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Overland flow velocity and roughness properties in peatlands

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Abstract

Overland flow is an important component of peatland hydrology. Hydrological models of peatlands are being developed that require estimates of flow velocity and its controls. However, surprisingly little is known about overland flow velocities in peatlands. Some peatlands have also been drained using open ditches and these need to be incorporated into flow models. This paper presents field data on the velocity of overland flow and drain flow in upland peatlands. The relationships between flow velocity, vegetation cover, slope and water depth were explored. *Sphagnum* provided a significantly greater effective hydraulic roughness to overland flow than peatland grasses. In all cases, a significant break in process occurred for flows with water depths of around 1 cm so that there were two components of the roughness curve. This is consistent with partial submergence theory for very shallow flows where resistance increases with depth as the soil surface first becomes fully submerged. While each surface cover type should be considered separately, the results also suggest that a first order estimate of Darcy-Weisbach roughness and mean velocity can be based on a single parameter for each surface cover. This paper presents an empirical overland flow velocity forecasting model that can be applied to peatlands. The model combines the partially submerged component for flows with water depths below 1 cm with the fully submerged component for flows with depths up to 5 cm which are representative of the depths of flows that occur across peatlands.

Keywords: overland flow, roughness, peatland drainage, runoff, wetlands, vegetation

Introduction

A basic hydraulic property of overland flow is mean velocity and many hydrological and hydraulic models require a velocity component for flow. This is the case both for overland flow and channel flow (e.g. Beven and Kirkby, 1979; Refsgaard and Storm, 1995). An understanding of the hydraulics of shallow overland flows is required for modelling runoff and erosion (Dunne and Dietrich, 1980; Roels, 1984; Nearing *et al.,* 1999; Dunkerley, 2003) which in turn may aid understanding of the effects of management interventions designed to slow or reduce the rapid delivery of runoff and sediment to the drainage network. The presence of vegetation further complicates prediction of overland flow velocity. It is likely that, in any given study area, different vegetation covers and slopes result in spatially complex patterns of flow velocity, thereby affecting runoff production and sediment entrainment. Little is known about such topographical and ecological interactions. Furthermore, in studies of the effects of land cover and land management on runoff, most emphasis has been upon infiltration rather than the ways in which land cover or management alter the connectivity of runoff to the drainage network. However, if we are to understand the impacts of land management decision-making at the catchment-scale then the effects of connectivity upon the timing of runoff delivery must be understood at the catchment-scale (Lane *et al.,* 2006). This requires us to determine how long it takes source areas of overland flow to connect with the drainage network, and the aim of this paper is to present the first empirical evidence that allows us to model the relationship between vegetation cover and flow velocity on peatland slopes.

Overland flows in peatlands as compared with other environments

In temperate blanket peatlands, up to 80 % of the water movement across hillslopes can be produced as saturation-excess overland flow (Holden, 2006; Holden and Burt, 2003a, 2003b, Holden and Burt, 2002; Evans *et al*., 1999). Often, overland flow on these peats can be greater than 1 centimetre deep, particularly on long, gently sloping hillslopes that are common in moorland environments (Holden and Burt 2002; Evans *et al*., 1999), although maximum flow depths are generally much lower than those typical of channels. Overland flow on peatlands tends to have two components: a rapid component associated with larger water levels and a slower but significant flux through the upper litter layer. Peatland slopes can vary from zero to approximately 60 %. The vegetation cover on blanket peatlands is often dominated by *Sphagnum* mosses which do not have obvious stems, rather they have an intricate branching structure and are devoid of roots (Figure 1). The interaction of blanket peatland vegetation types and overland flow travel times has, to the authors' knowledge, hitherto never been reported.

