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SURFACE TENSION AND FRICTION COEFFICIENTS IN SHALLOW, LAMINAR OVERLAND FLOWS THROUGH ORGANIC LITTER

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ABSTRACT

This study investigates the contribution of surface tension forces to friction coefficients in shallow, laminar interrill flows. Friction coefficients in these flows are known to be increased greatly by organic litter and by stems. Fine litter provides extensive edges along which surface tension menisci can be drawn up, and evaluating the significance of this in the frictional retardation of flow was the primary objective of the experiments reported here.

Using both standardized 'litter particles' (small wooden blocks of fixed dimensions) and natural plant litter, meniscus behaviour and the Darcy–Weisbach friction coefficient were evaluated in shallow flows on a laboratory sand board. For some tests, the surface tension of ordinary water was reduced by 40 per cent by the addition of a surfactant, and the friction coefficient redetermined.

Results show that the presence of surface tension menisci flanking litter particles provides areas of deeper flow that are up to 7 mm in width and which can increase flow depths by 100–300 per cent. These zones support significantly higher flow speeds. Increased water depths within menisci are additionally associated with reduced depths beyond the menisci, so that an increase in the spatial variability of flow depths is a second consequence of meniscus formation.

These modifications of flow depth by surface tension menisci are shown to reduce rather than increase the overall friction coefficient applicable to the flow. Consequently, additional frictional retardation does not arise within the menisci flanking litter particles and so cannot account for the greater drag arising from litter than from other surface features. Different factors, possibly the direct obstruction of flow paths, must therefore underlie the frictional drag.

KEY WORDS: laminar flow; surface tension; organic litter; interrill flow; surface runoff; Darcy–Weisbach friction coefficient

INTRODUCTION

Friction coefficients are among the key input parameters for detailed hydrologic models used for the prediction and analysis of surface runoff. Empirical values can be derived using two differing approaches. Aggregate values for particular surfaces (such as a tilled soil or a heavily grazed grassland) derived in one location can be used for the analysis of flows there or at similar sites. It is not essential that the particular surface features that set the value of the roughness coefficient be known. Alternatively, in a reductionist approach, the surface features contributing to the measured friction coefficient (such as random surface roughness, preferred flow paths, surface stones, plant stems and plant litter) can be evaluated so that in principle, for a surface where these properties are known, a prediction of the applicable friction coefficient can be derived. This approach is more involved and requires more preparatory work, but holds the prospect of a more versatile and widely adaptable understanding of frictional retardation in surface runoff. More importantly, perhaps, it can allow the ranking of surface features in terms of the contribution that they make to the aggregate friction coefficient of a surface. Such an understanding could guide land management decisions relating to those features most important to conserving soil by minimizing the speed and erosivity of surface runoff, for example.

Examples of the reductionist approach include the rangeland friction factors derived by Weltz *et al.* (1992), who sought to identify the individual contributions made by litter and stones, and multiple studies by Abrahams, Parsons, and co-workers (e.g. Abrahams and Parsons, 1994).

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It has become clear from such work and from experiments both in the field and the laboratory (e.g. Dunne and Dietrich, 1980; Weltz *et al*., 1992; Dunkerley *et al*., 2001) that various features of the soil surface contribute differently to frictional retardation. In particular, litter may provide higher frictional retardation per unit projected surface cover than larger obstacles such as stones. One explanation hypothesized for this (Dunkerley *et al*., 2001) is that the greater edge-length developed on litter particles provides correspondingly more opportunity for the development of menisci related to surface tension draw-up of the water surface, with associated effects on flow depths and speeds.

The exploration of this hypothesis, and of meniscus development and its impact on flow behaviour, form the objectives of the present work. The main strategy used here to identify the effects of surface tension is to reduce its value by chemical means and observe the effects on flow properties. If this leads to a reduction in flow depth, for example, then it can be concluded that in ordinary water, surface tension acts to *increase* flow depths.

Surface tension in shallow overland flow

Surface or interfacial tension (γ) is exhibited at the air–water and the air–water–solid interfaces, and accounts for the important phenomenon of capillary rise. Commonly also called the surface free energy, surface tension arises from the forces acting between water molecules. For water at room temperature it is about 0·072 N m^{-1}, declining slowly at higher temperatures (Adamson and Gast, 1997). Whilst surface tension can be lowered by soaps and surfactants, it can also be increased somewhat by dissolved substances including salt. Ordinarily, the significance of surface tension in liquid motion is assessed in relation to the dimensionless Weber number, We, which is given by:

$$\mathrm{We} = \frac{\rho V^2 D}{\gamma} \tag{1}$$

where D is flow depth, V is flow speed, and ρ is water density. The Weber number, representing the ratio of inertial to surface tension forces, is considered to indicate a significant role for surface tension only when it adopts a value <1 (i.e. when surface tension forces exceed the effects of inertia within the flowing liquid), and this only occurs when the radius of surface curvature is of the same magnitude as the depth of the liquid (White, 1999, p. 294). Consequently, surface tension forces may be important in shallow flows along the margins of protruding obstacles such as particles of plant litter, where there are curving menisci, but much less significant in open parts of the flow where there is no marked curvature of the water surface.

Surface tension arises from unbalanced forces on molecules close to the water surface. The van der Waals-type attraction of molecules deeper below the surface is not offset by a corresponding attraction from above the surface. (Deeper in the liquid, the forces acting in all directions are equal). However, the attractive forces decay very rapidly with distance, so that the surface region of unbalanced forces is only a few molecular diameters in thickness (Adamson and Gast, 1997, p. 56). Consequently, though there is continuing molecular motion within the liquid (as well as interchange of vapour through the surface), and therefore some internal momentum transfer, molecules well below the surface are essentially unaffected by the unbalanced forces at the air–water interface.

