SCIENTIFIC BRIEFING

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Pressure variations in peat as a result of gas bubble dynamics

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Abstract

**Transient high pore-water pressures, up to 50 cm higher than ambient pressure, developed over the summer season at various depths in a shallow (1 m) fen peat. The excess pressures had a pattern of gradual increases and sharp drops, and their initiation and release typically corresponded to abrupt changes in atmospheric pressure. We conclude that these phenomena depend on gas bubbles (probably methane) generated by biological activity, both by clogging pores and by building up pressure as they grow. These transient and spatially discontinuous high-pressure zones were found using pressure transducers in sealed (backfilled) pits, but not in piezometers open to the atmosphere. Piezometers may provide a conduit for the release of gas and pressure, thus rendering them unsuitable for measuring this phenomenon.
Although the development of localized zones of high pressure causes erratic and unpredictable hydraulic gradients, we suggest that their effect on the flow of water or solutes is offset by the reduced permeability caused by the bubbles, which allows them to be sustained. These zones, however, probably deflect flows driven by the dominant hydraulic gradients. Furthermore, they may cause the peat volume to adjust (swell). The use and interpretation of traditional methods for estimating hydraulic head and conductivity in peat soils thus require great caution. Copyright © 2004 John Wiley & Sons, Ltd.**

Introduction

Peat volume and hydraulic properties undergo long-term changes as organic material accumulates and decomposes (e.g. Romanov, 1968; Clymo, 1984). The hydrological implications are well known (e.g. Ingram, 1983), manifested typically as less permeable soil at depth. However, in the short term (e.g. hourly to seasonally), variations in water-table level cause peat-volume changes by consolidation and swelling processes (Terzaghi, 1943), resulting in changes in both volume (Ingram, 1983; Almendinger *et al.*, 1986; Roulet, 1991) and hydraulic conductivity (Price, 2003).

Recently, the dynamics of gas bubbles in peat have been shown to affect the hydrological conditions. The bubbles are likely methane originating from microbial anaerobic processes. Trapped bubbles change the peat buoyancy and storage coefficients (Fechner-Levy and Hemond, 1996; Rosenberry *et al.*, 2003) and lower the hydraulic conductivity considerably (Reynolds *et al.*, 1992; Beckwith and Baird, 2001). They may even close off zones or layers so effectively that exchanges of water and dissolved compounds are restricted. Seasonal developments of such confining layers may take place in highly biologically active peat, further

trapping locally produced peat gas, creating overpressured zones within the peat that give rise to unexpected hydraulic gradients (Romanowicz *et al.*, 1995) and altering the void ratio and expansion/contraction properties (Price, 2003).

It has long been known that methane gas bubbles are abundant in deeper peat (Brown *et al.*, 1989; Romanowicz *et al.*, 1993, 1995), although the dynamics of gas bubbles and the magnitude of the excess pressure they cause is poorly understood. Recently, Rosenberry *et al.* (2003) revealed a consistent overpressure of 3–35 cm water height at 2 m depth in a bog.

Since anaerobic biological activity and methane gas production are normally greatest in layers close to the water table (Sundh *et al.*, 1992), overpressuring within shallower zones close to the water table is also likely occurring. Consequently, we believe that pressure in shallower peat may be affected by gas to a substantial and varying degree. Using a pressure sensor that was isolated from atmosphere, Rosenberry *et al.* (2003) also found variation in hydraulic head at 1 m depth that indicated presence of free gas, whereas no such responses were seen in an unsealed piezometer at the same depth. The presence of unconventional head distributions may go undetected in piezometers because they may act as vents for the release of gas. Moreover, piezometers may be too slow to respond to pressure changes caused by bubble formation and release within and between layers, and require too large a volume of water to equilibrate the piezometer (Hanschke and Baird, 2001).

