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Controls of sediment transport capacity in laminar interrill flow on stone-covered surfaces

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Abstract. Sediment transport capacity is an important control on soil erosion and deposition by overland flow. To investigate the controls of transport capacity in laminar interrill overland flow on stone-covered surfaces, 357 flume experiments were performed using a single sediment size. Multiple regression analyses reveal that transport capacity is positively related to excess flow power $\omega - \omega_c$, but the slope of the relation is steeper where $\omega < 0.3$ W m^{-2} than where $\omega \geq 0.3$ W m^{-2}. Transport capacity is positively related to rainfall intensity where $\omega < 0.3$ W m^{-2} and negatively related to rainfall intensity where $\omega \geq 0.3$ W m^{-2}. Transport capacity is negatively related to stone concentration and positively related to stone size irrespective of the value of ω. Finally, transport capacity is negatively related to fluid viscosity where $\omega < 0.3$ W m^{-2} and unrelated to viscosity where $\omega \geq 0.3$ W m^{-2}.

1. Introduction

Most physically based soil erosion models distinguish between the processes of soil detachment, transport, and deposition. In interrill areas these processes are due to the combined action of raindrops and overland flow. Where the soil surface is exposed to rainfall, raindrops play an important part in detaching soil particles, but overland flow usually has the dominant role in transporting these particles downslope. A basic control of the rate of soil erosion and deposition by overland flow is its transport capacity T_c, that is, the maximum sediment load that the flow is capable of transporting. Erosion occurs (assuming the surface is erodible) where the sediment load arriving from upslope is less than T_c, whereas deposition occurs where the sediment load is greater than T_c. Thus the ability of these physically based soil erosion models to accurately predict soil loss is contingent on their ability to estimate T_c.

This study is concerned with the transport capacity of laminar interrill flow. For present purposes, a flow is considered to be laminar if its Reynolds number Re, equal to $4q_w/\nu$, where q_w is flow discharge per unit width and ν is kinematic viscosity of the fluid, is less than 2000. In laminar interrill flow, sediment transport is accomplished by fluid lift and drag forces and by rain-flow transportation. Rain-flow transportation refers to the downslope movement of sediment in overland flow as a result of raindrops disturbing the flow. The mechanisms involved in rain-flow transportation have been described by *Moss et al.* [1979] and *Kinnell* [1991].

A number of studies have reported that rainfall enhances T_c in laminar interrill flow on low slopes [e.g., *Moss et al.*, 1979; *Guy et al.*, 1987; *Everaert*, 1991; *Kinnell*, 1991]. For example, *Moss et al.* [1979] noted that on slopes less than 4.7°, rainfall had a positive effect on T_c, but on steeper slopes it had little or no effect. They attributed the positive effect of rainfall to rain-flow transportation. *Everaert* [1991] observed that rainfall had a positive effect on T_c where shear velocities were less than 0.02 m s^{-1}, and he too ascribed this effect to rain-flow transportation. Where shear velocities were greater than 0.02 m s^{-1}, *Everaert* [1991] found that rainfall had a negative effect of T_c. *Meyer and Monke* [1965] also showed that rainfall could decrease as well as increase T_c. Still, the negative influence of rainfall on T_c is not widely recognized and is contrary to the conventional view of the effect of rainfall on T_c depicted in Figure 1.

Traditionally, studies of transport capacity of laminar interrill flow have been made on plane beds [e.g., *Kilinc and Richardson*, 1973; *Guy et al.*, 1987; *Lu et al.*, 1989]. However, natural hillslope surfaces are hydraulically very rough in that the flow depths are typically much less than the height of roughness elements (e.g., stones, plants, litter, and microtopographic protuberances). *Bunte and Poesen* [1994] examined the effect of stones on sediment yield from a flume whose bed consisted of a noncohesive sandy loam soil. Laminar overland flow was generated by trickle. *Bunte and Poesen* [1994] found that where the stones were pebbles (median diameter D_{50} = 1.5 cm), sediment yield increased with stone cover up to 25% and thereafter decreased. However, where the stones were cobbles (D_{50} = 8.6 cm), sediment yield increased monotonically with stone cover. *Bunte and Poesen* [1994] argued that for pebble covers less than 45% and cobble covers less than 80%, the flow was transport limited, thereby implying that T_c varied in the same manner as sediment yield with stone cover. *Bunte and Poesen*'s [1994] findings apply to overland flow in the absence of rainfall, but it is not clear whether they apply in the presence of rainfall.

