Hydrological hotspots in blanket peatlands:

spatial variation in peat permeability around a natural soil pipe

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Key Points

- Blanket peat hydraulic conductivity (*K*) is very variable over decimetre-scales
- Horizontal *K* is spatially structured, with *K* higher parallel to a soil pipe
- Spatial sampling of blanket peats to investigate sub-surface flow needs review

Abstract

Measurements were made of the hydraulic conductivity (*K*) of peat around a natural soil pipe in a blanket bog. This is the first investigation of decimetre-scale variability in both vertical *K* and horizontal *K* in blanket peats, which were found to be higher than indicated by previous research. This information suggests that it may be appropriate to reconsider (I) the spatial sampling strategies employed to investigate sub-surface flow in blanket peatlands, and (II) how field data are used to parameterise flow models. Critically, there was spatial structure in the heterogeneity, with a wedge of high-*K* peat directly above the pipe forming a hydrological conduit between near-surface peat and the perennially-flowing pipe. There was also significantly greater horizontal *K* parallel to the pipe's orientation compared with horizontal *K* perpendicular to the pipe. Determinations of the triaxial anisotropy of *K*, undertaken for the first time in peat soils, revealed substantial directional variations in *K*. The *K* around the pipe-peat interface was investigated; however, sample length dependency of *K* for peat samples precluded the investigation of a hypothesised low-*K* skin around the pipe.

1. **Introduction**

Blanket peat occurs on poorly-drained and gently-sloping terrain, usually in cool, oceanic areas such as the Pacific coast of Alaska, Newfoundland, Nova Scotia, Patagonia, the British Isles, Hokkaido, and New Zealand [*Charman*, 2002; *Evans and Warburton*, 2007; *Gallego-Sala and Prentice*, 2012]. Blanket peat catchment runoff is often dominated by saturation-excess overland flow and near-surface throughflow [*Evans et al.*, 1999; *Holden and Burt*, 2002a; 2003a; *Holden et al.*, 2008]. However, numerous studies have highlighted the importance of preferential throughflow via macropores and natural soil pipes in many different peatland systems including blanket peatlands [*Baird*, 1997; *Dimitrov et al.*, 2010; *Holden*, 2004; 2005c; d; 2006; 2009a; b; *Holden and Burt*, 2002b; c; *Holden et al.*, 2001; *Holden et al.*, 2002; *Ingram*, 1978; *Jones*, 2004; *Smart et al.*, 2013; *Worrall et al.*, 2009]. In peatlands, pipes occur in a variety of topographic settings and a range of depths [*Holden*, 2005c]; they are not restricted to particular layers such as the root mat or the interface with the underlying mineral substrate [*Holden and Burt*, 2002c] and there is currently little mechanistic understanding of their development [*Holden*, 2005b]. In blanket-peatland catchments in northern England, pipes have been found to convey around 10-14% of stream flow [*Holden and Burt*, 2002c], contributing 22% of catchment aquatic carbon flux [*Holden et al.*, 2012a].

Improved hydrological understanding of how pipes function in peatlands will help us to understand the role of pipes in peatland carbon cycling since peatland hydrological and carbon-cycling processes are closely related [*Holden*, 2005a; *Holden et al.*, 2009]. Such understanding is also particularly relevant given that research has indicated that environmental change may be linked to increased pipe densities in peatlands [e.g., *Holden*, 2005d]. If we are to include pipes in peatland models, given their importance to streamflow and aquatic carbon fluxes, then there is a need to understand the nature of water and carbon flow into pipe systems and therefore a need to understand the hydraulic conductivity (*K*) (L T^{-1}) of peat around pipes.

Water discharge from pipes is traditionally conceptualised as having two components [*cf. Jones*, 1982]: (I) baseflow produced by influent seepage according to the *K* and saturation state of the surrounding soil matrix [*Germann*, 1990; *Jones and Connelly*, 2002], and (II) quickflow produced by bypassing flow during rainfall and snowmelt events [*Gilman and Newson*, 1980; *Jones*, 2010]. Contemporary understanding of blanket peatlands suggests *K* is extremely low in all but the near-surface peat, which should greatly restrict pipeflow generation via soil-seepage and inhibit pipeflow during periods without overland flow or shallow throughflow [*Holden and Burt*, 2002c; *Smart et al.*, 2013]. In the 17.4-ha Cottage Hill Sike study catchment in the northern Pennines of England, hydrometric monitoring of eight pipes revealed rapid pipeflow responses to precipitation, suggesting good hydrological connectivity between pipes and near-surface peat [*Holden et al.*, 2012a; *Smart et al.*, 2013]. However, there were perennially-flowing pipes which, when data were upscaled to all of the pipe outlets identified in the catchment, were estimated to contribute flow equivalent to 12 % of the discharge at the catchment outlet. Ephemerally-flowing pipes were estimated to produce discharge equivalent to 2 % of flow at the catchment outlet. During low stream flows (lowest 10 %), perennially-flowing pipes were estimated to generate 20 % of streamflow. Thus, relatively important seepage into these pipes must have been occurring despite previous work suggesting that most of the peat mass has a low *K*.

Few studies have looked at the *K* of blanket peat [*Baird*, 2012]. *Hoag and Price* [1995] reported *K* values of 1.6 cm s^{-1} in the upper 0-0.2 m to 1.0 x 10^{-7} cm s^{-1} at 0.5 m depth in a

Newfoundland blanket bog. *Holden and Burt* [2003c] reported K values of *c.* 1.0 x 10^{-5} to 1.0 x 10^{-7} cm s^{-1} within 0.1-0.8 m of the surface of blanket peat in Moor House in the northern Pennines of England. Previous studies such as *Hoag and Price* [1995], *Holden and Burt* [2003c], and *Holden* [2005c] used piezometer slug tests to measure K. Such tests cannot be used to estimate anisotropy and may be unreliable, particularly if piezometers are not optimally installed and 'developed' [*Baird*, 1997; *Baird and Gaffney*, 1994; *Baird et al.*, 2004; *Surridge et al.*, 2005]. *Lewis et al.* [2012] obtained K estimates at two depths for a transect across a blanket bog in southwest Ireland, using the modified cube method [*Beckwith et al.*, 2003a]. Their K_H and K_V estimates at 0.1-0.2 m depth ranged from *c.* 10^{-5} to 10^{-2} cm s^{-1} and *c.* 10^{-5} to 10^{-2}, and at 0.3-0.4 m depth were *c.* 10^{-5} to 10^{-2} cm s^{-1} and *c.* 10^{-5} to 10^{-3}, respectively; which are higher for the named depths than reported from blanket peatlands elsewhere in the British Isles [*Holden*, 2005c; *Holden and Burt*, 2003c]. *Lewis et al.* [2012] reported systematic changes in both horizontal (K_H) and vertical (K_V) hydraulic conductivity, with lower values at the bog margin indicating some K structure at the landscape scale.

