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Field experiments on the resistance to overland flow on desert hillslopes

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Abstract At-a-section and downslope variations in resistance to overland flow on desert hillslopes have been investigated by performing a series of experiments on six runoff plots in southern Arizona. The surfaces of these plots are irregular and covered with stones. As overland flow increases, the stones and microtopographic protuberances, which constitute the major roughness elements, are progressively inundated, thereby altering the flow resistance. Analyses of 14 cross sections reveal that the relation between the Darcy-Weisbach friction factor f and the Reynolds number Re has two basic shapes: convex-upward and negatively sloping. These shapes are explained in terms of the simultaneous operation of two processes. The first is the progressive inundation of roughness elements and increase in their wetted upstream projected area as discharge increases. This process causes f to increase. The second is the progressive increase in the depth of flow over already inundated parts of the bed as discharge increases. This process causes f to decline. Whether the f-Re relation has a positive or a negative slope depends on whether the first or the second process dominates, and this depends on the configuration of the bed and level of discharge. These findings have profound implications for the mathematical modelling of overland flow on desert hillslopes, as the computed overland flow hydrograph is very sensitive to the form of the f-Re relation. The downslope analyses indicate that there is a general tendency for f to decrease down the runoff plots, owing to the progressive downslope concentration of flow. This finding contrasts with Emmett's conclusion that f remains approximately constant downslope because of ponding behind microtopographic highs, notably vegetation mounds. Our finding appears to be more representative than Emmett's of sparsely vegetated desert hillslopes.

INTRODUCTION

In desert landscapes virtually all runoff from hillslopes occurs in the form of overland flow. On such hillslopes, overland flow generally appears as a shallow sheet of water with threads of deeper, faster flow diverging and converging around surface protuberances, rocks, and vegetation. As a result of these diverging and converging threads, flow depth and velocity vary markedly over short distances, giving rise to changes in the state of flow. Thus, over a small area the flow may be wholly laminar, wholly turbulent, wholly transitional, or consist of patches of any of these three flow states (Horton, 1945). Abrahams *et al.* (1986) termed this patchy kind of overland flow *composite* flow.

The resistance to overland flow offered by the surface of a hillslope may be expressed by a hydraulic roughness coefficient. The coefficient used in this study is the dimensionless Darcy-Weisbach friction factor f defined by

$$f = \frac{8gRs_e}{v^2} \qquad (1)$$

where g is the acceleration due to gravity, R the hydraulic radius, S_e the energy slope, and v the mean flow velocity. Resistance to flow generally varies with rate of flow, and this variation is normally examined by plotting f against the dimensionless Reynolds number Re on log-log axes. The definition of Re employed here is

$$Re = 4vR/\upsilon \qquad (2)$$

where υ is the kinematic fluid viscosity.

The relationship between f and Re is well established for pipes and smooth channels (Chow, 1959, p. 9-10), and laboratory experiments and theoretical analyses since the 1930s have shown that a similar relationship obtains for shallow flow over a plane bed with either a smooth or rough surface, provided that the surface is completely submerged by the flow (e.g. Horton *et al.*, 1934; Woo & Brater, 1961; Emmettt, 1970; Yoon & Wenzel, 1971; Shen & Li, 1973; Phelps, 1975; Savat, 1980). In these circumstances, the shape of the *f-Re* relation is a function of the state of flow: the relation has a slope of −1.0 where the flow is laminar and a slope close to −0.2 where the flow is turbulent (e.g., Horton *et al.*, 1934; Emmett, 1970; Morgali, 1970; Yoon & Wenzel, 1971; Shen & Li, 1973). The situation is less clear where the flow is transitional. In some experiments, the slope of the *f-Re* relation becomes positive in the transition zone (e.g., Phelps, 1975), whereas in others it does not (e.g., Yoon & Wenzel, 1971; Savat, 1980).

The form of the *f-Re* relation is of fundamental importance to the mathematical modelling of overland flow. Whether a model is based on the Saint Venant equations (Woolhiser & Liggett, 1967; Woolhiser, 1975) or employs the kinematic-wave approximation (e.g., Henderson & Wooding, 1964; Woolhiser & Liggett, 1967; Foster *et al.*, 1968; Lane & Woolhiser, 1977; Dunne & Dietrich, 1980; Moore, 1985), it needs to take into account the resistance to flow of the hillslope surface. In the past this usually has been done by incorporating into the model a relation between f and Re or surrogates thereof. The most widely used relation has been the conventional one for shallow flow over a plane bed. This relation generally has an adjustable parameter, such as the intercept of the laminar flow portion of the relation. In some cases the value of the intercept has been estimated from experimental data (e.g. Dunne & Dietrich, 1980), whereas in others it has been obtained by optimization (e.g. Woolhiser *et al.*, 1970; Woolhiser, 1975; Lane & Woolhiser, 1977). Studies have shown that the computed overland flow hydrograph is very sensitive to the value of the intercept (e.g. Woolhiser, 1975; Dunne & Dietrich, 1980), and as Fig. 1 shows, it is also extremely sensitive to the slope coefficient of the f-Re relation.