Unlike peatland flows, there has been a long history of research into vegetation impacts on both channel and floodplain flow, commonly where the bed slope is less than one percent (e.g. Freeman et al., 2000; Järvelä, 2004; Nepf et al., 2007; Nepf, 1999; Leonard and Luther, 1995; Lane and Hardy, 2002). Many of these studies have flow depths sufficient to allow determination of vertical velocity profiles in relation to plant structure and flow interactions (e.g. Wilson and Horritt, 2002; Nepf and Koch, 1999; Nepf and Vivoni, 2000; Ghisalberti and Nepf, 2004; Lightbody and Nepf, 2006) and the bending of plant stems in the flow (Copeland, 2000). Green (2005) reviews attempts to model flow resistance in vegetated streams and Lane and Hardy (2002) also review floodplain flow approaches. It is not clear how, if at all, the results from these studies transfer to the question of overland flow and furthermore many published studies deal with larger aquatic plants, particularly woody plants that have large diameter stems protruding into the flow and which are frequently modelled as cylinder fields. There have been several attempts to study resistance laws for channels with more flexible aquatic vegetation (e.g. Kouwen and Fathi-Moghadam, 2000). Many approaches have been developed that simply try to fit Manning or Darcy-Weisbach type formulae to the case in question, although more recently physically-based approaches have been presented (e.g. Freeman et al., 2000; Nepf et al., 2007; Lane and Hardy, 2002) including attempts to incorporate bending stems (Copeland, 2000). In addition to river and floodplain environments, work has also explored salt marsh flow-vegetation interactions (e.g. French and Stoddard, 1992) and wetland flows (Nepf, 1999; Nepf et al., 2007). Even where vegetated, rivers, floodplains, wetlands and salt marshes differ from the hillslope flows commonly found in peatlands because they all have a slope that rarely exceeds 1 % and, under certain scenarios, deeper water levels.

Since flows are so shallow, there is reduced likelihood of vegetation stems bending in the flow (Copeland, 2000). The vegetation and soil structure are also quite different from the salt marshes and floodplain wetland environments that have been commonly studied in the flow resistance literature (see Ingram, 1983). Peat soils tend to have an upper porous layer known as the 'acrotelm' that allows shallow subsurface flow to occur at rapid rates at the same time as saturation-excess overland flow (Holden and Burt, 2003a).

There is some work that is relevant to the study of the overland flows on hillslopes (e.g. Emmett, 1970), but these studies have often been limited to very shallow overland flows of the order of a few millimetres in depth (e.g. Dunkerley *et al*., 2001; Kuhn and Bryan, 2003) with a particular emphasis on semi-arid environments. These differ from peatlands because: (1) they have a much lower percentage vegetation cover; (2) they are generally associated with infiltration-excess overland flow, where flow paths are shorter as they can only be sustained as long as rainfall intensity plus run-on from upstream exceed local infiltration capacity; and (3) they commonly have been managed in very different ways. For instance, some semi-arid environments, especially in southern Europe, have been managed to retain runoff for agriculture. In some temperate environments, the peatlands have been drained to allow more efficient runoff. These open land drains (ditches), sometimes of high density (e.g. Holden et al., 2006; Holden et al., 2004; McDonald, 1973), transport water and sediment directly to the stream network (Holden et al., 2007b). They were commonly cut directly into the peat, often running parallel to the hillslope contours. The depths of channel flow in these drains range from zero to a few centimetres. Many peatland drains now have revegetated floors. This vegetation is likely to influence the speed of water delivery through the drains and into the downstream channel network. There have been no studies, to the authors' knowledge, on the impact of peatland drains or drain revegetation on channel flow velocities.

Given the dominance of floodplain or channel flow resistance studies, where channels are in excess of 10 cm (e.g. Järvelä, 2004) and an emphasis on overland flows in very different environments, surprisingly little is known about the influence of surface vegetation on shallow overland flow velocity in peatlands. This information is now needed urgently as both semi-distributed and distributed models of peatland hydrological response are being combined with high resolution topographic data in order to predict the nature of saturation and hydrological connectivity of saturation-excess overland flows across hillslopes (Lane *et al*., 2003; Lane *et al.,* 2004). While the resistance formulae commonly used in hydraulics for river and floodplain flows were not derived for overland flow characterisation, they are very commonly used to describe overland flow (e.g. Dunne and Dietrich, 1980; Baird *et al*., 1992; Grayson and Moore, 1992; Scoging *et al*., 1992). A consistent flow law, preferably based on the Darcy Weisbach friction factor (which can be used in situations where depth dependence is necessary) that could be applied to peatland flow modelling would be useful. If there are large differences between vegetated and unvegetated drain channels, or between overland flows through different surface vegetation types, then this may not be achievable, but we do not have the data to test for such differences. Hence, in this paper, we investigate the impacts of vegetation cover, slope and water depth on flow velocities both within drains and over peatland surfaces and develop physically-based equations to describe these impacts.

