

ORGANIC LITTER: DOMINANCE OVER STONES AS A SOURCE OF INTERRILL FLOW ROUGHNESS ON LOW-GRADIENT DESERT SLOPES AT FOWLERS GAP, ARID WESTERN NSW, AUSTRALIA

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ABSTRACT

Thirty-six runoff plot experiments provide data on flow depths, speeds, and Darcy–Weisbach friction coefficients (f) on bare soil surfaces, and surfaces to which were added sufficient extra plant litter or surface stones to provide projected cover of 5, 10 and 20 per cent. Precision flow depth data were derived with a computer-controlled gantry and needle gauge for two different discharges for each plot treatment.

Taking a fixed flow intensity (Reynolds number, $Re = 150$) for purposes of comparison shows means of $f = 17.7$ for bare soil surfaces, $f = 11.4$ for added stone treatments, and $f = 23.8$ for added litter treatments. Many individual values of f for stone treatments are lower than for the bare soil surface, but all litter treatments show increases in f compared to bare soil.

The lowering of f in stone treatments relates to the submerged volume that the stones occupied, and the associated concentration of flow onto a smaller part of the plot surface. This leads to locally higher flow intensities and lower frictional drag along threads of flow that the obstacles create.

Litter causes higher frictional drag because the particles are smaller, and, for the same cover fraction, are 100 times more numerous and provide 20 times the edge or perimeter length. Along these edges, which in total exceed 2.5 m g^{-1} (equivalent to 500 m m^{-2} for a loading of 2 t ha^{-1}), surface tension draws up water from between the litter particles. This reduces flow depth there, and as a consequence of the lower flow intensity, frictional drag rises. Furthermore, no clear passage remains for the establishment of flow threads.

These findings apply to shallow interrill flows in which litter is largely immobile. The key new result from these experiments is that under these conditions, a 20 per cent cover of organic litter can generate interrill frictional retardation that exceeds by nearly 41 per cent that of a bare soil surface, and twice that contributed by the same cover fraction of surface stones. Even greater dominance by litter can be anticipated at the many dryland sites where litter covers exceed those tested here. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: interrill roughness; plant litter; surface stones; Darcy–Weisbach f ; Fowlers Gap Australia

INTRODUCTION

Infiltration-excess overland flows provide an important link between slopes and stream channels in desert and semi-desert areas (drylands). The speed and the competence of these flows influence the amounts of soil and other materials transported from interrill areas. The conditions governing their properties must be resolved for management-oriented modelling of water erosion, human impact, and vegetation change in dry croplands and rangelands (Bryan, 2000). Much work in this direction has been conducted in support of modelling programs including WEPP (Water Erosion Prediction Project), KINEROS2 and EUROSEM (Weltz *et al.*, 1992; Smith *et al.*, 1995; Morgan *et al.*, 1998).

Studies of crop residues such as straw fragments have shown that these materials can protect soils from water erosion (Kramer and Meyer, 1969), as well as affecting interception losses, soil moisture retention, and other factors (e.g. Ji and Unger, 2001). Gilley and Kottwitz (1995) used flume experiments to study the roughness coefficients arising from combinations of crop residues (stem fragments) derived from corn,

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wheat and sunflower. The fragments were much larger than most dryland litter particles, typically being up to 25–40 cm in length, and up to 2.5 cm in diameter, and were glued to the flume bed orthogonally to the flow direction. Gilley and Kottwitz (1995) were able to demonstrate a decline in the Darcy–Weisbach friction coefficient f as flow Reynolds number increased. Furthermore, obstacle volume was found to be a significant determinant of roughness and a predictor of how different sources of roughness (such as mixtures of crop residues) might combine to yield an aggregate roughness coefficient that was not necessarily the sum of the roughness expected from each component of the surface treatment.

In comparison, the part played by smaller leaf, flower, and other dryland plant litter in affecting the properties (depth, speed, friction coefficient) of shallow interrill overland flows is not well known. Studies of dryland environments have shown that as a result of substantial litterfall (e.g. 3.43 t ha⁻¹ a⁻¹ for a site in the Sonoran Desert; Búrquez *et al.*, 1999) litter may cover 20–75 per cent of the soil surface. Whilst some dryland litter particles are readily moved by airsplash (Geddes and Dunkerley, 1999), larger litter particles such as twigs may well exhibit low mobility in shallow flows on low-gradient surfaces (<2°), and so act as obstacles to flow in the same way as highlighted by Gilley and Kottwitz (1995) for larger crop residue fragments.

Laboratory experiments on a glued-sand board (Dunkerley *et al.*, 2001) suggested that small particles of organic litter distributed across a surface carrying laminar flow contribute greater frictional drag per unit cover fraction than do large stone-like obstacles. In these experiments, a litter loading of 2 t ha⁻¹ (about 20 per cent areal cover) resulted in a Darcy–Weisbach friction coefficient (see Equation 5 below) of less than 8. However, the experiments of Dunkerley *et al.* (2001) were conducted on a planar surface. In natural drylands, surface microtopography is always present (though often subtle), and this steers some filaments of flow through preferred pathways in low-lying parts of the surface, leaving higher points with only a shallower flow. Also, in the presence of microtopography, some pathways by which flow filaments might move laterally around a clump of litter particles on the planar flume of Dunkerley *et al.* (2001) would not be available owing to local high points in the microtopography along those pathways. In consequence, flow paths may be more sinuous, and associated with larger friction coefficients, on a natural surface than in a laboratory flume. In the case of field trials, infiltration along the runoff path provides an additional factor that might perturb flow depths and friction coefficients, in comparison with the impermeable flume used by Dunkerley *et al.* (2001). The significance of plot-scale variations in infiltration related to the steering of flow by microtopography has been demonstrated by Esteves *et al.* (2000).

This study therefore set out to use field experiments to address three main goals.

