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Flow through macropores of different size classes in blanket peat

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Abstract

Blanket peats are important source areas for runoff in many northern European headwaters. The upper peat layer (20 cm) is dominant in producing flow in blanket peat catchments. However, little information exists on the relative roles of different size classes of macropore in water movement in this upper peat layer. This study uses results from tension infiltrometer experiments to assess the role of different size class of macropores in runoff generation. Infiltration measurements were performed under four surface cover types (bare, *Eriophorum*, *Calluna* and *Sphagnum*-dominated), at four soil depths (0 cm, 5 cm, 10 cm and 20 cm) and at four water tensions (0 cm, -3 cm, -6 cm and –12 cm). Macropore flow was found to be an important pathway for runoff generation. Only 22 % of the flow in the upper 20 cm of peat occurred in pores smaller than 0.25 mm in diameter. The remaining portion of flow was equally divided between those pores between 0.25 mm and 1 mm in diameter those pores greater than 1 mm in diameter. Most of the flow in upland blanket peat was generated from only a small volume of the peat. At the surface around 80 % of flux was generated through only 0.26 % of the peat volume while at 5 cm depth, while percolation rates were an order of magnitude slower than at the surface, 85 % of the flux was generated from only 0.01% of the peat volume. Infiltration and effective porosity both declined by over two orders of magnitude over the top 20 cm of the peat. The variability in flow and effective porosity was found to be similar between different pore size classes.

Keywords

Peat, Macropores, Runoff, Infiltration, Tension infiltrometer, Effective porosity

1. Introduction

Peat covers 3 % of the world's landmass but is much more important in terms of its role in delivering water and sequestering carbon (Holden, 2005b). Research on blanket peats has shown that runoff production tends to be very flashy and dominated by quickflow response with very little baseflow (Burt, 1995; Holden and Burt, 2003a; Holden and Burt, 2003b; Price, 1992). Flow production is controlled by the saturated state of the peat mass and the low hydraulic conductivity of the lower peat layers such that near-surface and saturation-excess overland flow dominate (Evans et al., 1999; Holden and Burt, 2003b; Holden, et al. 2007).

While saturation-excess overland flow and near-surface flow dominate the runoff response of blanket peat catchments, it has also been shown that bypassing flow is an important process in these systems (Holden, 2005a; Holden, 2005c; Holden, 2006; Holden and Burt, 2002; Holden et al., 2001; Ingram et al., 1974; Jones, 2004). Natural soil pipes (generally considered to be larger than 1 cm in diameter) have been shown to contribute 10 % of discharge to the stream in deep peat catchments (Holden and Burt, 2002) while flow in pores larger than 1 mm in diameter has been shown to contribute approximately 30 % to the infiltration process (Holden et al., 2001). Blodau and Moore (2002) found, using a tracer in Ontario peats, that 20 to 50 % of the tracer was recovered from depths at which the tracer would have been absent if preferential flow had not occurred. Others have shown that macropores can locally impact the rate of water transmission through peats (Chanson and Siegel, 1986; Ingram et al., 1974).

Baird (1997) studied a fen peat with a tension infiltrometer finding that macropore flow contributed between 51 and 78 % of the flow at the peat surface.