The edges of any wettable obstacles standing within overland flow, such as plant stems, litter or stones, provide sites where interfacial molecular forces arising between the water and the solid in contact with it can draw up the water surface across which surface tension produces a strongly curved meniscus. Direct observation shows that there is extensive formation of such menisci in shallow flows across litter-bearing surfaces or in flow through grass or stones. Around particles of litter protruding through the water surface, curving menisci can extend over distances of several millimetres, across which the water surface is lifted by amounts of the order of 1–3 mm above the general level of the flow beyond the meniscus (measurements are reported later). Such lift can amount to 300 per cent of the depth of shallow interrill flows. Because of the volume of water contained within the broad meniscus, particles of litter can affect properties of the flow across a larger area of the surface than is directly covered by the litter. The draw-up of water in the menisci must affect flow depths in the larger area surrounding a wetted litter particle, since the source for the liquid contained within the meniscus can only be the adjacent flow. If flow depths are affected by the withdrawal of water into extensive menisci, then so too must flow speeds and hence friction factors. To the author's knowledge, no data are presently available to allow the effects of this on water motion to be revealed. In deep and turbulent flows such as rill flows, surface tension effects are almost certainly negligible. However, in thin interrill flows that may be laminar and less than one or a few millimetres in depth, the effects seem capable of exerting a significant influence on flow depths and friction coefficients. The exploration of this idea forms the goal of the work described below.

Little prior investigation of surface tension in interrill flow seems to have been carried out. Turner *et al.* (1978) suggested that in laminar flows, extra drag in flow through plant stems would arise from surface tension forces in the menisci around stems as flow deepened. They carried out tests using wooden pegs with a meniscus length of about 50 m m^{-2}. The pegs were suspended above a flume and lowered so that menisci were developed when the pegs touched the water surface. This was done to eliminate any form drag arising from submerged pegs and permit the quantification of meniscus effects alone. Turner *et al.* (1978) experienced difficulties with drag from the ends of the pegs and with turbulence, but concluded that drag related to the menisci was small in relation to the form drag arising from pegs immersed in the flow itself. These findings are considered further later.

MATERIALS AND METHODS

The experimental design adopted here was to take replicate measurements of flow depths, speeds and friction coefficients in shallow flows passing across a sloping glued-sand board on which had been scattered known amounts of plant litter. Ordinary water was tested first, and then surface tension was reduced by adding a chemical surfactant. Changes in flow properties between water and surfactant experiments were then used to identify those properties of the flow that were affected by surface tension, and to quantify the effects, especially in relation to flow depths and friction coefficients.

Measuring surface tension

The du Noüy apparatus was used to measure surface tension. This consists of a balance from which is suspended a small, horizontal loop of fine platinum wire. This loop is placed in contact with the liquid surface in a small container. The loop is then withdrawn upwards, producing an attached annulus of water held by surface tension. This annulus eventually breaks from the platinum loop, and the maximum downward force on this loop prior to this rupture is recorded by the balance. The surface tension is then expressed as the force per unit of length of the platinum wire (in units of N m^{-1}). With a ring of diameter R and weight W_{ring}, the total weight W_{tot} recorded on a balance as the ring is withdrawn is:

$$W_{tot} = W_{ring} + 4\pi R\gamma \qquad (2)$$

with the term 4 arising because the surface tension extends along both the inside and the outside of the ring.

A commercial liquid surfactant, designed to improve the water absorbency of garden soils, was used to reduce the surface tension forces. Trials showed that even trace amounts of this surfactant lowered γ dramatically. In the flow experiments, the concentration adopted was 1 ml per litre, a level at which there was little further decline in γ as concentration of surfactant was increased. Repeated determinations confirmed that at this concentration, the mean value of γ was 0·034 N m^{-1}. The value of γ was checked at intervals during all tests, and additional results are presented later.

The flow-board system

Tests were carried out on a sand board 0·5 m wide and 1·2 m long. This had been heavily varnished and sprinkled with medium sand whilst still wet. Excess sand was later brushed off to yield an essentially planar surface carrying a granular roughness. The sand board was set at a slope of 1·2 and flow fed onto it from a perforated pipe at the upslope end. At the bottom of the board, the water discharged into a reservoir from which it was continually recirculated by peristaltic pumps. Nominated flow rates could be set and held to about 1 per cent accuracy.

A computer-controlled X-Y-Z gantry was set up and levelled above the flow board (Figure 1). This allowed a stepper-motor-driven needle gauge to be carried to nominated (X,Y) coordinates and then lowered automatically at each of a grid of sample points, and the water surface elevation mapped with a resolution of 25 m. The system also carried a switch which was activated when a solid object (the bed or a litter particle) was touched. Flow depths were determined by first mapping the bed elevations prior to turning on the pumps, and later subtracting these from the water surface elevations at the same test points. Fuller details are provided in Dunkerley *et al.* 2001 and Dunkerley 2001.

In each test, five flow rates were imposed on the board in sequence, the discharges being 10, 20, 30, 40 and 50 $\text{cm}^3\ \text{s}^{-1}$. For each flow rate, the water surface elevation was mapped at 64 points evenly spaced over a 0·5 m × 0·5 m test area in the centre of the flow board. For each test treatment and liquid (sand board bare or with litter added, and ordinary water or water with added surfactant) the sequence of five flow rates was replicated five times. For tests with litter, the distribution of particles on the board was varied haphazardly for each replicate test, by collecting and then reapplying the litter. The same litter particles were reused to make the replicate tests as similar as possible apart from the altered spatial distribution of the particles. Litter was added to achieve a projected cover of 20 per cent, which lies within the range of published areal loadings from drylands and elsewhere, for which cover fractions of up to 70 per cent have been reported (Woolhiser *et al.*, 1970, Johnson and Gordon, 1988: Martinez Carretero and Dalmasso, 1992). This was achieved by applying a litter loading of 80 g m^{-2}, as verified by repeated trials assessing cover by point-counting on a grid with 100 nodes.