1. To derive values for f for low-gradient, litter-bearing dryland surfaces in the Australian arid zone. These data would provide empirical data on the magnitude of f in low-gradient drylands, to augment the limited existing knowledge base.
2. To compare the values for f derived on real microtopography with those derived by Dunkerley *et al.* (2001) on a planar flume. Results from this goal were sought to evaluate the importance of microtopographic steering of preferred flow pathways, and to assess the divergence in estimates of f from laboratory experiments with organic litter and from *in situ* testing in the landscape.
3. To evaluate the relative importance of organic litter and of large inorganic obstacles (surface stones) in generating frictional retardation of shallow overland flows on a low-gradient surface in the Australian arid zone. The purpose of this work is to provide further evidence to be used in ranking the roles of organic and inorganic surface features in influencing shallow overland flows. Such data provide an aid to the field assessment of pertinent site characteristics and to the parameterization of them for incorporation in runoff and erosional models of the kind cited earlier.

THE FIELD AREA AND RESEARCH METHODS

Thirty-six runoff plot experiments were carried out at the Fowlers Gap Arid Zone Research Station, located 110 km north of the city of Broken Hill, in arid western New South Wales, Australia. In this area, low-gradient chenopod shrublands commonly take the form of mosaics composed of relatively well-vegetated patches separated by unvegetated, generally stone-covered, zones (Dunkerley and Brown, 1995). The plots

measured 2 m long and 1 m wide and were located in shrub interspaces in one well-vegetated patch on a surface sloping at about 1°. They were underlain by aridisols that are texturally sandy loams (means of textural analyses by wet sieving of sands and gravels and sedimentation analysis of fines were gravel 14.2 per cent, sand, 56.3 per cent, silt 26.4 per cent, and clay 3.1 per cent). The plots were only 5 m apart, and presented identical surface appearance, being essentially free of vascular plants but carrying a crust formed by cyanobacteria, and scattered small quartz stones, and one or a few very small (<10 cm tall) chenopod shrub seedlings. Each of the three runoff plots was used to carry out 12 different experiments in which the plot surface conditions were manipulated in order to vary the litter or surface stone cover, using materials obtained from the surrounding landscape. The plots were used repeatedly (after suitable drying time described later) in order to eliminate the variability in microtopography, surface permeability, gradient and other properties that would have been introduced had 36 different plots been used. This left the surface treatment as the main variable affecting flow properties among the repeat runoff tests, so facilitating subsequent data analysis. Experiments were nevertheless conducted on three plots in order to ensure that the results were repeatable, and to avoid the possibility of conducting all work on a single unrepresentative test plot (such as the site of a former chenopod shrub root system or termite gallery network).

Each plot was first studied bare, and then following the addition of 5 per cent, 10 per cent and 20 per cent surface cover of surface stones collected from nearby natural surface stone populations. The same stones were used on each plot (being collected at the end of each experiment and reused), and the three axes of 100 of them selected at random were measured to the nearest 1 mm in order to characterize their dimensions. Finally, after removal of the stones, each plot was tested following the addition of 1 t ha⁻¹ and then 2 t ha⁻¹ of plant litter. Pre-weighed air-dry litter was sprinkled on by hand to give an even distribution over the whole plot. The litter, collected nearby, consisted of leaves and flower parts together with small twig pieces and a small amount of animal dung. Several 1 g samples were spread onto graph paper, photographed and the image analysed to determine particle dimensions in the separate categories of leaf, twig, and flower/seed/bark fragments. Similar litter samples were used for the determination of litter volume per gram and litter density, by volumetric displacement tests in small graduated measuring cylinders. In these tests, a wetting agent was added to the water to ensure that air bubbles were not held among the spiny litter particles, potentially causing an under-estimation of density.

Water was fed onto the top of each plot from a perforated pipe that had 20 outlet holes drilled at equal distances along its length. For each surface condition, two different water discharges were used, yielding 12 test conditions for each plot. No simulated rain was applied, in order to eliminate confounding intensity and drop size effects, and the variations in intensity that would have arisen among the replicate tests because of the disturbing effects of wind and pump pressure. Though many studies suggest that the additional retardation of flow that results from drop impact is relatively small (Shen and Li, 1973; Savat, 1977; Katz *et al.*, 1995), the values of f derived here will be lower than would have been determined in the presence of raindrops. The simplification achieved by neglecting drop impact at this stage is considered worthwhile, not least because the primary goal was to rank the retardation arising from litter and from stones.

At the toe of each plot, runoff caught in a gutter was directed to a pit where volumetric gauging was carried out every few minutes. The feed rate to the top of the plot was similarly gauged volumetrically. The 15 cm tall plot side walls were of sheet steel, hammered into the soil to a depth of about 4 cm.

A computer-controlled measuring gantry (Dunkerley *et al.*, 2001) was set up above the plot. This had stainless steel tracks on which a rolling carriage was moved by stepper motors to an orthogonal grid of 64 points set out to cover the central 1 m² of the plot, leaving a 0.5 m long buffer at the top and bottom of the plot where no measurements were made. A motorized needle gauge with a resolution of 25 µm was mounted on the carriage and mapped soil surface and water surface elevations. Flow depths were found by subtraction. Mapping the 64 points required about 15 minutes, and flow was kept constant for this period. Owing to the needle-gauge measuring system, there was no disturbance of the shallow and slow-moving flows studied.

All plot treatments were photographed from above, for later calculation of the appropriate cover fraction by counting 225 nodes on an orthogonal graticule overlaid on the image. Water temperature was taken periodically to allow the determination of viscosity from the polynomial relationships provided in Weast (1979). Surface slope was determined on eight transects evenly spaced across the 1 m plot width from the elevations of

the soil surface mapped by the gantry, and a mean plot slope determined. 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. Variability in flow depths was assessed by calculating the standard deviation of the 64 measured water depths in each test, while mean flow rate for each test was taken as the mean of the plot inflow and outflow rates. This procedure is based on the assumption that infiltration losses along the 1 m flow path where depth measurements were made were spatially uniform. Mean flow velocities were calculated from the relation:

$$Q = \bar{w}\bar{d}\bar{u} \quad (1)$$

where Q is the volumetric flow rate (discharge) provided by a flow whose mean width, depth, and speed are \bar{w} , \bar{d} , and \bar{u} . Effective mean flow width, w' , was calculated by subtracting from the plot width of 1 m that fraction occupied by obstacle stones. This procedure is defensible since the stones used were typically bladed (see Results) and were able to be emplaced with their a–b planes resting on the soil surface. The unit discharge, q , was calculated from:

$$q = \frac{Q}{w'} \quad (2)$$

To characterize the flows, the following parameters are used. Flow Reynolds numbers (Re) were calculated from the relation:

$$\text{Re} = \frac{4\bar{u}\bar{d}}{\bar{\nu}} \quad (3)$$

The Froude number (F) was determined from:

$$F = \frac{\bar{u}}{\sqrt{g\bar{d}}} \quad (4)$$

To characterize retardation of flow, the Darcy–Weisbach relation:

$$f = \frac{8g\bar{d}S}{\bar{u}^2} \quad (5)$$

was employed, with S being the ground slope determined from the eight parallel elevation transects gathered by the gantry system for each plot.