Given the potential for altered flowpaths, confusing and perhaps misleading hydraulic gradients, or given that piezometers venting gas may unintentionally influence head gradients, this peatland phenomenon needs to be investigated. The objectives of this paper were to determine (1) the magnitude and spatial (vertical) distribution of overpressured zones within a shallow peat deposit; (2) the frequency and timing of events and their relation to associated hydrological (water table) and atmospheric (barometric) processes; and (3) the sensitivity to this process of piezometer pipes open to atmosphere versus pressure transducers in backfilled voids (constituting 'closed' systems that require miniscule water exchange to equilibrate and which are sealed to the atmosphere to avoid gas leakage).

Methods

Data were collected at a poor, open fen site (46°40′N, 71°10′W) close to the village of St Charles de Bellechasse, Québec. The study area is a 3 ha unharvested remnant in a patterned fen peatland subjected to drainage and peat cutting over the last 10 years. Small (<2 m) trees (*Larix* spp. and *Betula* spp.) occur sporadically. On ridges there are patches of low Ericaceae shrub, whereas grasses and sedges sparsely cover lawns and shallow pool areas. The instrumentation was located at *Sphagnum* lawns, encircling ~150 m² pools in two closely situated sub-sites. One of the sites, called 'experimental', was drained on *d* (day of year) 161 in early June 2002 by digging a shallow drain from the pool to the drainage network. The other site was an undrained sub-site called 'control'.

The peat thickness was approximately 1·0 m at the experimental site before drainage and about 1·2 m at the control site. The moss layer is dominated by *Sphagnum papillosum, S. magellanicum* and *S. majus*. Dominating vascular plants are *Rhyncospora alba* and *Carex* spp.

Field measurements were made from early May to late September 2002. The water table was monitored continuously with recording wells combined with manual measurements every week. Pore water pressure was automatically recorded with pressure transducers (KPSI 173, Pressure Systems Inc., Hampton, VA, USA) buried in the peat at depths 25, 40, 60 and 85 cm at both sites and also at 100 cm at the control site. The notation is C25, C40, C60, C85, C100 and E25, E40, E60 and E85 for the control and experimental site sensors respectively. The insertion cavities were sealed with peat mud for the first 10 cm and then with a 10 cm bentonite layer to avoid preferential flows and escape of gas. The transducer diaphragms were not vented to the atmosphere, thus measuring absolute pressure without relating to atmospheric pressure. To get hydraulic head variation, correction for atmospheric pressure variation had to be made. Air pressure data were obtained from a barometer (Vaisala PTB210, Vaisala Oyj, Helsinki, Finland). The transducers were later recalibrated in the laboratory; no sign of drift was found. Pressure was also monitored manually at the same depths with 2·5 cm i.d. piezometers, with 10–20 cm screen length. All hydraulic-head measurement results were adjusted

with respect to vertical displacement of sensors, caused by peat vertical compression and swelling. The displacements of the sensors were estimated by using elevation sensor rods (Price, 2003), anchored at the same depths as sensors. Rainfall was measured with a tipping-bucket rain gauge, and evapotranspiration was measured with lysimeters (0·074 m^2 surface area, 25 cm deep) by weighing twice per week.

Results

In the period May–July, precipitation (310 mm) was close to long-term normals (Environment Canada, 2003) with 80–110% of normal monthly precipitation. August to early September was very dry, with only 16 mm of rain, followed by heavy rains with intermittent dry periods later in September. Evapotranspiration averaged 4·2 mm day^{-1} during June and July, 2·8 mm day^{-1} in August and 1·5 mm day^{-1} in September.

The water tables responded according to the weather conditions with relatively small variation until the beginning of August, after which the water table declined to maximum depths of 43 cm and 27 cm at the experimental and control sites (Figure 1). The artificial drainage on d 161 lowered the water table at the experimental site approximately 20 cm (Figure 1).

Hydraulic heads

Hydraulic head at all piezometer pipes deviated little from the local water table, suggesting that the vertical gradients were very small throughout the season. In contrast, at both the control (Figure 2) and experimental sites the pressure transducers indicated large differences in hydraulic heads between different depths during certain times. At both the control site (Figures 2 and 3) and the experimental site (Figure 3), head remained elevated for a prolonged period, although it varied substantially with time at each level.