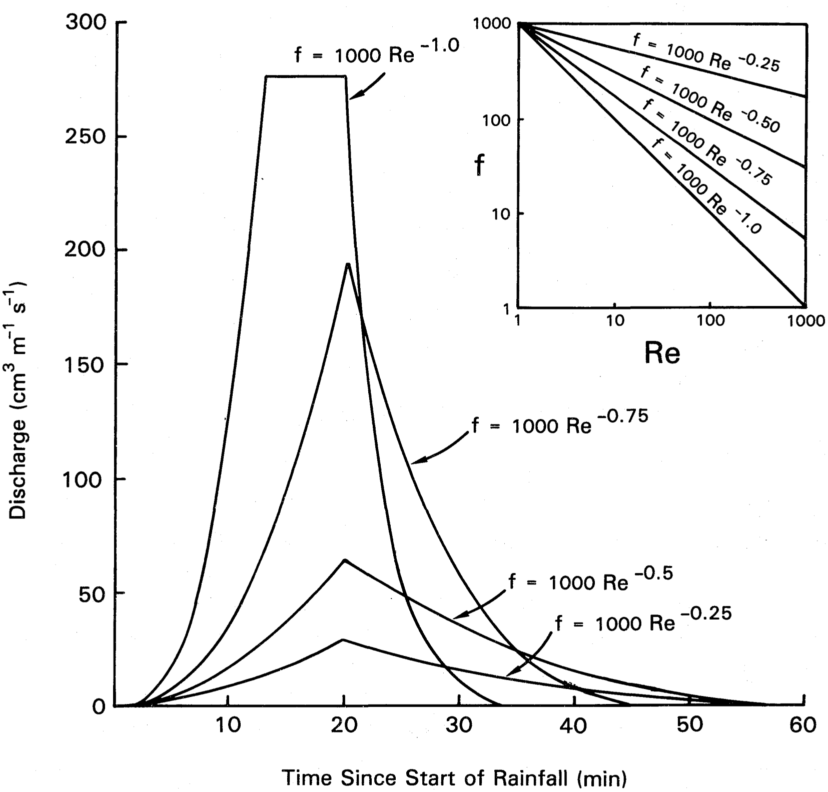

Fig. 1 Overland flow hydrographs predicted by the kinematic-wave model (Woolhiser, 1975) modified to allow for the effect of infiltration on the recession limb (Dunne & Dietrich, 1980). The figure shows the sensitivity of the hydrograph to the slope coefficient of the f-Re relation (inset) when all other factors remain constant, namely: slope length = 100 m, gradient = 0.09, rainfall duration = 20 min precipitation excess = 10 mm h^{-1}, *infiltration capacity = 5 mm* h^{-1}.

Although the conventional *f-Re* relation has been widely used in overland flow modelling, it is not at all clear that this relation applies to desert hillslopes, particularly as the irregular and stone-covered surfaces of such hillslopes induce composite overland flow. There has been no previous study for the *f-Re* relation on desert hillslopes. However, Roels (1984) computed the *f-Re* relations for 12 small (0.5 m^2) runoff plots with rilled and prerilled surfaces in the Ardeche drainage basin, France. Although *Re* ranged in value from 75 to 14 000 (with most observations being in the range $175 < Re < 7000$), none of the *f-Re* relations exhibited either a break or reversal in slope indicative of the transition from laminar to turbulent flow. Disregarding the relation for plot 12 which was on bare rock, the remaining 11 relations had slopes ranging from −0.07 to −0.90. Roels interpreted these negatively sloping *f-Re* relations as signifying that the flow was either transitional or turbulent. However, it is conceivable that the form of these relations reflected not so much the state of flow as of the character of the ground surface.

From Roels' descriptions of his plots it is evident that their surfaces were highly irregular and covered with stones that protruded above the flow. The microtopography and stones would not only have contributed to the flow resistance but would have given rise to composite flow. When composite flow prevails, a given *Re* value for a plot or cross section cannot be associated with a single state of flow. Thus, it is hardly surprising that Roels' *f-Re* relations depart from the conventional relation for shallow flow over a plane bed. Roels' study therefore casts doubt on the applicability of the conventional *f-Re* relation to desert hillslopes with irregular surfaces and points to the need for further field studies of the relation between *f* and *Re*.

Whereas Roels was concerned with the variation in flow resistance at a cross section, Emmett (1970) investigated the variation in this property down a hillslope. Using simulated rainfall to generate overland flow, he analysed the downslope variation in *f* with *Re* in seven hillslopes plots in semiarid Wyoming, USA. Emmett noted that flow resistance consists of both particle resistance (offered by sand grains and plant stems) and form resistance (caused by topographic irregularities), and he concluded that form resistance was the more important on the hillslopes he studied. He found that the slopes of the *f-Re* relations for his seven plots ranged from −0.80 to 1.00 and averaged 0.08. That flow resistance (on the average) remained approximately constant downslope was ascribed to two opposing effects on flow resistance which tended to cancel one another out. These effects were the downslope increase in flow depth and the downslope decrease in runoff efficiency owing to ponding behind microtopographic highs.

This paper presents the results of a field investigation of the variation in resistance to overland flow both at-a-section and downslope on desert hillslopes in southern Arizona. The at-a-section analyses examine the form of the *f-Re* relation and the factors that control this form, whereas the downslope analyses focus on whether *f* increases, decreases, or remains constant downslope and the reasons for this behaviour. The findings of both sets of analyses deviate in important ways from those of previous studies and have significant implications for runoff and erosion on desert hillslopes.

STUDY AREA, METHODS, AND DATA

Six runoff plots, hereafter referred to as P1, ..., P6, were established on hillslopes ranging in gradient from 6° to 33° in the Walnut Gulch Experimental Watershed, Tombstone, Arizona (31° 43'N, 110° 41'W). The plots, which were approximately 5.5 m long and 1.8 m wide, were underlain by Bascal gravelly fine sandy loam (W. E. Emmerich, personal communication, 1986) developed on weakly consolidated, coarse Quaternary alluvium. The surfaces of the plots were largely covered by gravel that had weathered out of the underlying material. The vegetation on the hillslopes is dominated by desert shrubs, notably sandpaper bush *(Mortionia scabrella)* and creosote bush *(Larrea tridentata)*. However, the runoff plots were located between shrubs and had only a sparse cover of forbs and grasses that were clipped 1-2 cm above the ground for the runoff experiments. The locality has a warm, semiarid climate with a mean annual precipitation of 288 mm and a mean monthly temperature range of 8° to 27°C (Osborn, 1983).