Experiments were conducted in mid-summer, and maximum daily temperatures commonly reached 46 °C. The runoff plots were exposed to full sun and to gusty, hot winds, and the soil dried almost completely during the hours between tests. (A typical 20-minute test would have allowed only about 3–4 mm of water infiltration into these soils, and at least 3 hours, and commonly 12 hours, separated successive tests.)

RESULTS

General plot and experimental conditions

The mean slope of each plot was <1 (Table I). Contour maps of the three test sites show that microrelief amplitude reached nearly 20 mm (Figures 1, 2, and 3). Plot 1 had an elevated zone reaching 10 mm in height in the top centre of the mapped area, Plot 2 had quite an even slope to the lower left, while Plot 3 had a lower-lying zone along its left-hand side. These subtle features were not detected during plot installation,

Table I. Summary of key characteristics for the three experimental plots

Plot no.	Gradient (degree)	Microrelief amplitude (mm)	Surface roughness Ω (mm)	Mean infiltration rate (std dev) (mm h^{-1})
1	0.94	13.4	2.71	11.1 (4.08)
2	0.74	27.9	4.58	12.3 (4.01)
3	0.61	7.1	1.68	7.0 (2.57)

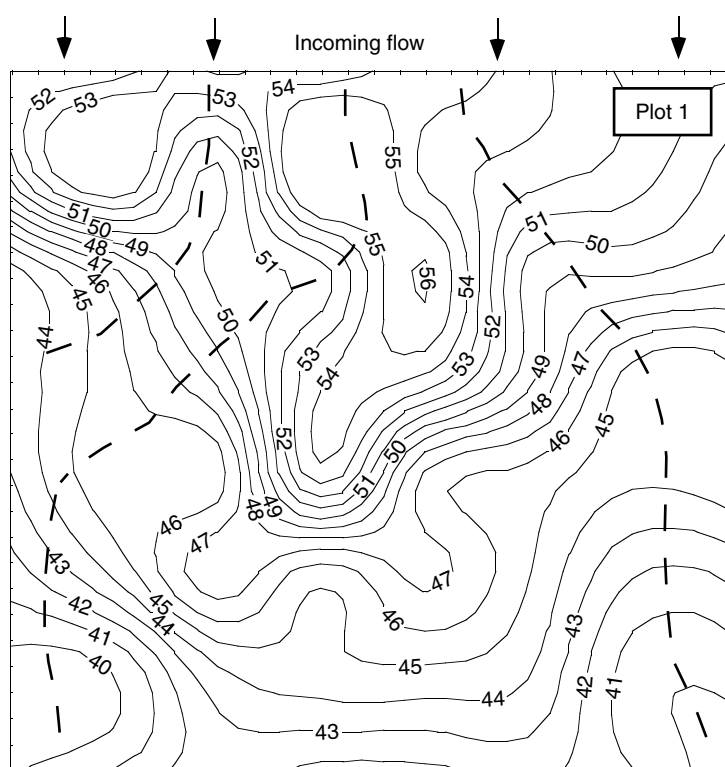


Figure 1. Contour map of the central part of plot 1 where flow depth data were collected. The area mapped is $800 \text{ mm} \times 800 \text{ mm}$ and the contour interval is 1 mm. Elevations are taken from an arbitrary datum located just downslope of the runoff plot. The locations of principal flow threads on the bare plot are indicated

and to the observer the experiment site appeared quite uniformly sloping and essentially planar. Plot surface roughness Ω was less than 5 mm (Table I).

Mean imposed discharges lay in the range $24\text{--}48 \text{ cm}^3 \text{ s}^{-1}$ (Table II) and mean flow depth was 2.45 mm, though the greatest depths recorded were 8–10 mm. All flows were laminar (mean Re was 177) and subcritical (mean F was 0.103). The individual test parameters from bare soil, litter and stone tests are set out in Tables III, IV and V. Water temperatures commonly exceeded 30 °C. The plot surfaces were completely inundated by the imposed flows, though the stones were always emergent. Dye tracing confirmed that there were deeper and faster flow threads along routes following microtopographic lows, with shallower and slower flow covering more elevated areas. The threads of flow were partially obstructed by the added stones and more so by the added litter. Apart from small displacements and some floating motion by very small particles, the added litter was not transported by the imposed flows, and remained substantially in place.