In laminar interrill flow, the viscous forces become important relative to the inertial forces, and T_c might be expected to be related to fluid viscosity, but the nature of this relation is unclear where the boundary is rough and the flow is disturbed by raindrops. On the one hand, because sediment particles are entrained by viscous drag, T_c might be expected to be posi-

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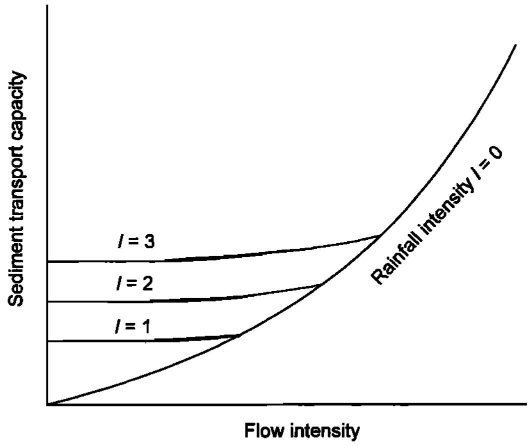

Figure 1. Conventional view of the relation between sediment transport capacity, flow intensity, and rainfall intensity. All units are arbitrary and the scales are arithmetic. After *Kirkby* [1980, Figure 1.4]. Copyright John Wiley and Sons Limited. Reproduced with permission.

tively related to fluid viscosity. On the other, sediment particles are also entrained by disturbances to the flow generated by raindrop impact and surface roughness. Because such disturbances are damped by increases in viscosity, T_c might be expected to be negatively related to fluid viscosity. Which of these two relations dominates has yet to be determined.

This paper reports on a set of flume experiments aimed at elucidating the controls of T_c in laminar interrill flow on stone-covered surfaces. To limit the experiments to a manageable number, only a single sediment size was used, and the analysis focuses on the effects of excess flow power, rainfall intensity, stone concentration, stone size, and fluid viscosity on T_c.

2. Experimental Setup and Methods

The flume was 5.2 m long and 0.4 m wide with a smooth aluminum bed and Plexiglas walls (Figure 2). It consisted of two parts: a lower part 3.6 m long and an upper steeper part 1.6 m long. For the experiments the lower part of the flume was inclined at four slopes θ, 2.0°, 2.7°, 5.5°, and 10.0°, and was covered by a well-sorted silica testing sand with median diameter of 0.74 mm (ASTM C-190) and a density ρ_s of 2650 kg m^{-3}. During the experiments, sand was supplied from a vibrating hopper to the upper part of the flume and traveled down the flume either very largely or entirely as bedload. *Hu and Hui*'s [1996] equations indicate that the proportion of grains transported by rolling or saltation ranged from 77 to 100%. Water entered the upper part of the flume by overflowing from a head tank. The water inflow of 43.4–264 cm^3 s^{-1} was controlled by a gate valve and measured with a rotameter. The density of the water ρ was assumed to be 1000 kg m^{-3}, while the kinematic viscosity ν was determined from water temperature, which ranged from 6.5° to 35°C. Fixing ρ while varying ν with temperature can be justified on the grounds that ρ varies by less than 0.05% over the measured range of temperature, while ν varies by almost a factor of 2.

During the experiments simulated rainfall was applied at intensities I of 0.9, 1.8, and 2.7 mm min^{-1} from one, two, and three Spraco-Lechler full cone jet nozzles [*Luk et al.*, 1986] mounted 0.3 m apart and 3.6 m above the center of the flume. The raindrop sizes, determined by the flour pellet method [*Laws and Parsons*, 1943], varied from 0.4 to 4.8 mm and had median values for the three intensities of 1.6, 2.0, and 2.4 mm, respectively. Drop size increased with rainfall intensity because the spray cones intersected when the second and third nozzles were operating, causing the water drops to collide and form larger drops. Given that the flow velocity from each nozzle exceeded 5 m s^{-1}, established by dividing the outflow from the nozzle (0.000185 m^3 s^{-1}) by its cross-sectional area (0.000033 m^2), and taking into account that the maximum angle of spray with respect of vertical fall path was 60°, it was calculated that all but the smallest drops reached terminal velocity. From the terminal velocity–drop size relation [*Laws*, 1941; *Gunn and Kinzer*, 1949] and the measured drop size distributions, the total kinetic energies of the three intensities were computed to be 0.24, 0.65, and 1.19 J m^{-2} s^{-1}, respectively. These kinetic energies are 48, 68, and 85%, respectively, of the energies of natural rainstorms at the same intensities [*Kinnell*, 1973]. The spatial uniformity of the rainfall was evaluated using eight rain gages during nine 30-min events. The coefficient of variation averaged 0.093, indicating a highly uniform distribution. Water discharge Q at the end of the flume was calculated by adding the rainfall onto the flume to the water inflow from the head tank.