Each plot was equipped with separate sprinkle and trickle systems to simulate rainfall and overland flow, respectively. The design and operation of these systems have been described elsewhere (Luk *et al.*, 1986). Eight experimental runs, designated R1, ..., R8, were performed on each plot. During the first run, rainfall alone was applied to each plot at a rate of 145 mm h^{-1} for approximately 40 minutes. A natural rainstorm of this intensity and duration has a recurrence interval in excess of 200 years at Walnut Gulch (Osborn, 1983). A rainfall intensity of 145 mm h^{-1} was selected because trial and error revealed that an intensity of this order was necessary to generate Horton overland flow. Even then, overland flow during the first run on P5 and P6 was so shallow that no depth measurements were attempted. During the second run, rainfall at a rate of 72 mm h^{-1} for approximately 30 minutes was combined with overland flow, which was trickled onto the upper part of each plot at a rate of 572 cm^3 s^{-1}. A natural rainstorm of this intensity and duration has a recurrence interval of about 10 years at Walnut Gulch (Osborn, 1983). During the remaining six runs, overland flow alone was applied to each plot at inflow rates of 572, 733, 908, 1067, 1233, and 1400 cm^3 s^{-1} for R3 to R8, respectively. The only exception was P1-R3 where the inflow rate was 533 cm^3 s^{-1}.

The outflow rate for each run was measured volumetrically by directing the flow at the lower end of the plot into a collecting trough and periodically measuring the time required to almost fill a 2 litre bottle. The weight of the fluid in each bottle was subsequently measured in the laboratory, and its volume determined by assuming a density of 1 g cm^{-3}.

Three cross sections, henceforth identified as C1, C2, and C3, were established on each plot at 1.25, 3.25, and 5.25 m from the top of the plot. Discharges Q at these cross sections were computed by assuming that infiltration and evaporation losses were uniformly distributed over the plot. During all but a few runs, which are identified below, the outflow rate eventually became more or less constant. When this occurred, the depth of flow to the nearest millimetre was measured with a thin scale at 5 cm intervals across each cross section, and these measurements were averaged to yield the mean flow depth d. The mean velocity (v) was calculated by dividing Q by $w.d$, where w is the width of the cross section. Owing to the stony and uneven nature of the ground surface, a combination of sheet-metal strips and cement walls was used to delimit the runoff plots. As a result, the cross sections vary somewhat in width.

As in all previous field studies of overland flow, d is employed in place of R, and S_e is approximated by local ground slope S. The value of S for each cross section was determined by laying a 0.3 m long board along the flow lines of the two or three major threads of flow, measuring the gradient of the board in each case, and averaging these gradients (Table 1). υ was estimated from water temperature, and f and Re were calculated using equations (1) and (2).

The analyses undertaken in this study are described in the following two sections. The analyses in the first section are concerned with the at-a-section variation in f and are based on R3 through R8. R1 and R2 were excluded because they involve rainfall, which is an additional factor influencing resistance to flow (Yoon & Wenzel, 1971; Shen & Li, 1973). The analyses in the second section focus on the downslope variation in f. Data from all eight runs are analysed, but the analyses of R1 and R2 are performed separately from those of R3 through R8.

AT-A-SECTION ANALYSES

Depth versus discharge

Emmett (1970) demonstrated that the hydraulic geometry approach to river channels pioneered by Leopold & Maddock (1953) could also be employed to analyse the hydraulics of overland flow. The simple log-linear version of the hydraulic geometry relations used by Leopold and Maddock was generalized to include curvilinear trends by Richards (1973) who utilized log-quadratic functions. In this study we are concerned only with the relation between d and Q. The log-quadratic form of this relation is

$$\log d = f_1 + f_2 \log Q + f_3 (\log Q)^2 \qquad (3)$$

For each of the three cross sections on the six plots, d was plotted against Q on log-log graph paper (Fig. 2), and a quadratic equation of the form of equation (3) was fitted by least squares to each scatter of points, with the quadratic term being included only if its contribution to the explained variance was significant at the 0.10 level. Inasmuch as the variance accounted for by the fitted equations always exceeds 90%, the equations closely approximate their equivalent structural relations (Mark & Church, 1977).