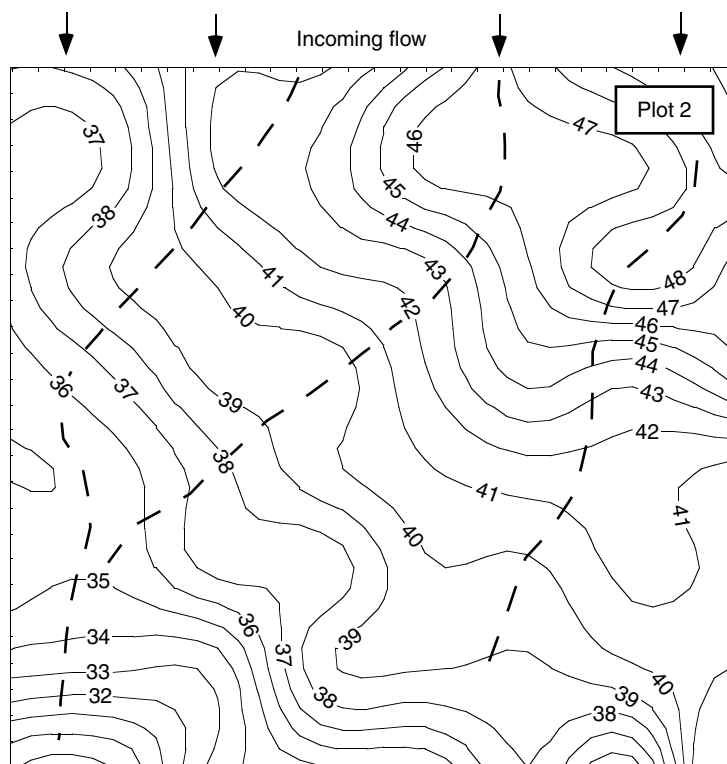


Figure 2. Contour map of the central part of plot 2 where flow depth data were collected. The area mapped is 800 mm \times 800 mm and the contour interval is 1 mm. Elevations are taken from an arbitrary datum located just downslope of the runoff plot. The locations of principal flow threads on the bare plot are indicated

Properties of the added stones and organic litter

The mean diameter of the stones added to the plots to create obstacle roughness was 32.4 mm (standard deviation 7.8 mm), the smallest being 18 mm and the largest 56 mm in diameter. Stones were bladed in shape, with an average maximum projection sphericity (Folk, 1968; value for a sphere 1.0) of 0.64. Mean long axis dimension was 2.25 times the mean short axis dimension. Stone cover was found to have been estimated well during the application of 5 per cent and 10 per cent covers, but underestimated for the 20 per cent covers, which were about 5 per cent too low. The litter covers resulting from the 1 t ha⁻¹ and 2 t ha⁻¹ loadings were almost on the targets of 10 per cent and 20 per cent respectively (the litter loadings were based on prior trials used to determine the required dry weights). Litter area and edge length per gram are striking (Table VI). Edge length in particular exceeds 2.5 m g⁻¹, so that in the 2 t ha⁻¹ treatments (or 200 g m⁻²), litter edge length amounted to >500 m m⁻². In a 1 g sample of litter, there were on average 106 particles, so that their mean weight was 9.4 mg. In the 2 t ha⁻¹ treatment, there were >21 000 litter particles per square metre, compared to 243 stones per square metre in the 20 per cent stone cover treatment. Taking the mean stone size of 32.4 mm diameter, the wetted edge length amounted to <25 m m⁻², or only 5 per cent of the edge length exhibited by the 2 t ha⁻¹ litter treatment.

Mean litter density when dry was found to be 0.22 g cm⁻³. Assuming that all of the 2 t ha⁻¹ (200 g m⁻²) litter treatment was fully submerged, this amounts to 909 cm³ occupied by the litter particles. In the mean flow depth of 2.8 mm, the plot carried 5600 cm³ of water and litter, so that about 16 per cent of the volume below the water surface was occupied by litter particles. This is close to the 20 per cent that would be anticipated on the basis of the projected cover fraction. Given that the 20 per cent stone cover was underestimated, and was actually about 15 per cent, the submerged volume of stones at the target 20 per cent cover was fortuitously

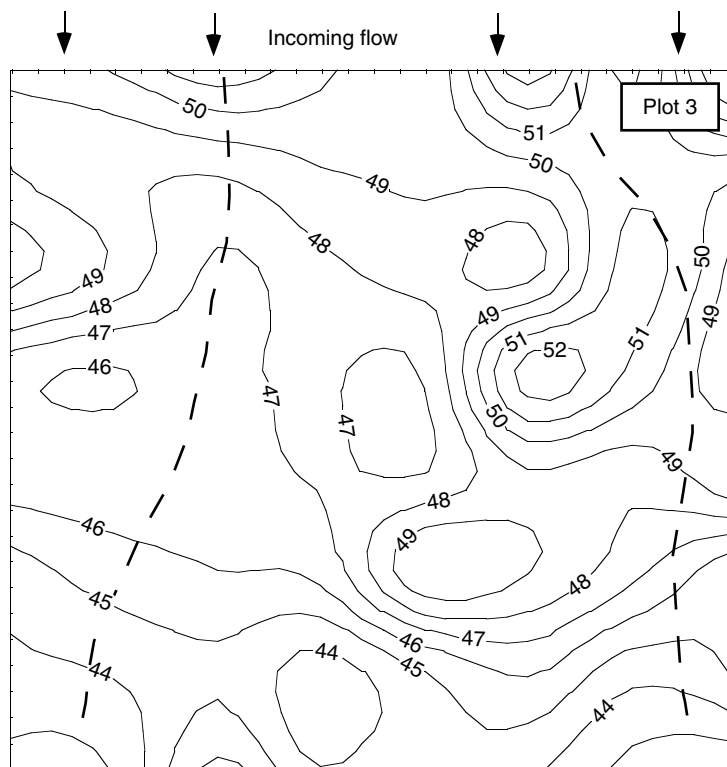


Figure 3. Contour map of the central part of plot 3 where flow depth data were collected. The area mapped is 800 mm × 800 mm and the contour interval is 1 mm. Elevations are taken from an arbitrary datum located just downslope of the runoff plot. The locations of principal flow threads on the bare plot are indicated

Table II. Summary flow hydraulic parameters across all surface treatments for plots 1–3

Plot no.	Range of imposed flows Q ($\text{cm}^3 \text{s}^{-1}$)	Range of Re (Equation 3) (dimensionless)	Range of F (Equation 4) (dimensionless)	Range of mean flow speeds (cm s^{-1})	Maximum flow depth (mm)
1	28.5–47.9	140.3–270.2	0.059–0.287	0.99–3.51	9.07
2	24.7–45.8	101.9–257.4	0.054–0.140	0.68–2.06	8.63
3	19.6–38.1	95.2–228.3	0.049–0.123	0.64–1.83	9.48

nearly identical to that of the litter at 20 per cent cover, so avoiding confounding differences among the plot treatments.