Methods

Site

Field measurements were obtained for the Upper Wharfe catchment, UK (54^{o} 13' N, 2^{o} 13' W). Blanket peat up to 2 m deep overlies shallow glacial tills and mixed Carboniferous sandstones and limestones (Merrett and Macklin, 1999). The peats in the area are dominated by *Eriophorum* (cotton grasses) and *Sphagnum* (mosses). Shrub species such as *Calluna* (ling, heather) on the peats are rare. The water table in the peats is usually within 30 cm of the surface for most of the year and rises rapidly to the surface during rainfall events, frequently producing extensive saturation-excess overland flow (Holden, 2006). There are extensive areas of peatland drains.

Overland flow

A total of 256 bounded overland flow plots were established each being 0.5 m wide by 6 m in length. Plot slopes ranged from 0.01 to 0.55 m m^{-1}. Surface slopes were measured using a total station and plots were chosen which had uniform slopes throughout their length. Four surface cover categories were chosen with 64 plots consisting of a surface cover of *Sphagnum*, and 64 on each of *Eriophorum, Sphagnum-Eriophorum* mix and bare surfaces. Water was supplied to each plot via a variable-speed pump and hosing. Water was pumped onto the plot until flow became uniform from the plot outlet. Rhodamine WT dye was then injected and travel times determined using an automatic logging fluorometer. This allowed both leading edge (time of first arrival of dye; Dunkerley, 2001) and centroid travel times to be calculated. This meant that the problems associated with the visual timing of dye front arrival discussed by Abrahams *et al.* (1986), Dunkerley (2001) and Dunkerley (2003) were avoided. Also, with the spatial scale of the plots used, absorption effects were sufficiently small for the results to be reliable. The experiment was repeated at four different discharges (these were determined by the settings of the pump which provided flow at Q1 = 0.05, Q2 = 0.08, Q3 = 0.2 and Q4 = 0.5 litres s^{-1}) for each plot so that in total 1024 measurements of travel times were performed. Mean water depths were measured on each plot by using a calliper placed on 10 random points per plot. The flow did not totally submerge vegetation during the experiments, except for some of the *Sphagnum*-covered plots. The research design excludes responses to raindrop impact.

Drain flow

For the drain flow measurements, 64 open surface drain reaches of 30 m length were chosen with a relatively uniform slope, channel width and depth within each reach. Natural flow events were used for the experiments and the dye and fluorometer were used to measure travel times. The experiment was repeated four times on each drain reach at different discharge rates. The experiment was also repeated for 64 drain reaches that were naturally revegetating. The vegetation had grown on the floor and walls of the drains but the drains were still hydrologically functioning. Half of these drain reaches were revegetating with *Sphagnum*, and half (i.e. 32) with *Juncus* (tall thick stemmed grass). In total there were 512 drain flow measurements.

Theory and analysis

Use of the fluorometer allowed the time of the fastest flow, V_m, and the centroid or mean flow, $\overline{V}$, to be measured. For a parabolic (laminar) flow profile, where velocity is zero at the bed and reaches a maximum at the surface (Katz *et al.*, 1995):

$$\overline{V} = 0.67V_m \qquad [1]$$

However, the presence of vegetation and an uneven soil surface will probably lead to a divergence from this form and so a coefficient, α, is needed that depends on the roughness properties of the surface and vegetation (Li *et al.,* 1996; Dunkerley, 2001) and which describes the relative difference between peak and centroid dye arrival time:

$$\overline{V} = \alpha V_m \qquad [2]$$

Resistance to flow is commonly described by the Darcy Weisbach equation:

$$\overline{V}^2 = \frac{8g}{f}\overline{d}S \qquad [3]$$

where S is the slope and g is gravitational acceleration. It is possible to relate the dimensionless friction factor, f, to the ratio of depth, $\overline{d}$ to an effective roughness diameter, k (Robert, 2003) using a relation of the form:

$$\frac{1}{\sqrt{f}} = A + 1.77\ln\left(\frac{\overline{d}}{k}\right) = A + 4.07\log_{10}\left(\frac{\overline{d}}{k}\right) \quad [4]$$

where *A* is an empirically defined constant. Therefore *k* is calculated from equation 4 and this relationship is shown in Figure 2. For the low ratios of depth to roughness encountered in overland flow, in which the roughness elements are not submerged grains or bedforms, but where leaves and stems protrude from the flow, [4] becomes problematic because of difficulties in determining the effective depth of overland flow and because of the distribution of roughness elements within the flow depth. This problem is commonly recognised in rivers partly as a reference height issue (e.g. Lane *et al*., 2002) and it becomes more severe in overland flow studies because of the difficulty in determining exactly the elevation at which velocity becomes zero. The second aspect to this problem is that Equation [4] assumes that roughness elements are on the bed, and fully submerged. In many overland flow situations involving vegetation some or all roughness elements are only partially submerged and/or extend through the flow as vegetation stems, which may be branched and/or progressively dragged down by the flow. To avoid these problems, we do not take these relationships as given, but test the extent to which they hold for the special case of overland flow on the surfaces studied here.

It is often customary to plot *f* as a function of *Re* (e.g. Chen, 1976; Dunne and Dietrich, 1980; Gilley *et al*., 1992; Abrahams and Parsons, 1994; Dunkerley *et al*., 2001)*, or f* as a function of $\overline{V}$. However, as Kouwen and Fathi-Moghadam (2000) and Lane and Hardy (2002) point out, these plots commonly display a spurious correlation because the same parameter is used in estimating terms on both sides of the plot. For example, a plot of *f* against $\overline{V}$ may be dominated by the $1/\overline{V}^2$ versus

$\overline{V}$ pattern, which even if random numbers were used for $\overline{V}$ would still produce a log-linear correlation.

Savat (1980) showed that overland flow, with the high Froude Numbers and roll waves characteristic of shallow flows, significantly crosses between the laminar (f~ Re^{-1}) and turbulent (f~$Re^{-1/4}$) flow regimes, indicating that the solid line in Figure 2 becomes steeper at low depths corresponding to the laminar flow regime. An alternative approach has been presented by Lawrence (1997), based on work by Phelps (1975). This expresses the frictional resistance of partially and completely submerged large grains or boundary elements, and indicates that resistance increases with increasing depth (the curved dotted lines on Figure 2). Takken and Govers (2000) also recognised that effective roughness and flow velocities reflected grain textures, the overall cross-sections of the flow and its tortuosity, making it difficult to estimate equivalent roughness except by working back from the observed flow. From these studies of shallow flows, it seems most relevant to note that an empirical approach may be most appropriate, but that there may be a change in behaviour as the soil surface first becomes fully submerged.

Results

Our data suggest that surface cover exerts a strong control over overland flow velocity in peats. Table 1 provides the means and standard errors for the overland flow velocities. The velocity of overland flow ranged from 0.191 $m \cdot s^{-1}$ to 1.22 x 10^{-4} $m \cdot s^{-1}$ with a mean of 0.029 $m \cdot s^{-1}$. As would be expected, mean overland flow velocity was significantly higher for bare surfaces than for vegetated surfaces for all discharge categories. The velocities associated with *Sphagnum* were significantly lower than for other vegetation types at p <0.001 for *Eriophorum* and bare surfaces, and p = 0.03 for

Sphagnum versus *Eriophorum-Sphagnum* mixed surfaces. This suggests that *Sphagnum* is better at attenuating flow velocities than the other cover types tested.