Water temperatures were monitored using a platinum resistance thermometer and viscosity calculated from the polynomial relationships set out by Weast (1979). From the depth data, mean flow depth was calculated for each discharge (excluding those points where a litter particle was present), and hence mean flow speed was deduced by using the relation:

$$\bar{V} = \frac{Q}{W\bar{D}} \tag{3}$$

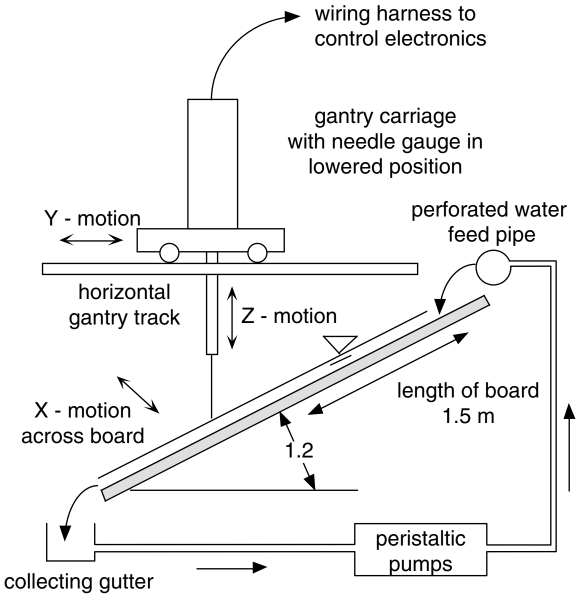

Figure 1. Schematic diagram of the experimental apparatus (not to scale). For simplicity, carriage rollers for only one direction of gantry motion are shown. For high flow rates, a bank of peristaltic pumps was employed

The width of the flow was set to a constant 50 cm by two side rails attached to the flow board.

Also determined for each test condition were the Darcy–Weisbach friction coefficient:

$$f = \frac{8gDS}{V^2} \tag{4}$$

the flow Reynolds number:

$$\mathrm{Re} = \frac{4DV}{\nu} \tag{5}$$

and the Froude number:

$$F = \frac{V}{\sqrt{gD}} \tag{6}$$

where D is the mean flow depth (cm), V is the mean flow speed (cm $\mathrm{s^{-1}}$), S is the dimensionless energy slope, ν is the kinematic viscosity ($\mathrm{cm^2\ s^{-1}}$) and g is the acceleration due to gravity (cm $\mathrm{s^{-2}}$).

The plant litter

The litter used was collected from an arid shrubland near Broken Hill in western New South Wales, Australia. It consisted of flower parts, leaves, twig fragments, and a small component of animal dung. This was air-dried, and weighed prior to hand distribution on the flow board. Typical weights and dimensions of the particles are reported in Table I. Some of the litter was angular or spiny, so that the individual fragments did not separate readily, and there was some clumping of litter as it was applied to the board. Thus, whilst an even distribution was sought during the application, there were some concentrations of litter and some bare patches remained.

The density of the litter material when wet was estimated from volumetric displacement tests to be about 1·0 g $\mathrm{cm^{-3}}$.

Integrated measures of frictional retardation

In laminar flow on planar surfaces, the relationship of f and Re commonly takes the form:

$$f = a\mathrm{Re}^{-b} \tag{7}$$

where a and b are empirically fitted constants. On smooth surfaces, b takes the value -1, so that Equation 7 can be rewritten:

$$f = \frac{K}{\mathrm{Re}} \tag{8}$$

The value of K then provides a measure of surface roughness, and is derived from multiple values for f measured across a range of flow intensities (Re values). Published values of K range from <100 on smooth surfaces to $>12\,000$ on rough surfaces (Chen, 1976). However, when the slope of the f–Re relation departs from -1 (as it may do on natural or other rough or uneven surfaces), the K term becomes inapplicable and cannot serve as a measure of roughness.

Table I. Dimensions and weights of the principal components of the organic litter used in both the water and surfactant experiments

Litter item	Mean (max.) dimensions: length × diameter (mm)	Mean (max.) weight (mg)
Flower parts	7 × 7 (9 × 5)	9 (18)
Leaves and leaf parts	12 × 7 (40 × 14)	9 (122)
Twigs and wood fragments	43 × 1 (63 × 5)	72 (1194)

In the litter tests reported below, the slopes of the f–Re relations did depart from the value of $-1{\cdot}0$. Therefore, in place of K, two alternative measures of overall surface retardation are adopted here:

(a) a direct comparison of the individual value of the Darcy f at the flow of 30 $\mathrm{cm}^3\ \mathrm{s}^{-1}$, which was in the middle of the range of flows applied to each test treatment;
(b) the definite integral of the f–Re relation (namely, the area beneath the curve), in its power function form, across the range of Reynolds numbers employed in the tests. Here, the integration is made across the interval $50 < \mathrm{Re} < 450$, which encompasses the range of imposed flow intensities. Taking this integral provides a valid measure of the total roughness generated in each test condition, regardless of whether the slope of the graph of f against Re (Moody plot) is close to -1 or departs significantly from this value.