Despite field observations that suggest significant spatial variability in K over several orders of magnitude both horizontally and vertically, many peatland modellers either use a single 'representative' value of K [e.g., *Ingram*, 1982; *Rietkerk et al.*, 2004] or only consider vertical changes in K [e.g., *Ballard et al.*, 2011; *Dunn and Mackay*, 1996; *MacAlister*, 2001; *Reeve et al.*, 2000]. A range of models, including the recently-developed DigiBog model [*Baird et al.*, 2011; *Morris et al.*, 2011a], allows for both vertical and lateral variation in K but require field data to support such parameterisation. One of the key issues with modelling peatland hydrology is our limited understanding of spatial controls on peat hydraulic properties [*cf. Baird*, 1995; *Baird et al.*, 2008; *Belyea and Baird*, 2006; *Beven*, 2001; *Chappell and Ternan*, 1992; *Holden and Burt*, 2003b; c; *Lewis et al.*, 2012; *Rosa and Larocque*, 2008].

Jones [1975; 1981] and *Jones et al.* [1991] suggested that *overall* hydraulic conductivity (i.e. matrix and macropore components combined) might show some systematic variation around pipes. They hypothesised that K might increase with proximity to pipes, due to higher density of surface-connected macropores that feed these pipes. Additionally, they suggested that, in organic soils, pipes may facilitate oxygen ingress to the soil, increasing mineralisation of organic matter and potentially increasing porosity and permeability. Work on a brown earth soil by Jones (1975) showed K_H was greatest ~0.1 m directly above a soil pipe, decreasing by two orders of magnitude to the pipe roof and walls, and by another order of magnitude to the pipe floor. However, samples were collected from a stream bank, so it is possible that any macropore drainage networks may have discharged to the stream bank, potentially concealing pipe-related patterns. Additionally, sample sizes were unreported, and K estimates were derived using permeameter-type methods [after *Klute*, 1965] which may overestimate K [*Jones*, 1975]. *Jones et al.* [1991] investigated K around a perennial pipe in a peaty gley podzol using sample cores from three transects, and found mean K_H increased with proximity to the pipe over a 5-m distance, but by less than a factor of two (3×10^{-4} cm s^{-1} versus 1.8×10^{-4} cm s^{-1}). However, proximity to the pipe was inferred from surface vegetation, and the sampling frequency, sample sizes and method of K determination were unreported. A macropore drainage network supplying a pipe may increase K (including macropore and matrix components) with proximity to the pipe [*cf. Nieber and Sidle*, 2010], resulting in K_H perpendicular to the pipe (K_{H1}) being greater than K_H parallel to the pipe (K_{H2}) (as shown in Figure 1). Conversely, it is also possible that systematic structural differences in the peat, which may have influenced the formation of the pipe in the first instance could cause higher K parallel to the pipe ($K_{H2} > K_{H1}$). Such lateral anisotropy in K could have significant implications for simulations of water movement through peat around natural soil pipes. However, despite the development of suitable techniques [e.g., *Beckwith et al.*, 2003a], lateral anisotropy in *K* has never to our knowledge been investigated in peat soils. Furthermore, although *Rycroft et al.* [1975] anticipated triaxial anisotropy in the *K* of peat due to triaxial anisotropy in other structural/physical properties [*cf. Boylan and Long*, 2007; *Kazemian et al.*, 2011; *Zwanenburg*, 2005], this too has never been investigated.

Although the *K* of the pipe-peat interface is critical for parameterising models of peat-pipe water flow [*Jones et al.*, 1991], to our knowledge variations in *K* across the pipe-peat interface have not been investigated. It is possible that increased oxidation increases *K* at the pipe-peat interface as outlined above, or conversely, that a bacterial/oxyhydroxide biofilm lining the pipe may be pushed against soil pores by effluent seepage from the pipe but not by influent seepage, thus acting like a one-way valve [*cf. Butler and Healey*, 1998].

Finally, a number of studies have shown that *K* can change over periods of hours to days, and such changes have been attributed to (I) blocking of peat pores by biogenic gas accumulation [*Baird and Waldron*, 2003; *Beckwith and Baird*, 2001; *Reynolds et al.*, 1992], (II) changes in the pore-water chemical make-up causing pore dilatation/ constriction, capable of modifying *K* in a matter of hours [*Comas and Slater*, 2004; *Hoag and Price*, 1997; *Kettridge and Binley*, 2010; *Ours et al.*, 1997], and (III) the movement and redistribution of biogenic gas bubbles (an extension of the first idea), due to changing hydraulic gradients during *K* determinations, potentially altering the active macroporosity [*Baird and Waldron*, 2003; *Beckwith and Baird*, 2001]. Effects due to II can be reduced or eliminated by using water collected from the field when conducting *K* tests in the laboratory, thus allowing other controls to be investigated.

Using laboratory tests, we examined small-scale spatial variations in *K* (combining macropore and matrix components) of blanket peat around a natural soil pipe. Our study sought to: (I) measure fine- (decimetre-) scale variability in *K* in a blanket peat soil; (II) test whether peat soils can exhibit significant triaxial anisotropy in *K*; (III) establish whether there are systematic spatial variations in lateral anisotropy of *K* around a natural soil pipe; and, (IV) test whether there is a change in *K* at the peat-pipe interface.

2. Methodology

2.1. Site description

Cottage Hill Sike is a 0.174 km^2 sub-catchment of Trout Beck in the Moor House National Nature Reserve, northern England (Figure 2). The entire catchment is covered in peat which is typically 3-4 m deep but with deeper patches up to 8 m. Further details may be found in *Johnson and Dunham* [1963], *Dinsmore et al.* [2011], *Holden and Rose* [2011] and *Billett et al.* [2012]. Monitoring at five locations within the catchment suggests that water tables are within 0.05 m of the surface for 83% of the time, falling rarely below 0.2 m, and runoff response is dominated by saturation-excess overland flow and shallow throughflow in the upper few centimetres of peat [*Dinsmore et al.*, 2011; *Holden and Burt*, 2003c] with total pipeflow contributing an estimated 14% of annual streamflow [*Smart et al.*, 2013].

Discharge from the pipe has been intensively studied to elucidate the role natural soil pipes play in blanket peatland carbon dynamics [*Billett et al.*, 2012; *Dinsmore et al.*, 2011; *Holden et al.*, 2009; *Holden et al.*, 2012a; *Smart et al.*, 2013]. Labelled ‘P3’ in that published work (see above), the shallow pipe discharges directly to the surficial drainage network from an outlet ~0.25 m below the peat surface [*Holden et al.*, 2012b]. Where excavated (see below) at 54°41’47N”, 2°22’58”W, the pipe was ~0.3 m beneath the peat surface and *c*. 10 m upslope of the pipe outlet.