Friction factor versus Reynolds number

Four of the 18 cross sections, namely P2-C3, P3-C3, P6-C2, and P6-C3, were

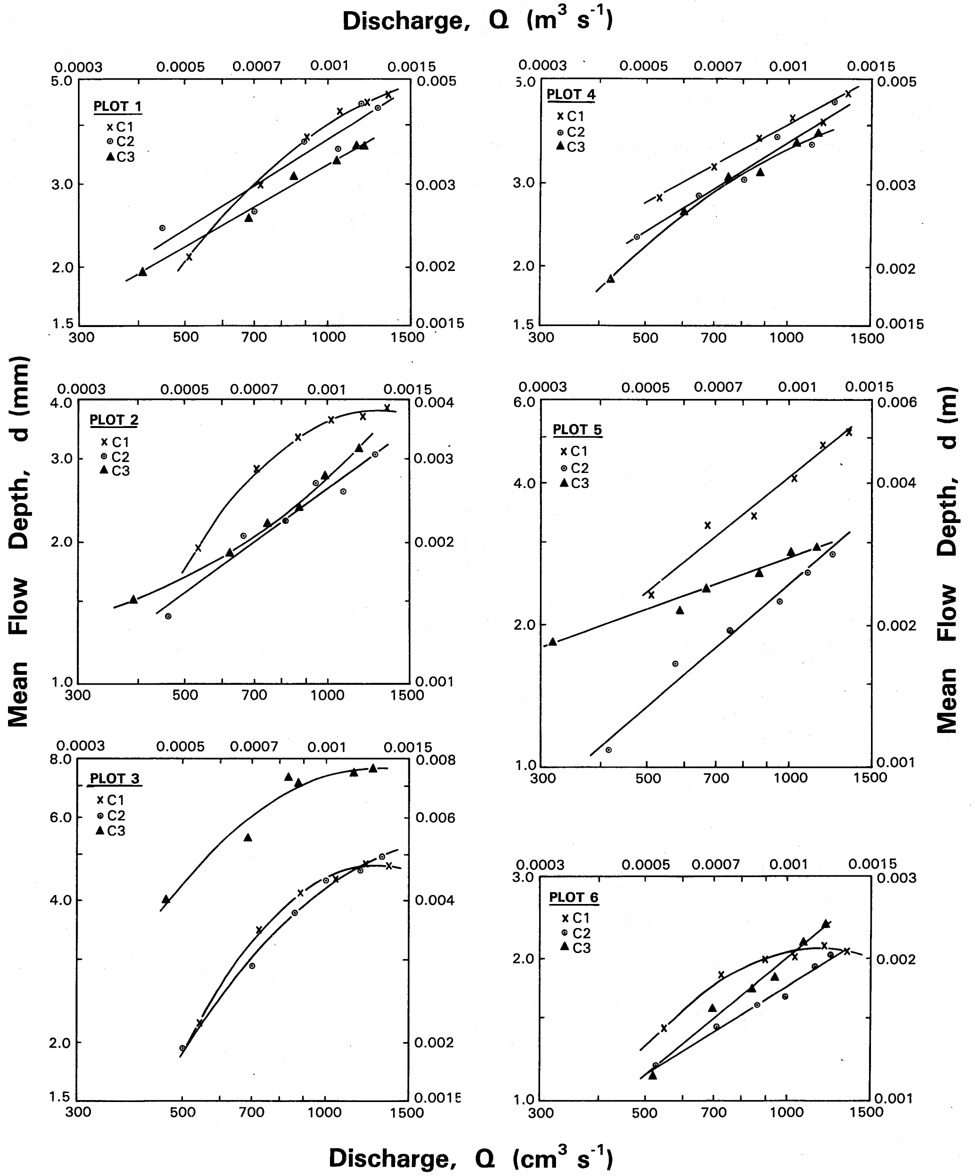

Fig. 2 Graphs of mean flow depth against discharge.

discarded from the analyses because they were affected by erosion of a plunge pool beneath a rock step, formation of an organic dam, or scouring by debris flows. For the remaining 14 cross section f was plotted against Re on log-log axes (Fig. 3). The relation between f and Re for each cross section was then determined algebraically from the corresponding d-Q relation (Abrahams *et al.*, 1986). Because the general form of the d-Q relation is log-quadratic, so is the general form of the f-Re relation:

$$\log f = k_1 + k_2 \log Re + k_3 (\log Re)^2 \qquad (4)$$

The computed *f-Re* relations for the 14 cross sections are graphed in Fig. 3. Six of these relations are convex-upward with vertices within the observed range of *Re*. The remaining eight relations are linear, three being positively sloping and five negatively sloping. The range of k_2 values for the negatively sloping relations is −0.078 to −0.893, which is similar to that reported by Roels (1984).