Little research has been done on the comparative roles of macropores of different sizes in conducting water through peats. Porous media physics would suggest that it is likely that the larger pores play a significant role in transporting water through peats rather than the smaller pores but field and laboratory determinations have been rare. Carey et al. (2007) employed tension infiltrometer measurements and image analysis on subarctic organic soils to assess the role of different pore sizes in peat water transmission. They found that total effective porosity was 1.1×10^{-4} which accounted for only 0.01% of the total soil volume with macropores (defined as those pores larger than 1 mm in diameter) accounting for approximately 65% of the water flux at saturation. Effective porosity is the interconnected pore volume that contributes to fluid flow. This compares to total porosity which is the proportion of the soil mass that is filled by pore spaces as opposed to solid material. Values of effective porosity have been well reported for agricultural soils. For example, Azevedo et al. (1998) found that 86 % of the flow in a loamy agricultural soil occurred through 0.02 % of the soil volume. It may be that similar values occur in blanket peats but this has hitherto not been determined. While Carey et al (2007) examined water flows through pores of different sizes in subarctic organic soils, to the author's knowledge there has been no work to examine water flux or effective porosity related to pores of different size classes in intact blanket peats. Most of the research carried out on macroporosity in blanket peatlands has been done on mined peat stockpiles for power stations in order to determine the most productive water retention and rewetting characteristics. Holden and Ward (1996) found that in some rewetted milled peat stores the water content at depth in the profile was greater than near the surface, suggesting a short-circuiting of water flow through them. Some evidence came from ‘wet fingers’ that were observed in the field (Holden and Ward, 1997). Further evidence came from Holden (1998) who examined air-dried milled peat from the surface of a drained bog. From core samples, outflow was similar to the spray rate and little water accumulated in the peat. Bypassing flow paths appeared to form readily.

Macroporosity is important for transport characteristics of solutes (Ours et al., 1997; Reeve et al., 2001) and indirectly influences peatland gas exchange (Siegel et al., 1995). Since most of the runoff in blanket peatlands is generated within the upper peat, these layers will also be important in terms of solute production. Runoff emerging from blanket peat catchments suffers from several water quality problems, including high concentrations of dissolved organic carbon which is associated with discolouration. In the UK, which hosts 15 % of the world’s blanket peat deposit, the headwater blanket peats are sources for large quantities of solutional discolouring organics, which are an expensive and growing problem for water supply companies (Mitchell and McDonald, 1992; Mitchell and McDonald, 1995; Mitchell, 1990; Worrall et al., 2003; Worrall et al., 2006). Understanding flow through differently sized peat pores would enable us to improve our transport models, and our understanding of dissolved organic carbon production and solute transport. This is because the flow pathway, pore sizes, tortuosity and continuity will have an impact on water residence time and the interactive surface area that the solution can come into contact with (Allaire et al., 2002a; Allaire et al., 2002b).

Blanket peat is formed from the residue of vegetation that grows on it. For this reason its structure is likely to be partly affected by the surface vegetation. The structure of plant roots and litter produced by living vegetation will also interact with the upper peat layer to impact its structure and the potential for bypassing flow. Furthermore, bare peats often suffer from desiccation in dry spells and frost-heave in cold spells (Gilman and Newson, 1980; Tallis, 1973). Thus, unprotected peats may have a different structure in the upper layers due to these physical processes. It would be expected that the vegetation cover type would have some control over the proportion of flow moving through different pore size classes. Additionally Bradley and Van Den Berg (2005) examined infiltration in a flood-plain wetland peat formed largely from reeds and found large changes in water flow through large and small pores with depth. As peat properties can change rapidly with depth it is also expected that depth will control the proportion of flow moving through different pore size classes in blanket peat.

This paper aims to examine the role of a range of pore sizes in the infiltration and percolation process in blanket peat and to assess whether the flow in the different pore size classes is affected by vegetation cover type and distance from the peat surface. Unpublished data collected during the course of experiments performed by Holden et al. (2001) will be examined for the first time in this paper. It is hypothesised that i) flow through small pores (<0.25 mm in diameter) plays only a small role in infiltration and percolation in the upper 20 cm of blanket peat; ii) that the vegetation cover type controls the proportion of water that flows through different macropore size classes and iii) that effective porosity will be effected by vegetation cover type.

Some authors have classified pores into macropores, mesopores and micropores, where the latter corresponds with the small pores associated with the soil matrix (Luxmoore, 1981). Definitions of the size of such features vary. In this paper four pore size classes with the ranges <0.25 mm, 0.25-0.50, >0.50-1.00 mm and >1.00 mm are investigated. In order to avoid confusion these pore sizes classes are not given descriptive terms here.