2.2. Field sampling

Cubic peat samples (Figure 3) were collected for laboratory determination of *K*, the latter using the modified cube method [*Beckwith et al.*, 2003a; *Surridge et al.*, 2005]. Various sized cubes have been used for modified cube method investigations, including 5 cm [125 cm^3, *Iwanek*, 2008], 7.5 cm [422 cm3, *Beckwith et al.*, 2003a], 8 cm [512 cm^3, *Rosa and Larocque*, 2008], and 10 cm [1000 cm^3, *Lewis et al.*, 2012]. Although scale-dependency in the modified cube method has not yet been quantified [*Kruse et al.*, 2008; *Rosa and Larocque*, 2008], larger samples are more likely to encompass preferential flowpaths [*Beven and Germann*, 1982; *Butler and Healey*, 1998], as well as be less sensitive to sample boundary disturbance [*Chappell and Ternan*, 1997; *Chason and Siegel*, 1986]. To balance the conflicting objectives of being sufficiently large to incorporate some macropores whilst being small enough to enable small-scale investigation, 10 cm (1000 cm^3) cubes were collected. Samples were extracted via an access trench rather than by coring, in order to maximise the accuracy of pipe-proximity and orientation measurements. The trench was excavated using spades, and the sampling face was cleaned with a sharpened trowel prior to sample extraction. Steel boxes (internal areas of sides: 100 cm^2), with a sharpened cutting edge to minimise sample compression and fibre entrainment during insertion [*Surridge et al.*, 2005] and a removable fourth side to facilitate sample extraction in the laboratory, were driven horizontally into the trench wall (Figure 3b). Field-testing demonstrated samplers cleanly severed roots up to 9 mm in diameter and also very poorly decomposed *Sphagnum papillosum* Lindb. litter. To maximise sampling density and facilitate examination of possible decimetre-scale heterogeneity whilst minimising interference between adjacent samplers, samplers were deployed systematically at ~3 cm intervals, at depths ranging from ~4 cm to ~50 cm below the surface. Sample B8 was compressed during sampling and was discarded. In addition to the six pipe-peat interface samples in the main set, three further interface samples were collected. Once extracted, the peat samples within their sample box were wrapped in cellophane and stored at 4°C to minimise drying, oxidation, and decomposition [*Chappell and Ternan*, 1997; *Ours et al.*, 1997; *Rosa and Larocque*, 2008].

2.3. Laboratory analysis

The modified cube method is a relatively new laboratory technique, developed by Beckwith *et al.* (2003a, after *Bouma and Decker*, 1981) for estimating directional K for the same small soil sample. Although laboratory K determinations have some unavoidable errors due to sample disturbance [*Baird et al.*, 2004; *Chappell and Ternan*, 1997; *Hendrickx*, 1990], the modified cube method is cheap and straightforward to use, avoids errors associated with preferential flow along instrument walls, and may provide a more accurate estimation of soil K than piezometer slug tests [*Baird et al.*, 2008; *Beckwith et al.*, 2003a; *Rosa and Larocque*, 2008; *Surridge et al.*, 2005]. Where possible, the outer *c.* 1 cm of samples was carefully removed using a non-serrated sharp knife as an additional precautionary measure against potential disturbance of samples during acquisition [*Iwanek*, 2008; *Lewis et al.*, 2012]. Samples were dabbed dry and quickly dipped into molten paraffin wax, a few mm at a time to minimise wax infiltration into macropores [*Rosa and Larocque*, 2008], until the sample was entirely encased. Two opposing faces were then exposed, and upwards wetting for ≥ 2 hours was used to help expel gas bubbles from the samples [*Beckwith et al.*, 2003a], although some residual gas would have remained. Cottage Hill Sike runoff water was used for both the sample wetting and subsequent K tests to minimise any pore dilation effects that have been reported when non-site water has been used (see *Ours et al.*, 1997). K determinations were undertaken using constant head gradients across the samples. Hydraulic gradients were generally less than 1.03, except in the case of the variable thickness pipe interface samples where they ranged from 1.1 to 25. In particularly high-K cases, the gradient was reduced to 0.1. K values were determined by applying Eq. 1:

Eq. 1. $$K = \frac{Q}{A} \times \frac{\Delta L}{\Delta H}$$

(assuming Darcian flow), where Q is discharge [mL s^{-1}], A is effective cross-sectional area (the smaller of the two exposed sample faces) [cm^{2}], ΔL is the sample thickness [cm], and ΔH is the head difference across the sample [cm]. Discharge (Q) was the average discharge of at least two consecutive measurement runs of similar duration to examine temporal variability in K. K values were standardised to 20°C to account for thermal-viscosity effects [*Hendrickx*, 1990; *Surridge et al.*, 2005]. After each test, the exposed faces were dabbed dry, resealed, the sample rotated, and the process repeated on two new opposing faces. Because bubbles trapped within the peat preclude complete saturation, the K estimates reported herein are for positive pore water pressures, rather than truly-saturated conditions as often mistakenly reported [*cf. Baird and Waldron*, 2003; *Faybishenko*, 1995].

Sample disturbance during acquisition was minimal, with negligible compression or entrainment of fibres. Due to the method of laboratory wetting of the samples (upwards wetting – see above), their biogenic gas content may have been lower than the *in-situ* contents [*Beckwith and Baird*, 2001] which would result in an overestimate of K; however, this possible bias is probably offset to some extent by the slight compression of samples observed during wax encasement. The latter was most significant in fibrous, poorly-humified samples, which may result in some underestimation of K in the highest-K samples.

Anisotropy may be expressed as the $\log_{10}$ of the K ratio [*cf. Beckwith et al.*, 2003a; b; *Chason and Siegel*, 1986]. Unlike unlogged ratios, the $\log_{10}$ of the ratio has the same magnitude when the relative difference is the same; with values of 0 indicating isotropy, 0.3 indicating a factor of two difference, and 1 indicating an order of magnitude difference. Samples were classed as triaxially anisotropic when all three biaxial anisotropy ratios (K_V/K_{H1}, K_V/K_{H2}, and K_{H1}/K_{H2}) exceeded a given threshold, the sensitivity of which was explored (Table 2).

In total, nine pipe-peat interface samples were collected. As the pipe-peat interfaces had not been subject to smearing during sample acquisition, these were not encased in wax so as to avoid damaging any surface biofilm/skin. K was determined for influent (K_{IN}) and effluent (K_{OUT}) flows across the interfacial peat. K_{IN} was straightforward to determine, with near-unity hydraulic gradients; however, for K_{OUT} , variations in sample thicknesses led to a range of different hydraulic gradients operating across the sample, making it inappropriate to apply equation (1) to the whole sample. The problem of multiple hydraulic gradients was resolved by assuming that flow through the sample was rectilinear and that each sample comprised a series of 1 × 1 cm flow paths, each with an individual hydraulic gradient. A semi-distributed model was used to calculate Q for each flowpath, solving K in order to match observed ΣQ with simulated ΣQ. K estimates from the semi-distributed model were slightly lower than estimates derived from mean sample thickness, with reductions proportional to sample thickness variability.