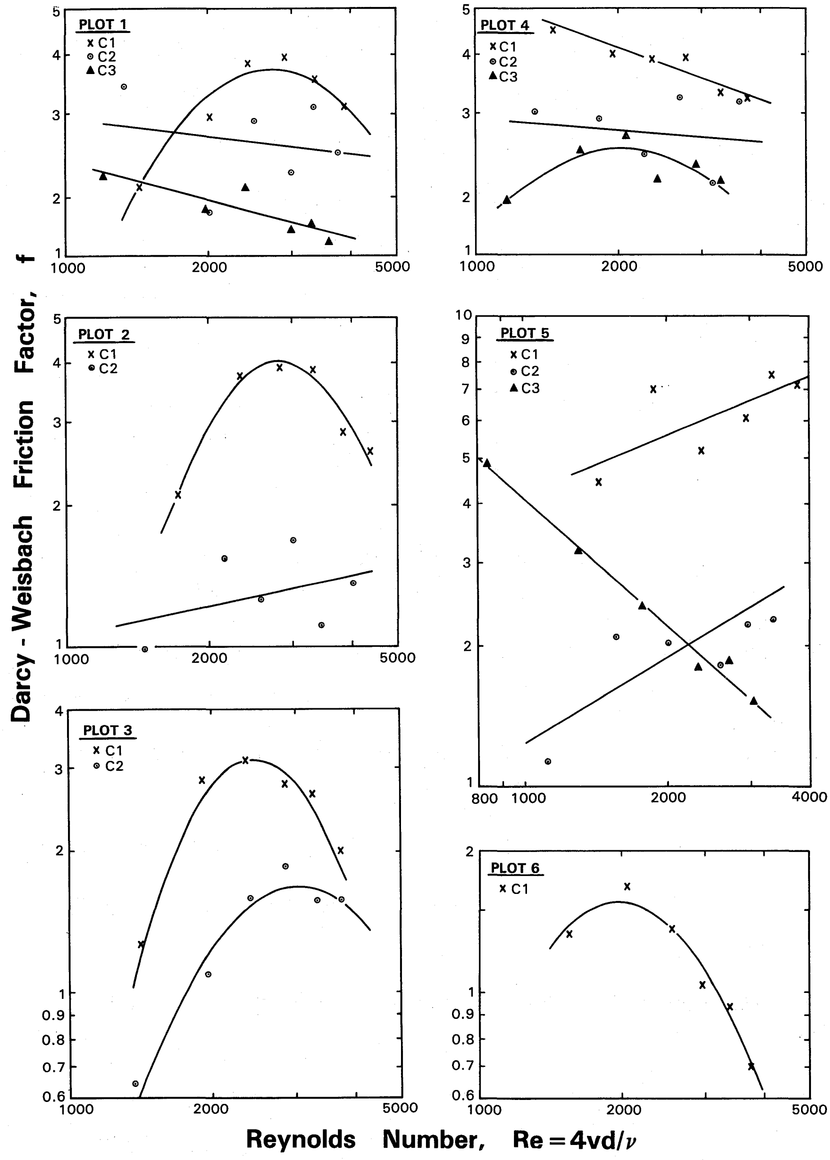

Fig. 3 Graphs of Darcy-Weisbach friction factor against Reynolds number.

Inundation of roughness elements

The shapes of the *f-Re* relations in Fig. 3 bear no resemblance to the conventional *f-Re* relation for shallow flow over a plane bed. Thus it is unlikely that they can be explained in terms of changes in the state of flow, and some other explanations must be sought. Abrahams *et al.* (1986) proposed that these shapes can be understood in terms of the simultaneous operation of two processes. As discharge and hence *Re* increase (a) the flow progressively inundates the protruding roughness elements, thereby increasing the wetted upstream projected area of these elements and the resistance to flow (Herbich & Shulits, 1964); and (b) the depth of flow over already inundated portions of the cross section increases, thereby increasing relative submergence (i.e., the ratio of flow depth to height of the drowned roughness elements) and causing flow resistance to decline (Bathurst, 1985). Whether the *f-Re* relation has a positive or negative slope at a particular value of *Re* depends on whether the first or the second process dominates.

On many, if not most, desert hillslopes (depicted schematically in Fig. 4) the *f-Re* relation is convex-upward because when discharge is low but increasing, the flow progressively inundates roughness elements, causing the wetted upstream projected area of the elements to increase rapidly, and *f* to increase. However, a point is soon reached when most of the elements are largely or wholly submerged, and any further increase in discharge is

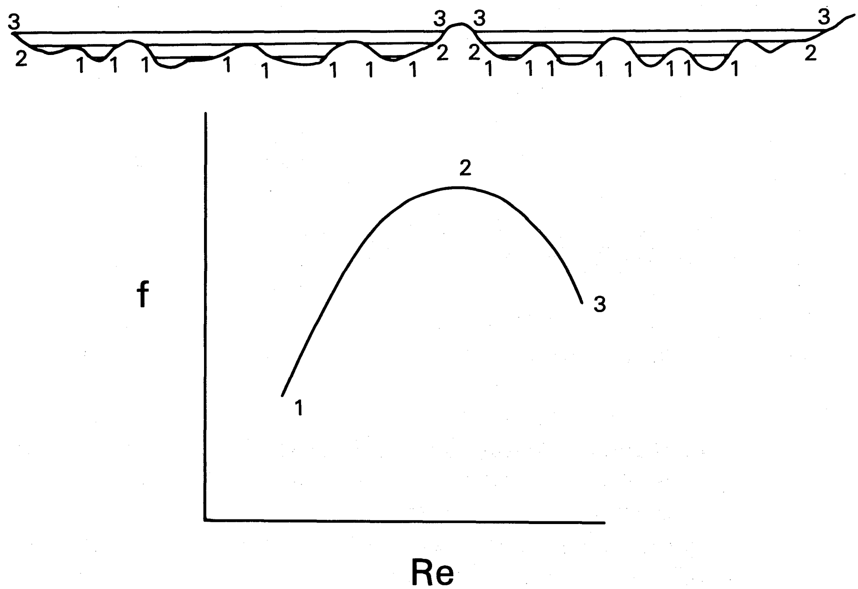

Fig. 4 Sketch of a hypothetical ground surface with intermediate-sized roughness elements of varying height showing how the progressive inundation of such a surface gives rise to a convex-upward f-Re relation. The numbers identify particular water surface levels and their corresponding f and Re values.

accompanied by a progressively slower rate of increase in wetted upstream projected area of the elements. As discharge increases, so does depth of flow. Eventually the effect of this process outweighs that of increases in wetted upstream projected area of the roughness elements, and f begins to decrease. An example is provide by P2-C1 (Fig. 5(a)).

Negatively sloping *f-Re* relations appear to be produced by two types of bed configurations (shown schematically in Fig. 6). The first is an almost planar bed with many small roughness elements and perhaps the occasional, widely spaced, large element. Even at low flow virtually all the small elements are submerged, and f is relatively large. As discharge increases, the wetted upstream projected area of the roughness elements increased only slowly because all the elements save the largest are already submerged. Meanwhile, most of the bed becomes drowned under greater depths of flow, causing f to decline. P4-C1 is an example of this bed configuration (Fig. 5(b)).

The second type of bed configuration is characterized by pronounced concentrations of flow; such as in rills. Roels' (1984) field experiments were conducted on this kind of surface. As discharge increases, the flow remains confined within the rills, and depth of flow within each rill increases rapidly.