Global application of [2] gave a mean value of α of 0.35 (standard error = 0.01). Surface cover type was a significant factor (p = 0.022) in determining α, with bare and *Eriophorum-Sphagnum* mixed surfaces having significantly lower values of α than total *Eriophorum* or *Sphagnum* covers. Slope was only found to be a significant control over α for those plots with some *Sphagnum* cover and it was not a significant control of α for bare or *Eriophorum*-covered slopes. Water depth had a significant positive control (p <0.001) over α for all surface covers.

The extent to which the overland flow in peat adheres to the Darcy-Weisbach expression [3] can be seen by plotting $1/\sqrt{f}$ against mean flow depth, with depth on a logarithmic scale to allow comparison with Figure 2. Figure 3 shows the results obtained for *Eriophorum* as an example. Scatter in the data within a particular surface cover type such as *Eriophorum* may relate to differences in coverage or maturity of plants. To reduce the large scatter of the raw data, the values have been sorted by depth and medians taken for consecutive runs of 19 points, and these median values are also plotted. It may be seen that the data falls into two groups, which can be separated around the depths of 0.007-0.01 metres. RMA (reduced major axis) regression has been applied to the median values in each group. This method emphasises the functional relationship between the two variables without giving causal preference to either one. Comparison with Figure 2 shows a similar region of shallow flows with gradually increasing roughness (reducing $1/\sqrt{f}$), and a deeper region in which there is a stronger logarithmic decrease of roughness with depth.

Figure 4 summarises the ‘dog-legged’ relationships, derived in the same way, for each of the four surface covers, showing relationships that are significant for the median points except in the case of the *Sphagnum* cover.

Darcy-Weisbach roughness Equation [4] suggests an exponent that varies with the ratio of flow depth to roughness length. Following Equation [4], the depth exponent of *c.* 2/3 should be only approximately valid over the range $10<d/k<10^4$, with much larger exponents needed at lower relative depths, with an exponent of about 1.5 for $0.5<d/k<2$. These values correspond to the straight lines drawn in Figure 2.

If the Darcy-Weisbach roughness is derived from [3], according to [4], then the root of f should be inversely proportional to the logarithm of depth. While it is possible to fit such a linear relationship, as shown in Figure 4, the slope of the line is very much smaller (0.014 - 0.046) than the constant of 1.77 in [4], indicating that relative roughness changes only very little with depth. This seems compatible with the conditions prevailing in shallow overland flows where uniform vegetation and surface grain properties extend throughout the range of flow depths experienced.

For flow in ditches, flow depths, although small, are somewhat higher than for the overland flow measurements, so that the lower leg of the relationship seen in Figures 3 and 4 is less evident. Data for *Juncus* alone shows only very poor correlation, and data for *Sphagnum* and unvegetated surfaces has been combined with the overland flow data to produce a single relationship, shown in Figures 5 (*Sphagnum*) and 6 (unvegetated). The regression coefficients and correlation coefficients are summarised in Table 2, using the median data in all cases, so that significance levels are only indicative since they are not based on the raw data.

First it is noted that not all bed roughness elements are submerged during overland flow, and that the effects of roughness elements along the margins (often multiple margins) are much more important than for normal stream flow. Second it is noted that vegetative elements commonly extend through the entire flow. Third it is noted that different species have different distributions of roughness elements with height. Thus *Sphagnum* appears to be almost uniformly distributed through the flow (as would be expected given its structure shown in Figure 1), whereas *Eriophorum* and *Juncus* present more cylindrical stem elements that go through the full flow depth. Some other species branch near the base, so that effective roughness elements increase with flow depth. Finally vegetation may be dragged down into the flow (Freeman et al, 2000), so that roughness is dynamically reduced at high flows.

Overall then, the Darcy-Weisbach roughness equation [3] may be a valid definition of the gross roughness, but the relationship to depth and roughness [4], which is based on classical roughness theory and the logarithmic velocity profile, appears to be only valid for flows greater than about 1 cm deep, and with regression coefficients substantially less than the value in Equation [4]. This low dependence of roughness on flow depth may suggest that the effective ratio of depth to roughness does not change as rapidly with depth as for a strict grain roughness, and may be linked to the concept of roughness elements (plant stems) extending through the flow.