2. Study site

The experiments were performed at the Moor House National Nature Reserve, North Pennines, England (54^o 41’ N, 2^o 23’ W). This is one of the largest areas of blanket bog in the UK and as a UNESCO Biosphere Reserve is recognised for its worldwide importance. Lower Carboniferous sequences of interbedded limestone, sandstone and shale provide a base for a glacial till (Johnson and Dunham, 1963). The overlying glacial till has resulted in poor drainage which has led to the development of a one to four metre thick deposit of blanket peat on around 70 % of the reserve. Peat formation began in the late Boreal as bog communities began to replace birch forest, macro-remains of which are commonly found at the base of the peat (Johnson and Dunham, 1963). The vegetation is dominated by *Eriophorum* sp. (cotton grass), *Calluna vulgaris* (ling heather) and *Sphagnum* sp. (moss). There are also some areas of bare peat, although many of these areas are now revegetating (Evans and Warburton, 2005). The upper 5 cm of the intact vegetated soil is generally poorly humified, graded H2-H3 on the Von Post (1922) scale, with a black-brown coloured peat with living roots. Below this to 10 cm depth the peat is a slightly humified (H3-H4) brown peat overlying darker brown *Eriophorum-Calluna-Sphagnum* peat (H4). The peat, then, very gradually becomes more humified with depth, with decomposition almost complete by 1.5 m depth (H9). Further details on the peat at the study site are provided in Johnson and Dunham (1963) and Holden et al (2001). Dry bulk densities range from 0.15 g cm^{-3} at the surface to 0.18 g cm^{-3} at 20 cm depth gradually increasing to 0.27 g cm^{-3} at 50 cm depth. Total porosity of the blanket peat at the site is typically within the range of 90 to 97 % which corresponds well with total porosity for blanket peats reported elsewhere (Bozkurt et al., 2001).

3. Methods

A tension disk infiltrometer similar to that designed by Ankeny et al. (1988) was used in the study during summer 1999. A 100 m x 100 m area was used for sampling and contained the four most common surface types found at the field site (*Calluna, Eriophorum, Sphagnum* and bare peat). Infiltration measurements were taken at eight randomly chosen sites for each cover type and at four depths (0 cm, 5 cm, 10 cm and 20 cm) at each site. At each location vegetation was carefully cut back to the peat surface and a fine layer of moist silica sand was applied to smooth out irregularities and improve contact between the base of the porous disk of the infiltrometer and the soil surface. The instrument was supported with a clamp-stand structure to prevent the weight of the instrument compressing the peat surface and was shaded to prevent sunlight heating the water reservoir. Infiltration measurements were performed until steady-state was achieved. The measurements were performed with supply heads of -12 cm, -6 cm, -3 cm and 0 cm. According to capillary theory, infiltration at these soil water tensions will exclude pores of equivalent diameter greater than 0.25 mm, 0.5 mm and 1 mm, respectively, from the transport process. In this paper these values form the distinction between four pore size classes <0.25 mm, 0.25-0.50, >0.50-1.00 mm and >1.00 mm. Hydraulic conductivity values for each tension were calculated using the method outlined by Reynolds and Elrick (1991). A problem with data collection is related to the assumption that the hydraulic conductivity of the soil prior to the test is substantially below that which prevails during the test when the soil saturates and this may not hold true in peat, particularly if the water table is high. However, Holden et al. (2001) showed that within the context of the large range of values of hydraulic conductivity within blanket peat, the errors produced during this study would be minor. They also showed that the concerns surrounding Wooding's (1968) assumption of isotropy would also result in minimal errors for these tests.