The definite integral of the relation of Equation 7 in the range Re_{min} to Re_{max} was found from the relation:

$$\int_{\mathrm{Re}_{min}}^{\mathrm{Re}_{max}} a\mathrm{Re}^{-b} = a\left(\frac{\mathrm{Re}_{min}{}^{1-b}}{-1+b} - \frac{\mathrm{Re}_{max}{}^{1-b}}{-1+b}\right) \qquad (9)$$

The form of the meniscus and flow beneath it

In order to understand the form and dimensions of the meniscus, several detailed cross-sections of curving menisci near litter particles were mapped in greater detail. To achieve a regular form, small wooden blocks with square cross-sections of 6 mm × 6 mm and 47 mm in length were used as standardized ‘litter’ particles. These were placed on the sand board (both singly and in groups) in a steady discharge and the menisci mapped by recording water depth every 2·8 mm along 56 mm traverses of the gantry spanning the obstacle. The height of meniscus draw-up was then determined from the difference between mean water level beyond the meniscus and the highest point of contact between water and the obstacle. Likewise, the width of the curving meniscus was identified by visually estimating the distance at which the water surface elevation fell to the average open-water value (refer to Figure 3).

To determine flow speeds through menisci, dye timing was used. The wooden blocks just mentioned were set out in two end-to-end columns, 8 mm apart, and running 50 cm down the flow board. This was done to make a meniscus sufficiently long that dye timing could be carried out. Fluorescein dye was then injected into the flow above the narrow channel so formed, as well as on the open board to either side, and dye arrivals timed with a stopwatch over the 50 cm path, using anticipation to minimize reaction time delays as the dye cloud approached the start and end position. Ten replicate measurements were made of flow within the confined menisci between the two columns of wooden blocks and in the open flow beyond. Since prior work has shown that there is no reliable way to derive mean flow speeds from the surface speeds indicated by dye arrival (Dunkerley, in press), the speeds are compared unadjusted below and taken as indicative of the relative values of the mean speeds in open flow and beneath a meniscus.

RESULTS

Flow characteristics and surface tension

All flows were laminar and subcritical, with mean depths in the range 1·24–2·83 mm. The shallowest flow recorded was 0·14 mm and the deepest 3·41 mm (Tables II and III summarize results for water and surfactant tests).

Friction coefficients reached values of 10–12 in the shallowest flows, falling to <3 in the deepest.

There was almost no motion of the litter particles on the flow board, only five small leaf fragments being caught in a strainer positioned at the outlet of the runoff collecting gutter from the >50 experimental runs.

All f–Re relations (Moody plots) were linear and negatively sloping, and yielded statistically significant power function relationships (Figure 2). Reporting of the derived friction coefficients is preceded by a brief account of the form of menisci mapped in detail, and of flow speeds through menisci.

Table II. Summary of flow conditions for surfactant experiments

Discharge (cm^3 s^{-1})	Mean flow depth, D (mm)	Mean flow speed, V (cm s^{-1})	Mean flow Reynolds number, Re	Mean Froude number, F	Mean Darcy–Weisbach f
10	1·32	1·53	81·3	0·135	9·23
20	1·72	2·34	162·1	0·181	5·13
30	2·13	2·83	244·0	0·179	4·36
40	2·50	3·22	325·4	0·207	3·97
50	2·75	3·66	407·1	0·223	3·37

Table III. Summary of flow conditions for water experiments

Discharge (cm^3 s^{-1})	Mean flow depth, D (mm)	Mean flow speed, V (cm s^{-1})	Mean flow Reynolds number, Re	Mean Froude number, F	Mean Darcy–Weisbach f
10	1·33	1·51	78·7	0·132	9·62
20	1·69	2·37	159·3	0·184	4·96
30	2·03	2·96	240·2	0·209	3·83
40	2·33	3·44	319·3	0·223	3·23
50	2·54	3·93	399·8	0·249	2·71

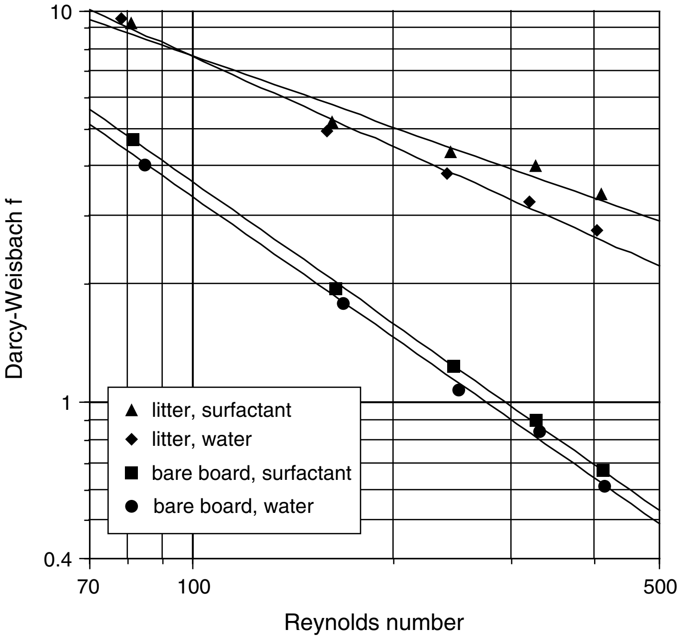

Figure 2. Moody plots for the bare sand board and for the litter experiments. Both water and surfactant results are shown. All plotted points represent means of five replicates of each of the five flow rates shown on the diagram

In initial water tests, surface tension was 0·072 N m^{-1}. However, some surfactant contamination of the pumping system was caused by preliminary surfactant trials, and this proved difficult to eradicate. Thus, during the plain water tests, the surface tension was slightly depressed, with a mean of 0·06 N m^{-1} (standard deviation (s.d.) 0·005 N m^{-1}, $n = 16$). With surfactant added, surface tension fell initially to 0·03 N m^{-1} but some increase occurred as a foam developed in the reservoir from which water was recirculated, so that the mean value during the surfactant tests was 0·037 N m^{-1} (s.d. 0·003 N m^{-1}, $n = 10$). Thus the mean surface tension reduction was about 40 per cent.