Infiltration on the runoff plots

In all tests, the discharge leaving the bottom of the plot was lower than that fed on at the top, the difference reflecting infiltration losses along the 2 m flow path, together with minor evaporative loss. The latter is estimated by scaling of annual pan evaporation at the study site to have been no more than 0.3 mm h⁻¹, or 2.5 per cent of the mean rate of water loss on the plots. Allowing for this evaporative loss, the mean infiltration rate was 9.8 mm h⁻¹.

The repeated use of each of the three plots for 12 successive experiments led to no systematic trends in infiltration rates through time, although there is a suggestion of a small initial decline on plots 1 and 3. This is

Table III. Laminar flow behaviour for the six treatments (each exposed to two flow rates) on experimental plot no. 1

Plot treatment*	Unit flux q ($\text{cm}^2 \text{ s}^{-1}$)	Mean flow depth d (mm)	Froude number (F)	Reynolds number (Re)	Mean flow speed u (cm s^{-1})	Darcy–Weisbach f (Equation 5)
Bare H	0.47	1.76	0.21	236	2.70	3.11
Bare L [†]	–	–	–	–	–	–
5% stone H	0.45	1.88	0.18	226	2.41	4.15
5% stone L [†]	–	–	–	–	–	–
10% stone H	0.54	2.20	0.17	270	2.47	4.66
10% stone L	0.53	1.52	0.28	265	3.51	1.59
20% stone H	0.39	1.79	0.17	195	2.19	4.79
20% stone L	0.39	2.18	0.12	192	1.77	8.98
1 t ha ⁻¹ litter H	0.36	2.06	0.12	177	1.73	8.90
1 t ha ⁻¹ litter L	0.31	2.46	0.08	154	1.26	20.02
2 t ha ⁻¹ litter H	0.42	2.86	0.09	207	1.46	17.24
2 t ha ⁻¹ litter L	0.28	2.85	0.06	140	0.99	37.17

* H, high imposed flow rate; L, low imposed flow rate. [†] Data for these runs was deleted owing to experimental failures.

Table IV. Laminar flow behaviour for the six treatments (each exposed to two flow rates) on experimental plot no 2

Plot treatment*	Unit flux q ($\text{cm}^2 \text{ s}^{-1}$)	Mean flow depth d (mm)	Froude number (F)	Reynolds number (Re)	Mean flow speed u (cm s^{-1})	Darcy–Weisbach f (Equation 5)
Bare H	0.46	2.41	0.12	232	1.89	6.85
Bare L	0.25	2.41	0.07	131	1.02	23.58
5% stone H	0.45	2.19	0.14	257	2.06	5.27
5% stone L	0.33	2.08	0.11	188	1.58	8.37
10% stone H	0.39	2.80	0.09	198	1.42	14.04
10% stone L	0.33	2.90	0.07	165	1.12	23.22
20% stone H	0.43	2.14	0.14	229	1.99	5.47
20% stone L	0.32	2.27	0.09	178	1.42	11.38
1 t ha ⁻¹ litter H	0.39	3.35	0.07	196	1.18	24.27
1 t ha ⁻¹ litter L	0.21	3.11	0.04	102	0.68	67.92
2 t ha ⁻¹ litter H	0.35	2.94	0.07	177	1.21	20.39
2 t ha ⁻¹ litter L	0.25	2.83	0.05	127	0.89	35.88

* H, high imposed flow rate; L, low imposed flow rate.

illustrated for each plot by comparing the mean infiltration loss rate in the first three tests to the mean of the last three of the 12 tests. The results show means of 13.1 mm h⁻¹ and 11.4 mm h⁻¹ (plot 1), 10.9 mm h⁻¹ and 12.8 mm h⁻¹ (plot 2), and 8.8 mm h⁻¹ and 7.2 mm h⁻¹ (plot 3). Nevertheless, the results show that whilst infiltration rates on plots 1 and 2 were indistinguishable statistically, rates on plot 3 were lower (the difference was significant at $\alpha = 0.005$ by small-sample t -test; Freund, 1974).

Flow depths in relation to surface treatments

The variation of flow depth between bare, stone and litter treatments provides insights into flow conditions. Unfortunately, the severe operating conditions in the field led to variations in pump operation so that applied discharges could not be reproduced exactly in successive experiments. This leads to some difficulty in strict comparison of the experiments. Nevertheless, it is clear from the results that flow depth was greater for bare plots than for those with added stone cover, though the effect is only about 0.2–0.3 mm (Table VII). The

Table V. Laminar flow behaviour for the six treatments (each exposed to two flow rates) on experimental plot no. 3

Plot treatment*	Unit flux q ($\text{cm}^2 \text{s}^{-1}$)	Mean flow depth d (mm)	Froude number (F)	Reynolds number (Re)	Mean flow speed u (cm s^{-1})	Darcy–Weisbach f (Equation 5)
Bare H	0.38	2.43	0.10	216	1.56	8.39
Bare L	0.27	2.63	0.06	145	1.03	20.69
5% stone H	0.39	2.52	0.10	180	1.57	8.50
5% stone L	0.25	2.44	0.07	115	1.03	19.20
10% stone H	0.41	2.24	0.12	196	1.83	5.58
10% stone L	0.24	1.98	0.09	116	1.20	11.46
20% stone H	0.44	2.39	0.12	228	1.83	5.98
20% stone L	0.24	1.99	0.09	124	1.19	11.78
1 t ha^{-1} litter H	0.35	3.23	0.06	142	1.08	23.21
1 t ha^{-1} litter L	0.19	3.03	0.04	79	0.64	61.05
2 t ha^{-1} litter H	0.34	2.95	0.07	150	1.17	17.96
2 t ha^{-1} litter L	0.21	2.67	0.05	95	0.79	35.94

* H, high imposed flow rate; L, low imposed flow rate.

