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 watertable 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 overpres- 
sured zones within the peat that give rise to unex- 
pected 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 bub- 
bles are abundant in deeper peat (Brown et al., 1989; 
Romanowicz et al., 1993, 1995), although the dynam- 
ics of gas bubbles and the magnitude of the excess 
pressure they cause is poorly understood. Recently, 
Rosenberry et al. (2003) revealed a consistent over- 
pressure 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 pres- 
sure in shallower peat may be affected by gas to a 
substantial and varying degree. Using a pressure sen- 
sor 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 piezome- 
ter 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 
fluence head gradients, this peatland phenomenon 
needs to be investigated. The objectives of this paper 
were to determine (1) the magnitude and spatial (ver- 
tical) 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 transduc- 
ers 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 Bel- 
lechasse, Québec. The study area is a 3 ha unhar- 
vested 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 Eri- 
caceae shrub, whereas grasses and sedges sparsely 
cover lawns and shallow pool areas. The instrumenta-
tion was located at Sphagnum lawns, encircling 
~150 m² pools in two closely situated sub-sites. One 
of the sites, called ‘experimental’, was drained on 
day (day of year) 161 in early June 2002 by digging a 
shallow drain from the pool to the drainage net-
work. 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 Rhynchospora alba and 
Carex spp.

Field measurements were made from early May 
to late September 2002. The water table was moni-
tored continuously with recording wells combined 
with manual measurements every week. Pore water 
presure was automatically recorded with pressure 
transducers (KPSI 173, Pressure Systems Inc., Hamp- 
ton, 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 inser-
tion 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 
straps were not vented to the atmosphere, thus 
measuring absolute pressure without relating to atmo-
spheric pressure. To get hydraulic head variation, cor-
rection for atmospheric pressure variation had to be 
made. Air pressure data were obtained from a barom- 
eter (Vaisala PTB210, Vaisala Oyj, Helsinki, Finland). 
The transducers were later recalibrated in the labora-
tory; 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 m² 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 day 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:

$$p_e = h_s - wt$$  \hspace{1cm} (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 day 177–178 (Figure 3), and at C100 on day 245, whereas it was zero at C60 and C85 all season. At the experimental site, excess pressure commenced on day 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 C85, 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 day 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
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 day 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 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)
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 dilatation 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 = dε/dσ’, 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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