Water temperatures varied only slightly about a mean of 20 C, and consequently viscosity remained comparable among replicate tests.

The meniscus: detailed form and flow speed measurements

The closely mapped menisci around the small wooden blocks (using water without surfactant) showed that meniscus draw-up averaged 2·9 mm, and that the water surface was elevated across a zone 7·3–9·9 mm wide flanking the edges of the obstacle. Tests in which two wooden obstacles were more closely spaced than the width of a fully developed meniscus (i.e. less than about 7 mm apart) showed that as a result of the smaller radius of curvature exhibited by the constrained meniscus, the water surface was held at a higher elevation between the obstacles than in the open water beyond their outer edges (see Figure 3). This is analogous to the greater capillary rise observed in tubing of smaller inside diameter. In this way, the water depth is increased between litter particles which lie sufficiently close together that meniscus radius of curvature is lessened. The importance of this result is indicated later.

Replicate meniscus profiles taken with surfactant confirmed the expectation that the width of the meniscus and the height of the meniscus are both diminished when surface tension is lowered. According to the results of Figure 3, the maximum meniscus rise was reduced by about 0·5 mm in surfactant tests, and the width of the meniscus reduced by 2–4 mm.

The dye timing tests showed clearly that flows were faster in the deeper water contained under menisci. As a dye cloud arrived at the upstream end of the narrow wooden channel described previously, streams accelerated along the menisci on the outside edges of the two columns, as well as along the channel itself. Downslope, these exited from the menisci well ahead of the main dye cloud that travelled outside of the zone of menisci. In addition, the dye was flushed from the menisci more rapidly. The dye arrival timing showed that the mean surface flow speed was 10·4 cm s^{-1} (s.d. 0·95 cm s^{-1}) through the menisci but only 7·3 cm s^{-1} (s. d. 1·1 cm s^{-1}) in the open flow. In the menisci the surface flow was about 42 per cent faster than flow on the open board. By small-sample t-test (Freund, 1974), the difference in mean speeds is significant at the level $\alpha = 0{\cdot}005$.

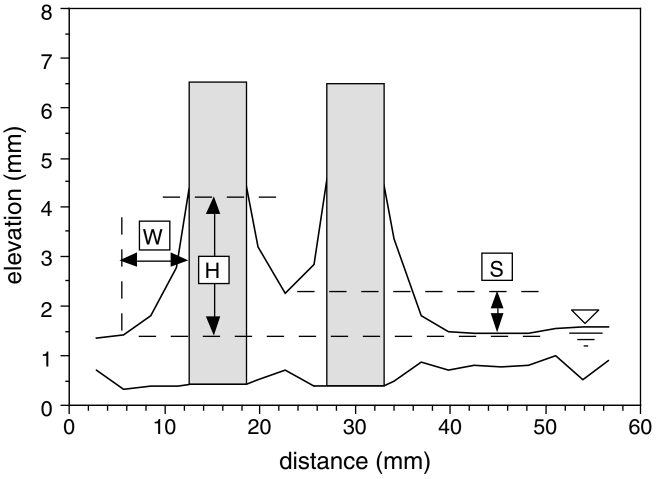

Figure 3. Detailed profile of a meniscus developed in water along the margins of two small wooden blocks (shaded). The bed and water surface profiles are each based on 20 measured elevations evenly spaced. The width and height of the left-hand meniscus are indicated by W and H respectively. The zone between the two blocks is narrower than would allow the full development of two menisci, and the super-elevation of the water surface there is indicated by the S on the right-hand side of the diagram. Note that vertical exaggeration is 5·3×

Flow depths and their variability in litter tests

Mean depths were greater in surfactant runs than in water, with the exception of the lowest flow rate (10 cm^3 s^{-1}), where the difference was smaller than the resolution of the measurement system, and could thus not be quantified. The difference in depth increased steadily with discharge, reaching 0·21 mm (8·1 per cent) at 50 cm^3 s^{-1}, the largest imposed flow (Tables IV and V). By small-sample t-test, differences in mean depth between water and surfactant were statistically significant at $\alpha = 0{\cdot}01$ or better at the three highest imposed flow rates, but not significantly different at the lower two.

Maximum depths, in contrast, were always greater in water runs than with surfactant, and minimum depths lower. That is, water runs exhibited a wider range in flow depths in comparison with the relative uniformity of depths in surfactant runs. Clearly, therefore, the *distribution* of depths differed between water and surfactant runs (Figure 4).

Statistical analyses of the distributions of the 55–60 measured depths in each run (some of the 64 observation points occupied by litter particles were not included in these calculations) confirmed this. Surfactant runs all exhibited a smaller standard deviation in flow depths, reduced positive skewness and reduced kurtosis (the distributions were less leptokurtic). The standard deviation of depths was 12·5 per cent lower in surfactant than water at 10 cm^3 s^{-1}, the difference rising steadily to 18·7 per cent lower at 50 cm^3 s^{-1}. Moreover, in the same sequence the maximum depth difference diminishes from 16·0 per cent shallower in surfactant at 10 cm^3 s^{-1} to only 8·9 per cent shallower at 50 cm^3 s^{-1}. Finally, in water the mean slope of the d–Q relation is 0·0307, whilst in surfactant it rises to 0·0364. By small-sample t-test, this difference is significant at $\alpha = 0{\cdot}005$.

