

FLOW THREADS IN SURFACE RUN-OFF: IMPLICATIONS FOR THE ASSESSMENT OF FLOW PROPERTIES AND FRICTION COEFFICIENTS IN SOIL EROSION AND HYDRAULICS INVESTIGATIONS

DAVID DUNKERLEY*

School of Geography and Environmental Science, Monash University, Victoria, Australia

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ABSTRACT

Soil surface microtopography produces non-uniform surface run-off, in which narrow threads of relatively deep and fast flow move within broader, shallower, slower-moving regions. This kind of flow is probably widespread, given that microtopography is itself common. Methods used to record the properties of surface run-off include grid- or transect-based depth observations, with a single mean flow speed derived by calculation from $V = Q/WD$, and the use of dye timing to estimate velocity, with an effective mean depth calculated from $D = Q/WV$.

Because these methods allow only single, flow-field mean values to be derived for V or D , neither is well suited to non-uniform flows. The use of depth data to derive a flow-field mean V furthermore implicitly applies area weighting to the depth data; likewise, the use of dye speeds for V inherently overestimates mean V because dye dominantly follows the faster flow threads. The associated errors in derived parameters such as friction coefficients are not readily quantified and appear not to have been addressed previously.

New field experiments made on untilled soil surfaces in arid western NSW, Australia, explore these circumstances and the implications for deriving meaningful measures of flow properties, including friction coefficients. On surfaces deliberately chosen for their very subtle microtopography, average thread velocities are shown to be commonly 2.5 times greater than the flow-field mean, and locally 6–7 times greater. On the other hand, non-thread flow speeds lie below the flow-field mean, on average reaching only 84 per cent of this value, and often considerably less. Flow-field means conceal the existence of regions of the flow field whose properties are statistically distinct. Results confirm that a reliance on flow-field average depths yields estimates of friction coefficients that are biased toward the shallower, high-roughness parts of the flow, while if dye speeds are relied upon the results are biased toward the deeper, smoother threads of flow. A new approach to the evaluation of friction coefficients in non-uniform flows is advanced, involving the determination of separate coefficients for threads and non-thread zones of the flow field. In contrast, flow-field friction coefficients as they are customarily derived in run-off plot experiments subsume these distinct coefficients in proportions that are generally unknown. The value of such coefficients is therefore questionable. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: flow threads; microtopography; surface run-off; friction coefficients

INTRODUCTION

The hydraulic characteristics of shallow overland flows have been widely investigated in hydrologic and erosional research. Most work has proceeded on the simplifying assumption that surface run-off can be treated as though it is hydraulically uniform (i.e., that it exhibits constant depth and speed that are mutually adjusted). This notion has allowed a range of shorthand means to be adopted for collecting the kinds of flow data needed to determine run-off depths or speeds, or to estimate friction coefficients. For example, some studies determine run-off speeds by direct measurement of tracer plume motion, using correction factors to convert surface speed to an equivalent profile mean through the depth of the flow (reviewed by Dunkerley, 2001). Others deduce flow speed without direct measurement, on the basis of measured flow depth. This approach commonly uses the relation

$$V = Q/WD \quad (1)$$

* Correspondence to: D. Dunkerley, School of Geography and Environmental Science, Box 11 A, Monash University, Victoria 3800, Australia. E-mail: David.Dunkerley@arts.monash.edu.au

where on a walled run-off plot or flume, width W and imposed discharge Q are both constrained experimentally, and depth D is directly measured (e.g., using a hand-held rule; Abrahams *et al.*, 1986). This approach of solving for an unknown term is also used to estimate flow depth when speed is directly observed, using $D = Q/WV$ (e.g., Fox *et al.*, 1997).

The use of these varying approaches hinders the comparison of results from diverse studies. Different experimental errors and sensitivities follow from the use of dye timing of speed (for example, varying with the length of track across which the timing is done, whether first arrival or plume centroid arrival is recorded) to subsequently estimate depth, or of depth (number of depth readings, definition of the 'bed level', precision of observation) to subsequently estimate speed. However, the most significant intrinsic problem with these methods is the underlying assumption that the flow can be treated as though it were uniform. The implicit assumption that depth and speed are linked by a single equilibrium relationship – that of uniform flow across a surface of homogeneous properties – clearly denies the possibility that the flow in fact involves some kind of spatial pattern of relatively deep but slow-moving areas (such as overflowing patches of ephemeral ponding) as well as deep but fast-moving areas following thalwegs across the soil surface. Given that both kinds of flow are in fact highly likely to be present (threads having been noted in published accounts of surface run-off for at least 30 years), the selection of sites where depth is measured in order to derive an estimate of flow speed, and the interpretation that is placed on the resulting data, clearly become significant issues.

Nature and importance of water flow across soil surface microtopography

The foregoing discussion suggests that one key influence on the applicability of methods for recording speed and depth in shallow overland flows is the influence of soil surface microtopography upon the properties of surface run-off. Few natural soil surfaces are planar and free of subtle undulations or prominences. Soil surfaces may be uneven owing to the presence of rill incision or other kinds of scour or deposition, as well as tillage or cultivation artefacts. However, on natural dryland surfaces and in other untilled environments, there is often a more subtle form of microtopography marked not by well-defined incised micro channels, but instead by gentle surface undulations on a scale of millimetres to centimetres that is the result of wind and water sculpture and sediment deposition across changing slope forms and gradients, modified by local protection provided by plants, stones, or litter. During run-off, water preferentially follows low-lying tracks across surfaces like this, to form flow threads that are deeper and that move faster than the flows on higher areas of the soil surface. Such tracks were mapped by Emmett (1970) on run-off plots on Wyoming, and have been noted by others since. Emmett (1970) used dye injection to visualize and sketch flow threads, and showed that the threads sometimes bifurcated or merged as the flow travelled downslope, so forming a rather complex network. Local prominences on the surface, perhaps pedestals associated with plants, or stones lying on the soil, caused the flow to deviate and/or to bifurcate; low points or constrictions produced flow convergence and the merging of threads. Erosional processes are also probably modified in significant ways by these interactions of flow and microtopography. Some of these links have been explored (e.g., Römkens *et al.*, 2001), though it appears that much remains to be learned. For example, the relation of thread occurrence and properties (such as physical dimensions, propensity to bifurcate) to slope gradient has not been explored. In relation to the processes of hillslope run-off generation, it is increasingly being realized that the tortuosity and connectedness of flow threads as concentrated flow paths is a parameter with great potential significance for the hydrologic and erosional responses on plot to hillslope scales. The spatial distributions and interconnectedness of bare soil interspaces and plant patches – that is, their geometry – are known to exert a more significant influence on run-off and erosion than the absolute amount of foliar cover or of bare interspace soil (Weltz *et al.*, 1998). Percolation theory has been applied to the analysis of run-off and flow thread pathways (e.g., Davenport *et al.*, 1998) though there is uncertainty about how the relevant properties of surfaces and the flows crossing them scale with spatial extent and storm size or run-off event magnitude. A conceptual framework for considering the linkages between microtopography and run-off has been proposed by Kirkby (2001). He has pointed out that the action of emergent roughness elements in subdividing the flow into threads probably involves a hierarchy in which the most active or important elements will have greater size, and thus probably become more widely spaced, in larger run-off events as well as in the downslope direction as flow accumulates. Smaller elements become submerged and less effective in thread formation as flow increases. Kirkby (2001) has also highlighted the potential importance of distinguishing

between the roles of cross-slope and downslope roughness, the latter perhaps of greater importance to the formation of detention ponds than to the focusing of flow threads. At present there appear to be no experimental data that would allow such hierarchies of roughness and flow thread formation to be explored further.