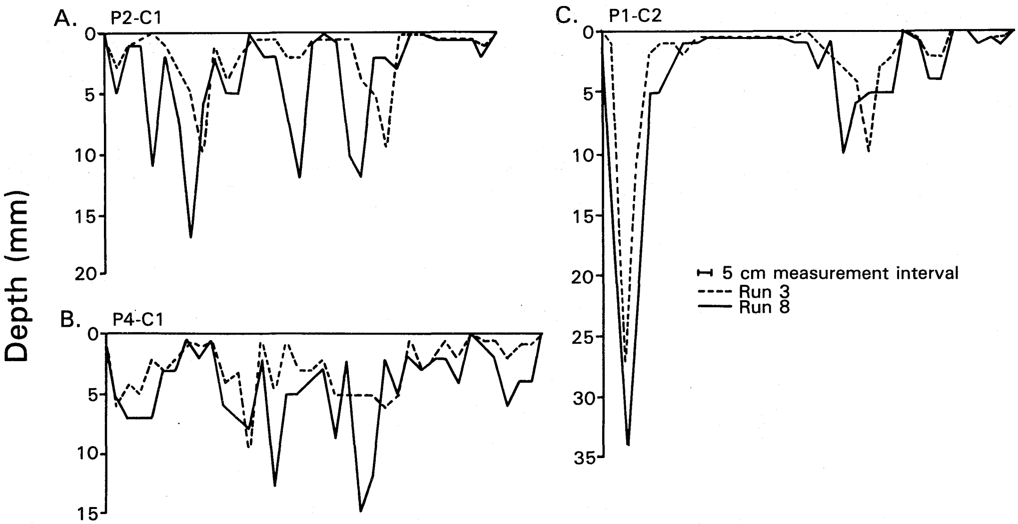

Fig. 5 Graphs of selected cross sections drawn from depth data. On these graphs the water surface is depicted as a horizontal line across the entire cross section. Inasmuch as no information is available on the height of the protuberances above the flow, each protuberance is depicted as either a point or a horizontal line at the same height as the water surface. (a) P2-C1 has intermediate-sized roughness elements of varying height, the progressive inundation of which produces a convex-upward f-Re relation. (b) P4-C1 is almost planar with multiple small roughness elements, which become drowned at low flow and give rise to a negatively sloping f-Re relation. (c) P1-C2 is rilled and has a negatively sloping f-Re relation.

Thus, each rill becomes hydraulically more efficient, and the *f* value for the cross section decreases. P1-C2 is an example (Fig. 5(c)).

For some of the cross sections on our plots positively sloping *f-Re* relations were obtained. These relations appear to be the left-hand limbs of convex-upward relations whose vertices lay beyond the observed range of *Re*. The relatively rapid increase in the wetted upstream projected area of the roughness elements as the flow inundates the cross section and causes *f* to increase cannot continue indefinitely as *Re* increases, so the slope of the *f-Re* relation must eventually become negative.

Thus it is concluded that *f-Re* relations for desert hillslopes have two basic shapes: convex-upward and negatively sloping. These shapes arise from the progressive inundation of ground surfaces with different configurations. As overland flow on desert hillslopes is composite, changes in state of flow are difficult to define and appear to have relatively little influence on the shape of the *f-Re* relation. Although some progress has been made in linking the shape of the relation to the configuration of the ground surface, the linkage is obviously complex and requires a great deal more study.

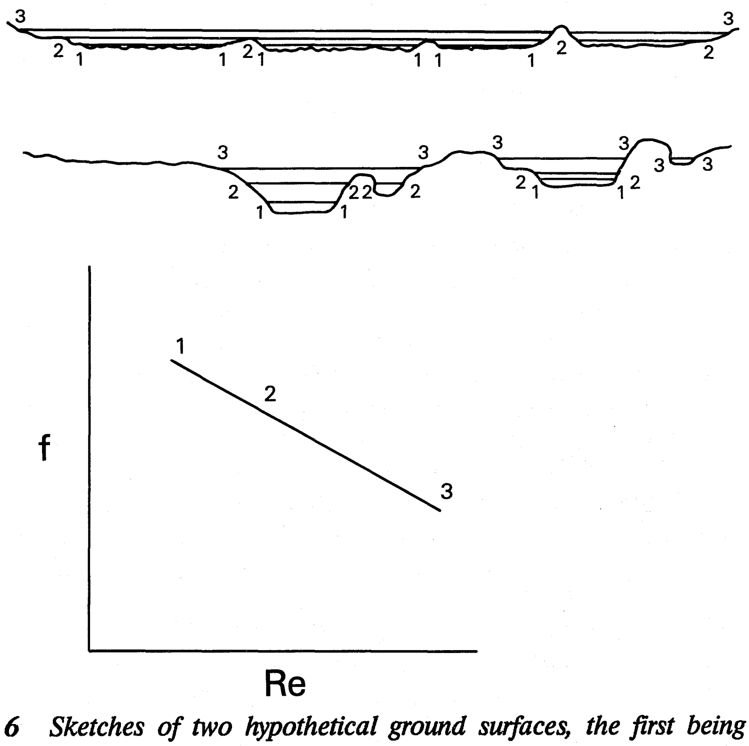

Fig. 6 Sketches of two hypothetical ground surfaces, the first being almost planar with multiple small roughness elements and the second being rilled, showing how the progressive inundation of such surfaces gives rise to negatively sloping f-Re relations. The numbers identify particular water surface levels and their corresponding f and Re values.

DOWNSLOPE ANALYSES

Overland flow without rainfall

The at-a-section analyses were concerned with the variation in f with respect to Re, where $Re = 4Q/w\upsilon$ and w and υ are constant. However, Re cannot be used in the analysis of downslope changes in resistance to flow because, although Q always decreases systematically downslope, Re does not. This is because irregularities in the walls of the runoff plots cause w to vary between cross sections. Indeed, during some runs w actually decreases downslope from one cross section to the next by a larger proportion than Q decreases, causing Re to increase. Consequently, Re does not always decrease downslope and is an unreliable indicator of the downslope direction. Therefore in the downslope analyses f was analysed with respect to Q rather than Re. Furthermore, because of the variation in w, the downslope relations between f and Q could not be computed algebraically from those between d and Q, as in the at-a-section analyses. Accordingly, the relations between f and Q were determined empirically.