Flow speeds

For each imposed discharge, mean flow speeds were greater in water than surfactant, though the difference was small (1·5 per cent) at the lowest imposed flow rate. The differences were statistically significant (small-sample t-test) at $\alpha = 0{\cdot}01$ or better for the three highest flow rates but not for the lower two. The difference rose steadily and at 50 cm^3 s^{-1}, the mean flow speed in water was 6·8 per cent higher than in the surfactant trials (Tables I and II). In both liquids, mean flow speed was related to discharge by a statistically significant

Table IV. Parameters of the distribution of flow depths in surfactant experiments. These data were derived from the pooled data of the five replicate experiments for each flow rate

Discharge (cm^3 s^{-1})	Mean flow depth, D (mm)	Standard deviation of depths (mm)	Number of observations	Minimum depth (mm)	Maximum depth (mm)	Skewness	Kurtosis
10	1·32	0·45	269	0·135	3·310	1·218	2·399
20	1·72	0·43	269	0·535	3·310	1·064	1·670
30	2·13	0·41	269	0·835	3·560	0·690	1·011
40	2·50	0·42	269	1·060	3·810	0·450	0·766
50	2·75	0·41	269	1·285	4·060	0·459	0·856

Table V. Parameters of the distribution of flow depths in water experiments. These data were derived from the pooled data of the five replicate experiments for each flow rate

Discharge (cm^3 s^{-1})	Mean flow depth, D (mm)	Standard deviation of depths (mm)	Number of observations	Minimum depth (mm)	Maximum depth (mm)	Skewness	Kurtosis
10	1·33	0·51	284	0·185	3·410	1·225	2·483
20	1·69	0·49	284	0·610	3·785	1·141	2·371
30	2·03	0·48	284	0·835	4·035	0·951	1·969
40	2·33	0·49	284	1·035	4·260	0·879	1·716
50	2·54	0·49	284	1·160	4·410	0·873	1·772

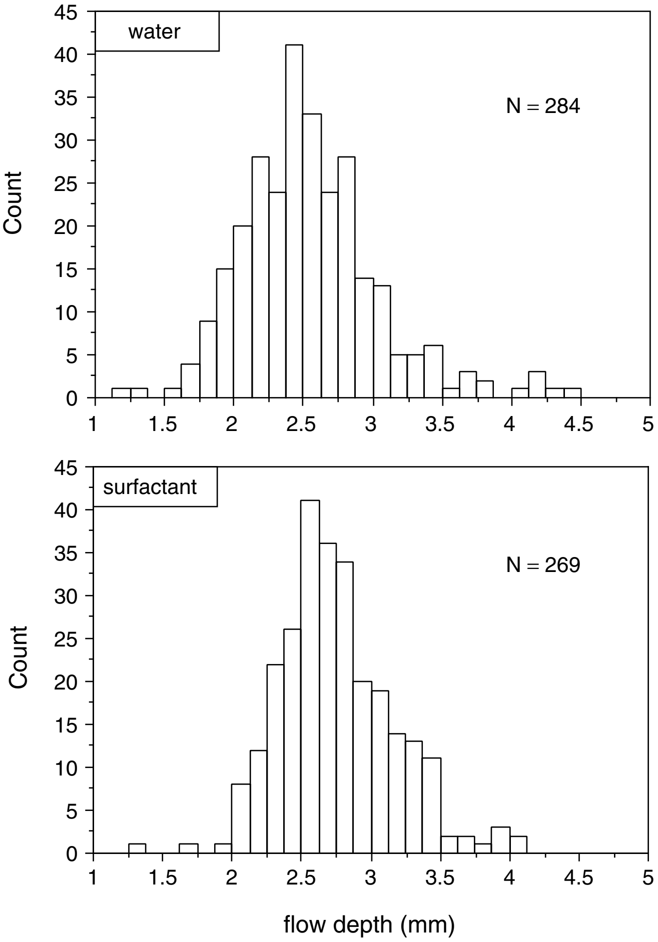

Figure 4. Pooled frequency distributions of flow depth for the five replicate water and five replicate surfactant experiments at a flow rate of 50 cm^3 s^{-1}. Note the greater frequency of depths less than about 1·25 mm in the water data, and the greater frequency of depths greater than about 2·5 mm in the surfactant data

power function regression, and these relationships confirmed that mean flow speed increased more slowly with discharge in surfactant runs than in water runs.

Friction coefficients in litter tests

All tests with surfactant exhibited higher friction coefficients. For example, the mean f for the five replicate water runs at 30 cm^3 s^{-1} was 3·8 but increased to 4·4 in the surfactant runs, an increase of 15·8 per cent. The differences were statistically significant at $\alpha = 0{\cdot}01$ or better for the three highest flow rates but not for the lower two. Likewise, the mean integral of the f–Re function (Equation 9) for these same replicates increased from 1866 in water to 2041 with surfactant (a 9·4 per cent increase). In the lowest imposed flows (10 cm^3 s^{-1}), the value of f was very similar in water and surfactant runs, but the difference widened with increasing flow rate, to reach 24·5 per cent (higher in surfactant than in water) at 50 cm^3 s^{-1}.

In the litter tests, the slope of the f–Re relation also differed between water and surfactant runs. For water the overall mean slope was −0·77, while for surfactant it was only −0·59 (a 22 per cent reduction). Neither slope is close to the smooth-surface laminar flow value of −1·0. The slopes are statistically different, as well as statistically different from −1, at $\alpha = 0{\cdot}005$. The lower slope in the surfactant runs signifies a reduced dependence of f on Re under these conditions.