Non-incised soil surface microtopography has other consequences for the disposition of rain and run-off water. Surface depressions can create detention ponds from which infiltration takes place and that overflow and become increasingly better connected as flow increases. This has great significance for the processes of run-off generation and for spatial patterns of soil water uptake. The need to understand linkages and connectedness of flow paths indicates that, for the purposes of predicting and understanding surface flow, statistical measures of surface roughness (variograms, correlation distances) may provide too little information relevant to flow thread behaviour (Darboux *et al.*, 2001). Dunne *et al.* (1991) demonstrated that there may be differences in soil macroporosity and consequently in water uptake (infiltration) rates between low-lying and elevated parts of the microtopography. The greater water uptake in elevated locations contributes to an observed increase in infiltration rate with rainfall intensity, and to an apparent dependence of infiltration rate on hillslope length, that arises as flow depth increases downslope and more completely inundates the microtopography. Clearly, patterns of water uptake depend upon both the surface form and the pattern of inundation that arises during run-off. Experimental data developed by Dunne *et al.* (1991) showed that owing to progressive inundation plot-scale infiltration rate may rise by hundreds of per cent as rainfall intensity increases. Similar findings were reported by Fox *et al.* (1997) from work on laboratory soil trays in which shallow flow threads were observed. Investigations of this kind confirm that infiltration rate is not solely determined by the soil matrix, but rather depends on a range of other factors including the dynamics of the flow crossing the surface and the extent to which the form and amplitude of the microtopography allows or precludes broad sheet flow or more concentrated thread flow. (Other analyses have suggested some additional causes for variation in water uptake rate with rain intensity, including the hydraulic impact of drops driving water into void spaces that open from the soil surface. A review of several hypotheses can be found in Foley and Silburn (2002). Despite the evidence of Dunne *et al.* (1991), uncertainty remains about the generality of any microtopographic influence on infiltration rates. Indeed, some modelling results have pointed to an important role for flow threads that is contrary to that of Dunne *et al.* (1991). For example, Esteves *et al.* (2000) modelled numerically the flow of surface run-off at the scale of a large plot (5 m wide and 14 m long) and inferred that in a rain event of 24.5 mm infiltration depths were several millimetres greater along threads than beyond them. They hypothesize that greater thread water depths drive water entry into the soil surface, making threads loci of infiltration that exceeds that arising on elevated parts of the soil surface. These predictions have not been verified by direct measurement, and it seems possible that if distributed data on soil hydraulic conductivity were available the conclusions might have been more in accord with the findings of Dunne *et al.* (1991). It is in any case evident that plot-scale infiltration depths must depend in part on the extent of any differentiation of soil texture and porosity across the microtopography, and on the relative depths and flow durations of flow thread and non-thread regions of the run-off field crossing the surface. Other surface characteristics such as loadings of litter and/or stones, tendency to form surface seals, and exposure to the impact of raindrops probably contribute to spatial variations in infiltration rate that may be modulated by position within the microtopography. For example, raindrop impact energy expended at the soil surface would inevitably differ between relatively deeply inundated thread locations and more shallowly covered high points. Recent experiments have confirmed that variations in ponding depths do significantly influence soil detachment (Gao *et al.*, 2003).

In the light of the ideas already noted, it appears that in order to understand better the spatial behaviour of infiltration, splash detachment, and the speed, depth and sediment transporting ability of surface run-off, experimental data on flow threads and their properties, and the dependencies of these on the morphology of the soil surface and its microtopography, are needed. As Lawrence (2000) emphasized, the level of understanding of overland flow hydraulics that is needed for physically based modelling of soil erosion and transport has not been achieved to the extent that might be expected in light of the long history of work in this area. The existence and role of flow threads have been noted in a diverse literature. Despite this, there has been little documentation of their properties, and especially quantifying the differences between the hydraulics of thread flow and of the broader, non-thread zones of interrill run-off. An examination of the behaviour of flow threads may in turn suggest the need for an examination of their role in conveying detached soil particles through the interrill zone.

In the work on an unrilled plot referred to earlier, Esteves *et al.* (2000) highlighted the role of deeper flow threads for soil water uptake, but lacked distributed depth and speed data against which to assess their modelled surface flows. They expressed the view that new kinds of instrumentation will be needed to allow the necessary distributed data to be collected. Moreover, in the absence of suitable data, they made the simple presumption that a fixed Darcy–Weisbach friction coefficient of 0.25 applied across the whole plot surface, that is, to both thread and non-thread flows. This circumstance could not actually apply, since flow depth is a key control on frictional retardation, and threads are likely to be both deeper and faster than adjacent non-thread flows. Depths across most of their plot were modelled as being <1 mm, but threads were predicted to carry flow mostly 2–4 mm deep but up to 11–12 mm deep. This exemplifies the need for spatially distributed flow data collected with the intent of delineating threads and non-thread flows, and sufficient to confirm their differing depth and speed properties. Failing this, models like that of Esteves *et al.* (2000) remain essentially untested.

In many published studies that have proceeded on the uniform flow assumption, the run-off being investigated must similarly have carried thread and non-thread flow of distinctively differing depth and speed. For example, in experimental work on run-off plots in Arizona, Abrahams *et al.* (1986, p. 347) noted the existence of ‘two or three main threads’. Nevertheless, their analysis proceeded on the uniform flow assumption. Although the existence of flow threads has thus been quite widely recognized, there have been few attempts to delineate threads systematically in the way achieved by Emmett (1970), and seemingly none in which thread properties have been determined. Emmett (1970) did not focus on the hydraulics of the threads and wider flow separately, but rather pooled the data to generate composite indices of the flow. It now seems necessary for experimenters to target flow thread behaviour and evaluate its significance in both hydrology and erosion studies.

The need to explore these matters further highlights the need for suitable, carefully tested and evaluated approaches for describing spatially complex shallow flows containing flow threads and areas of slower flow or of ponding. A first attempt at developing such approaches forms the subject of this paper.

AIMS OF THE RESEARCH

The aim of the work was to explore the pattern of flow depths and speeds on natural, uncultivated soil surfaces where only minimal, non-incised microrelief was present. Typical, almost featureless dryland surfaces were sought deliberately for the experimental work. It was reasoned that there would be relatively slight development of flow threads and other kinds of non-uniform flow on such surfaces, so that conclusions drawn about the significance of flow threads should be conservative. On surfaces showing a larger microrelief amplitude, such as tilled surfaces or those with shrub or grass tussock mounds, larger departures from uniformity than any found here would then be expected.