To test for a low-K pipe-peat interface, the first few centimetres of pipe-peat interface were removed from seven suitable samples, which were then resealed and reopened to clear potential smearing due to cutting, before the non-interfacial sub-sample was re-tested for K (see Figure 4). This experimental design only investigates the possibility of a low-K skin in the interfacial peat. To investigate potential sample length dependency in this approach, eight non-interfacial samples were also halved, resealed, reopened, and re-tested.

3. **Results**

3.1. General observations

The peat around the pipe-peat interface was darker then that further away from the interface (Figures 3a and 8), indicating a higher-level of humification, and a dense mass of living roots within the pipe extended for over a meter of excavation. During sample extraction, a number of large macropores (up to 3 cm in diameter) were observed connecting diagonally to the pipe.

Differences in percolate volumes between consecutive K determinations of the same sample and the same orientation exceeded a factor of two and an order of magnitude in 12% and 2% of cases, respectively. In 67.1% of cases (n = 164), the second K value was lower than the first.

3.2. Spatial heterogeneity in K

K_H ranged over seven orders of magnitude (1.38 cm s^{-1} to 3.03 x 10^{-6} cm s^{-1}) with a mean K_{H1} of 3.49 x 10^{-2} cm s^{-1} (σ = 2.19 x 10^{-2} cm s^{-1}) and K_{H2} of 1.17 x 10^{-2} cm s^{-1} (σ = 5.64 x 10^{-2} cm s^{-1}). K_v ranged from 2.10 x 10^{-1} cm s^{-1} to 1.78 x 10^{-6} cm s^{-1} with a mean of 6.61 x 10^{-3} cm s^{-1} (σ = 3.34 x 10^{-2} cm s^{-1}). Both K_H and K_V ranged over six orders of magnitude between laterally-adjacent samples (Figure 5). Directly above the pipe, a wedge of fibrous, poorly-humified, high-K_V (10^{-1} to 10^{-3} cm s^{-1}) peat extended downwards to the pipe roof at ~0.3 m depth; other than this feature, there were no discernible systematic variations in K (K_V, K_{H1} or K_{H2}) with proximity to the pipe. This structure is depicted schematically in Figure 6, along with a number of connecting large macropores (≥1 cm in diameter).

3.3. Anisotropy

The biaxial anisotropy in K between each of the three axes measured (K_V, K_{H1}, and K_{H2}) for the main set of 40 samples is shown in Figure 7. The biaxial anisotropy summary statistics, provided in Table 1, reveal that vertical > horizontal anisotropy, as indicated by greater-than-unity untransformed K ratios, occurred in 53% (K_V/K_{H1}; n = 21) and 60% (K_V/K_{H2}; n = 25) of cases. A non-parametric paired difference test demonstrated a significant difference between K_{H1} and K_{H2} (Wilcoxon Signed Rank: w = 2.379; p = 0.017; n = 40); with $K_{H2} > K_{H1}$ in 62.5% (n = 25) of cases (Table 1). Therefore, there appears to be spatial structuring in lateral K around the natural soil pipe, with K higher parallel to the direction of pipeflow. Classification of triaxial anisotropy is sensitive to threshold value (Table 2), but using a threshold of a factor of two difference ($\log_{10}$ values of ±0.3) leads to 25% (n = 10) of samples being classified as triaxially anisotropic.

3.4. Pipe-Peat Interface

There was no visual evidence of any biofilm at the pipe-peat interface, although the peat forming the pipe walls and bed was dark and appeared well humified (Figure 8). A non-parametric paired difference test revealed no significant difference between influent (K_{IN}) and effluent (K_{OUT}) K (Wilcoxon Signed Rank: $w = 1.472$; $p = 0.141$; $n = 8$). Removal of the pipe-peat interface increased K in five out of seven samples, causing mean and median $\log_{10}(K)$ (untransformed units of cm s^{-1}) increases of 0.24 and 0.11 respectively; although this was statistically non-significant (Wilcoxon Signed Rank: $w = 1.014$; $p = 0.310$; $n = 7$). Reducing the length of eight, randomly-selected samples not encompassing the pipe-peat-interface by ~50% increased K in 7 out of 8 cases, with mean and median $\log_{10}(K)$ increases of 3.39 and 0.59 respectively (data not shown), a statistically significant difference (Wilcoxon Signed Rank: $w = 2.380$; $p = 0.017$; $n = 8$).

4. Discussion

4.1. General Observations

Although only a single pipe section was examined, the observation of a dense mass of roots inside the pipe is important because natural soil pipes are widely perceived as relatively clear, if tortuous, conduits; a perception based on fiberscope studies in non-peatland environments [e.g., *Terajima et al.*, 2000] and photographs of pipe outlets in peatlands [e.g., *Holden*, 2005a; 2008; *Holden and Burt*, 2002c; *Holden et al.*, 2009; *Holden et al.*, 2012b; *Jones*, 1975]. Flow resistance within pipes is poorly understood, despite its importance for pipeflow simulations particularly with regards to in-pipe hydrodynamic pressures which determine exchanges of water with surrounding soil, influencing pore-water pressures and slope stability [*Kosugi et al.*, 2004; *Warburton et al.*, 2004].

The visually-striking wedge of high-K peat above the pipe revealed by the trench (Figure 3a) may indicate that this pipe formed through vegetative overgrowth of a pre-existing surface channel [*cf. Anderson and Burt*, 1982; *Holden and Burt*, 2002c; *Holden et al.*, 2009; *Jones*, 1981; *Thorp and Glanville*, 2003; *Tomlinson*, 1979] although the wedge may, of course, have resulted from the presence of the pipe. Although the former contention is based on process inference from morphological characteristics, it is supported by observations of intermittent vegetation coverage atop several other surface channels in the Cottage Hill Sike catchment, possibly exhibiting different stages of overgrowth, and could be tested by peat carbon dating in future work. Dissolved CO_2 and dissolved organic carbon exported during rainfall events from this pipe is relatively modern, based on ^{14}C and $\delta^{13}C$ analysis [*Billett et al.*, 2012]. The modern carbon leaving the pipe could originate from the peat wedge above the pipe and plant root exudates, although it should be noted that carbon associated with pipeflow at the pipe outlet will have been derived from locations along the pipe and not just at the location of the sampling trench.

The large macropores revealed during field sampling are unlikely to be well-represented by the sampling strategy that was employed, because, although macropores increase K when aligned to flowpath direction [*cf. Nieber and Sidle*, 2010], very few macropores directly connected opposite sample cube faces. A number of large (~1-3 cm diameter) macropores were observed along the apparent boundary between the near-surface higher-K and the underlying lower-K peat, supporting Holden and Burt's [2003c] suggestion that preferential throughflow is common along the acrotelm/catotelm boundary due to the K discontinuity.