Discussion

Looking at the similarities between Figures 3 to 6, there seems to be a fairly consistent pattern of roughness variation, and a consistent set of differences between the different types of cover, which is in agreement with intuitive observations about the relative resistance offered. Flows over bare surfaces are substantially faster than for *Eriophorum*, which is, in turn, faster than for *Sphagnum*. Mixtures of *Eriophorum* and *Sphagnum* are intermediate between the two pure surfaces. *Juncus*, although not giving significant results, has rates similar to *Sphagnum*.

In all cases there is a significant break in process between flows with a water depth greater than *ca*. 1 cm and flows with a water depth less than *ca*.1 cm. This is consistent with the break in process shown in Figure 1, indicating that the ground surface is only partially submerged in shallower flows, following the theory of Lawrence (1997). Within the range of error of the experimental data, the slopes of the falling and rising limb of the curves shown in Figures 3-6 ($f^{0.5}$ vs. depth) increase and decrease together, so that a first order estimate of Darcy-Weisbach roughness (and then mean velocity) can be made on the basis of a single parameter for each surface cover. The general form of this forecasting model is then:

$$\frac{v}{\sqrt{8grs}} = \frac{1}{\sqrt{f}} = Max\left[A - B_1 \log_{10}\left(\frac{d}{k}\right), A + B_2 \log_{10}\left(\frac{d}{k}\right)\right] \qquad [5]$$

where A= 0.005, B_1 = 0.1 B_2 and k = 0.01 m to account for the consistent break in process we found at depths of around 1 cm.

Values for B_2 are estimated as follows, following the range of values in Table 2:

Bare	1.3
Eriophorum	0.3
Eriophorum/Sphagnum mix	0.2
Sphagnum and *Juncus*	0.1

Figure 7 has been constructed to compare the observed values of $f^{0.5}$ for all raw data points with the estimates of Equation (5). It can be seen that there remains a substantial scatter, with a 10-fold range either way needed to contain 90 % of the data and a 2.1-fold range containing the middle 50 % of the data. Since the observed values vary across two orders of magnitude, this is a worthwhile compression of the data. The correlation coefficient between observed and estimated values is 0.581 which is significant at $p<0.001$. Additionally, the simplicity of this empirical model is a major advantage over more complex fluid dynamic models and reduces the amount of data required to produce estimates of overland flow velocity across peatlands for use in travel time and flood wave generation studies.

Figure 6 immediately leads to an expression to forecast mean velocity. It can be seen that velocity increases very slowly with depth until the surface is fully submerged. It then increases rapidly to begin with and more slowly as depth increases up to the limit of the data (c. 5 cm). Note that we have not measured velocity profiles through the water column and that the above comments are with respect to the experiments we conducted on flows which achieved different depths. It is necessary to bridge between the two legs of the roughness curve, to ensure that velocity does not decrease with water depth at any stage. This is done in general by combining the two expressions into a continuous empirical curve: Thus if $f_1^{-0.5} = A - B_1 \log_{10}(r/k)$ and $f_2^{-0.5} = A + B_2 \log_{10}(r/k)$, the combined estimate of roughness is taken as:

$$f^{-0.5} = \frac{1}{m}\ln\left[\left(\exp(f_1^{-.5})\right)^m + \left(\exp(f_2^{-.5})\right)^m\right] \qquad [6]$$

Where m is chosen to ensure that the velocity increases monotonically with water depth. In practice, $m\sim3$ for bare surfaces and rises to ~150 for *Sphagnum*, changing inversely to the values of B_2. These curves are indicated in Figures 3, 5 and 6. The form of Equation [6] has been chosen to allow the combination of positive and negative values, and to converge on $f_1^{-0.5}$ and $f_2^{-0.5}$ respectively at small and large depths.