The particular questions for which answers were sought were these:

- (1) Do faster-moving flow threads arise even on smooth and non-incised surfaces that exhibit only subtle microtopography?
- (2) If so, can their properties be estimated separately from those of the non-thread zones of the run-off field? What do such individual analyses reveal about thread and non-thread flow properties?
- (3) Can statistically distinct friction coefficients be estimated for each zone of the run-off field?
- (4) If so, what are the implications for studies in which, deliberately or unwittingly, distributed data encompassing both kinds of flow have been pooled in order to derive flow-field mean properties and friction coefficients?

EXPERIMENTAL METHODS

Experiments were carried out at the Fowlers Gap Arid Zone Research Station in western New South Wales, Australia. The soil surfaces were almost unvegetated and carried only rare small quartz stones, though patches of loose quartz granules less than 3 mm in diameter were common in places. The soils are known from previous work (Dunkerley, 2000) to be textural loams with a water uptake rate of about 8.5 mm h⁻¹. All work was done in an area of intershrub soil sloping at about 1.5°. The surface appeared essentially planar and smooth, and no

signs of flow incision such as rills or proto-rills were evident. Steel strips embedded in the soil were used to delimit four run-off plots 1 m wide and 2 m long. The plots were only 1–3 m apart and are considered replicates. One of these plots was tested for several days prior to work on the three remaining plots, from which the bulk of the results presented later are derived. The test plot was used to observe the nature of the surface flows using repeated dye injection and optical tachometer measurements, and to test apparatus and flow measurement protocols. Only non-critical results from this plot are reported here owing to soil surface disturbance caused by prolonged use.

Water was delivered to the top of each plot at a range of rates provided by digitally controlled peristaltic pumps and fed onto the soil via a perforated pipe. Multiple imposed discharges in the range $26.6\text{--}80\text{ cm}^3\text{ s}^{-1}$ were used. At the downslope edge all flow was directed into a steel gutter and thence into a pit from which it was continuously pumped back to a supply tank in order to conserve water, the work being done during severe drought conditions. Discharge was gauged volumetrically at the gutter outlet, and water temperatures were measured using a platinum resistance thermometer. Viscosity was determined from the relationships given in Weast (1979). The microtopography of each plot was mapped using the computer-controlled x - y - z gantry and electronic needle gauge system of Dunkerley *et al.* (2001), which was carefully levelled above the plot. Plot surface roughness, Ω , was expressed as the standard deviation of the soil surface elevations, following removal of the mean trend in elevations arising from the overall slope gradient. Slope gradient was estimated from the mean of the slope on each of the seven columns of elevations determined by the gantry. Interpolated contour maps with a 1 mm contour interval were prepared using the SURFACE III+ package V2.6 (Kansas Geological Survey, 1995). Cross-sections of thread locations were prepared from these maps in order to portray the form of the topographic thalwegs followed by flow threads. Prior to mapping elevations on a fixed grid of 49 points in an array of seven rows and seven columns, the soil surface was dampened with a mist spray to make it conductive. Subsequently, during run-off, the gantry returned to the same grid locations and mapped the water surface elevation. Flow depths were found by subtraction. All elevations and depths were recorded with a precision of 25 μm . These provide probably the most precise distributed flow depth observations yet reported for shallow overland flows. Flow speeds were determined by injections of 0.5 mL of fluorescein dye at three evenly spaced locations (left of centreline, centreline, and right of centreline) on each plot. Measurements at these locations were made across two marked flow paths of 50 cm and 150 cm, and repeated three to four times at each imposed flow rate. Mean travel times and flow speeds were later derived. The long path covered most of the length of the run-off plots; the shorter path was positioned at the mid-point of the longer path. Dye speeds (surface speeds) were converted to equivalent profile means using a value of $\alpha = 0.56$, following Dunkerley (2001). In addition, in selected experiments, virtual 'spot' readings of flow speed were collected opportunistically using the optical tachometer system of Dunkerley (2003), using a 40 mm flow path and a 10 mm floating reflective target. These provide flow speed estimates derived over the shortest flow path yet achieved in field studies of surface run-off, with the greatest potential to reveal speeds point-by-point along flow threads.

During data reduction, about 15 gantry depth measurement points lying within the flow threads were identified on the plot maps; a set of points of comparable size was selected from points lying away from threads. Mean depths were then computed to represent thread and non-thread flow conditions. The estimation of thread widths is less straightforward. Flow threads follow topographic thalwegs, but lie within the broader flow field. The 'divides' or thread margins are themselves inundated and carrying flow, and there is evidently a transition zone where relatively deep, fast thread flow grades into shallower, slower-moving non-thread flow. Nor are the threads of constant width along their course; rather, dye visualization showed narrowing at some places and widening elsewhere. Detailed topographic sections presented later suggest 'channel' widths of up to 15 cm, while the dye plume behaviour suggested that a width of 10 cm was more typical of the zone of fast flow. Nothing appears to have been published on the behaviour of shallow threads immersed in a broader flow, and the nature of the transition zone will require more detailed and controlled experiments than was possible under challenging field conditions. Therefore, given the preliminary nature of this study of thread behaviour, a fixed thread width of 10 cm is adopted in all later calculations. This makes estimated of thread discharge and other parameters presented below somewhat conservative; it also undoubtedly overlooks fluctuations in width along the track of the flow threads which was suggested by dye plume behaviour. If indeed the threads are on average wider than the dye behaviour suggested, perhaps approaching the width of the inundated microtopographic

'channels' (i.e., perhaps nearer 15 cm in width), then the proportion of the surface run-off moving along the threads would be larger than is estimated later in this paper. The issue of how to formulate the most meaningful criteria for delineating flow threads when surface inundation is complete clearly will demand further detailed work.

Dye timing and optical tachometer results were processed to derive flow speed data for threads and non-threads. It is known that dye, once injected, drains toward flow threads, since these follow the low points of the microtopography (e.g., Emmett, 1970). Consequently, dye injections made at evenly spaced points selected without regard to their location in relation to flow threads, and if the speeds are integrated across a track of significant length, perhaps 1–2 m, will include some non-thread flow and some thread flow. It can therefore be concluded that under such conditions of dye timing, $V_{\text{dye}} \leq V_{\text{th}}$. Here V_{th} refers to the true thread speed and V_{dye} refers to the mean speed of dye motion across a marked distance.

If shorter dye tracks lying wholly within pre-identified threads are used for measurement, the indicated speed should be much more closely that of the thread flow alone, so that $V_{\text{dye}} = V_{\text{th}}$. (This emphasizes one of the potential causes of distortion in dye timing data: that the flow path used for timing not only alters the achievable timing accuracy, but is also likely to change the proportion of thread and non-thread speeds that are lumped in the aggregate flow travel time). Likewise, optical tachometer data collected wholly within a thread are capable of indicating local thread speeds alone.