Each downslope analysis examined the variation in f as Q declined from C1 to C3 during a single run on a given plot. Because there were only three cross sections, the relation between f and Q had to be computed from a maximum of three points. So we chose to represent it by a simple log-linear equation of the form.

$$\log f = j_1 + j_2 \log Q \qquad (5)$$

Inasmuch as P6-C2 and P6-C3 had been earlier discarded, only one cross section remained on P6, and it was impossible to compute any f-Q relations for this plot. P2-C3 and P3-C3 had also been discarded, leaving two cross sections each on P2 and P3. The f-Q relations for these plots were therefore calculated from just two points. For the remaining three plots the structural relation between f and Q for each run was estimated by computing the reduced major axis (Miller & Kahn, 1962, p. 204-205).

Downslope f-Q relations were determined for a total of 30 runs on five plots. For 28 of the relations, the computed correlation coefficients exceed 0.60 (Table 1), signifying at least modest linearity in the data. The correlation coefficients for the remaining two relations are −0.10 and −0.13, denoting essentially no linearity. These two relations were therefore disregarded. The computed values of j_2 for the remaining 28 relations range from 2.39 to 62.71 and have a mean of 11.05 (Fig. 7). Thus all the values of j_2 are positive, indicating that when there is a systematic change in f as discharge decreases down the runoff plots; it always decreases. When discharge increases downslope under natural rainfall, resistance to flow might be expected to decrease owing to an increase in relative submergence (Emmett, 1970). However, inasmuch as discharge always decreases down the runoff plots during R3 through R8, the decrease in f cannot be explained in this way, and one must seek another explanation.

The decrease in f appears to be due to the progressive concentration of flow

Table 1 Slope and correlation coefficients for downslope friction factor-discharge relations

Plot	Run	Downstream change in discharge*	Slope coefficient (j_2)	Correlation coefficient
P1	R1	-	--**	--
	R2	D	70.57	0.73
	R3	D	-0.23	-0.10
	R4	D	7.68	0.85
	R5	D	9.33	0.97
	R6	D	62.71	0.99
	R7	D	12.41	0.94
	R8	D	5.46	0.99
P2	R1	-	--**	--
	R2	D	10.76	1.00***
	R3	D	5.17	1.00
	R4	D	14.15	1.00
	R5	D	15.12	1.00
	R6	D	10.53	1.00
	R7	D	9.73	1.00
	R8	D	9.34	1.00
P3	R1	I	-0.28	1.00***
	R2	I	-151.05	1.00
	R3	D	8.70	1.00
	R4	D	35.90	1.00
	R5	D	20.85	1.00
	R6	D	8.04	1.00
	R7	D	19.63	1.00
	R8	D	6.00	1.00
P4	R1	-	--**	--
	R2	D	32.68	0.83
	R3	D	3.51	1.00
	R4	D	3.03	0.98
	R5	D	2.50	0.75
	R6	D	3.76	0.99
	R7	D	2.54	0.75
	R8	D	2.65	0.89
P5	R1	-	--****	--
	R2	D	4.92	0.78
	R3	D	-0.44	-0.13
	R4	D	2.39	0.61
	R5	D	3.26	0.76
	R6	D	6.35	0.81
	R7	D	8.94	0.91
	R8	D	9.62	0.96

* *D = decrease; I = increase*
** *Constant discharge not attained.*
*** *The perfect correlations for the runs on this plot are due to the relations being fitted to only two points.*
**** *Overland flow was too shallow for accurate depth measurements to be made.*

down the runoff plots. On P1, P2, P3 and P5 this concentration of flow is aided by the plot walls. On these plots some of the overland flow is directed by the microtopography toward one of the side walls where it forms a major thread that continues downslope adjacent to the wall. However, even where the flow is not confined by the side walls, it tends to concentrate downslope, as on P4. Thus the field experiments suggest that on the desert hillslopes under study, f decreases downslope owing to a tendency for overland flow to concentrate in that direction.

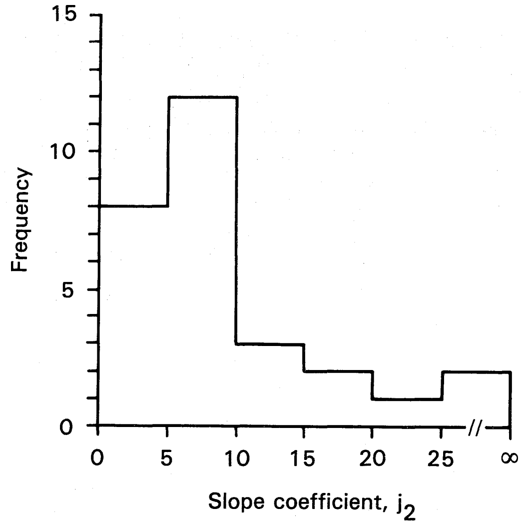

Fig. 7 Frequency distribution of the slope coefficient in the downslope f-Q relation for runs without rainfall.

Overland flow with rainfall

There is some question, however, whether these field experiments using overland flow without rainfall accurately simulate overland flow during natural rainstorms. In a recent study, Dunne & Aubry (1986) have argued that when overland flow occurs in the absence of rainfall, it is inherently unstable and incises rills. On the other hand, when it is accompanied by rainfall, rainsplash diffuses sediment from protuberances into rills and eradicates these features. Thus the possibility must be considered that the progressive concentration of overland flow down the runoff plots during R3 through R8 was the result of incision in the absence of rainfall and does not represent the actual situation in these desert hillslopes under natural rainfall. If overland flow does not concentrate downslope under rainfall, then f may not decrease downslope.