The procedure presented by Watson and Luxmoore (1986) and Wilson and Luxmoore (1988) was used to calculate effective porosity volumes whereby effective porosity, θ, associated with each size class was calculated from Poiseuille's equation by:

$$\theta = (8\ \mu\ K_m) / (\rho\ g\ r^2)$$

where μ is the viscosity of water, ρ is the density of water, g is the acceleration of gravity and r is the minimum radius for the size class. Hence, the effective porosity value is a minimum estimated value. The pore flow, K_m, was calculated as the difference between conductivities at a given pressure head and the next higher pressure head (Azevedo et al., 1998). The water temperature was measured for each tension infiltrometer experiment allowing improved determinations of μ and ρ. Several assumptions are made in applying Poiseuille's equation to the calculation of effective porosity and these include laminar flow, cylindrical pores, and minimum pore radius as the true pore radius. It may be that many of the capillaries in peats are very short, non-uniform and not well-connected such that these assumptions are not met. This should be borne in mind when interpreting results below. Statistical testing was carried out using ANOVA.

4. Results

4.1 Infiltration rates

Infiltration rate was significantly controlled by vegetation cover, soil depth and water tension ($p < 0.001$). Infiltration was significantly greater at 0 cm than at any of the other tensions in the plots. There was a large decrease in infiltration rates from 0 to -3 cm tension showing that under saturated flow conditions, flow in pores > 1 mm in diameter is a significant pathway for water movement. Figure 1 presents mean measured infiltration rates at 0, -3, -6, -12 cm water tension for the peat plots under each vegetation cover type and for the four tested soil depths. Infiltration rates declined rapidly with soil depth indicative of a sharp reduction in hydraulic conductivity. The steepest decline in infiltration rates appears to occur over the top 5 cm of the peat. This was found to be more pronounced for the larger tensions applied, suggesting that flow in pores > 1 mm declines much more rapidly with depth than flow in smaller pores.

Vegetation cover type significantly controlled infiltration rate from the tension infiltrometer and Figure 1 suggests that *Sphagnum* and bare peat have different hydraulic properties to *Eriophorum* and *Calluna* peats. Figure 1 shows that infiltration rates into blanket peats covered with *Eriophorum* and *Calluna* follow broadly the same pattern of change with depth. For bare peat, infiltration was greater at 10 cm depth than at 5 cm depth for all water tensions except 0 cm tension. This suggests that flow in pores < 1 mm in diameter was more prominent at 10 cm depth.

The coefficient of variation (CV) was calculated for infiltration rates for each category of depth, tension and vegetation cover type as shown in Table 1. CV was much smaller at the surface (57 %) than deeper within the peat. Infiltration rates appear more variable below a *Sphagnum* or *Calluna* cover than below an *Eriophorum* or bare peat.

4.2 Flux by pore size class

Figure 2 plots the proportion of flow moving within pores of different size classes for each treatment. There is generally approximately the same proportion of flow moving between pores of between 0.25 and 0.5 mm in diameter as there is moving between pores of between 0.5 and 1 mm in diameter. The total flow in pores > 1 mm in diameter is greater than the total flow between any of the other pore classes examined. The depth with the largest proportion of flow occurring in pores > 0.25 mm was 5 cm for bare, *Eriophorum* and *Calluna* peats. For *Sphagnum*-covered peats the proportion of flow in pores > 0.25 mm increased with depth over the 4 depth categories studied.

It is possible from Figure 2 to examine the proportion of flow occurring in pores < 0.25 mm in diameter as this is the residual flow (i.e. up to 100 %) not accounted for by flow through the pores shown by the bars on the chart. Flow in pores < 0.25 mm in diameter accounts for less than 50 % of the flow on average in all but one case (bare peat at 10 cm depth) and the proportion of flow is typically between 20 and 30 %.

