PLOT-SCALE SEDIMENT TRANSPORT PROCESSES ON A BURNED HILLSLOPE AS A FUNCTION OF PARTICLE SIZE

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Abstract Soil moisture, rainfall, runoff, and sediment transport data were collected from four 1-m^2 hillslope plots after the 2000 Hi Meadow Fire in Colorado. Data were collected daily during three summers, two of which were affected by drought. Maximum 30-minute rainfall intensities, I_{30}, were less than 20 mm h^{-1} and the average runoff volumes per plot were less than 4.7 L per storm. The data were separated into three sediment transport processes based on rainfall intensity and runoff magnitude: (1) dry ravel, (2) rainsplash, and (3) rainflow and then into eight different particle size classes (D_i). For each class, dry ravel transport had a non-linear dependence on initial soil moisture, θ_i, with a maximum at intermediate values of θ_i (5-9 % cm^3 cm^{-3}). Dry ravel transport rates were small for low θ_i, which may be caused by a cementation process, and also small for high θ_i, which may be caused by increased surface tension. Rainsplash transport was confined to the I_{30} domain from 1-7 mm h^{-1} was proportional to $D_i(I_{30}^{\max})^{0.63}$. Rainflow transport ($I_{30}$ > 7 mm h^{-1}) in shallow flows (h < 2 mm) was most likely dominated by particles rolling. It had a non-linear dependence on D_i with maximum transport of sediment in the 2-4 mm size class. Transport also depended on stream power, but critical stream power was essentially zero, which may indicate that the rainsplash preceding runoff detached soil for transport by overland flow.

INTRODUCTION

Increased runoff, erosion, and a spectrum of sediment transport processes are a consequence of fire and a major concern of land managers. At the hillslope scale, three soil erosion processes are possible after a fire: dry ravel, rainsplash, and rainflow. Dry ravel is the detachment of soil and transport of sediment by mechanisms other than water, such as wind or animal activity (Burkalow, 1945; Anderson et al., 1959; Rice, 1982; Wells, 1987; Shakesby and Doerr, 2006). Dry ravel has been documented during fires when sediment stored upslope against bushes, shrubs, and woody debris moves downhill as these obstacles burn (Wohlgemuth and Hubbert, 2008). Rainsplash is the detachment of soil by rain drop impacts (Poesen and Savat, 1981; Hartley and Julien, 1992) and the subsequent transport downhill, especially on steep slopes (Gabet and Dunne, 2003; Johansen et al 2001) and on slopes where fire has removed obstacles and smoothed the surface (Abrahams et al., 1986; Lawrence, 1997; Pannkuk and Robichaud, 2003). Rainsplash transport depends on the kinetic energy or momentum of rain drops with diameter, d [m]. When the soil particle diameter, D_i [m] > d, then the transport has been reported to be ~ D_i^{-3} and when D_i < d, it is ~ D_i^{-1} (Carson and Kirkby, 1972). Rain drop momentum has been related empirically to the rainfall intensity, I [mm h^{-1}] (Laws and Parsons, 1943; Gunn and Kinzer, 1949). Rainflow is sediment transport by shallow, overland flow in rivulets where detachment of soil is augmented by rain drop impacts (Moss and Green, 1983). In laboratory studies, rainflow reaches a maximum transport rate when the water depth is ~ 2-3 d (Moss and Green, 1983; Moss, 1988). At this threshold depth, rain drops can still penetrate the shallow water and detach soil particles, which are then entrained in the overland flow. The focus of this paper is to determine relative magnitude of the three sediment transport processes on a burned hillslope as a function of D_i.

FIELD SITE

The site was on a hillslope burned by the 2000 Hi Meadow Fire (4,370 ha) in the Colorado Front Range 50 km southwest of Denver, Colorado (fig. 1). It had a northwest aspect, slope of 0.27, and an elevation between 2420-2460 m (Moody et al., 2007). Mean annual precipitation is 424 mm. About half of the precipitation falls during the summer months (June-September) from convective rainstorms, which are typically short duration but high-intensity (Moody et al., 2007). The 2-, 10- and 100-year return periods for maximum 30-minute rainfall intensities, I_{30}^{max} are 29, 50, and 83 mm h^{-1} (Miller et al., 1973; Moody et al., 2007), and the 30-minute rainfall generally represents 79 percent of the total rainfall during a convective storm (Miller et al., 1973).