The flume bed was covered with stones to mimic a desert hillslope. Three groups of stones were collected from a local river bed. The stones in the three groups were similar in shape (with a mean Corey shape factor $c/(ab)^{1/2}$ ranging from 0.566 to 0.605) and in roundness (with all groups having a modal roundness index of 5 on *Powers*' [1953] six-point scale) but different in size. Because the stones were randomly placed in the flume with their a-b planes parallel to the bed, stone size was measured by $(a + b)/2$. The median values of this index D_r were 2.80, 4.55, and 9.13 cm for the three groups. The proportion of the bed covered by stones C ranged from 0 to 0.3. Owing to the shallowness of the flows, the stones always protruded above the water surface.

The mean flow velocity u was determined by a salt-tracing technique described elsewhere [*Li and Abrahams*, 1997]. With Q and u known, mean flow depth d was calculated using $d = Q/uw$ and $w = W(1 - C)$, where w and W are the mean flow width and the flume width, respectively. The outflow of water and sediment from the flume was sampled, and sediment concentration C_s was determined gravimetrically. Sediment transport capacity T_c was then obtained from $T_c = q_w C_s$, where $q_w = Q/w$.

In total, 357 experiments were undertaken representing 48 different combinations of flow, stone, and rainfall properties

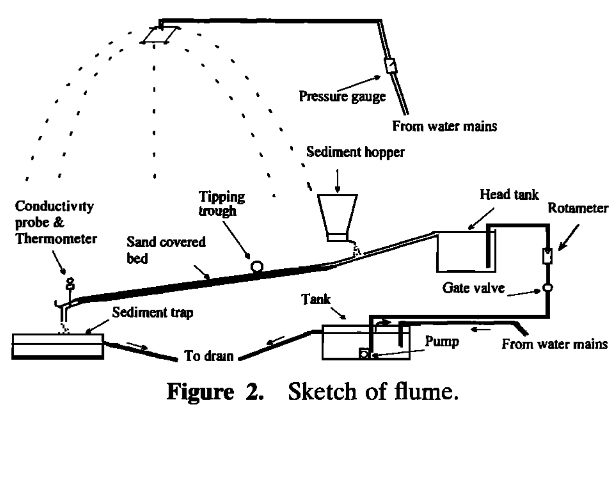

Figure 2. Sketch of flume.

(Table 1). For the experiments, Re ranged from 878 to 1996, indicating a laminar flow regime. The original intention was to analyze the experiments as a single sample. However, Figure 3 suggests that the data should be divided into two samples. Figure 3a contains a plot on logarithmic axes of T_c against flow power $\omega = \tau u$, where $\tau = \rho g d S$ is bed shear stress, g is the acceleration of gravity, and $S = \sin \theta$ is the energy slope. The graph shows that where $\omega < 0.3$ W m^{-2} rainfall has a positive effect on T_c. The same data are plotted in Figure 3b on arithmetic axes. The graph suggests that where $\omega \geq 0.3$ W m^{-2}, rainfall has a negative effect on T_c, a suggestion supported by statistical analyses later in the paper. It thus appears that the variables controlling T_c depend on the value of ω. Figure 3 also reveals a large overlap between the plotted points for the experiments with and without rainfall. This is because other variables beside I and ω, such as C, D_r, and λ, influence T_c. To unravel the influences of these variables on T_c, the data were divided into two samples according to whether ω was greater or less than 0.3 W m^{-2}, and the relevant variables were subjected to multiple regression.

3. Multiple Regression Analyses

Before regression analyses could be performed, two issues had to be addressed. The first was the determination of critical flow power, and the second was the form of the regression model.