Figure 3 shows mean values for flow within pores > 1 mm in diameter as a proportion of all infiltrating water by vegetation cover type and depth. Both depth and vegetation cover type significantly controlled the proportion of flow in the larger pores (p <

0.001). Flow contributions in pores > 1 mm are greater at 5 cm depth than for other layers, except below a *Sphagnum* cover. In general *Sphagnum*-covered peats are associated with a greater role for macropores in the infiltration process. In non-*Sphagnum* covered peat the depth control is evident, with a maximum proportion of flux for pores > 1 mm occurring at 5 cm and a minimum at 20 cm depth. Surface flux contributions for pores > 1mm in the blanket peat were between 21 % (minimum) and 68 % (maximum) irrespective of vegetation cover.

4.3 Effective porosity

Effective fractional porosity data were highly variable, and positively skewed, ranging from 6804 cm^3 m^{-3} to 0.002 cm^3 m^{-3} and a skewness of 4.74. A logarithmic transformation was therefore applied before conducting ANOVA so that the variability between the categories is more constant. This enabled the main assumptions of ANOVA (equal variance between categories) to be met and reduced skewness to -0.26. The ANOVA (Table 2a) shows that depth, vegetation cover type and pore size can be accepted as controls upon effective porosity, although vegetation cover type is the weakest of these three controls. Table 2b, c and d present ANOVA results for depth and vegetation cover controls for each pore size class. It is clear that depth was a dominant control for each pore size. Vegetation cover became more significant for the larger pore sizes such that for pore sizes > 1 mm in diameter p = 0.052. This may be because plant structures and rooting which form the peat itself affected the structure of larger pores more than smaller ones. The effective porosity at the surface of bare peats was around twice that of the vegetated peats.

Effective porosity decreased rapidly with depth (Figure 4) and increased with decreasing pore size class (Table 3). Most runoff appears to be generated through only a small proportion of the peat. Table 3 shows that at the peat surface approximately 80 % of the flow was generated through only 0.26 % of the peat volume. Table 4 shows that CVs are greater at depth and below an *Eriophorum* cover (120 %) than other cover types. *Sphagnum* peats have the lowest CVs with a mean of 82 %. There appears to be little difference in CVs of effective porosity between pore size classes suggesting that variability is the same within different pore size classes in the peats tested.

5. Discussion

The results above show that pores < 0.25 mm in diameter play only a minor role in infiltration and percolation in the upper 20 cm of blanket peat. Of the percolating water measured over the upper 20 cm of the peat mass, only 22 % moved through pores smaller than 0.25 mm in diameter. Given that most runoff in blanket peat is produced by the upper 20 cm (Holden and Burt, 2003a) this is an important finding. At the peat surface 80 % of the flow occurred through 0.260 % of the peat volume. While flow rates were an order of magnitude lower at 5 cm depth, 85 % of the flow at this depth occurred through 0.010 % of the soil volume. 67 % of the flow occurred through 0.014 % of the soil volume at 10 cm depth, while at 20 cm depth 60 % of the flow at this depth occurred through just 0.003 % of the soil volume. However, flow rates at 20 cm depth were two orders of magnitude lower than at the peat surface.

Azevedo et al. (1998) found that 86 % of the flow in a loamy agricultural soil occurred through an effective porosity of 190 cm^3 m^{-3} (equivalent to 0.019 % of the soil volume). These results are also in line with values obtained for forested soils by Wilson and Luxmoore (1988) and Watson and Luxmoore (1986). For peatlands, the only other reported results with which to compare these findings come from the subarctic work of Carey et al. (2007). Where comparable data between the two studies are available the results are similar. For example, comparison of Table 3 in this study with Table IV in Carey et al. (2007) shows similar results for the number of pores m^{-2} and effective porosity for pore class sizes between 0.25 and 0.50 mm in diameter (or 0.277 to 0.448 mm as it is in Carey et al., 2007) and pore classes between 0.50 and 1.00 mm in diameter at the peat surface. The similarity in peat macropore properties (proportion of flow in pores > 1mm) between the subarctic site and the blanket peat of northern England was also pointed out by Carey et al. (2007) when they compared their results to the blanket peat work of Holden et al. (2001).