Periods of excess pressure

We have adopted the term excess pressure (p_e), defined here as:

$$p_e = h_s - \text{wt} \qquad (1)$$

where h_s is the head at the sensor and wt is water table level. Excess pressure p_e, therefore, expresses the deviation in head from the local water table. There was no clear difference in the variation pattern of p_e between the experimental and control sites over the season. At the control site, excess pressure was initiated at 25 cm (C25) and 40 cm (C40) depths on d 177–178 (Figure 3), and at C100 on d 245, whereas it was zero at C60 and C85 all season. At the experimental site, excess pressure commenced on d 172, 174, 178 and 210 at E85, E40, E25 and E60 respectively. The variation of p_e over time is shown in Figure 3 only for C25, C40, E40, E60 and E85, since these sensors show occurring patterns of p_e variation within the profiles. For the sake of clarity, the pressures at C60, C85, C100 and E25 are thus not shown. The typical pattern of the excess pressures was a gradual build up followed by a sharp drop. For some periods and sensors, the releases of p_e occurred when a threshold value was reached. The rate of rise in p_e varied considerably over time at all sensors, with maximum rates exceeding 10 cm water per day. Often, there were periods (e.g. after d 230 for C25) when p_e did not increase significantly, but rather varied as a mirror reflection of the atmospheric pressure variation. This effect occurred as the absolute
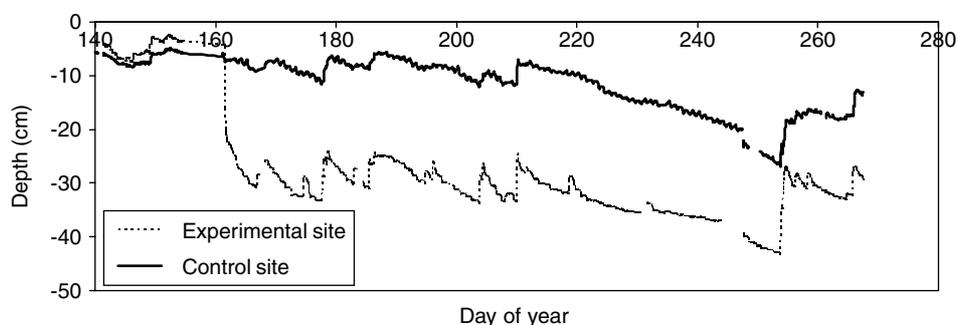
Figure 1. Variation of water-table level at the two sub-sites
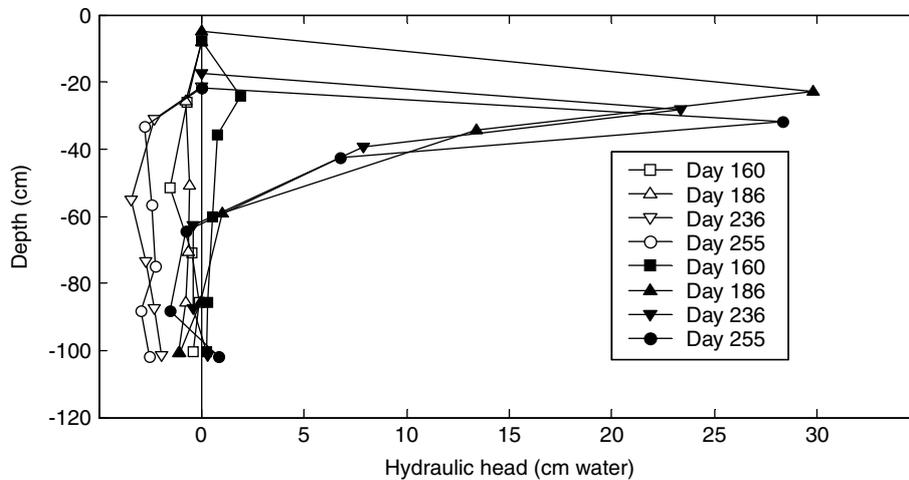
Figure 2. Vertical variation of hydraulic head in relation to water table at the control site on four different days of the year, as measured in piezometer pipes (open symbols) and by buried pressure transducers (filled symbols)

pressures at the sensors did not fully follow changes in atmospheric pressure, hence giving a reversed response in p_e. This suggests that the variation of ambient soil water pressure (caused by variation in water table or in atmospheric pressure) was highly damped at the sensor. In contrast to the sharp drops in p_e, gradual decreases of p_e were generally associated with increases in atmospheric pressure. At the time of the drainage in d 161, there was also an excess pressure initiated at E85 which declined slowly the following days (Figure 3). This is a pattern seemingly caused by low conductivity restricting the water to equilibrate with the lowered water table. However, the open piezometer at E85 did not show this pattern.