Flow speeds were also derived using Equation 1, and based on the grid of 49 depth measurements spanning the flow field, collected by the gantry. Given that flow threads are relatively narrow, and that the bulk of the area of soil surface is covered by non-thread flows, the depth data in such a set of observations are weighted according to the *area* occupied by thread and non-thread flows. Ordinarily, therefore, non-thread data would dominate numerically in such a set, but a small number of depth readings derived from thread locations might be included. Thus, speeds derived in this way would slightly *underestimate* true non-thread speeds, owing to the inclusion of some deeper thread depths in the calculation.

Speed calculations using gridded depth observations and Equation 1 are problematic in non-uniform flows. The bulk of the flow may be carried in a few relatively deep and fast-flowing threads, while most of the depth data would be derived from the areally dominant, but shallower and slower-moving non-thread zones. In these circumstances, the use of Equation 1 leads to erroneous results. At sites where microtopography perhaps resulted in deeper and more dominant flow threads, the non-thread zones carrying a small fraction of arriving flow would be left shallower and slower-moving. But Equation 1 would suggest a faster flow-field mean speed, since the true cross-sectional area of the flow is likely to be underestimated. In other words, an areal bias potentially exists in gridded depth data that overweights the shallow non-thread flows in the calculation of mean flow depth. Thus, the speed estimates derived from gridded depth data probably *underestimate* true mean flow speeds and *overestimate* non-thread speeds. Thus, while the outcome in any real case depends upon the grid used for depth sampling and on the spatial distribution of thread and non-thread flows, it is probable that commonly, $V_{\text{ff}} \geq V_{\text{nth}}$, where V_{ff} identifies the apparent flow-field mean and V_{nth} refers to the true mean speed of flow in non-thread zones.

Therefore, in interpreting the field data, it was concluded that true thread speeds were likely to exceed the speeds integrated across the 1.5 m dye tracks, while true non-thread speeds were likely to lie below the speeds derived from the depth observations using Equation 1. Examples, confirmation and further clarification of these points are provided when results are analysed.

In processing flow-field data, the following relations were employed:

$$\text{Reynolds number:} \quad \text{Re} = \frac{4DV}{\nu} \quad (2)$$

$$\text{Froude number:} \quad \text{Fr} = \frac{V}{\sqrt{gD}} \quad (3)$$

$$\text{Darcy–Weisbach friction coefficient:} \quad f = \frac{8gDS}{V^2} \quad (4)$$

Table I. Surface characteristics of the experimental run-off plots

Plot	Mean gradient ($^{\circ}$)	Surface roughness Ω	Relief amplitude (mm)
1	1.48	12.05	21.98
2	1.55	10.67	28.30
3	1.89	12.80	27.43
4	0.97	6.44	15.8

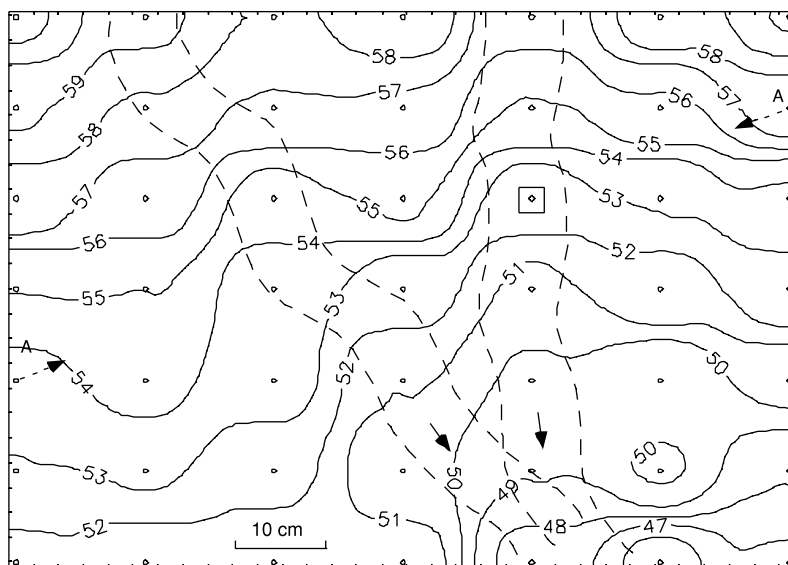


Figure 1. Contour map of Plot 4. The contour interval is 1 mm. The line of the topographic cross-section of Figure 2 is marked A-A. Also marked are the positions of two threads of flow. Arrows indicate the direction of flow (from top to bottom of the figure). The 49 small circles on a 7×7 grid represent the locations where elevation (and later, flow depth) was measured. The grid point marked with a square is the location of the water depth readings plotted on the cross-section of Figure 2. The elevations are referred to an arbitrary datum

where D is mean flow depth, V is mean flow speed, g is the acceleration due to gravity, S is plot gradient, and ν is kinematic viscosity.

RESULTS

General observations on plot surfaces and flow behaviour

The plots had similar slopes, all of them less than 2° , and roughness Ω (after removal of the hillslope gradient influence) was in the range 6.4–12.8 mm (Table 1). Plot 4 had both the smallest gradient and the lowest roughness, Plot 3 the steepest gradient and largest roughness. The form of a typical plot surface (Plot 4) is shown in Figure 1, where the positions of the flow threads are also identified.

Under all imposed flow rates, the whole of the soil surface was inundated, although at the lower discharges there were local high points on the soil surface where flow was shallow and sluggish. Surface tension forces may have been involved in drawing up and detaining some water in these locations. On all plots and at all flow rates, dye injections confirmed that there were threads of faster-moving flow following slightly sinuous tracks. The run-off water was non-turbid and there was no erosion of the broad plot surfaces that were anchored by cyanobacterial crusts. Weather conditions were mixed, with some days reaching 37°C with gusty winds and dust storms, while others were cool and calm. On windy days, there was almost certainly some buffeting of the flow and disturbance to measured depths, but this could not be eliminated. Each day, work was typically begun before

Table II. Imposed discharge and resulting flow-field mean properties for the 11 experimental runs on Plots 2, 3, and 4

Plot	Q (cm ³ s ⁻¹)	D (mm)	V (cm s ⁻¹)	f	Fr	Re
2	53.3	1.82	2.93	3.49	0.22	226.6
2	40.0	2.01	1.99	8.33	0.14	174.4
2	26.6	2.12	1.26	21.89	0.09	116.4
3	40.0	1.58	2.53	4.05	0.20	168.5
3	66.7	2.44	2.73	5.39	0.17	284.3
3	53.3	2.56	2.08	9.72	0.13	224.5
3	80.0	3.15	2.54	8.02	0.14	344.9
4	40.0	2.31	1.73	12.68	0.11	143.8
4	53.3	2.87	1.86	13.65	0.11	196.5
4	66.7	3.32	2.01	13.53	0.11	246.5
4	80.0	3.66	2.18	12.62	0.12	296.4

sunrise, and continued for about 8 h (terminating before the hottest part of the day), so that water temperatures were variable. Observations of water temperature were made at frequent intervals (about every 15 min) so that viscosity could be reliably estimated individually for all experimental runs.