The combined estimates for velocity are sketched in Figure 8, which shows the estimated change of velocity with water depth on a 10 % gradient, for unvegetated surfaces, *Eriophorum* and *Sphagnum*. The sharpness of the step where behaviour changes from submergence dominance to roughness behaviour, at water depths of around 0.01 m, is not well defined, depending strongly on the values of the exponent m in Equation [6], which is not well constrained. However, the forecasts share a generally low increase of velocity with overall water depth until the surface is submerged, followed by a rapid increase of velocity ($\sim d^2$) and then a progressive decline in the rate of increase, eventually falling to the Manning equation value of $d^{2/3}$.

The expression for roughness retains a constant exponent of 0.5 for gradient, and this is confirmed by other research with an immobile bed. However, where the bed is mobile (bare peat), this dependence no longer appears to hold (Govers *et al*, 2007) and velocity may become independent of gradient.

The value of α is often used as a correction factor by workers studying overland flow travel time (e.g. Beuselinck *et al.*, 1999). It is easier to measure the time of arrival for the leading edge of a tracer than it is to measure peak or centroid times. Emmett (1970) found that α was between 0.5 and 0.6 for laminar flow and was close to 0.8 for turbulent flow. For overland flow in the present study, the mean value of α was 0.35. Slope was a significant control over α for overland flow plots only where *Sphagnum* was present; α was greater on steeper slopes. This is in direct contrast to the flume study of Li *et al*. (1996), who found α varied inversely with slope. Water depth was also a significant factor in determining α on the overland flow plots. Therefore, for overland flow, a uniform α is not reasonable. Similarly a large scatter of α values was determined for the peat drains signifying that a uniform value of α would not be appropriate. Therefore conversion of leading edge travel times to estimate mean flow velocities in peatlands is not appropriate. This is in line with laboratory work by Dunkerley (2001), who examined α on sandy surfaces and verifies approaches that measure the whole dye wave to determine centroid travel times rather than relying on leading-edge travel times and the correction factor.

Conclusions

Many saturated slopes such as those in peatlands frequently experience overland flow depths of the order of a few millimetres to a few centimetres. *Sphagnum* provided a significantly greater effective roughness to overland flow than other surface types. *Sphagnum,* with its dense branching and uniform structure with depth, has been lost from many peatlands through land management (e.g. over-grazing) or sulphate deposition (Holden *et al.,* 2007a). This will have implications for overland flow travel times potentially leading to shortened stream lag times. Indeed even if a peatland surface remains fully vegetated, our results suggest that if the vegetation type is altered then flow velocities could change leading to alterations in the timing of runoff delivery from slopes to streams. Re-establishment of *Sphagnum* (Holden *et al*., 2007a) on degraded (especially bare) peatlands may therefore be important for reducing the potential for sheet erosion and downstream flood peaks more than *Eriophorum* or *Eriophorum-Sphagnum* mixes.

In all treatments studied in this paper, a significant break in process occurred at a depth of around 1 cm. This is an important finding as it represents non-linear feedback whereby overland flow velocity increases dramatically once a critical depth range is passed. This is consistent with partial submergence theory for very shallow flows where resistance increases with depth as the soil surface first becomes fully submerged. However, the results also suggest that a first order estimate of Darcy-Weisbach roughness and mean velocity can be based on a single parameter for each surface cover and the paper presents an empirical forecasting model that can be applied to peatlands for partially and fully submerged surfaces. Therefore, better representations of overland flow travel times across blanket peatlands will now be possible if vegetation cover maps are available and if empirically-based equations are used for each cover type. Of course mean velocity, which was described in this paper, is only one component of the velocity field across a surface and there are likely to be variations in vertical and lateral velocity profiles between cover types that are worthy of exploration in future work.