4.2. Non-steady *K*

Although non-steady *K* has often been observed in peat soils, particularly during the initial stages of *K* determinations, the causes of non-steady *K* are often ignored [*Lewis et al.*, 2012; *Rosa and Larocque*, 2008]. As noted above, there are three main hypotheses to explain non-steady *K*: (I) blocking of peat pores by biogenic gas accumulation [*Baird and Waldron*, 2003; *Beckwith and Baird*, 2001; *Reynolds et al.*, 1992], (II) changes in the pore-water chemical make-up causing pore dilatation hours [*Comas and Slater*, 2004; *Hoag and Price*, 1997; *Kettridge and Binley*, 2010; *Ours et al.*, 1997], and (III) the movement and redistribution of biogenic gas bubbles [*Baird and Waldron*, 2003; *Beckwith and Baird*, 2001]. The variation in *Q* observed between consecutive *K* determinations occurred over a matter of minutes, far too quickly to be explained by a build-up of biogenic methane, thus ruling out the first hypothesis as a viable explanation. Given that (I) *K* increased in 32.9% of cases and that (II) Cottage Hill Sike catchment runoff water, assumed to be chemically very similar to the peat soil water, was used for the *K* determinations, it is also unlikely that non-steady *K* id due to II. Our results are compatible with III, altered active macroporosity due to mobile bubbles within samples [*Beckwith and Baird*, 2001]. The mobility of entrapped gas bubbles and their influence on *K* within peat soils, and indeed differences in the peat structural properties such as the orientations of hydrologically functional macropores, could be investigated using techniques such as neutron imaging or 3-D computed tomography [e.g., *Kettridge and Binley*, 2008; *Rezanezhad et al.*, 2009], and it is suggested that future experimental studies may benefit from paying greater attention to standardising the causes of non-steady *K*, perhaps through careful consideration of hydraulic gradients [*cf. Kruse et al.*, 2008].

4.3. Spatial heterogeneity in *K*

Both *Surridge et al.* [2005] and *Baird et al.* [2008] have argued that modified cube method estimates are more accurate for determining the hydraulic conductivity of peat soil than piezometer head-recovery tests, although the integrated K estimate offered by the latter may be more appropriate for parameterising hydrological models. Thus, selection of the most appropriate method must consider the purpose of the data collection. The maximum K values observed are five orders of magnitude greater than those previously reported at these depths for UK blanket peats [*Holden*, 2005c; *Holden and Burt*, 2003c]. Although micro-topographic variability meant upper tier sample depths varied from ~0.05 to ~0.13 m below the surface, both K_V and K_H over 10-cm distances laterally varied by more than six orders of magnitude, compared to the two orders of magnitude variation reported previously for peat elsewhere on the Moor House National Nature Reserve [*Holden*, 2005c; *Holden and Burt*, 2003c]. The K values reported by *Hoag and Price* [1995] for blanket peat in Newfoundland are similar to those observed herein, with minimum K one order of magnitude lower. The seven orders of magnitude range in K observed in the data presented herein suggests that the K of blanket peats may be more variable than was clear from previous reports, and is similar to the difference in K between gravel and clay mineral soils [*Domenico and Schwartz*, 1990]. Further empirical and fine-scale numerical modelling work is required before we understand scaling of permeability in blanket peat, and the concept of *representative elementary volume* may be useful for understanding water movements in peat soils [*cf. Binley et al.*, 1989].

The wedge of poorly-decomposed high-K *Sphagnum* peat found above the pipe roof coincided with a local surface depression which concentrates saturation-excess overland and near-surface flow above the pipe, facilitating drainage of the surface and near-surface peat. This may partly explain the perennially-, as opposed to ephemerally-, flowing nature of this pipe, as well as its rapid hydrological response to rainfall. The high-K wedge of peat also helps explain the geochemical, isotopic and hydrometric evidence of good connectivity between near-surface peat and pipeflow in this pipe [*Billett et al.*, 2012; *Holden et al.*, 2012a; *Smart et al.*, 2013]. Thus, the zone directly above the pipe can be considered a hydrological hotspot [sensu *Morris et al.*, 2011c], and the pattern of *K* we found further demonstrates the inadequacy of the acrotelm-catotelm model of ombrotrophic peatlands [*Ingram*, 1978] due to the model's omission of horizontal heterogeneity in important peat properties [*cf. Holden*, 2005d; *Holden and Burt*, 2003b; *Holden et al.*, 2012a; *Morris et al.*, 2011b].

4.4. Anisotropy

This investigation found $K_{H1} > K_V$ and $K_{H2} > K_V$ in 53% and 63% of cases, respectively (n = 40), similar to *Lewis et al.* [2012, n = 22] who report $K_H > K_V$ in 64% of samples from an Irish blanket bog. Vertical/horizontal anisotropy in *K* appears slightly less common in blanket peat compared with modified cube method investigations of other peats types. For example, $K_H > K_V$ in 78% of samples was reported for raised bog peat [*Beckwith et al.*, 2003a n = 400] and 76% in minerotrophic peat [*Rosa and Larocque*, 2008 = n 28], although there are few studies on anisotropy of peat.

Modelling studies examining the individual and combined effects of heterogeneity and anisotropy in soil *K* have reported that heterogeneity, rather than vertical/horizontal anisotropy is more influential to the movement of subsurface water [*Beckwith et al.*, 2003b; *Seo and Choe*, 2001]. The observation of co-location between high-*K* peat and the pipe appears to support this contention. To our knowledge, lateral anisotropy in *K* (K_{H1}/K_{H2}) has never before been investigated in any peat soil. Pairwise comparison demonstrated a significant difference between K_{H1} and K_{H2}, with $K_{H2} > K_{H1}$ in 62.5% of samples. This finding suggests that in the immediate vicinity of the pipe, there may be some lateral flowpath alignment parallel to the pipe. The data presented here suggest that there is some spatial structuring in *K* around natural soil pipes, which should support future efforts to characterise pipe flow generation and formation and to represent pipes in process-based numerical simulations. However, incorporating such spatial structuring risks reducing model generality and would increase computational demands [*Morris et al.*, 2011c].

4.5. Pipe-Peat Interface

To our knowledge our work is the first to examine the *K* of the pipe-peat interfaces. Any restriction on hydrological exchanges between the pipe and surrounding peat, such as a low-*K* skin or a one-way valve effect [*cf. Butler and Healey*, 1998], would be very important to include in hydrological models of blanket peats [*Jones et al.*, 1991]. However, no significant difference was found between influent and effluent flows, although only a small sample set was available. The removal of the pipe-peat interface non-significantly increased *K* in five out of seven samples, which could indicate the presence of a natural low-*K* skin. Mechanistically, a low-*K* skin could be caused by the forcing of suspended particulate matter into pores at the pipe-peat interface by high hydraulic gradients during surcharged pipeflow conditions, a speculation supported by the observation of fine, well-humified peat lining the pipe walls and bed similar to the ‘thin veneers of fine material’ on pipe walls and floors reported previously [*Jones*, 1975]. The lower hydraulic gradients produced during influent flow from the peat to the pipe would probably be insufficient to clear these blockages. However, reducing the sample length of eight samples was found to significantly increase *K*. This suggests that there is a sample-length dependency in *K*. In soils with a significant degree of macroporosity, such as peat, where macropores are either randomly or obliquely orientated to the direction of *K* determination, reducing sample length should logically increase macropore connections between opposing sample faces, thus increasing *K*.