To investigate this possibility the downslope f-Q relations were analysed for the first two runs on each plot. During R1 simulated rainfall alone was applied to each plot, and during R2 rainfall was combined with inflow trickled onto the upper end of each plot. Certain runs, however, had to be excluded from the analysis. Specifically, P5-R1 and P6-R1 were excluded because the overland flow was so shallow that accurate depth measurements could not be made. P1-R1, P2-R1, and P4-R1 were omitted because during these runs the outflow continued to increase after measurements began. Thus steady state conditions, which are essential for any downslope analysis, did not obtain. Finally, P6-R2 was discarded because severe erosion during the run significantly altered the shapes of C2 and C3. Six runs therefore remained. However, the analyses of three of these runs, namely P2-R2, P3-R1, and P3-R2, were limited to two cross sections, as the mean flow depths were inflated by the scouring of a plunge pool at P2-C3 and the impounding of water behind an organic dam at P3-C3.

During two of these six runs, P3-R1 and P3-R2, discharge increased downslope, whereas during the other four runs, P1-R2, P2-R2, P4-R2, and P5-R2, it decreased. Table 1 shows that where discharge increased downslope j_2 is negative, and where discharge decreased downslope it is positive. In other words, f decreased down the runoff plots during all six runs. That f should decrease, despite a downslope decrease in discharge, during four of the runs implies that the decrease in f was the consequence of an increase in hydraulic efficiency associated with the progressive downslope concentration of flow. An examination of the cross sections for the six runs reveals that this concentration of flow was aided by a side wall during only one run. These results are consistent with those for overland flow without rainfall and leave little doubt that f decreases down the desert hillslopes under study during natural rainfall, and that this decrease is due to the progressive downslope concentration of flow.

This conclusion contrasts with Emmett's (1970) finding that f remains approximately constant down the semiarid hillslopes he investigated in Wyoming. Emmett attributed the fact that f does not decrease down his hillslopes to ponding of the flow behind microtopographic highs, notably vegetation mounds. There were few vegetation mounds on our runoff plots, and the only ponding we observed was behind occasional organic dams or in rare plunge pools. Thus the discrepancy between Emmett's and our findings appears to be due to differences in the relative importance of ponding, and this seems to be related to the density of vegetation mounds. On other hillslopes different factors may be important, so care must be taken in generalizing from either Emmett's or our findings. Even so, it seems likely that in desert landscapes where vegetation is sparse and ponding is rare, our findings will apply more widely than Emmett's, and overland flow will concentrate downslope, causing resistance to flow to decline.

SUMMARY AND CONCLUSION

This paper describes a series of experiments performed on six runoff plots in semiarid southern Arizona aimed at investigating both at-a-section and downslope variations in resistance to overland flow on desert hillslopes. The surfaces of these plots were irregular and covered with stones. As overland flow increased, the stones and microtopographic protuberances, which constituted the major roughness elements, were progressively inundated, thereby altering the flow resistance.

Analyses of 14 cross sections on the runoff plots suggest that at-a-station *f-Re* relations have two basic shapes: convex-upward and negatively sloping. These shapes can be understood in terms of the simultaneous operation of two processes. The first is the progressive inundation of roughness elements and increase in their wetted upstream projected area as discharge increases. This process causes flow resistance to increase. The second is the progressive increase in depth of flow over already inundated parts of the cross section as discharge increases. This process causes flow resistance to decline. On some hillslopes the first process dominates at low discharges and the second at high discharges to produce a convex-upward *f-Re* relation. However, on other hillslopes the first process never dominates, and the *f-Re* relation is negatively sloping over the full range of *Re* experienced. The present analyses indicate that this can occur where the flow remains concentrated as discharge increases or where the roughness elements are sufficiently small that they are rapidly submerged at low discharges.

This study therefore suggests that the conventional *f-Re* relation for shallow flow over a plane bed does not apply to desert hillslopes and should not be employed in mathematical models of overland flow on such hillslopes. In view of the sensitivity of the computed hydrographs to the *f-Re* relation, there is an urgent need to develop a practical and reliable method of estimating this relation for a given hillslope. The apparent dependence of the *f-Re* relation on the configuration of the surface suggests that the development of such a method will require a closer study of the connection between the relation and surface morphology. Given the irregular character of the ground surface and the composite nature of the flow on desert hillslopes, there is great scope for using laboratory experiments for this purpose. However, these experiments will need to be performed on realistic irregular surfaces, rather than on the planar ones employed heretofore.

The downslope analyses of f both with and without rainfall, indicate that there is a general tendency for f to decrease down the runoff plots owing to the progressive downslope concentration of flow and consequent increase in hydraulic efficiency. f decreases down the plots despite the fact that during almost every run discharge decreases downslope. Thus one might expect that during major natural storms when discharge increases downslope, the decrease in f would be even more pronounced.

This finding contrasts with Emmett's (1970) conclusion that f remains approximately constant downslope. The discrepancy appears to be due to the greater incidence on Emmett's hillslopes of ponding behind microtopographic highs, notably vegetation mounds. It therefore seems likely that our findings have wider applicability than Emmett's on desert hillslopes with sparse vegetation covers.

It remains unclear why there is a strong tendency on the hillslopes under study for overland flow to concentrate downslope, and further research is required on this subject. Whatever the reason, it appears certain that this tendency promotes the development of rills, which give rise to higher erosion rates than unconcentrated sheetflow (Kirkby & Kirkby, 1974; Meyer *et al.*, (1975). Thus the high drainage densities and sediment yields typically associated with semiarid environments may stem from this tendency. Further studies of downslope variations in flow resistance are therefore required. However, these need to be conducted at a larger scale than the runoff plots investigated here, ideally at the scale of the entire hillslope.

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