Flow properties

In terms of flow-field means, all flows were laminar and subcritical (Table 2). Mean flow depths mostly lay in the range 2–4 mm, while the extreme recorded individual depths were 0.025 mm (the minimum resolvable) and 7.25 mm. Flow-field mean speeds derived using Equation 1 lay in the approximate range 1–3 cm s⁻¹. Dye timing along flow threads yielded speeds typically in the range 3.5–8 cm s⁻¹ when measured on a 150 cm flow path, with slightly higher maxima on the 50 cm path, while the optical tachometer data on a 4 cm flow path showed that there were local thread speeds up to 15.1 cm s⁻¹. One such fast-flowing thread was observed to have a very small headcut, a few millimetres high and convex upstream, toward the top of Plot 2; this lay outside of the area where gantry data were collected.

An analysis of flow thread behaviour

Except when by chance injection points lay on flow threads, the dye plumes once released moved sluggishly through shallow, non-thread areas, toward low-lying parts of the soil surface and there merged with deeper flow threads. The dye plumes then accelerated dramatically. On the three plots, contour form suggests flow thread widths of about 10–15 cm. Nevertheless, as outlined earlier, a constant thread width of 10 cm, consistent with the dye observations, is adopted in subsequent calculations. If indeed the threads were up to 15 cm wide, then the values derived below are conservative estimates of thread properties.

Recognition of threads is aided by plotting topographic sections orthogonal to the flow directions identified from dye and from the soil surface contour maps, using the gantry elevation data. (The elevation data permit contours to be interpolated at close intervals, such as 0.5 mm, so that a topographic profile may have >20 known elevations, even though the gantry measurement grid was only 7 rows × 7 columns). Figure 2 presents an example from Plot 4, showing a section constructed orthogonal to the two threads detected on this plot.

Topographic sections across the two threads (Figure 2) show that, even at the lowest imposed discharges, the topographic divide between the threads was overtopped by up to several millimetres. Thus, the flow threads are confirmed as having the form of deeper zones within a broad moving sheet of surface run-off. They are clearly not separate small 'channels' flanked by non-inundated higher parts of the soil surface.

Properties of thread and non-thread flows

Depths in threads were consistently greater than in the remainder of the flow (Table 3). The ratio D_{th}/D_{nth} (where again the subscripts refer to thread and non-thread zones of the flow field) averaged 2.40 across the 11 runs on Plots 2–4, and reached a maximum 3.96 in the smallest imposed discharge on Plot 4. Average D_{th} across the 11 runs was 3.29 mm (Table 2) while for D_{nth} the average was 1.45 mm. Not surprisingly, D_{ff} results derived

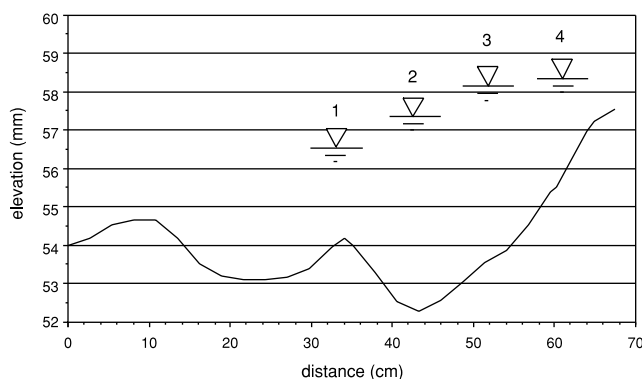


Figure 2. Cross-section across the two flow threads on Plot 4. The line of section is marked A-A on Figure 1. Note the extreme vertical exaggeration of 42 times. The water surface symbols labelled 1–4 indicate the depths recorded at the gantry measurement point lying on the axis of the right-hand thread (and identified in Figure 1 with a small square) at four successively increased imposed flow rates. These imposed flows are specified in Table 2

Table III. Properties of thread and non-thread regions of the experimental flows on Plots 2, 3, and 4. Each repeat experiment on a given plot is at a different imposed discharge, as detailed in Table 2. Estimated thread discharge is based upon a fixed thread width of 10 cm (see text for details)

Plot	Thread flows				Non-thread flows			
	D_{th} (mm)	V_{th} (cm s^{-1})	f_{th}	Conveyed fraction of imposed Q (%)	D_{nth} (mm)	V_{nth} (cm s^{-1})	f_{nth}	Conveyed fraction of imposed Q (%)
2	2.15	5.3	1.25	42.7	1.02	3.76	1.18	57.3
2	2.26	4.0	2.32	39.5	1.16	2.35	3.45	60.5
2	2.34	3.43	3.27	60.5	1.28	1.02	20.05	39.5
3	2.18	5.47	1.19	59.7	0.71	2.86	0.14	40.3
3	3.14	6.66	1.16	62.7	1.37	2.27	4.34	37.3
3	3.31	6.51	1.28	80.8	1.77	0.72	55.91	19.2
3	4.00	8.22	0.97	82.2	2.12	0.83	50.44	17.8
4	3.29	4.37	2.82	71.9	0.83	1.69	4.76	28.1
4	4.07	4.38	3.47	66.9	1.33	1.66	7.91	33.1
4	4.64	4.76	3.56	66.2	1.89	1.49	13.95	33.8
4	4.83	4.93	3.25	59.5	2.49	1.62	15.58	40.5
Mean	3.29	5.28	2.23	63.0	1.45	1.84	16.16	37.0
s.d.	0.99	1.39	1.07	13.36	0.56	0.91	19.38	13.36

using all 49 readings were of intermediate value, averaging 2.53 mm. The magnitude of the differences among the different measures varied among the plots, depending to some extent on the number of depth observation points that happened to fall on thread flows. If chance determined that a sizeable number did so (as was the case with Plot 4), this was sufficient to lift D_{ff} . This point is considered again below when recommendations for better observation protocols are considered. Small-sample t -tests (Freund, 1974) confirm that across the 11 runs, D_{th} , D_{nth} and D_{ff} average depths form three statistically distinct distributions.