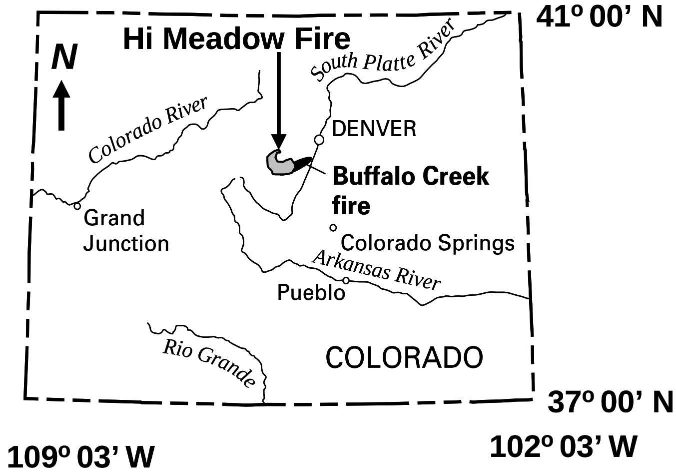


Figure 1 Location of the 2000 Hi Meadow Fire in Colorado.

METHODS

Soil moisture, rainfall, runoff, and sediment flux were measured at four hillslope plots during the summer months (June-September) of 2002, 2003, and 2004. Plots were square, with an area of 1 m^2, bounded by metal edging, and located at 10, 20, 40, and 80 m from the top of the hillslope. Seven surface sediment samples were collected randomly in 2002 from within a 100-m x 100-m area surrounding the four plots to characterize the source material available for transport (see Table 6, Moody et al., 2007). Soil samples (cores 0.03 m deep and 0.0475 m in diameter) were collected each morning adjacent to the plot, placed in metal soil cans, sealed, and the soil moisture content θ_i [% mass] was measured gravimetrically. Soil moisture content was recalculated as % cm^3 cm^{-3} using a bulk density of 1.43 g cm^3 (± 0.02 g cm^3) based on 76 volumetric samples collected on site.

Cumulative rainfall was recorded each morning at each plot and represented rainfall from the previous day plus any rain that fell earlier in the morning. Data from one recording, tipping bucket rain gage deployed at the top of the hillslope were analyzed to determine the start times, stop times, duration, cumulative volume, and rainfall intensities for each storm. Rainfall was grouped into 5-minute intervals. A single storm was defined as a span of time longer than 10 minutes during which there was no period, without rain, longer than 3 hours (autocorrelation of rainfall in this area was found to be < 0.01 at a lag of 3 hours). Thus, the minimum interstorm interval was 3 hours. Typically, a convective rainstorm would develop in the late morning and rain would fall during the afternoon, but on some days there were multiple storms separated by more than 3 hours. Total rainfall, storm duration, maximum 5-, 10-, 15-, 30-, 60-minute, and average rainfall intensities were computed for each storm.

Runoff volume and sediment amounts were collected daily, with a few exceptions, at the bottom of each plot in 1-m wide Gerlach traps (Gerlach, 1967; Moody and Martin, 2001). Cumulative runoff was measured for each plot by using graduated cylinders accurate to ± 2 mL. No measurements were made during runoff of the flow depth, *h* [m], or the cumulative flow width, λ [m], in the rivulets on the plots.