5. Conclusions

To our knowledge this is the first study to examine decimetre scale spatial variability in both vertical *K* and horizontal *K* in *blanket* peat, which was far greater in both vertical and horizontal directions than was clear from previous investigations of blanket peatlands. This high-resolution work suggests that it may be appropriate to reconsider the spatial sampling strategies employed to investigate hydrological processes in peatland.

Determinations of triaxial anisotropy in *K* were undertaken for the first time in peat soils. These determinations are sensitive to threshold assignment, although a threshold of a factor of two difference suggests a quarter of samples are triaxially anisotropic in *K*. The significant difference in the pairwise comparison between K_{H1} and K_{H2} supports an inference that there is some alignment of lateral flowpaths parallel to the pipe, although there was a high degree of variability in this pattern. Importantly, a wedge of high-*K* peat directly above the perennially-flowing pipe that we studied forms a hydrological conduit between the high-*K* near-surface peat and the pipe at ~0.3 m depth. Combined with a linear local depression in the surface microtopography, this is likely to facilitate pipeflow generation through drainage of the high-*K* near-surface layer during both event (storm flow) and normal (low-flow) conditions.

The observation of non-steady discharge during *K* determinations over short timescales supports previous inferences that bubbles within the soil structure may be mobilised during hydrodynamic conditions, resulting in fluctuating permeability.

The hydraulic conductivity of the pipe-soil interface is important for flow connectivity between the pipe and the surrounding soil. We found no significant difference between influent and effluent flows across the interfacial pipe-peat samples. The pipe-peat interface was removed to try to test for the presence of a low-*K* skin; however, performing the same reduction in sample length on non-interfacial peat significantly increased *K*. This suggests that there is a dependency in *K* on sample length in macroporous peat soils, which precluded accurate investigation of interface properties using this approach. In other words, comparison of *K* measurements between samples of different lengths is inappropriate.

Importantly, we examined a single transect of a single pipe, in one environmental setting. Thus, it is impossible to infer how representative our findings are of natural soil pipes more generally, particularly as pipe networks in blanket peatlands are thought to vary according to hillslope position [*Holden*, 2005c; *Holden et al.*, 2002]. Therefore, while these findings indicate even greater complexity in peatland hydrological systems than is currently represented in state-of-the-art simulations [e.g., *Baird et al.*, 2011; *Morris*, 2010; *Morris et al.*, 2011a], they cannot be uncritically extrapolated. Future research could usefully prioritize comparison of the differences between perennially-flowing pipes and ephemerally-flowing pipes in blanket peat catchments.

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Table 1. Summary statistics of biaxial anisotropy.

	$\log_{10}(K_{H1}/K_{H2})$	$\log_{10}(K_V/K_{H1})$	$\log_{10}(K_V/K_{H2})$
Maximum	1.07	2.68	2.10
Minimum	-1.61	-1.65	-1.91
Mean	0.12	1.13	0.69
Median	-0.13	-0.03	-0.02
% where $\log_{10}(K_a/K_b)$ is < 0	62.5%	52.5%	60.0%

Table 2. Triaxial anisotropy in hydraulic conductivity. Threshold values are $\log_{10}(K$ ratio), derived independently for each of the three pairwise combinations of measured K values.

Threshold $\log_{10}(K$ ratio):		0.05	0.1	0.15	0.2	0.25	0.3	0.35
Triaxially anisotropic samples	***n***	32	27	20	18	11	10	6
	Proportion*	80%	68%	50%	45%	28%	25%	15%

*out of 40 samples, where K ratio is (K_V/K_{H1}, K_V/K_{H2}, and K_{H1}/K_{H2})

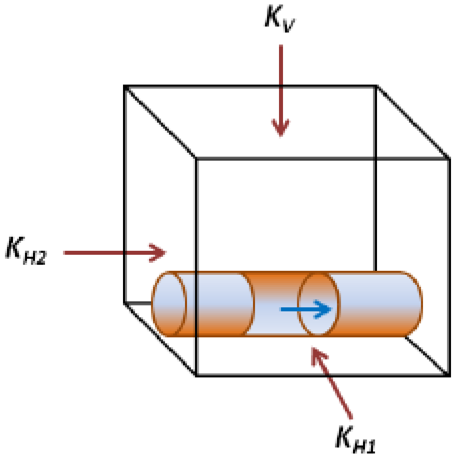


Figure 1. Orientation notation for K around a natural soil pipe.

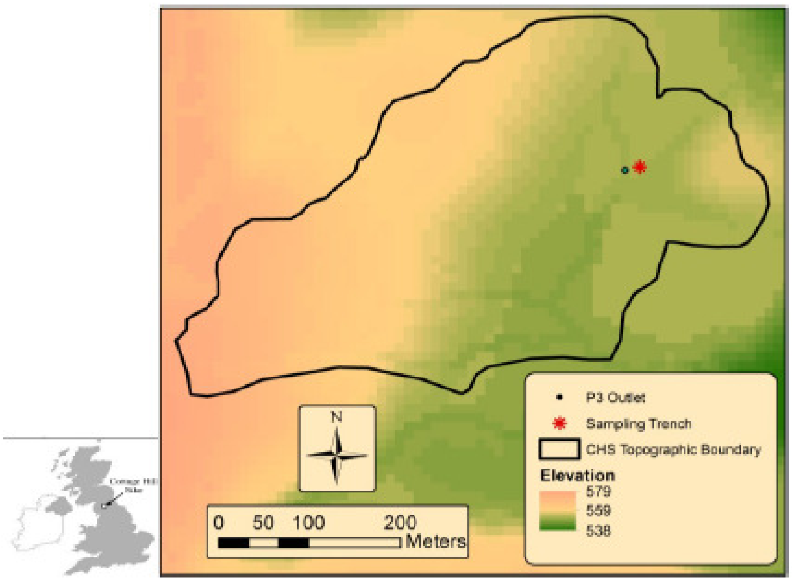


Figure 2. Location of the study pipe outlet (P3) and sampling trench within the Cottage Hill Sike study catchment shown on a 100 m^2 DEM, with elevation shown in meters above mean sea level. The entire catchment has a blanket peat cover.