Similar trends were found in flow speed data. Since V_{ff} is found using Equation 1, and D_{ff} is intermediate between that of thread and non-thread zones, the flow field mean of 2.17 cm s^{-1} would likewise be expected to fall between that of thread and non-thread zones. As noted earlier, the dye timing must generally have underestimated thread speeds, and yields little information on non-thread speeds. Nevertheless, the mean dye speed, 5.28 cm s^{-1} , lies well above the flow-field mean (denoted by the subscript 'ff'). Across the 11 runs, the ratio V_{dye}/V_{ff} averaged 2.46 (Table 4). Given that dye plumes always merged into thread flow, timing of non-thread speeds was not possible. As an alternative, non-thread speeds are estimated as follows. The discharge conveyed through non-thread zones was found by summing the thread flows (using $Q = WDV$) using the fixed 10 cm width

Table IV. Ratios of thread and non-thread depths, flow velocities, and friction coefficients for the 11 experimental runs on Plots 2, 3, and 4. The subscripts are as follows: 'th' indicates a thread parameter, 'nth' a non-thread parameter, and 'ff' a flow-field mean parameter

Plot	Depth		Velocity		Friction coefficient	
	Thread D_{th}/D_{ff}	Non-thread D_{nth}/D_{ff}	Thread V_{th}/V_{ff}	Non-thread V_{nth}/V_{ff}	Thread f_{th}/f_{ff}	Non-thread f_{nth}/f_{ff}
2	1.18	0.56	1.81	1.28	0.30	0.34
2	1.13	0.58	2.01	1.18	0.25	0.41
2	1.11	0.61	2.72	0.81	0.14	0.92
3	1.38	0.45	2.16	1.13	0.21	0.04
3	1.29	0.56	2.44	0.83	0.17	0.81
3	1.29	0.69	3.13	0.35	0.10	5.75
3	1.27	0.67	3.24	0.33	0.10	6.29
4	1.42	0.36	2.53	0.98	0.16	0.38
4	1.42	0.46	2.35	0.89	0.18	0.58
4	1.39	0.57	2.37	0.74	0.18	1.03
4	1.32	0.68	2.26	0.74	0.19	1.24
Average	1.29	0.56	2.46	0.84	0.18	1.62
s.d.	0.11	0.10	0.44	0.31	0.06	2.21

(conservative), measured depth D_{th} and dye speeds V_{th} (conservative), and deducting this from the total imposed flow. Using the residual fractional width of the plot lying beyond the threads, and the measured non-thread depths, the relation used was $V_{nth} = Q_{nth}/W_{nth}D_{nth}$. The average speed across the 11 runs using this estimation procedure was 1.84 cm s^{-1} . The average value of the ratio V_{nth}/V_{ff} was 0.84 (Table 4). Small-sample t -tests (Freund, 1974) confirm that across the 11 runs thread and non-thread mean speeds form statistically distinct distributions. By the same test, thread speeds are shown to be distinct from the flow-field mean, while non-threads speeds are not.

Across the 11 runs, the analysis of thread conveyance of flow outlined above yielded a mean fraction of 63.0 per cent of the imposed flow moving in flow threads (Table 3). There were two 10 cm wide flow threads on each plot, so that this flow is conveyed in only 20 per cent of the plot width. The residual 37.0 per cent of the flow is conveyed in non-thread areas that occupy 80 per cent of the plot width.

Given that statistically distinct distributions of depths and speeds were established for thread and non-thread flows, separate estimates of Darcy–Weisbach friction coefficient were derived for these zones, using Equation 3. Here, f_{th} is the friction coefficient for threads, and f_{nth} is the coefficient for the non-thread flows. Across the 11 runs, these indicated average values of $f_{th} = 2.23$ and $f_{nth} = 16.16$. Flow-field means yielded the intermediate average $f_{ff} = 10.31$. Small-sample t -tests (Freund, 1974) confirm that across the 11 runs f_{th} and f_{nth} are statistically distinct. Likewise, f_{th} and f_{ff} are statistically distinct, but f_{nth} and f_{ff} are not.

Given that the dye injections from which speeds were judged were evenly spaced on each plot, and that injection points were not located to target thread flows, it is interesting to consider briefly the effect on estimated friction coefficients if these speeds had been used in Equation 3. Across the 11 runs, the average Darcy f derived from the gantry data (f_{ff}) was 10.31. If the dye speeds were used (instead of flow-field mean speeds estimated from Equation 1), the average Darcy f declined to 1.72. On average, therefore, gantry estimates based on depth data were more than 5.5 times higher than those based on dye speeds. On the other hand, the value of f_{th} noted earlier was 2.23, reasonably close to the estimated mean of 1.72 based on dye speeds. Thus, it is clear that where flow threads are present, the use of uncorrected dye speeds results in estimated friction coefficients that are biased toward actual thread friction coefficients and which depart significantly from the true flow-field mean.

A consideration of different approaches to flow description and analysis

Approaches to predicting the mutual adjustment of depth and speed in uniform laminar flow are readily available (e.g., White, 1999). Provided that the flow is uniform, the behaviour of both flow parameters can be predicted when flow width and imposed discharge are both known (e.g., Myers, 2002). However, these equilibrium flow properties break down when the flow is non-uniform. The difficulty facing many experimental

programs is that the state of flow, including the presence and significance of flow threads, backwaters or ponded areas, and other perturbations such as surface tension controls, can be very difficult to detect by eye. This is especially so in the field if the flow is shallow and non-turbid, when the flow presents the appearance of a relatively uniform sheet. Under these conditions, the speed of motion is difficult to detect without the injection of a tracer, and even then an assessment of the whole run-off field cannot be made without repeated tracer injections. If using dye, this becomes time consuming because of the delay required to allow the dye cloud from one injection to clear before another can be observed and timed reliably. This can create uncertainty about whether uniform flow relationships can validly be applied to particular instances of surface run-off.

An assessment of the state of the flow field as a whole can, however, be made using data on flow depth and speed. Conventional flow-field means can provide an adequate basis for this analysis, on the basis of a form of 'null hypothesis' that the flow is uniform and contains no (or only relatively minor) flow threads, backwaters, etc. If this assumption holds, then the flow properties should accord with those predicted by conceptual analyses of shallow uniform flow hydraulics. Significant departures from the predicted behaviour then suggest that there was indeed significant departure from the assumed uniformity of flow (and/or errors or inadequacies in the original flow measurements).

Take as an example the relationships among depth, speed, and discharge for laminar flow across a surface having granular roughness but immersed in uniform laminar flow. According to Myers (2002), the following relations hold:

$$D = k + \sqrt[3]{\frac{3\nu q}{g \sin \theta}} \quad (5)$$

$$V = \frac{k}{q} + \sqrt[3]{\frac{3\nu}{gq^2 \sin \theta}} \quad (6)$$

In these relations, q is the flux in $\text{m}^2 \text{s}^{-1}$, k is the roughness height (m) and θ is the surface gradient.

These relationships demonstrate that in free, uniform flow the mean forward speed should rise such that

$$V \approx aQ^{2/3} \quad (7)$$

where a is a coefficient of proportionality whose value should be maximized when frictional drag from surface roughness is minimized, and a rise in imposed Q is associated with a relatively small increase in flow depth. Correspondingly, the relation for flow depth in free uniform flow is

$$D \approx bQ^{1/3} \quad (8)$$

where again b is a coefficient of proportionality, and flow depth rises less rapidly with imposed Q than does flow speed. Continuity is thus satisfied in accordance with the relation

$$Q = aQ^{2/3} bQ^{1/3} \quad (9)$$

which reduces to

$$Q = abQ \quad (10)$$

so requiring that $ab = 1$.

If these relationships are not demonstrated in flow depth and speed data collected in a surface run-off field, then it can be concluded that, in terms of flow-field averages, depth and speed are not mutually adjusted. Given that in any more closely uniform component flow within the flow field, such as thread flows, these mutual adjustments must apply more closely, a departure from them in flow-field averages suggests the likelihood that,

in calculating flow-field averages, thread and non-thread flows were present and perhaps at equilibrium, but were lumped together in the data processing to yield values that did not apply to either flow component.