3.1. Critical Flow Power

Where there is some critical value of flow power ω_c below which bed sediments do not move, the appropriate measure of flow power to be related to T_c is excess flow power $\omega - \omega_c$. However, the determination of ω_c is problematic. Where rainfall accompanies interrill flow, raindrops continue to disturb the bed and lift particles into the flow as flow power diminishes and approaches zero. It follows that sediment transport takes place under rainfall no matter how small the flow. Consequently, for the present experiments with rainfall, ω_c was assumed to be zero. This assumption is supported by *Moss et al.*'s [1979] observations of rain-flow transportation on zero slopes.

For the experiments without rainfall, there appears to be no way of computing ω_c. Accordingly, for every experiment without rainfall, ω_c was assigned the value 0.020 W m^{-2}. This value was chosen because it is the mean of ω_c (standard deviation = 0.0067 W m^{-2}) for a parallel set of 237 experiments involving transitional and turbulent overland flows on stone-covered beds. The method of calculating ω_c in these experiments is described by *Abrahams et al.* [1998]. Although predicting critical transport conditions for laminar flows from analyses of transitional and turbulent flows may not be strictly valid, the estimated value of ω_c seems reasonable and so is used in the absence of any better approach.

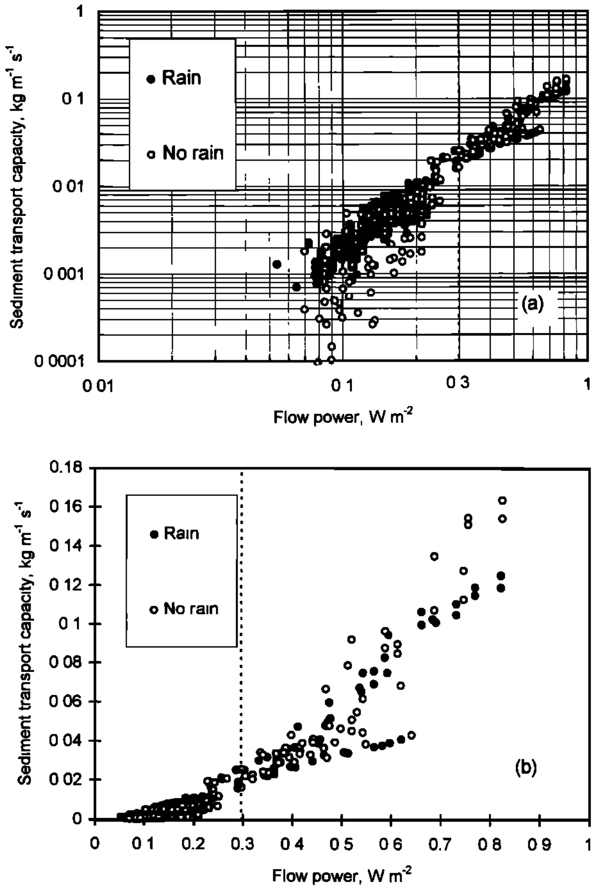

Figure 3. Graphs of transport capacity T_c versus flow power ω (a) on logarithmic axes, showing the positive effect of rainfall on T_c where $\omega < 0.3$ W m^{-2}, and (b) on arithmetic axes, showing the negative effect of rainfall on T_c where $\omega \geq 0.3$ W m^{-2}.

Table 1. Experimental Design

Slope S, deg	Stone Size D_r, cm	Stone Coverage C	Temperature T, °C	Rain Intensity I, mm min^{-1}
2.0	0.00	0.00	7	0, 1.8, 2.7
2.0	0.00	0.00	35	0, 1.8, 2.7
2.0	2.80	0.25	7	0, 1.8
2.0	2.80	0.25	35	0, 1.8
2.0	4.55	0.15	7	0, 1.8, 2.7
2.0	4.55	0.15	35	0, 1.8, 2.7
2.0	4.55	0.25	7	0, 1.8, 2.7
2.0	4.55	0.25	35	0, 1.8
2.0	9.13	0.25	7	0, 1.8
2.0	9.13	0.25	35	0, 1.8
2.7	0.00	0.00	20	0, 0.9, 1.8, 2.7
2.7	2.80	0.08	20	0
5.5	0.00	0.00	7	0, 1.8, 2.7
5.5	0.00	0.00	20	0, 0.9, 2.7
5.5	2.80	0.08	20	0.9, 1.8, 2.7
5.5	2.80	0.25	7	0, 1.8, 2.7
10.0	0.00	0.00	20	0, 0.9, 2.7
10.0	2.80	0.08	20	0, 0.9, 2.7