Table VI. Area and edge length of a typical 1 g sample of the litter used in the plot treatments. The litter is classified as leaves, twigs, and other fragments (including flower parts, seeds, and bark fragments)

Parameter	Leaves		Twigs		Other	
	Area (cm^{-2})	Edge length (cm)	Area (cm^{-2})	Edge length (cm)	Area (cm^{-2})	Edge length (cm)
Mean	0.22	1.97	0.21	4.34	0.17	1.77
Std dev.	0.15	0.64	0.18	2.89	0.15	0.72
Number	38	38	24	24	44	44
Maximum	0.71	3.5	0.81	11.45	0.63	4.28
Minimum	0.03	0.78	0.04	1.05	0.03	0.63
Total	8.25	74.8	5.13	104.0	7.62	77.9

reduction in mean flow depth in the presence of obstacle stones is achieved despite the volumetric displacement of depth that they would cause. It would appear that flow threads whose path is influenced by the obstacle field must travel at higher speeds and shallower depths than the flow travelling outside the threads. Outside the threads, there is evidence of local backwater effects caused by large stones or clusters of stones. For example, with the exception of the 5 per cent stone cover treatment at the lowest imposed flow rate, and despite their lower mean depths, all stone treatments involved maximum flow depths that were deeper than any found on the bare plots (Table VII). In contrast to the behaviour of flow through stones, in all litter treatments mean depths were greater than for bare plots or for stone treatments (maximum depths were comparable to the stone treatments). It thus appears possible that the greatly more numerous and broadly distributed litter particles inhibit the evolution of relatively fast but shallow flow threads as seems to be the case with the more widely spaced obstacle stones.

The above arguments suggest a need to resolve separately thread and backwater effects even on very low-gradient surfaces with low microrelief, such as those tested here. It appears that even on such relatively smooth surfaces, protruding obstacles like stones may create threads and backwaters. Rather than apply relations like Equations 3, 4 and 5 to flow-field mean data, it may be more helpful to resolve the varying flow conditions across the surface.

Friction coefficients for shallow flow on the plot surfaces

Despite the diverse surface treatments applied to the runoff plots, friction coefficients derived for the bare soil surfaces, stone and litter treatments all declined with increasing Re (Figure 4), as is commonly but not

Table VII. Properties of the distributions of flow depth for each surface treatment and flow rate. Data from the three test plots have been pooled to generate these results

Plot treatment*	Mean flow depth (mm)	Standard deviation of flow depths (mm)	Number of depth observations [†]
Bare, H	2.21	1.27	183
Bare, L	2.52	1.22	126
5% stone, H	2.21	1.38	172
5% stone, L	2.27	1.21	118
10% stone, H	2.34	1.36	156
10% stone, L	2.15	1.35	159
20% stone, H	2.08	1.27	151
20% stone, L	2.04	1.38	144
1 t ha ⁻¹ litter, H	2.87	1.55	170
1 t ha ⁻¹ litter, L	2.86	1.36	168
2 t ha ⁻¹ litter, H	2.91	1.68	162
2 t ha ⁻¹ litter, L	2.79	1.56	159

[†] The number of depth observations varies owing to the exclusion of sample points occupied by a stone or litter particle. * H, high imposed flow rate; L, low imposed flow rate.

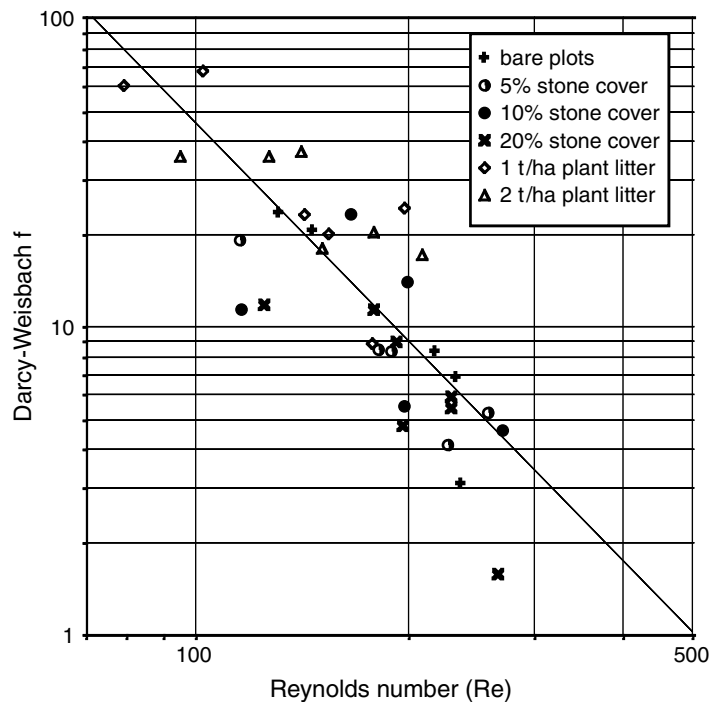


Figure 4. Relationship of Darcy–Weisbach friction coefficient (f , Equation 5) to flow Reynolds number (Re , Equation 3) for bare soil, added stone and added litter treatments. The least-squares power function regression model is indicated by the fitted line

universally observed in laminar flow. All relationships between f and Re were suitably described by power function regression models (Table VIII), and as suggested by Figure 4, the exponent of Re was negative (and departed from the smooth-surface value of -1) in all cases. The details of friction coefficients for bare soil, stone, and litter treatments are set out separately below.

Table VIII. Constants in the power function relations linking f and Re (taking the form $f = aRe^b$), probability levels and statistical significance for these relations, and the resultant value of f at $Re = 150$ listed for comparative purposes

Surface treatment	a	b	Probability*	Darcy f at $Re = 150$ (Equation 5)
Bare soil	1.93×10^7	-2.774	0.0019 (s)	17.7
5% stone	1.14×10^5	-1.833	0.012 (s)	11.7
10% stone	5.06×10^3	-1.198	0.326	12.5
20% stone	6.94×10^3	-1.304	0.086	10.1
1 t ha ⁻¹ litter	2.01×10^5	-1.814	0.042 (s)	22.7
2 t ha ⁻¹ litter	5.99×10^3	-1.094	0.061	24.9

* (s) indicates significant at $\alpha = 0.05$ level.