Flow on the sand board without litter

An increase in flow retardation in surfactant tests is noted even for the bare sand board (Figure 2). Here, the f–Re integral rises from 683 in water to 749 with surfactant (a 9·7 per cent increase). A part of this increases probably attributable to a more even distribution of flow across the board because of the better wetting. (Small areas where some of the varnish used to attach the sand coating to the board surface was exposed proved resistant to wetting in the water tests, with the development of slight meniscus curvature of the water surface. This was absent in surfactant runs, with slightly increased mean depth). In addition, curvature of the water surface as it traversed the slightly irregular surface of the sand board, with related surface tension effects, would also have been reduced in surfactant runs. Though the sand board was essentially planar, the hand-application of sand resulted in a slight unevenness in the surface, and this is reflected in the range of depths (typically 0·5–2·0 mm) exhibited even by 'uniform' flows on the sand board.

Despite differing in friction coefficient, both water and surfactant runs on the sand board without litter yielded f–Re slopes steeper than the litter tests. The mean slope was $-1{\cdot}173$, which differs statistically from $-1{\cdot}0$ at $\alpha = 0{\cdot}005$, as might be anticipated for a rough granular surface.

DISCUSSION

The preceding results confirm that flow depths near litter particles are modified by surface tension phenomena. When surface tension was lowered with surfactant, *mean* flow depths were increased by a fraction that rose with imposed discharge, while *maximum* depths fell and *minimum* depths rose. Overall, surfactant flows were deeper and of more uniform depth. Furthermore, mean depths rose less rapidly with discharge in water tests than with surfactant because a fraction of the imposed flow travelled within the deeper menisci, leaving a diminished remainder to raise depths over the broad surface of the sand board. This effect is partly the result of the lowered frictional drag experienced by flow within the deeper water menisci, which reduces the mean flow depth associated with a given imposed flow rate. This explains the increasing difference in mean depths between water and surfactant at higher discharges, since in the surfactant runs less water was drawn into deep, narrow menisci so that more of the additional imposed flow was distributed evenly across the board surface, experiencing a proportionally greater frictional retardation there than within the menisci.

Correspondingly, *mean* flow speeds were lower in surfactant runs than water runs of the same imposed discharge, because the deep areas associated with menisci were reduced in height and width by the surfactant. Mean flow speeds in water were 0·27 cm s^{-1} (about 7 per cent) faster than in surfactant for $Q = 50$ cm^3 s^{-1}. However, it is important to recall that the relatively deep flows within menisci and the somewhat shallower ones on open parts of the board mean that flow speeds are locally variable (as shown in the dye timing tests). Using mean values for the flow as a whole conceals this important variability.

In surfactant tests, the increasing mean depth combined with reduced flow speeds as just described results in a proportional increase in f, as a result of the V^2 term in the denominator of Equation 4. For example, consider the mean depth and velocity data, together with the computed f values, for $Q = 30$ cm^3 s^{-1}. Under these conditions, the mean depth was increased by 5 per cent in the surfactant runs, and mean speed reduced by 4·3 per cent. From Equation 4, this should result in a 14·6 per cent increase in f. In fact, the mean of the measured values rose by 13·8 per cent, very close to this expected value.

The role of deeper flow within menisci

It is apparent that the surface tension draw-up around the periphery of a litter particle does not restrict the motion of the water beneath the surface tension film, but enhances it. (It was noted earlier that the surface tension 'skin' is only a few molecules in thickness, so that the bulk of the water contained beneath a meniscus can move freely.)

By analogy, during shallow interrill runoff under similar conditions in the landscape to those tested here on the sand board, surface tension effects are indeed one influence on the value of f, and they act to increase depths and speeds around the margins of litter particles, and presumably other wettable obstacles including stems and surface stones, so reducing the aggregate value of f. The effect of litter documented here may in part depend upon the particles being numerous and not too widely spaced on the surface, so that to some extent the flow can partly travel by moving from one meniscus into an adjacent one downslope. This issue of meniscus connectivity in relation to litter cover fraction will be explored in later work. It may provide one reason why slightly different values of f were obtained in the replicate experiments made here, in which there were identical litter particles present, but distributed differently across the board in each test.

The key conclusion to be drawn from this is that the larger roughness contributed by litter (and noted previously by Dunne and Dietrich (1980) and Dunkerley *et al.* 2001) cannot be explained by the frictional retardation of water along the extensive wetted surfaces. Were this the case, then the addition of surfactant should have reduced flow retardation, whilst in fact this increased flow retardation. Consequently, other mechanisms must be sought to account for the greater drag arising from litter.

However, in the case of taller protruding obstacles where some of the meniscus volume lies well above the general water surface elevation, free passage of flow beneath the meniscus would be restricted. It is likely that this would be the case with some of the menisci drawn up along the surfaces of blades of an erect grass, for example. As mentioned earlier, in tests with wooden pegs suspended *above* the water surface and lowered to contact it, Turner *et al.* (1978) did record an increase in friction coefficient attributable to meniscus formation. This is perhaps not surprising since isolated menisci were drawn up above the general level of the flow. In this configuration, it would not be possible for flow to pass speedily through the menisci.

The presence of flow speeds 40 per cent faster in menisci than in open water has potential significance for mechanisms of sediment transport. In experiments with simulated straw mulch (made of fibreglass) and erodible soil, Kramer and Meyer (1969) found increased soil loss under certain mulch loadings, and especially for certain soil particle size ranges. They concluded that the mulch must in some way have increased flow velocities across the surface. The present results provide an understanding of how this can arise, deeper meniscus flow being a possible explanation. It is also possible that deflection of flow by the litter particles is involved. Additionally, it is conceivable that under certain conditions, local patches of turbulence are caused by litter particles, and that these patches are related to local scour of the kind described by Poesen *et al.* (1994) from turbulent flow. Indeed, in soils that exhibit very low thresholds of shear for grain entrainment, it may be that eddies arising within laminar flow may act in this way. Much remains to be learned about the detailed processes by which such flows interact with deformable surfaces.