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Table 1. Mean, standard errors and sample size for $\overline{V}$ (velocity; m · s^{-1}) by vegetation cover and discharge

	Eriophorum	*Sphagnum*	*Eriophorum-Sphagnum* mix	Bare	All
0.05 l s^{-1} St. error N	0.00268 0.00021 64	0.00074 0.00006 64	0.00195 0.00015 64	0.00851 0.00055 64	0.00347 0.00024 256
0.08 l s^{-1} St. error N	0.01123 0.00059 64	0.01105 0.00155 64	0.00847 0.00061 64	0.01268 0.00050 64	0.01086 0.00047 256
0.20 l s^{-1} St. error N	0.03668 0.00245 64	0.02343 0.00120 64	0.02318 0.00172 64	0.05036 0.00198 64	0.03341 0.00117 256
0.50 l s^{-1} St. error N	0.08445 0.00559 64	0.02437 0.00117 64	0.03830 0.00236 64	0.12682 0.00289 64	0.06849 0.00304 256
All St. error N	0.03376 0.00251 256	0.01490 0.00083 256	0.01798 0.00115 256	0.04959 0.00310 256	0.02906 0.00114 1024

Table 2. RMA semi-log regressions in overland flow over different surface covers

Asterisks indicate level of significance using median values (** p = 0.01; *** p= 0.001). All overland flow regressions are significant except for *Sphagnum*. Combined ditch and overland flow are only significant for deeper flows.

Flow type	Vegetation	D<=0.007 m $1/\sqrt{f}=a+b\ \log_{10}d$	D>=0.010 m $1/\sqrt{f}=a+b\ \log_{10}d$
Overland flow	*Eriophorum*	a= -0.0474 b= -0.0265 r^2= 0.339**	a= 0.5686 b= 0.2628 r^2= 0.493***
	Sphagnum	a= -0.0327 b= -0.0152 r^2= 0.025	a= 0.1093 b= 0.0431 r^2= 0.095
	Eriophorum-Sphagnum mix	a= -0.0317 b= -0.0175 r^2= 0.422***	a= 0.2082 b= 0.0967 r^2= 0.532***
	Bare	a= -0.0683 b= -0.0465 r^2= 0.389***	a= 0.8126 b= 0.4050 r^2= 0.451***
Ditch and overland flow combined	*Sphagnum*	a= 0.0003 b= -0.0024 r^2= 0.288	a= 0.1787 b= 0.0847 r^2= 0.270**
	Bare	a= -0.1739 b= -0.1004 r^2= 0.017	a= 2.7080 b= 1.3877 r^2= 0.655***
Ditch	*Juncus*	Insufficient data	a= 0.2636 b= 0.0847 r^2= 0.008

Figure captions

Figure 1. *Sphagnum* ground-cover on a peatland surface, with some localised grass swards.

Figure 2. The relationship between Darcy-Weisbach roughness ($f^{-0.5}$) and the ratio of mean depth to effective roughness (*d*/*k*) from Equation [4]. The dotted curve sketches the relationship proposed by Lawrence (1997) for shallow depths ($f \sim d/k$). The straight line indicates the theoretical fit according to Equation [4]. Between the range $10<d/k<1000$ the fit is consistent with Manning's equation for which $f^{-0.5} \sim (d/k)^{1/6}$. For the region $0.5<d/k<2$ the fit is more appropriate to overland flow, for which $f^{-0.5} \sim (d/k)^{1.0}$.

Figure 3. Plot of transformed Darcy-Weisbach friction factor against average flow depth for *Eriophorum* in overland flow. Dots indicate raw data points. Crosses indicate means of 19 adjacent values, sorted by depth. Grey lines indicate RMA regression lines based on median points, for depth categories <=0.007 and >=0.01 m. Black curve indicates bridging function.

Figure 4. Summary of RMA regression lines for overland flow, similar to Figure 3, for the four surface covers: *Eriophorum* (thick black line), mixed *Eriophorum/ Sphagnum* (dashed line), *Sphagnum* (thin black line) and Bare (grey line).

Figure 5. Combined ditch and overland flow data for *Sphagnum*

Figure 6. Combined ditch and overland flow data for bare (unvegetated) surfaces.

Figure 7. Comparing observed values of $f^{-0.5}$ with forecasts based on Equation [5] for all raw data points.

Figure 8. Modelled relationship between mean flow depth and velocity on a 10 % gradient.