Friction coefficients on the bare (unmodified) soil surfaces. On the soil surfaces f lay in the range 20–24 at the lower discharge, declining to 3–8 at the higher discharge. The least-squares f – Re power function model for bare soils (for which $r^2 = 0.86$) was:

$$f = 1.93 \times 10^7 Re^{-2.774} \quad (6)$$

This relationship is statistically significant, with $p = 0.02$. The slope of the f – Re Moody plot, -2.774 , departs from the smooth-surface laminar flow value of -1.0 and therefore the constant K in the relation $f = K/Re$ that is used to characterize roughness for smooth-surface laminar flows (White, 1999) cannot be used to describe the roughness of the soil surfaces. Thus, the alternative of taking the definite integral of the f – Re relation across a fixed range of Re , as proposed by Dunkerley (2002a), is employed as an alternative measure of surface roughness independent of Re . Integrating the above relation over the range $100 < Re < 200$ leads to the value of 2179.

Friction coefficients in the presence of added organic litter. When additional organic litter was scattered onto the plot surfaces, values of f rose to lie in the range 20–60 (peaking at 67.9 on plot 2). The mean f in both 1 t ha⁻¹ and 2 t ha⁻¹ treatments was different from that for the bare soils (both differences significant at $\alpha = 0.05$, by small-sample t -test; Freund, 1974). The slope of the f – Re relation declined in the litter treatments, though remaining more negative than the smooth-surface value of -1.0 . Therefore, integration across the range $100 < Re < 200$ is again used instead of the K term to characterize roughness across the range of imposed flows.

For 1 t ha⁻¹, the f – Re power function regression model is:

$$f = 2.01 \times 10^5 Re^{-1.814} \quad (7)$$

and the integral value is 2508.

For 2 t ha⁻¹, the f – Re power function regression model is:

$$f = 5.99 \times 10^3 Re^{-1.094} \quad (8)$$

and it thus appears that the slope of the relation declines toward -1.0 as more litter is added to the surface. For the relation of Equation 8, the integration yields 2607.

Friction coefficients with added surface stones. Friction coefficients arising when 5–20 per cent surface cover of stones had been placed on the soil surface were surprisingly little different from those measured for the bare plots (Table VIII). Indeed, t -tests (Freund, 1974) showed no significant differences among the mean f for the three different stone cover fractions, or between the stone treatments and the bare soil. An

explanation for this is offered below. Nevertheless, many individual determinations of f were lower with stones than for the same test surface bare, despite the many additional obstructions facing the flow. The integrated f -Re power functions for stone treatments yielded values of 1070–1318, consistently lower than the 2179 derived for the bare plots.

DISCUSSION

The results showed that friction coefficients were modified only slightly, and in some cases reduced, when stones were added to the previously bare plots. Two factors contribute to this. First, much of the roughness on the bare plots (and on the plots with stones added) evidently arises from the areas that sit higher in the microtopography, and which consequently carry shallow flows. In the laminar regime, as Figure 4 confirms for the present plot data, f rises steeply as Re (or depth) decline, so that shallow areas provide the locations of highest friction coefficients. Preferred flow paths steered by microtopographic low points contribute less roughness. Secondly, though the stones act as obstacles to the flow, they also occupy some of the volume beneath the water surface, and so by volumetric displacement, they increase flow depths over the fraction of the soil surface left uncovered. This mechanism was highlighted by Dunkerley *et al.* (2001) and has been explored in more detail by Dunkerley (2002b).

In contrast, f was increased significantly by the addition of organic litter providing about the same projected cover fraction as the stones. The mean f was 34.2 on plots with 1 t ha⁻¹ litter, compared with a mean of 12.5 for the bare plots and 8.06 for the 20 per cent stone plots. The integrated f -Re power functions yielded 2504 (1 t ha⁻¹) and 2613 (2 t ha⁻¹), values well above those found on the bare plots (2179) or the stone plots (maximum value was 1318 on 10 per cent stone plot). Because many of the small litter particles were submerged within the flow, or rested loosely upon the surface with some flow passing beneath and some flow above them, no adjustment was made to plot width in calculating the f from Equation 5 for litter treatments. To the extent that some of the plot width must have been obstructed by litter particles, the derived values of f will be too high. Nevertheless, this effect is not thought to be great. In particular, as noted earlier, the litter has low density, and some was positioned semi-buoyantly, allowing water to traverse the soil surface beneath the litter. The values of f associated with litter exceed those from stone treatments by a large margin (nearly 41 per cent, on average). Thus, not even the use of an unadjusted plot width of 100 cm in processing the stone treatment data (so ignoring any obstruction of width) would increase results to the values derived from the litter treatments.

Evidently, the much smaller but more numerous litter particles resulted in greater frictional retardation of the flow, and consequently greater flow depths, than did the fewer but larger quartz stones. One key difference between the two classes of obstacle is the length of the wetted particle perimeters in contact with the water. As noted above, the edge length was about 20 times greater for the litter treatments than for the stone. It was observed clearly in the field that along this greater contact length, surface tension forces drew up very extensive curving menisci. This effect has been investigated in some detail by Dunkerley (2002a), who showed that the storage of water in these deeper areas flanking an obstacle leads to a reduction in depth in areas away from the particle, from where water is drawn laterally to form the meniscus. Furthermore, Dunkerley (2002a) showed that the meniscus can be 7–9 mm in width on each side of a twig-like litter particle, and may be drawn up to 3 mm above the level of the nearby open flow. Thus, the area of deeper water surrounding a litter particle that has drawn up a continuous flanking meniscus can greatly exceed the area of soil surface directly covered by the particle itself. Furthermore, in shallow flow with protruding obstacles and menisci that trap water above the general level of the flow, the motion of that water can be inhibited and greater frictional retardation can be the result.

Consider a stone covering 1 per cent of a square metre of the soil surface, and having a diameter of 3.56 cm. If this same soil area is covered by 100 litter particles having a mean size of only 5 mm × 2 mm, and each is enclosed by a meniscus 5 mm in width, then the total area covered by litter and meniscus is nearly 18 times larger than for the single stone. In other words, litter particles covering 1 per cent of the surface would perturb flow depths over 18 per cent of the surface. Evidently, when litter cover becomes sufficiently high, the area affected by menisci potentially exceeds the plot area itself. In this case, as shown by Dunkerley (2002a), the

full development of menisci is inhibited, and adjacent menisci partially merge, resulting in bridging of the gap between close neighbouring particles, and the creation of deeper areas of flow that can sustain higher flow speeds and yield lower friction coefficients. The cover fraction when this effect begins to dominate has not been resolved for the litter of the study site.