The slope of the f–Re relation in litter tests

Consider now the differing f–Re slopes found in water and surfactant runs. The mean slope was about 23 per cent lower in surfactant (−0·59) than water (−0·77), and both were far from the smooth-surface value of −1. A departure from −1 is to be expected, since on a smooth surface relative roughness falls steadily with rising discharge because no major sources of drag contribute roughness apart from the declining boundary friction. However, where there are protruding obstacles, increasing obstacle drag can arise. If the wetted upslope projected area of obstacles increases with flow rate, for example, this may serve to slow the decline in f with rising discharge.

An examination of all of the Moody plots for the water and surfactant tests indicated that the value of f for the lowest imposed discharge (10 $\mathrm{cm}^3\ \mathrm{s}^{-1}$) frequently lay above the regression trend suggested by the four higher discharges. The relatively high f value in the shallow flows thus tended to increase the slope of the fitted power function model. In many cases, if the data point for 10 $\mathrm{cm}^3\ \mathrm{s}^{-1}$ is excluded from the regression model, the f–Re slope declines by about a further 0·1. The reason for the proportionally higher f value in the lowest flows is not clear. However, the tests were run by first establishing the lowest discharge on the sand board, and then distributing the litter across it. When placing litter particles, it was often noticed that the immediate draw-up of menisci around a particle caused the surrounding flow to become shallower, and in the shallowest flows, this undoubtedly increased the frictional retardation arising from the grain roughness of the sand board surface. Indeed, the grain roughness of the sand board may not have been fully inundated at the lowest flow rate. At higher flows, the increase in relative roughness arising from this effect would not have been so great, as the lowering of depth by meniscus draw-up would have been a smaller proportion of the total flow depth. However, the statistically significant difference in mean f–Re slopes for water and surfactant tests means that in some way, when litter is present, surface tension is systematically involved in setting the slope of this relation.

The shifts in the pattern of water depths related to meniscus development alter the statistical distribution of water depths and hence the pattern of local frictional flow retardation across the surface. The skewness and kurtosis of the distribution of depths both declined with increasing imposed discharge in water and surfactant runs. Both parameters were consistently lower in surfactant tests, and declined more rapidly with rising imposed discharge. Here then are additional parameters of the distribution of flow depths for which the difference between water and surfactant changes with imposed discharge, just as the mean depths themselves do. Apportioning the higher mean depth (and altered depth distributions) in surfactant runs among the contributing factors cannot yet be achieved. Certainly, the meniscus draw-up and related depth decline beyond the meniscus already referred to provides one factor. But in addition, the changing distribution of depths must alter the form drag arising on the wetted parts of the litter particles. Much remains to be investigated in this behaviour. The tests with wooden pegs and water suggested that, when menisci overlapped, the depth increase was greater than in a single meniscus. This effect was greatly diminished in surfactant tests with the same wooden pegs. Thus, much of the draw-up of water into menisci may arise in those areas where litter particles are sufficiently closely spaced that menisci overlap and surface curvature is increased.

The trends in mean depth reflect changing distributions of flow depth as Q increases. Water flows always have deeper maximum depths and shallower minimum depths. These results are taken to reflect meniscus draw-up (accounting for the deeper maxima in water) and the corresponding reduction in depth elsewhere (accounting for the shallower minima in water). As a result of this behaviour, water flows exhibit more variable flow depths across the sand board. Since the litter covered only about 20 per cent of the flow board, the area where menisci deepened flow depth was exceeded by the fraction where depths were reduced, so that *mean* depths were reduced. Necessarily, mean flow speeds thus were greater in water flows, and the derived f lower.

In surfactant, both the deepening within menisci and the related shallowing elsewhere were diminished. Thus, mean depths remained greater than in water, flow speeds less, and the derived f higher.

CONCLUSIONS

The primary conclusion derived from the present experiments is that, under the conditions tested, the extensive surface tension menisci flanking partially submerged litter particles (and perhaps stems and surface stones likewise) tend to reduce friction coefficients. This eliminates surface tension as a direct cause of the greater drag reported in shallow flows through litter of the kind studied here, and requires that other explanations be sought.

An important finding is that the menisci associated with litter are responsible for increased variability in flow depths. The development of menisci along the margins of litter particles was shown to simultaneously reduce minimum depths and increase maxima. Meniscus draw-up may give rise to shallower flows over the surfaces between the litter particles, and so increase flow roughness there. The deeper flow within menisci was shown by dye arrival timing to be associated with surface speeds >40 per cent faster than those in the open flow. Thus, whilst the mean flow speeds reported earlier are accurate, they conceal considerable local variation across the surface. The net consequences for frictional retardation of the flow are complex, since menisci may generate faster flow beneath the surface tension film, whilst at the same time causing reduced flow speeds in the spaces between litter particles. Much remains to be discovered about these mechanisms. In relation to sediment erosion and delivery studies made at the scale of a small runoff plot, it appears to be necessary to resolve the magnitude of these speed variations and to discover how they are associated with patchy sediment entrainment and transport, and with the elevated soil loss found by Kramer and Meyer (1969). Menisci may act as sediment transport corridors enhancing conveyance as well as providing locations for deeper and faster flow with the consequences for friction coefficients shown above.

In summary, important influences on local and on mean flow properties can arise from surface tension effects around litter particles in shallow, laminar interrill flows. The spatial arrangement of the litter appears to be important, involving the connectedness of menisci as a key factor. Further exploration of the role of particle spacing in affecting connectedness of flow paths may enhance our ability to interpret both shallow flow hydraulics and sediment motion in the presence of litter and crop mulches.

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