3.2. Regression Forms

Empirical sediment transport equations for overland flow are usually power functions [e.g., *Finkner et al.*, 1989; *Low*, 1989; *Govers*, 1992]. Consequently, models of this form were initially investigated using nonlinear regression, but convergence could not be achieved apparently because I, C, and D_r are frequently zero. Linear regression of log-transformed variables was therefore necessary, but the zeros still posed a problem insofar as the logarithm of zero is undefined. The problem was tackled in two ways. First, a small constant, specifically 0.001, was added to I, C, and D_r before log-transforming these variables (to the base 10). Second, I, C, and D_r were retained as arithmetic variables in the regression analyses. Thus the stepwise regressions took two forms. In the first, log T_c was regressed against log $(\omega - \omega_c)$, log $(I + 0.001)$, log $(C +$

Table 2. Multiple Regression Analyses

Sample	Sample Size	Regression Equation and Standardized Regression Coefficients	Coefficient of Determination
$\omega < 0.30$	259	$\log T_c = 6.796 + 2.230 \log(\omega - \omega_c) + 4.496 \log(I + 0.001) - 0.322 \log(C + 0.001) + 0.372 \log(D_r + 0.001) - 1.061 \log \nu$	0.733
		0.873 0.074 −0.847 0.717 −0.227	
		$\log T_c = -7.043 + 2.240 \log(\omega - \omega_c) + 0.037\, I - 1.211\, C + 3.232\, D_r - 1.093 \log \nu$	0.734
		0.877 0.877 −0.315 0.232 −0.233	
$\omega \geq 0.30$	98	$\log T_c = -0.579 + 1.754 \log(\omega - \omega_c) - 0.022 \log(I + 0.001) - 0.287 \log(C + 0.001) + 0.331 \log(D_r + 0.001)$	0.932
		0.858 −0.148 −1.342 1.094	
		$\log T_c = -0.662 + 1.705 \log(\omega - \omega_c) - 0.037\, I - 1.0218\, C + 2.068\, D_r$	0.937
		0.834 −0.161 −0.484 0.236	

0.001), log $(D_r + 0.001)$, and log ν, while in the second, log T_c was regressed against log $(\omega - \omega_c)$, I, C, D_r, and log ν.

3.3. Regression Results

The results of the multiple regressions are summarized in Table 2. For ease of comparison, the independent variables appear in the same order in each regression equation, even though this is not necessarily the order in which they entered the equation. Below each variable is the standardized regression coefficient associated with that variable. This coefficient indicates the relative contribution of the variable to log T_c. All regression coefficients are significantly different from zero at the 0.05 level.

For $\omega < 0.3$ W m^{-2}, all five independent variables enter both regression equations, the regression coefficients associated with each variable have the same sign, and the R^2 values are almost identical. For $\omega \geq 0.3$ W m^{-2}, only four independent variables enter the regression equations. Again, the signs of the regression coefficients associated with each variable are the same, and the R^2 values are very similar. Thus the form of the regression appears to make little difference to the basic results, which are discussed in the following section.

4. Discussion

4.1. Excess Flow Power

The standardized regression coefficients indicate that T_c is always positively related to $\omega - \omega_c$ and that $\omega - \omega_c$ has a major influence on T_c (Table 2). The unstandardized regression (slope) coefficients associated with $\omega - \omega_c$ are about 1.7 where $\omega \geq 0.3$ W m^{-2} and about 2.2 where $\omega < 0.3$ W m^{-2}. Figure 3a shows that the larger slope coefficients where $\omega < 0.3$ W m^{-2} are due to transport capacities for flows undisturbed by rainfall plotting below those for flows disturbed by rainfall.

4.2. Rainfall Intensity

The regression analyses indicate that T_c is positively related to I where $\omega < 0.3$ W m^{-2} and negatively related to I where $\omega \geq 0.3$ W m^{-2} (Table 2). These results are in keeping with Figure 3, which shows that rainfall has a positive effect on T_c where $\omega < 0.3$ W m^{-2} and a negative effect where $\omega \geq 0.3$ W m^{-2}. The positive effect is attributed to rain-flow transportation, which is the same conclusion reached by *Moss et al.* [1979] and *Everaert* [1991]. The negative effect is consistent with *Meyer and Monke*'s [1965] and *Everaert*'s [1991] findings and is ascribed to rainfall suppressing channel formation and increasing resistance to flow. In the present experiments where $\omega \geq 0.3$ W m^{-2} the flow displayed a more or less braided pattern, with concentrations of flow diverging and converging downslope irrespective of whether or not it was raining. However, the "channels" occupied by these concentrations were deeper and more sharply defined when rainfall was not occurring. Rainfall suppressed channel formation by degrading the channel banks and pushing (as opposed to splashing) sediment from the emergent bars into the channels. As a consequence, the channels were wider and shallower and the flow was slower with rainfall than without it. In addition, rainfall is presumed to have increased resistance to flow and reduced flow velocity as momentum was transferred from the flow to the rainfall mass to bring it up to the speed of the flow [*Yoon and Wenzel*, 1971; *Shen and Li*, 1973; *Katz et al.*, 1995]. Thus the tendencies for rainfall to suppress channel formation and to increase flow resistance both cause T_c to decline by reducing flow velocity.