Sediment flux, *q* [g m^{-1} h^{-1}], was calculated as the mass per unit contour length (1 m) divided by the time interval for each transport process. Sediment from each plot trap was dried at 105°C, and the mass was determined for eight half-phi size classes between <0.063 and 16 mm after sieving (Guy, 1969). Time intervals for each transport process are different. Dry ravel transport was assumed to happen at any time between sample collections and the time interval was taken to be 24 hours (or in some cases 48 hours), even though the duration of transport may have been much shorter. Rainfall duration was used to compute sediment flux for rainsplash and rainflow transport even though runoff only occurred after a rainfall intensity threshold was exceeded. Storm durations were relatively short, so that a sediment sample associated with rainsplash may have a contribution from dry ravel prior to or after a storm. Similarly, a sediment sample collected after a rainflow event potentially includes sediment transported by dry ravel and rainsplash prior to or after overland flow. Sediment data were separated into three sediment transport processes based on the amount of total rainfall and runoff (Table 1). Rainflow transport was analyzed, only for those days, in which all four plots generated runoff. Sediment data for each process were separated into particle-size classes and the sediment flux used in this paper was computed as the average mass of sediment from the four plots.

Table 1 Rainfall and runoff conditions associated with sediment transport processes during summer rainstorms. [A rainstorm was a period of continuous but possibly intermittent rainfall such that any continuous time interval with no rain was less than 3 hours]

Process	**Time scale**	**Total rainfall (mm)**	**Runoff (L or mm)**
Dry Ravel	Time period between sample collection, usually 24 hours	< 0.254	< 0.005
Rainsplash	Duration of rainstorm	> 0.254	< 0.005
Rainflow	Duration of rainstorm	> 0.254	> 0.005

RESULTS

<u>Source Sediment</u> Sediment available for transport within the plots was coarse with median diameters ranging from 0.9 to 4 mm. The percentage, p_i, of each particle size of this source sediment is given by the empirical equation:

$$p_i = 7.6D_i \qquad (1)$$

(R^2 = 0.92). This relatively coarse lag on the burned hillslope was the consequence of previous erosion during several rainstorms after the fire in 2001 (Gartner, 2003) and before this study began.

Initial Soil Moisture Daily gravimetric soil moisture content was computed from the soil samples collected each morning, but this did not necessarily correspond to θ_i at the time the rainfall started later in the day. To estimate θ_i, a statistical linear model was use to fit an exponential decay curve to data for five dry periods following rainstorms (ranging from 4 to 8 days). This decay curve had the form $\theta_i = \theta_{pre} e^{-at}$ where θ_{pre} was the pre-rain soil moisture content, *a* = 0.34 d^{-1}, and *t* [days] was the elapsed time from collecting θ_{pre} until the start of the rain. Values of θ_i at the start of rainfall ranged from 0.32-15.6 % cm^3 cm^{-3}.

Rainfall Intensity Convective rainfall during the summer months was unsteady and variable in duration (median range: 0.8-1.8 hours). Of the intensities computed to characterize this rainfall, the 30-minute rainfall intensity, I_{30} was most closely correlated with runoff (Martin and Moody, unpublished data), and therefore, was used in these analysis. Rainfall intensity for dry ravel was, by definition, zero. Intensities corresponding to rainsplash ranged from 0.5-6.6 mm h^{-1} and those for rainflow ranged from 1.5-19.3 mm h^{-1}.

Runoff Runoff was produced, at the 1-m^2 plot scale, when the rainfall intensity exceeded an I_{30} threshold, which was not one value, but a range of intensities from 0.5 to 7.0 mm h^{-1}. This threshold may depend on the spatial scale, on the soil infiltration rates after the fire (45 $\pm$ 16 mm h^{-1}; Martin and Moody, 2001), and on the value of θ_i (Martin and Moody, unpublished data). Average runoff from the four, 1-m^2 plots ranged from 0.005 to 4.728 L per storm and the median value was 0.250 L.

Sediment Flux Dry ravel transport was an order of magnitude less than rainsplash and two orders of magnitude less than the rainflow for the smaller particle sizes. Mean and standard deviation of the sediment fluxes, q, for dry ravel, rainsplash, and rainflow were 0.13 $\pm$ 0.20 g m^{-1} h^{-1}(n = 41), 4.7 $\pm$ 4.7 g m^{-1} h^{-1}(n = 29), and 8.9 $\pm$ 9.5 g m^{-1} h^{-1}(n = 12). Sediment flux for each process increased as a function of D_i (fig. 2), and was greatest for rainflow transport.