Vegetation cover type significantly controls the proportion of water that flows through the different pore size classes of blanket peat, although it does not have a significant impact on the proportion of flow moving through pores between 0.25 and 1 mm in dimater, except for at bare peat sites. For bare peat, flow in pores > 1 mm and between 0.25 and 1 mm in diameter appeared to vary in a different way with depth than the vegetated surfaces. The upper 5 cm was dominated by flow in pores >0.25 mm as with vegetated surfaces, but at 10 and 20 cm depth flow in pores < 0.25 mm diameter dominated. It may be that the surface vegetation impacts flow in the larger pores through root structures and litter, but these features do not have significant impacts at the smaller pore level. By default, a change in the proportion of flow through larger pores is likely to inversely impact the proportion of flow occurring through the smaller pores <0.25 mm diameter. Fauna associated with different plants may also play a role in the pore assemblage. However, the density of earthworms on peat soils is very low, ranging from one worm per 100 m^2 on *Eriophorum* dominated areas to 13 worms per 100 m^2 on *Calluna*-dominated areas (Svendsen, 1957). Peachey (1963) found enchytraeid worms in moorland soils contributed by far the greatest biomass. Worm ingestion and egestion of peat may result in decreased pore size and continuity. However, these worms (Oligochaeta) are typically 50 μm in diameter and are therefore not likely to be important in terms of the pore classes tested in this paper. Enchytraeidae tend to be more dominant under *Eriophorum* and *Calluna* covers, less abundant beneath *Sphagnum* and much less dense in bare peat (Springett, 1970.). Nevertheless, there may still be c. 20 000 enchytraeidae per m^{-2} in bare peat. It is more likely that the differences between bare peat and vegetated peat were a function of a combination of enhanced desiccation of the near-surface of bare peat combined with erosion into deeper, older more humified peat, meaning that at depths of 10 or 20 cm the peat is older and more decomposed that at the same depths under uneroded, vegetated conditions.

Infiltration rates into *Eriophorum* or bare peats were less variable than infiltration rates in *Sphagnum* or *Calluna* covered peats. Importantly, the variability was not controlled by water tension, clearly indicating that flow in pores > 1 mm in diameter was just as variable as flow in pores between 0.25 and 1 mm in diameter. This was corroborated by analysis of the variability of effective porosity as the variability in effective porosity did not differ with the pore size examined. Effective porosity was significantly affected by vegetation cover and increased with decreasing pore size. Effective porosity decreased by around two orders of magnitude over the top 20 cm of peat. This suggests that many pores > 0.25 mm diameter in the upper 20 cm of the peat are not likely to extend vertically into the peat by more than a few cm.

6. Conclusions

This paper examined the role of a range of pore sizes in the infiltration and percolation process in blanket peat assessed whether the flow in the different pore size classes was affected by vegetation cover type and distance from the peat surface. The paper tested three hypotheses which suggested that flow through small pores (<0.25 mm in diameter) would play only a small role in infiltration and percolation in the upper 20 cm of blanket peat, that the vegetation cover type controls the proportion of water that flows through different macropore size classes and that effective porosity will be effected by vegetation cover type. These hypotheses were all accepted. Flow through small pores <0.25 mm in diameter played only a small role in infiltration and percolation in the upper 20 cm of blanket peat accounting for just 22 % of the infiltration and percolation. Therefore, most of the flow in upland blanket peat was generated from only a small volume of the peat. At the surface, around 80 % of flux was generated through only 0.26 % of the peat volume while at 5 cm depth, where percolation rates were an order of magnitude slower than at the surface, 85 % of the flux was generated from only 0.01% of the peat volume. Infiltration and effective porosity both declined by over two orders of magnitude over the top 20 cm of the peat. The vegetation cover type (whether covered by *Eriophorum, Sphagnum, Calluna* or no vegetation) controls the proportion of water that flows through pores > 1mm in diameter, but did not have a significant impact on the proportion of flow moving through pores between 0.25 and 1 mm diameter. Effective porosity was significantly affected by vegetation cover and increased with decreasing pore size. The variability in flow and effective porosity was found to be similar between different pore size classes suggesting that pore hydraulic properties were just as variable within larger pores > 1mm as they are in smaller pores < 0.25 mm in diameter.