The analysis above suggests that the conventional view of the effect of rainfall on T_c depicted in Figure 1 needs to be modified. An alternative conceptualization is presented in Figure 4. In this diagram, rainfall is shown to have both positive and negative effects on T_c in laminar interrill flow, with the boundary between the two effects being denoted by ω_{b1}. The present experiments shed no light on what happens at higher flow powers in turbulent flow, but other research suggests that resistance to flow due to rainfall becomes insignificant in turbulent flow [*Yoon and Wenzel*, 1971; *Shen and Li*, 1973]. Moreover, it seems reasonable to suppose that as fluid lift and drag forces increase with flow power, the ability of rainfall to sup-

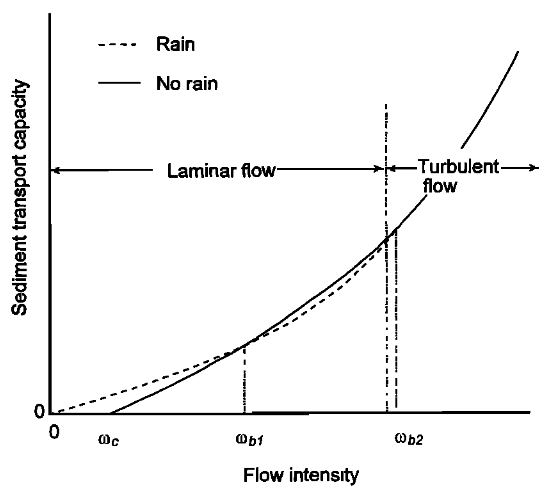

Figure 4. Proposed conceptualization of the effect of rainfall on the relation between sediment transport capacity and flow power. Rainfall intensity is constant. All units are arbitrary, and the scales are arithmetic.

press channel development diminishes. Thus at higher flow powers in turbulent flow, rainfall might be expected to have little or no effect on T_c, and this is confirmed by the experiments of *Abrahams et al.* [1998]. This second threshold marking the upper limit of the negative effect of rainfall on T_c is denoted by ω_{b2} in Figure 4.

4.3. Stone Concentration

Unlike I, the effect of stone concentration C on T_c does not depend on the value of ω: T_c is negatively related to C for both $\omega < 0.3$ W m^{-2} and $\omega \geq 0.3$ W m^{-2} (Table 2). The negative relation between T_c and C is attributed to an increase in C causing an increase in form resistance [*Abrahams et al.*, 1992; *Abrahams and Parsons*, 1994] which in turn causes a decrease in flow velocity and a decrease in T_c. An increase in form resistance also produces an increase in flow depth, which may reduce the ability of raindrops to entrain and transport bed sediments and so decrease T_c. The negative relation between T_c and C is inconsistent with *Bunte and Poesen*'s [1994] finding of a positive relation between these variables. They ascribed their positive relation to horseshoe vortices increasing in magnitude and intensity as C increases ($0 \leq C \leq 0.25\%$). Unlike *Bunte and Poesen*'s [1994] experiments, the present ones employed rainfall. Observations during these experiments suggest that rainfall partially suppresses or damps horseshoe vortices. Thus C effects T_c (1) by increasing roughness-induced vorticity, which increases T_c, and (2) by increasing form resistance, which decreases T_c. These two mechanisms operate simultaneously in any interrill flow on a rough surface. In *Bunte and Poesen*'s [1994] experiments ($0 \leq C \leq 25\%$) without rainfall, the first mechanism dominates, while in the present experiments with rainfall, the second mechanism dominates.