The above approach can be used to demonstrate that flow speeds observed by dye timing from evenly spaced injection points does not record flow speeds that are consistent with independently observed depths at the grid of measuring points spanning the whole of the target flow field. For example, on Plot 4, the following relations were established:

$$\begin{aligned}\text{Mean speed (dye, } 3 \times 150 \text{ cm paths)} &= 3.251 + 1.925Q^{0.66} \\ \text{Mean depth (gantry, 49 grid points)} &= -0.289 + 0.708Q^{0.33}\end{aligned}$$

These results indicate that

$$ab = 1.925 \times 0.708 = 1.36$$

This result is $\neq 1$, so that the depth and speed data are not in mutual adjustment. In contrast, when speed data are derived from the depth readings using Equation 1, the results are necessarily compatible since one is derived from the other. In this case the relation for the deduced flow speeds is different, taking the form

$$\text{Mean speed (calculated)} = 0.951 + 1.407Q^{0.66}$$

Using this result we have $ab = 0.708 \times 1.407 = 0.996$, which is acceptably close to unity.

Figure 3 shows the expected relation of V and Q for uniform flows, together with V_{ff} and V_{th} derived from plots 2, 3, and 4 of the current experiments. It is evident that the V_{ff} results suggest roughness heights of about the same value as the estimated V_{th} data. In both flow-field mean and thread results, Plot 4 demonstrates the largest roughness height, of 3–4 mm. This is consistent with the heavier cover of fine quartz gravel on Plot 4 than on the other plots. Likewise, Plot 2 demonstrates the lowest roughness height, of about 1 mm, in both flow-field mean and thread data. The roughness height for Plot 3 is intermediate between that of Plot 2 and Plot 4.

Similar conclusions are reached if the plot data are analysed in terms of flow depth in relation to imposed flow rather than flow speed (not shown). Thus, it can be concluded that despite the evident differences in flow depth and speed between flow threads and the flow-field mean properties derived from gridded depth data, both are consistent with laminar flow across soil surfaces having a roughness height of 1–4 mm. There is no suggestion in these results that threads exhibit lower surface roughness heights, though, as quantified above, threads

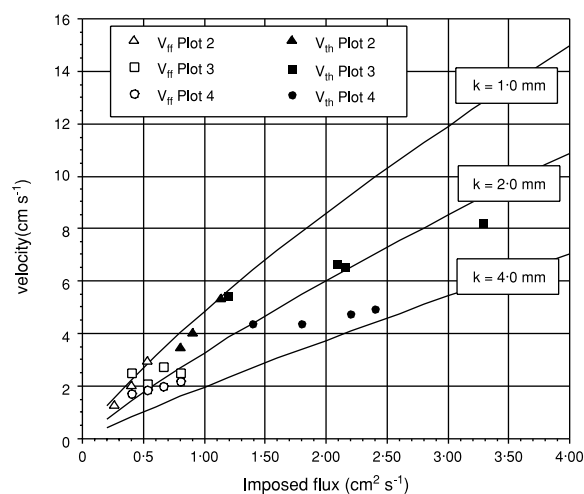


Figure 3. The predicted relationship between flow speed and flux for uniform laminar flow on surfaces of varying roughness height, based on Myers (2002). The three curves represent roughness heights of 1 mm, 2 mm and 4 mm. Open symbols correspond to flow-field mean properties, and closed symbols to flow thread properties

do exhibit lower friction coefficients owing to their greater depth and the deeper submergence of roughness elements.

DISCUSSION AND CONCLUSIONS

It is clear that the surface run-off on the experimental plots was non-uniform, and despite inundating the entire soil surface it contained identifiable threads of fast deep flow. The mean depth, flow speed and Darcy–Weisbach friction coefficient for thread and non-thread regions of the flow were statistically distinct. Thread flow conveyed most of the imposed discharge across the experimental plots in a small fraction of the total width.

Statistically different flow depths and speeds allow thread and non-thread zones to be distinguished. The thread speeds lay well above the flow-field mean (average 2.5 times faster) while the non-thread speeds were all much closer to it (average 0.84 times the mean). Thus, flow-field mean speed data, as conventionally derived using Equation 1, do indeed more closely reflect that of the areally extensive, non-thread parts of the surface run-off. Indeed, non-thread speeds and friction coefficients were not statistically distinct from the flow-field average, owing to this weighting of the flow-field mean by the areally extensive non-thread regions.

Similarly, in all of the 13 experimental runs, the D_{th} exceeded D_{ff} by an average of 1.3 times. Similarly, in all 13 runs, the D_{nth} was less than D_{ff} , the average multiplier being 0.56 times. While average D_{th} exceeded the D_{ff} in all runs, the multiplier was not as great as in the case of the comparison of speeds. Furthermore, on all plots the D_{th} became closer to D_{ff} as imposed Q was increased. This reflects the fact that the threads lie wholly *within* the flow field, and the additional depth fraction that is the result of the topographic depression of the thread thalwegs becomes less significant as the whole flow field deepens across both thread and non-thread zones. However, it is clear from the data that even though the microtopographic features steering the flow threads become increasingly deeply submerged as imposed Q rises, the threads continue to function. There is no evident tendency for them to dissipate or to alter their track significantly as the surface becomes more deeply inundated. Nevertheless, in rare instances new thread bifurcations, in which very small filaments diverged from the main thread, were noted at the highest imposed discharges.

It seems reasonable to speculate that just as injected dye inevitably moved toward and then along the threads, so too would soil particles detached from the shallow, non-thread areas. If this is correct, then the thread and non-thread zones may operate as sediment conveyors and sediment source areas, respectively. This is analogous to the notion of rill and interrill zones. Even if they do serve primarily as routes for water and sediment conveyance, there must be greater erosion of the threads at some stage, in order to lower their elevations and establish the thalweg that they follow. The presence of a small headcut along one thread suggests that this lowering may occur episodically as the very high thread speeds (up to 15 cm s^{-1} in the present experiments, and perhaps considerably greater in storm events where the run-off intensity is greater) exceed the critical force required to entrain the soil materials. All of the thread flow measured had Reynolds numbers indicative of laminar flow, and this was confirmed by observation of dye plumes. However, the optical tachometer results indicate the threshold of turbulence was probably reached locally along the threads. For instance, a thread of 4 mm depth and flowing at 15 cm s^{-1} yields $Re = 2400$. The onset of turbulence therefore seems probable in larger run-off events than those simulated here. If the reasoning about the role of threads as sediment conveyors is correct, then the interpretation of the mass and texture of soil materials delivered to the outlet of erosion plots may be appropriately made in relation to thread hydraulic properties, and not to the flow-field mean properties.