Given the dominance of flow through pores > 0.25 mm in diameter in blanket peats more work is required on understanding the biogeochemistry and the hydromorphology of these pores in order to improve our understanding of runoff production and solutional denudation in peatland catchments.

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Figure captions

Figure 1. Mean infiltration rate for blanket peat under the tension infiltrometer by depth and vegetation cover category for water tensions of a) 0 cm, b) -3 cm, c) -6 cm, d) -12 cm. Letters refer to surface cover type; B = bare, E = *Eriophorum*, C = *Calluna*, S = *Sphagnum.*

Figure 2. Contribution to flow by pore size classification for each vegetation cover and depth treatment. Standard error bars are shown.

Figure 3. Mean flow contribution, %, to saturated hydraulic conductivity for pores > 1 mm in diameter for each measurement depth by vegetation cover type. Letters refer to vegetation cover type; B = bare, E = *Eriophorum*, C = *Calluna*, S = *Sphagnum.*

Figure 4. Geometric mean effective macroporosity as determined by capillary theory and Poiseuille's equation for each measurement depth by vegetation cover type. Letters refer to vegetation cover type; B = bare, E = *Eriophorum*, C = *Calluna*, S = *Sphagnum.* Error bars are standard errors for each depth and vegetation category.

Table 1. Coefficient of variation, %, for infiltration rate with depth, cover type and water tension categories.

Depth, cm	0	5	10	20
	57	140	133	148
Cover type	Bare	*Eriophorum*	*Calluna*	*Sphagnum*
	104	96	130	146
Tension, cm	0	-3	-6	-12
	108	113	119	137

Table 2. Analysis of variance of effective porosity by depth, vegetation cover and pore size categories. a) For the whole dataset; b) for pores between 0.25-0.5 mm in diameter; c) for pores > 0.5 and < 1.0 mm in diameter; and d) for pores > 1.0 mm in diameter.

a)

Source	d.f.	F	Prob > F
Depth	3	205.3	0.000
Vegetation cover	3	6.91	0.000
Pore size class	2	220.0	0.000

b)

Source	d.f.	F	Prob > F
Depth	3	66.64	0.000
Vegetation cover	3	1.85	0.141

c)

Source	d.f.	F	Prob > F
Depth	3	66.46	0.000
Vegetation cover	3	2.28	0.083

d)

Source	d.f.	F	Prob > F
Depth	3	66.85	0.000
Vegetation cover	3	2.66	0.052

Table 3. Geometric mean of pore parameters estimated from the tension infiltrometer data and Poiseuille’s equation.

Soil depth (cm)	Pore diameter (mm)	No of pores (m^{-2})	Effective porosity ($cm^3\ m^{-3}$)	% water flux
0	> 1	4	58	37
	0.5-1	107	380	20
	0.25-0.5	2435	2169	23
5	> 1	0.7	10	45
	0.5-1	17	61	22
	0.25-0.5	361	32	18
10	> 1	0.2	3	33
	0.5-1	6	21	17
	0.25-0.5	137	122	17
20	> 1	0.1	1	28
	0.5-1	2	8	15
	0.25-0.5	53	47	17

Table 4. Coefficients of variation for effective porosity by depth, vegetation cover and pore size class category.

Depth, cm	0	5	10	20
	47	106	137	126
Vegetation cover	B	E	C	S
	100	120	113	82
Pore dia, mm	> 1	1 - 0.5	0.5 - 0.25	
	103	104	105	