At all sensors where excess pressure was observed, p_e was initiated after unusually high air-pressure conditions (>1025 mbar), when air pressure had reached the maximum and was decreasing. For all sensors, except E40, the initiation began when air pressure decreased to, or below, 1013 mbar. Sudden releases of excess pressures often occurred at different depths in each profile within a few hours. However, no instantaneous effects of a release in one layer were detected at adjacent pressure transducers.

Discussion

Certain locations within drained and undrained fen peat developed a transient soil-water pressure that was not equilibrated to the water table or to changes in atmospheric pressure. The transient pressure is presumably derived from biogenic gas formation (probably methane), which expels pore water from the peat matrix, but where local permeability is insufficient to allow equilibration of the pressure with the ambient water. Consequently, a localized increase of pressure occurs. The variation of pressure-increase rates indicates that the local permeability shifts infrequently. Bubbles clogging pores periodically could cause this effect. Times when a very low response to changes in atmospheric pressure or water table occurred indicate (1) gas in the closed zone increases the compressibility of the fluid and absorbs the pressure variations and/or (2) gas bubbles block the pores and, hence, damp the ambient pressure oscillations (Gardescu, 1930). We suggest, therefore, that the patterns of pressure we have observed here are connected to the dynamics of gas bubbles, closing off zones by blocking pores.

Development of localized overpressure

Small bubbles, migrating primarily upwards under the force of their own buoyancy may eventually become lodged within a restriction of the heterogeneous pore system. To reach higher layers, and eventually the surface, bubbles must exploit pore openings sufficiently wide, and the upward force must exceed adhesion and friction against the pore walls. At pore constrictions the bubbles require greater force to push them through a fixed opening, or they must enlarge a pore sufficiently to allow them to pass.
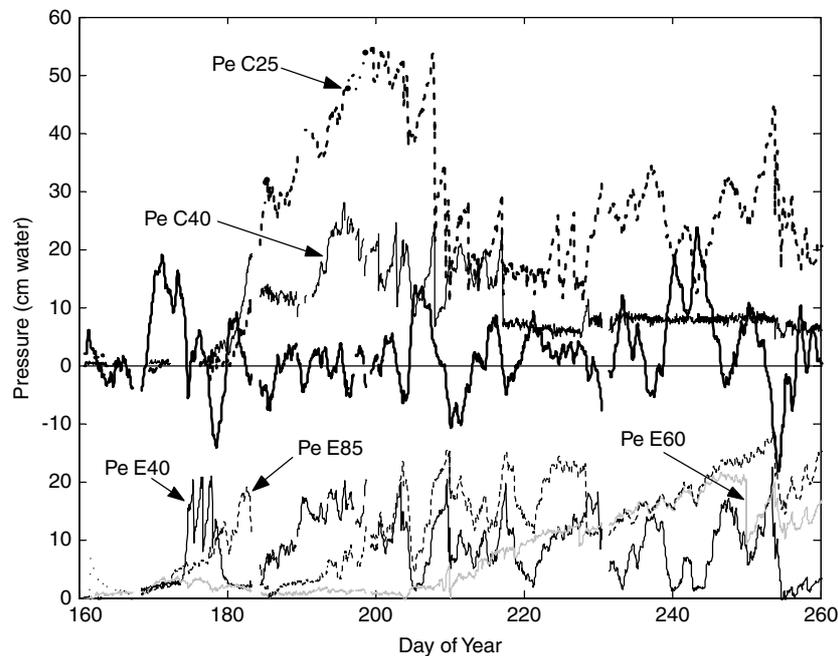
Figure 3. Air pressure deviation from 1013 mbar (thick black line, 1 cm water = 0·98 mbar) and variation of excess pressure (Equation (1)) as given by pressure transducers at locations C25 (thin line), C40 (thick line), E40 (thin line), E60 (grey line) and E85 (thick line). Note that the zero line for p_e at E40, E60 and E85 is shifted down