The difficulty in objectively and rigorously defining thread dimensions means that uncertainty is attached to the average depths, speeds, and friction coefficients presented earlier. The calculated friction coefficients depend upon the particular distribution of gantry observation points in relation to thread locations. On Plot 4, for instance, a series of gantry grid points happened to fall close to a thread thalweg. This would result in a flow-field mean depth there that was nearer to the thread value than would have been the case had the points by chance fallen slightly further away from the thread axes. On other plots, gantry observation points as close as possible to thread axes were chosen to estimate thread depths. But with evenly spaced depth observations, chance determines how closely any observation lies to the thalweg (maximum depth) of a thread. Thus, an important conclusion to arise from this work is that in non-uniform flows like those studied the collection of evenly distributed depth readings from cross-sections or from two-dimensional grids does not guarantee that

derived flow-field means are representative. Evidently, different locations of observation points could yield different mean depths.

In view of the limited body of preliminary results presented here, some aspects of flow behaviour have not been pursued. An instance is the behaviour of frictional retardation as imposed flow changes. Ideally, a wider range of imposed flows than was achieved in the present experiments would be employed to explore this. The current analyses do not suggest clear trends in friction coefficients with changing discharge. This is an area that will require attention in subsequent work. Certainly, it appears that arguments raised in the past about rising and declining trends in friction coefficients with changing discharges, and using flow-field mean data, may have been based on data blending thread and non-thread flows in unknown proportions.

Arising from the foregoing consideration of non-uniform flows and the difficulty of observing them without bias are some implications for measurement protocols likely to result in less biased estimates of flow properties than can arise with grid-based or cross-section-based depth data.

The selection of observation points is clearly of importance, since representative depth data are critical in flow hydraulics studies. In collecting data from non-uniform flows, evenly spaced sampling points on transects or grids are unsuitable unless the sample spacing is significantly less than the thread width. Failing this, chance may determine that the sampling points either under- or overrepresent the deeper flow threads. In the results presented earlier, it was shown that the mean of the grid-based depth data (D_{ff}) underestimated D_{th} but overestimated D_{nth} in all runs. Moreover, it consistently exceeded the average of thread and non-thread depths in all runs. A better approach would be to first use dye injection to identify and map flow threads, and then set up an array of sampling points that specifically targets, in equal numbers, the thread and non-thread zones of the flow field. Establishing a dense grid of measurement points covering the entire plot surface would work equally well but would be far more time consuming and involve larger amounts of redundant data. Thus, recognition of the zones of flow followed by stratified sampling appears to be the best approach to data collection.

Second, flow speeds are critical in the calculation of friction coefficients and in sediment entrainment calculations. Dye timing in the presence of flow threads inevitably leads to speed estimates biased toward the thread speeds (in the results presented earlier, overestimating V_{ff} by an average of 2.5 times). It is difficult to record non-thread speeds by timing dye motion before the flow drains toward a thread and then accelerates, because the path is short and erratic. 'Spot' readings using the optical tachometer can be used to estimate non-thread speeds provided that depths are sufficiently deep to float the reflective targets. However, when flows become very thin, influences such as surface tension prohibit the use of conventional kinematic equations in any case. Thus, the most workable procedure is the one adopted earlier. Dye is used to visualize threads and to estimate their width and geometry. Dye timing specifically targeting threads can then be used to estimate their speed. An approximate calculation of the discharge conveyed and summed across all threads then allows the residual discharge that is conveyed in non-thread areas to be found. Non-thread speed is then estimated from Equation 1.

It was shown earlier that individual estimates of friction coefficients (and depths and speeds) can be derived for thread and non-thread flows. If, for purposes of statistical analysis, a single value is needed in order to characterize an experimental plot, then a discharge-weighted value is probably the most appropriate. (This was attempted for instance by Fox and Bryan (1999), who sought to link measures of soil loss from laboratory trays to mean velocity of run-off). For instance, if 60 per cent of the run-off is conveyed in threads having $f = 2$, and the remaining 40 per cent in non-thread zones where $f = 10$, the Q -weighted value is $(2 \times 0.6) + (10 \times 0.4) = \text{approx } 5.2$. In a more marked case, such as run 5 on Plot 3, the values of f are 0.97 (threads) and 50.4 (non-thread), with 82 per cent of the flow conveyed in threads. This yields a Q -weighted estimate of $(0.97 \times 0.82) + (50.4 \times 0.18) = 9.86$. This is close to the flow-field mean based on gridded depth data ($f = 8.0$). However, the closeness of these two estimates conceals the very large differences in the primary data, including in this case flow-field mean speed and depth of 2.54 cm s^{-1} and 3.15 mm , compared with the thread values of 8.22 cm s^{-1} and 4.00 mm . As just observed, given such disparate flow properties, flow-field mean values are critically dependent on the particular balance of thread and non-thread depths employed in the calculations. This in turn is a function of the size and spatial distribution of threads in relation to the locations and spacings of the depth observation points. Considerable variability in results can be anticipated to arise from this cause in studies where sampling locations are established independently of any measures of flow thread size and location.

Studies like that of Fox and Bryan (1999) have employed dye tracing to estimate mean velocity. As already noted, this is problematic if flow threads are present, since the dye passes into these, resulting in estimates of mean flow speed that are significantly too high. They performed the conversion from surface speeds to mean speeds using a coefficient α of 0.36, citing evidence of such low values from Luk and Merz (1992). However, the field data analysed by Luk and Merz came from highly erosive loess soils in China, where not only were flow threads present, but also they changed position frequently. If surface speeds recorded in any study are in fact higher than the *mean* surface speed (owing to dye motion along fast threads), then necessarily the ratio V/V_s will be erroneously low. This effect was recognized by Emmett (1970). The use of a fixed coefficient α then becomes especially problematic in situations where the nature of thread development and hydraulics are likely to vary. This is certainly likely to be the case where imposed flow and slope gradient are changed in sequential laboratory experiments with soil trays. Thus, published results may well contain the effects of confounding factors like changing thread properties. This situation highlights the need for a greater recognition of the perturbations that can arise in experimental data when flow threads are present, and the need for these features to be recorded and measured wherever possible as an aid to the interpretation of experimental findings. It has to be emphasized that theoretical values of α , and those derived from uniform flow (e.g. the mean value of $\alpha = 0.56$ derived by Dunkerley, 2001) are applicable *only* to uniform flow. Because of the variable nature of thread development, values suitable for application in non-uniform flow are generally likely to be lower but, clearly, no generally applicable value is possible.

The results presented here are preliminary, reflecting a first attempt to resolve flow thread and non-thread conditions in shallow overland flow. Suggestions for revised data collection protocols have arisen from this preliminary work, including a move away from a reliance on evenly spaced depth observations to greater use of stratified sampling of thread and non-thread zones identified using preliminary dye tracing. It will probably prove helpful to supplement these observations with more detailed cross-sections of flow threads taken at intervals along their course. Additional field studies of the phenomena discussed are needed in order to support more general assessment of the proportions of flow conveyed in threads in other environments, and the hydraulic characteristics of these threads. One of the most interesting implications of this study is that flow threads may play a key role in conveying eroded soil particles across the interrill zone, and in determining the competence of surface run-off as an erosional agent. These are matters that will be addressed in subsequent work on flow threads.

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