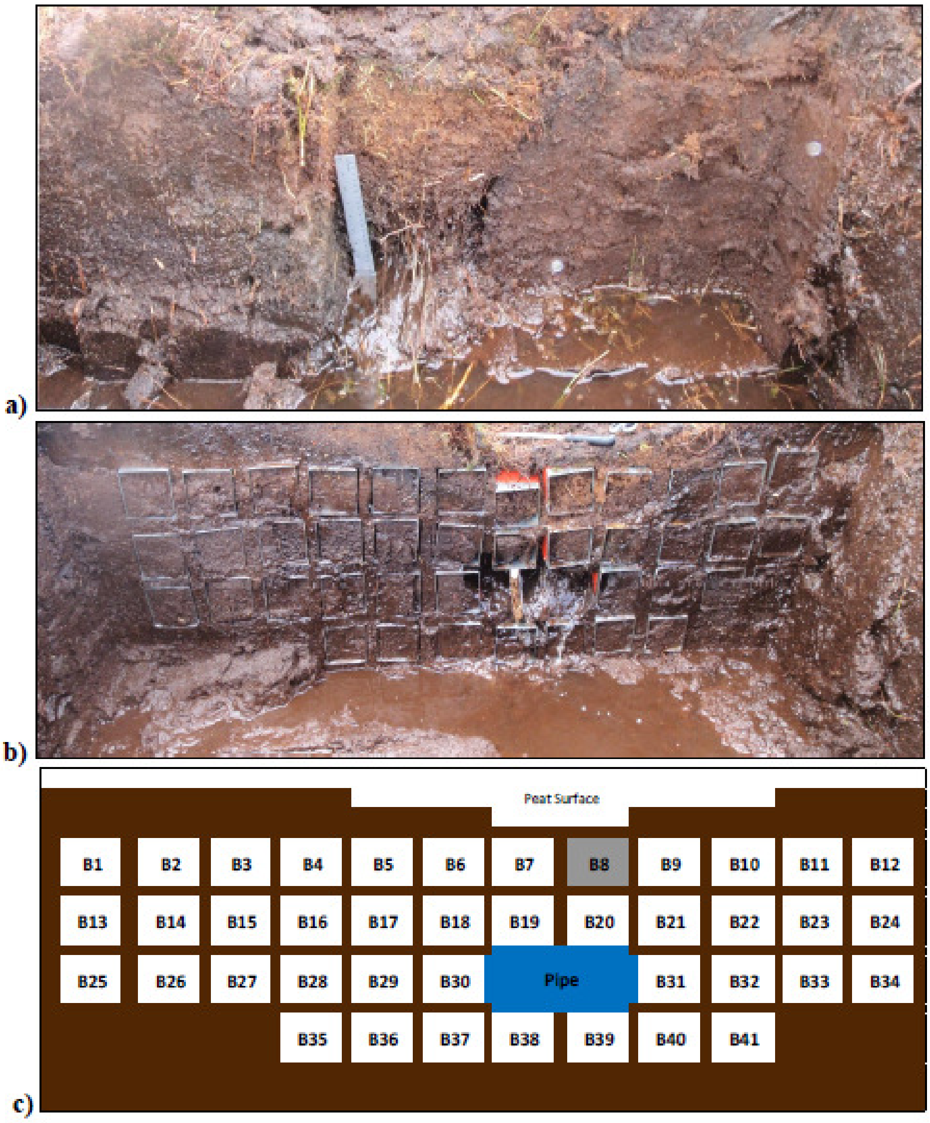


Figure 3. a) Photograph of the trench face, showing clear visual difference in peat colouration around the pipe; b) trench face with 41 deployed samplers (~3 cm intervals); c) Sample labelling system. (Note: sample B8 was compressed during sampler insertion, and was excluded from all subsequent analyses).

Figure 4. Pipe-peat interface removal. a) Sample with the Darcy test (influent) flow direction indicated by the arrow; b) cutting through an encased sample to remove the pipe-peat interface; c) re-determination of influent *K* through the shortened sample.

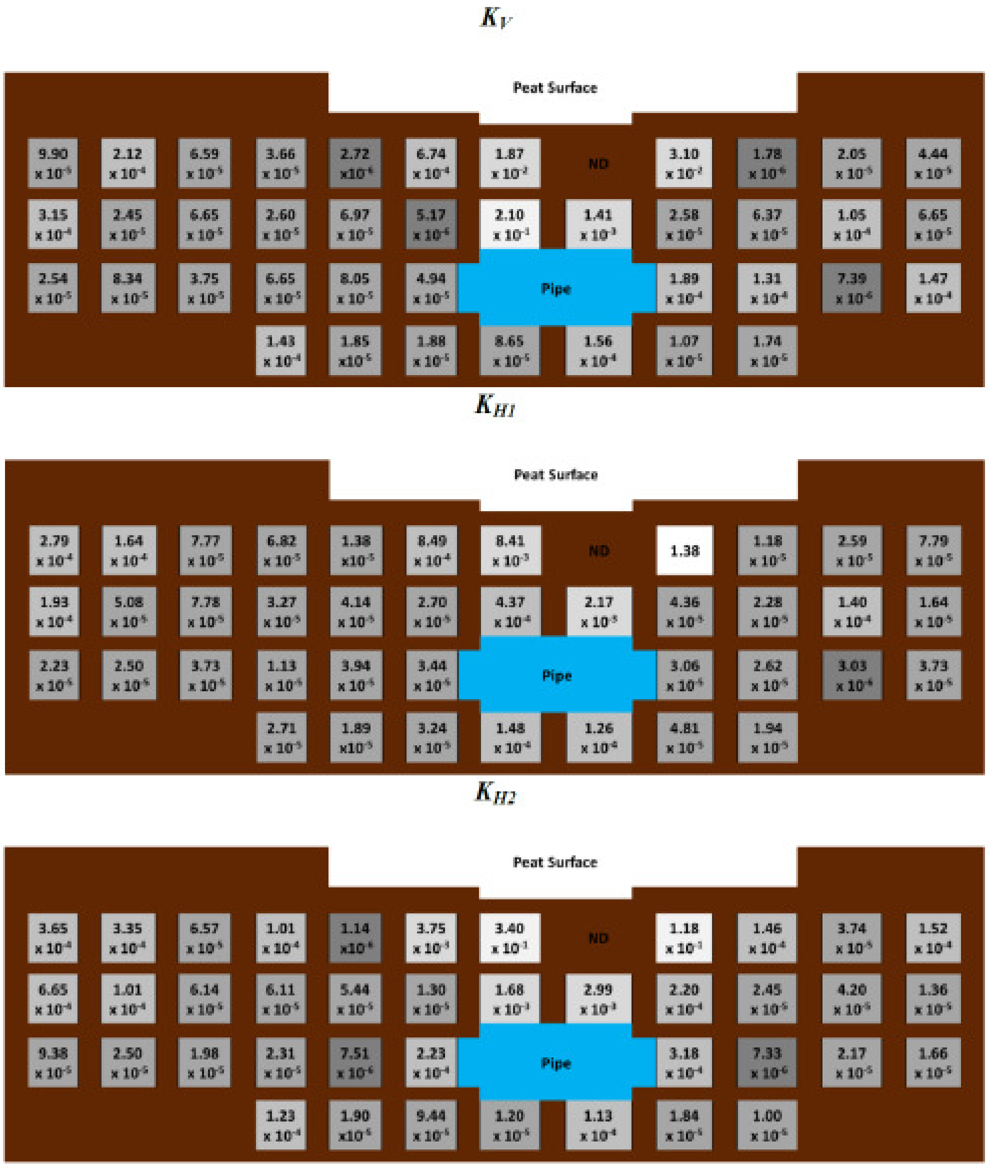


Figure 5. K_V, K_{H1} and K_{H2} values [cm s^{-1}].