4.4. Stone Size

The regression analyses show that stone size D_r is positively related to T_c regardless of ω (Table 2). There are two reasons for this relation. First, large stones deflect larger quantities of water than do small ones, thereby forming larger horseshoe vortices, which sustain greater transport capacities [*Bunte and Poesen*, 1994]. Second, a given concentration of large stones offers less resistance to flow than does the same concentration of small stones [*Abrahams et al.*, 1998, Table III], causing flow velocity to increase with D_r and T_c to increase. Large stones impede overland flow less than do small ones because, particularly at low concentrations, they tend to funnel the flow into well-defined threads that have higher velocities than the dispersed flow through a comparable concentration of small stones.

4.5. Viscosity

The regression analyses reveal that T_c is negatively related to flow viscosity ν where $\omega < 0.3$ W m^{-2} and unrelated to ν where $\omega \geq 0.3$ W m^{-2} (Table 2). Thus low-viscosity flows carry more sediment than high-viscosity ones at flow powers less than 0.3 W m^{-2} but not at higher flow powers. The negative effect of ν on T_c at low flow powers is attributed to viscous damping of eddies and vortices generated by raindrops and stones. Where $\omega \geq 0.3$ W m^{-2} it is speculated that the vortices produced by stones become sufficiently energetic that viscous damping no longer influences the ability of these vortices to sustain sediment transport, and so T_c becomes independent of ν.

5. Conclusions

A set of 357 flume experiments was undertaken to investigate the controls of T_c in laminar interrill flow on stone-covered surfaces. These controls vary according to whether ω is greater or less than 0.3 W m^{-2}. The principal conclusions are as follows.

1. Transport capacity is positively related to $\omega - \omega_c$, but the slope of the relation is steeper where $\omega \leq 0.3$ W m^{-2} than where $\omega \geq 0.3$ W m^{-2} because in the former but not the latter situation, interrill flows undisturbed by rainfall transport less sediment than do disturbed flows.

2. Transport capacity is positively related to rainfall intensity where $\omega < 0.3$ W m^{-2} and negatively related to rainfall intensity where $\omega \geq 0.3$ W m^{-2}. The positive relation is attributed to rain-flow transportation, and the negative relation is attributed to rainfall suppressing channel formation and increasing resistance to flow. At higher flow powers in turbulent flow, T_c is probably unrelated to rainfall intensity.

3. Transport capacity is negatively related to stone concentration irrespective of the value of ω. This is because an increase in concentration causes an increase in flow resistance, which in turn causes a decrease in flow velocity and a decrease in T_c.

4. Transport capacity is positively related to stone size regardless of ω. There are two reasons for this. First, large stones form larger horseshoe vortices which sustain greater transport capacities than do small stones. Second, a given concentration of large stones offers less resistance to flow than does the same concentration of small stones, causing flow velocity to increase with stone size and T_c to increase.

5. Transport capacity is negatively related to fluid viscosity where $\omega < 0.3$ W m^{-2} and unrelated to viscosity where $\omega \geq 0.3$ W m^{-2}. The negative relation is attributed to viscous damping of eddies and vortices generated by raindrops and stones. Damping disappears at high flow powers because the vortices produced by stones become sufficiently energetic that viscous forces are overwhelmed by disturbances to the flow.

Notation

a	length of the long axis of a stone, m.
b	length of the intermediate axis of a stone, m.
c	length of the short axis of a stone, m.
C	stone concentration.
C_s	sediment concentration, kg m^{-3}.
d	flow depth, m.
D_r	stone size, m.
D_{50}	median particle diameter, m.
g	acceleration due to gravity, m s^{-2}.
I	rainfall intensity, mm min^{-1}.
q_w	unit water discharge, m^2 s^{-1}.
Q	water discharge, m^3 s^{-1}.
Re	flow Reynolds number.
S	energy slope, sine.
T_c	sediment transport capacity, kg m^{-1} s^{-1}.
u	mean flow velocity, m s^{-1}.
w	flow width, m.
W	flume width, m.
θ	slope angle, deg.
ν	kinematic viscosity, m^2 s^{-1}.
ρ	water density, kg m^{-3}.
ρ_S	grain density, kg m^{-3}.
τ	shear stress, N m^{-2}.

ω unit flow power, W m^{-2}.

ω_{b1}, ω_{b2} boundary values of ω defining the ranges of flow power over which rainfall has a positive effect and a negative effect on transport capacity, W m^{-2}.

ω_c critical unit flow power, W m^{-2}.

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