Bubble volume varies inversely with applied pressure, and so could be altered by changes in atmospheric pressure. During a high-pressure period the bubbles become more mobile as their volume decreases. This does not guarantee their escape, however, and it may increase the likelihood of bubbles coalescing at some pore constrictions, thus increasing the abundance of larger bubbles. Subsequent decreases in air pressure resulting in bubble expansion cause more pores to become clogged, thereby reducing the permeability (Beckwith and Baird, 2001). In a biogenic 'hotspot' the reduction of permeability and the continued production of gas will cause the pressure to increase until a threshold is reached where pore-blocking bubbles are ejected (Gardescu, 1930) or the pore enlarges (Johnson *et al.*, 2002) to cause a sudden release of the pressure. Such overpressuring was observed in this study, as were threshold pressures associated with sudden release.

Spatial patterns of overpressure zones
The blocked overpressure zones appear to be local, not noticeably affecting pressure at adjacent transducers at other depths (or piezometers at the same depths). Nevertheless, they also seem to be very common, as most of the pressure transducers showed some effect of overpressure at one time or another. It is likely that the distribution of overpressure zones is associated with a localized discontinuity in the peat profile, including low permeability strata, wood inclusions, or even pressure transducers. Such discontinuities may form an obstacle to normal (vertical) gas bubble movement, enhancing the pore-clogging effect. Apart from the size of gas production, the distribution of overpressure zones then depends on the spatial distribution and density of such obstruction objects and their sizes. The larger the obstruction object, the larger the zone of disconnection/overpressure. Extended layers of low permeability peat have been shown to cause extensive zones of elevated pressure, yielding enough water to register changes in piezometers open to the atmosphere (e.g. Romanowicz *et al.*, 1993; Rosenberry *et al.*, 2003). Even if p_e in those broad zones is maintained throughout whole seasons, periodic and sudden peaks or drops in pressure also occur, but these are restored to the previous pressure within 5 min (Rosenberry *et al.*, 2003).

Anomalies between different measurements

In this study, the 'open' piezometers did not show any indications of high-pressure zones. This could occur if the zones of high pressure are not continuous all around the piezometer intake so that water 'escapes' through this 'window'. Or, pipes may provide a conduit for the release of gas. Additionally, open piezometers require a much larger exchange of water to equilibrate with ambient pressure than do electronic pressure sensors in sealed cavities, thus attenuating the response.

Implications

The high-pressure zones cause changes in hydraulic gradients. However, if these high-pressure zones are associated with bubble-induced pore blockages, then their effect on water flow in the peat would not be so much a change of the overall groundwater head gradients but rather the creation of patches of blocked flow. Development of such patches may substantially contribute to increased heterogeneity in flow paths and water chemistry and complicate implementation of hydraulic conductivity estimates. Extensive high-pressure zones may be the cause of seasonal gradient developments (so called flow reversals) as described by Devito *et al.* (1997).

Pressure build-up and release may also cause dilation effects measurable as strain ε, since increased water pressure decrease the effective stress σ' caused by the weight of the overlying material, for a given water pressure (Price, 2003). Assuming a coefficient of volume change m_v of 0.01 kPa^{-1} (Lang, 2002), and given that $m_v = d\varepsilon/d\sigma'$, a 10 cm (1 kPa^{-1}) excess pressure causes an expansion of 1% of the initial volume for the high-pressure zone. Since these zones are presumably of small size, the effect from the pressure build-up and releases in the individual zones on the total peat volume may, therefore, not be noticeable. However, if these zones converge or grow, e.g. below a low-permeability peat layer, the effects of pressure increases and releases may be considerable and affect the peat surface elevation (and perhaps piezometer elevation). Such surface elevation changes have been observed at the Glacial Lake Agassiz peatlands, Minnesota (Glaser *et al.*, 2004).

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