ($bS_s = 0{\cdot}08$) was greater than due to gravity drainage ($S_y = 0{\cdot}048$).

CONCLUSIONS

Peat soil is highly compressible, and consequently water storage changes result in volume changes in the peat. These are manifest as variations in the surface elevation. Where changes in water table elevations are large, such as in some natural bogs, and most mined or drained peatlands; where peat is especially thick; or where the peat is 'quaking' or 'floating', significant storage changes may arise from surface elevation changes. The nature of the surface elevation change depends on the compressibility (α) of the peat. Where the compressibility is low, water storage changes will occur primarily by gravitational drainage, followed by air entry, into the pores of the peat. In such cases, the specific yield (S_y) can adequately describe the storage changes for a given change in head. This is generally the case for mineral soils, and peat soils with a high bulk density such as well oxidized or compacted peat; where peat is shallow (e.g. <50 cm); and/or where water table fluctuations are small. In other peatlands, compressibility effects are probably important. Surface elevation changes have been important in the relatively few studies that report it (Almendinger *et al.*, 1986; Nuttle and Hemond, 1988;

Nuttle *et al.*, 1990; Roulet, 1991; Price, 1994). Consequently, water storage change associated with changes in peat volume may be important. If there is little water table drawdown (e.g. Roulet, 1991) the storativity of the peat may adequately be described by bS_s. Elsewhere, storativity should be estimated with $S_y + bS_s$.

The consequences of including the peat volume changes to estimate water storage changes were shown to be important to this study, on a drained peatland. It is essential where estimates of water storage changes are used in a water balance, especially where one of the other terms is calculated as a residual. However, there are other implications not explored by this study, namely the changes to the hydraulic parameters that govern water retention and flow. A reduction of the peat volume by shrinkage or compression entails a decrease in the size of pores. Consequently, saturation occurs at lower volumetric moisture content. If the compressibility is very high, the water table will remain close to the surface, and evapotranspiration may be promoted (Lafleur, 1990; Price, 1994) (i.e. water availability to plants is enhanced). If the compressibility is moderate, and significant shrinkage occurs, upward capillary flow to replenish water lost to evapotranspiration is hindered by the lower hydraulic conductivity. Furthermore, the higher water retention capacity will result in stronger soil suction, providing further limitations for plants. This is an important consideration for re-establishing *Sphagnum* mosses on mined peat (Price, 1997; Price *et al.*, 1998).

ACKNOWLEDGEMENTS

We are grateful for the financial assistance provided by the Natural Science and Engineering Council of Canada, and by Johnson and Johnson Ltd. Logistical assistance was also provided by Fafard et Frères, Ltèe. The field assistance of J.-F. Oullet, F. Quinty, and S. Campeau is appreciated.

REFERENCES

Almendinger JC, Almendinger JE, Glaser PH. 1986. Topographic fluctuations across a spring fen and a raised bog in the Lost River Peatland, Northern Minnesota. *Journal of Ecology* **74**: 393–401.

Bavina LG. 1975. Water balance of swamps in the forest zone. *Proceedings of the 1972 Minsk Symposium*. Unesco Press — I.A.H.S.: Paris; 297–303.

Bay RR. 1968. *Evapotranspiration from two peatland watersheds*. General Assembly of Bern. IAHS Publication, Bern, 78: 300–307.

Boelter DH. 1964. Important physical properties of peat materials. Quebec International Peat Congress, International Peat Congress, Quebec City. 150–154.

Chow TL, Rees HW, Ghanem I, Cormier R. 1992. Compactibility of cultivated Sphagnum peat material and its influence on hydrologic characteristics. *Soil Science* **153**: 300–306.

Environment Canada. 1982. Canadian Climatic Normals 1951–1980: Temperature and Precipitation, Quebec. Atmospheric Environment Service, Downsview, 216 p.

Environment Canada. 1992. *Historical Streamflow Summary, Quebec*. Water Survey of Canada: Ottawa; 526 pp.

Hobbs NB. 1986. Mire morphology and the properties and behaviour of some British and foreign peats. *Quarterly Journal of Engineering Geology* **19**: 7–80.

Ingram HAP. 1983. Hydrology. In *Ecosystems of the World 4A: Moores:Swamp, bog, fen and moor*, Gore AJP (ed), Elsevier Scientific, Amsterdam; 67–158.

Koerselman W. 1989. Groundwater and surface water hydrology of a small groundwater-fed fen. *Wetlands Ecology and Management* **1**: 31–43.

Lafleur PM. 1990. Evapotranspiration from sedge-dominated wetland surfaces. *Aquatic Botany* **37**: 341–353.

McFarlane IC. 1969. *Muskeg Engineering Handbook*. University of Toronto Press: Toronto; 297 pp.

McGarry D, Malafant KWJ. 1987. The analysis of volume change in unconfined units of soil. *Soil Science Society of America* **51**: 290–297.

McLay CDA, Allbrook RF, Thompson K. 1992. Effect of development and cultivation on physical properties of peat soils in New Zealand. *Geoderma* **54**: 23–37.

Moore TR, Roulet NT, Knowles R. 1990. Spatial and temporal variations of methane flux from subarctic/northern boreal fens. *Global Biogeochemical Cycles* **4**: 29–46.

Nuttle WK, Hemond HF. 1988. Salt marsh hydrology: implications for biogechemical fluxes to the atmosphere and estuaries. *Global Biogechemical Cycles* **2**: 91–114.

Morin G. 1981. *Atlas Régional du Saguenay-Lac-Saint-Jean*. Les Laboratoires de Géographie de L'université du Québec a Chicoutimi.

Nuttle WK, Hemond HF and Stolzenbach KD. 1990. Mechanisms of water storage in salt marsh sediments: The importance of dilation. *Hydrological Processes* **4**: 1–13.

Owen CR. 1995. Water budget and flow patterns in an urban wetland. *Journal of Hydrology* **169**: 171–187.

Price JS. 1992. Blanket bog in Newfoundland: 2. Hydrological processes. *Journal of Hydrology* **135**: 103–119.

Price JS. 1994. Water exchanges in a shoreline *Typha* marsh on Lake Ontario. *Journal of Hyrdology* **155**: 407–428.

Price JS. 1996. Hydrology and microclimate of a partly restored cutover bog, Quebec. *Hydrological Processes* **10**: 1263–1272.

Price JS. 1997. Soil moisture, water tension, and water table relationships in a managed cutover bog. *Journal of Hydrology* **202**: 21–32.

Price JS, Rochefort L, Quinty F. 1998. Energy and moisture considerations on cutover peatlands: Surface microtopography, mulch cover, and Sphagnum regeneration. *Ecological Engineering* **10**: 293–312.

Priestley CHB, Taylor RJ. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review* **100**: 81–92.

Pyatt DG, John AL. 1998. Modelling volume changes in peat under conifer plantations. *Journal of Soil Science* **40**: 695–706.

Roulet NT. 1991. Surface level and water table fluctuations in a subarctic fen. *Arctic and Alpine* **23**: 303–310.

Schlotzhauer SM, Price JS. 1998. Soil water flow dynamics in a managed cutover peat field, Quebec: 1. Field and laboratory investigations. *Water Resources Research* in press.

Schothorst CJ. 1977. Subsidence of low moor peat soil in the western Netherlands. *Geoderma* **17**: 265–291.

Vorob'ev PK. 1963. Investigations of water yield of low lying swamps of western Siberia. *Soviet Hydrology: Selected Papers* **3**: 226–252.