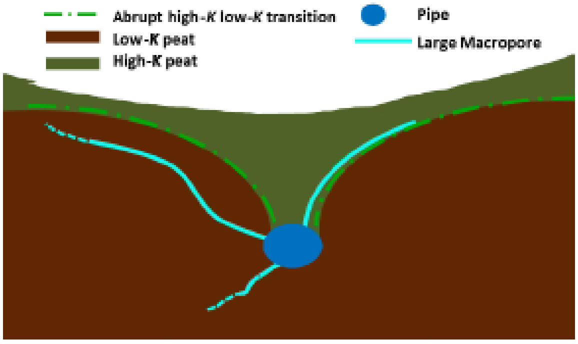
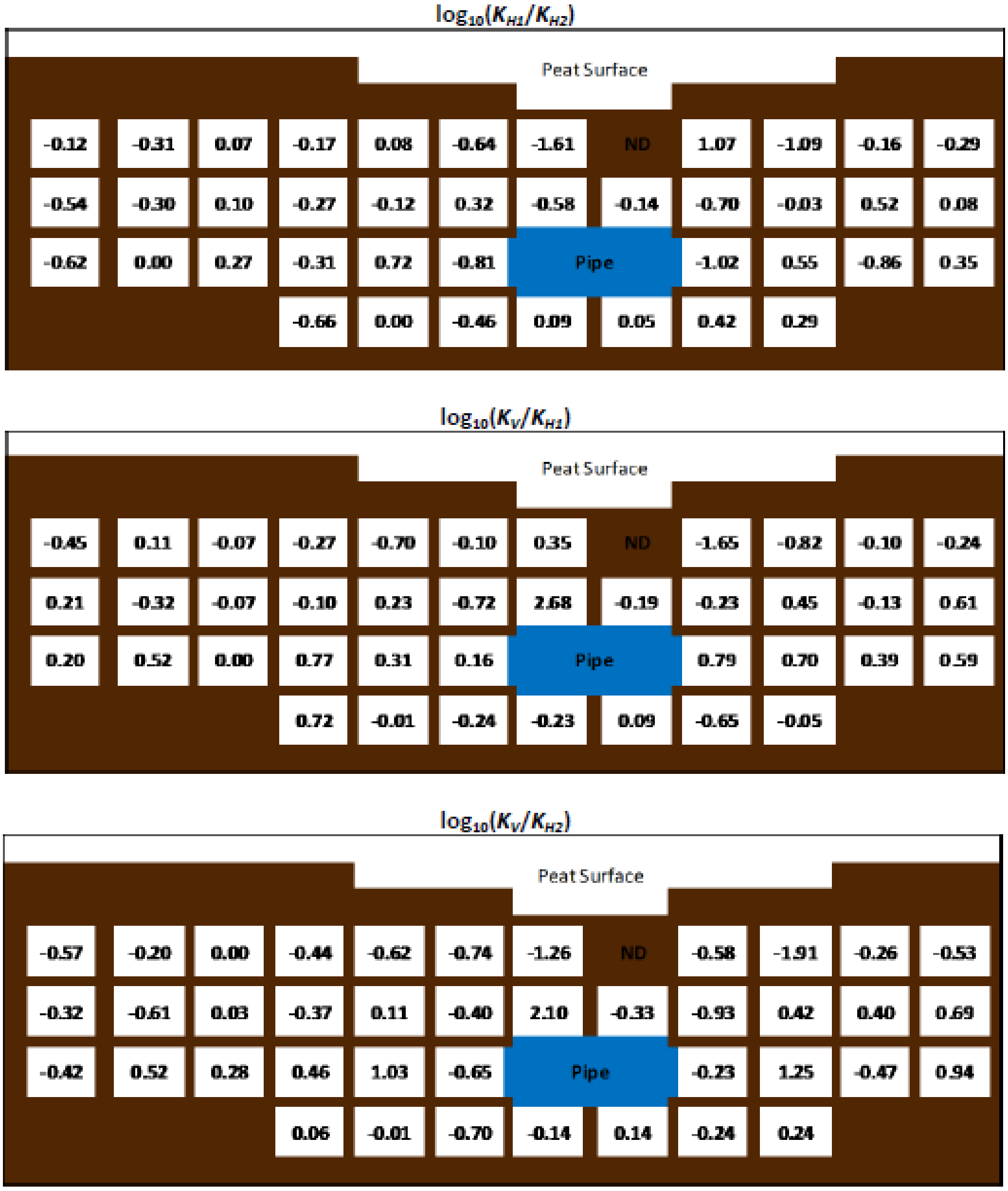


Figure 6. Schematic showing the high-*K*/low-*K* transition just above the pipe and the observed macropore network around the pipe. (Note: only macropores ≥1 cm in diameter are shown).



$\log_{10}(K_{H1}/K_{H2})$

-0.12	-0.31	0.07	-0.17	0.08	-0.64	-1.61	ND	1.07	-1.09	-0.16	-0.29
-0.54	-0.30	0.10	-0.27	-0.12	0.32	-0.58	-0.14	-0.70	-0.03	0.52	0.08
-0.62	0.00	0.27	-0.31	0.72	-0.81	Pipe		-1.02	0.55	-0.86	0.35
			-0.66	0.00	-0.46	0.09	0.05	0.42	0.29		

$\log_{10}(K_{V}/K_{H1})$

-0.45	0.11	-0.07	-0.27	-0.70	-0.10	0.35	ND	-1.65	-0.82	-0.10	-0.24
0.21	-0.32	-0.07	-0.10	0.23	-0.72	2.68	-0.19	-0.23	0.45	-0.13	0.61
0.20	0.52	0.00	0.77	0.31	0.16	Pipe		0.79	0.70	0.39	0.59
			0.72	-0.01	-0.24	-0.23	0.09	-0.65	-0.05		

$\log_{10}(K_{V}/K_{H2})$

-0.57	-0.20	0.00	-0.44	-0.62	-0.74	-1.26	ND	-0.58	-1.91	-0.26	-0.53
-0.32	-0.61	0.03	-0.37	0.11	-0.40	2.10	-0.33	-0.93	0.42	0.40	0.69
-0.42	0.52	0.28	0.46	1.03	-0.65	Pipe		-0.23	1.25	-0.47	0.94
			0.06	-0.01	-0.70	-0.14	0.14	-0.24	0.24		

Figure 7. Biaxial anisotropy, given as $\log_{10}$ (K ratio).

Figure 8. Pipe-peat interface at the pipe wall (sample A11)

Paper:
Cunliffe, AM, Baird, AJ and Holden, J (2013) *Hydrological hotspots in blanket peatlands: Spatial variation in peat permeability around a natural soil pipe.* Water Resources Research, 49 (9). 5342 – 5354

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