The results presented must be analysed in the context of litter abundance in drylands, some figures for which were presented earlier. Additional data are provided by Tracy *et al.* (1998), showing many cover fractions of 10–20 per cent in the Chihuahuan Desert of New Mexico. From arid Patagonia, del Valle *et al.* (1999) report litter loadings in intershrub spaces of up to $45.6 \pm 27.0 \text{ g m}^{-2}$, rising to $>200 \text{ g m}^{-2}$ beneath shrubs. A range of 22.0–71.6 per cent litter cover was documented on study plots within a semi-arid sagebrush (*Artemisia tridentata*) rangeland in Idaho, USA (Johnson and Gordon, 1988), while from Arizona, Tromble *et al.* (1974) reported litter cover of 20.3–50.3 per cent. Across a range of locations in the USA, Kidwell *et al.* (1997) reported interspace litter cover of 7.3–61.8 per cent, whilst in their study of overland flow on shortgrass rangelands in South Dakota, Woolhiser *et al.* (1970) recorded litter covers of 23–34 per cent. Martinez Carretero and Dalmasso (1992) reported 63 per cent litter cover of the soil surface among *Larrea* spp. shrubs, and 24 per cent in intervening bare areas, from an arid study site in Argentina. From these figures, it can be concluded that the cover fractions tested here are reached or exceeded in many drylands.

Comparing the estimates of f with published results

The results presented above can be compared with published data on interrill friction coefficients. Emmett (1970) derived estimates of f from field plots subjected to simulated rain. These spanned the range 0.33–3113, but most sites yielded values in the range 20–500. For savanna runoff plots in Kenya, Dunne and Dietrich (1980) derived power-function f – Re relations; solved for $\text{Re} = 150$ (the same value as used for comparisons among the present plot experiments) these indicate $f = 88.3$ for the Athi-Kapiti area, $f = 0.91$ for Amboseli and $f = 1.91$ for the Kilimanjaro plots. These plots carried some surface stones and a 10–40 per cent vegetation cover.

Weltz *et al.* (1992) derived a relation for the component of f attributable to organic litter, treated separately from soil grain or stone cover roughness:

$$flt = 113.73Rl^3 \quad (9)$$

where flt is the friction coefficient due to litter and Rl is the projected cover of unmovable litter (as a decimal fraction). For 10 per cent and 20 per cent litter cover, this predicts $f = 0.11$ and 0.91 respectively. These values are smaller than those derived here. Subtracting the f arising on the soil from the total on the 1 t ha^{-1} and 2 t ha^{-1} litter plots tested here yields estimates of flt of 5.0 and 7.2 respectively. Nevertheless, the aggregate values for f estimated by Weltz *et al.* (1992) for dryland plot surfaces lie in the range 5.8–107.6, a range which includes all of the new data presented earlier.

On rangeland plots in Arizona, Abrahams *et al.* (1994) derived values in the range $0.05 < f < 18.81$. They reported diverse relationships between f and Re (many positively sloping), and concluded that surface properties including litter cover exerted a stronger control over flow resistance than did flow rate.

Dunkerley *et al.* (2001) derived estimates of f from tests on an impermeable, planar sand board, employing dryland plant litter derived from the same site as the present field experiments. For a litter cover of 25 per cent, all values lay below $f = 8.0$. Indeed, at $\text{Re} = 150$, for this litter loading their data indicate $f = 6.3$. These values are notably lower than the new results derived on field plots, for loadings of similar litter particles. This suggests (though does not prove) that the natural microtopography, and the zones of shallower and deeper flow that it generates, may be involved in generating greater roughness than was developed on the planar flume, where flow depths were more uniform. Additional experiments targeting this hypothesis appear necessary.

In summary, a wide range of published estimates of f exists. The new data presented here for a low-gradient Australian dryland site appear in general accord with prior data. However, there are too few systematic studies of litter among these to draw firm conclusions about the relative roles of litter and stones. In particular, litter cover fraction appears to be an insensitive parameter by which to describe this complex source of depth

perturbation and frictional drag, and the data from various investigations may be better resolved when more appropriate parameters (perhaps including edge length per unit area, as employed here) become available.

CONCLUSIONS

It is evident that measurements of surface cover fraction of various materials do not by themselves provide a tool of suitable discrimination for the prediction or analysis of the frictional drag that they may generate in shallow flows. Large obstacles like the stones tested here caused little or no additional drag in excess of that arising from the surface of the mineral soil beneath. It is now clear that this is because they funnel deeper flow across the remaining uncovered surface, and locally increase the flow Reynolds number there. In laminar flow at least, these higher Reynolds numbers are associated with lower drag.

For litter providing the same projected cover fraction, in contrast, the more numerous and more evenly distributed particles provide no clear paths for the passage of flow threads. Additionally, depths are perturbed by extensive surface tension menisci that develop along all exposed flanks of the particles. This effect appears only to be important in frictional drag in shallow flows where the particles protrude and where the draw-up of water from intervening spaces results in lowering of depth there. This shallowing then results in lower flow Reynolds numbers and so, higher friction coefficients. Since the litter loadings and cover fractions tested here are exceeded in various drylands, it seems likely that litter provides a major source of frictional drag in shallow interrill flows, and one therefore deserving of greater study.

The field results suggest that flow threads and backwater effects in the presence of obstacles like surface stones, or else resulting from soil surface microtopography, may necessitate a focus on variability of flow conditions within a flow field, rather than the traditional reliance on flow-field mean values derived using relations like Equations 3, 4 and 5.

The new estimates of f for litter- and stone-bearing dryland interrill surfaces lie in the range 5.27–67.92. These values are higher than have been suggested by laboratory experiments, and suggest that variation in flow depths over microtopography may be of importance in determining the applicable value of f . Nevertheless, the results presented earlier show that a moderate litter cover can increase the value of f over that of a bare soil surface by >40 per cent, and contribute much greater roughness than an equivalent cover of surface stones. Given the evident importance of organic litter, better ways to parameterize soil surface cover (including measures of edge length and surface tension effects related to this) appear worthy of more attention.

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