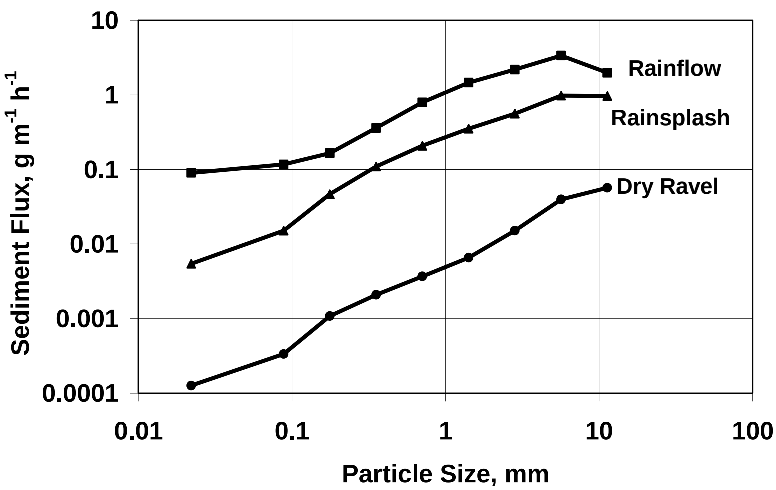


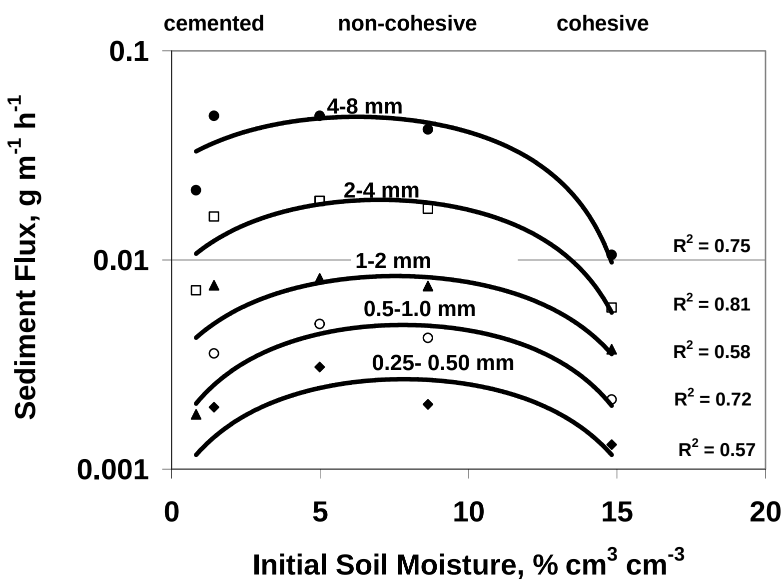
Figure 2 Magnitude of sediment transport for three processes from 1-m^2 plots on a burned hillslope.

DISCUSSION

Sediment transport data were not collected immediately after the fire, thus even the minimum measured soil moisture (0.32 % cm^3 cm^{-3}) is probably greater than the minimum immediately after a fire. Oven-dried soil moisture, which might approximate those after a fire, has been measured in the laboratory to range from 0.1 to 0.005 % cm^3 cm^{-3} (Moody et al., 2009). Therefore, the erosion response described in this paper reflects the conditions after a fire, but also after the first few rainstorms.

Dry Ravel Dry ravel transport depends upon animal activity, wind, and θ_i. Data were sorted into five soil moisture groups (0-1, 1-2, 2-7, 7-12, and 12-17 % cm^3 cm^{-3}) to investigate the dependence of transport on θ_i. Sediment flux, q_D [g m^{-1} h^{-1}], for each particle size had a minimum at low and high θ_i

(fig. 3) with a maximum between 5-9 % cm^3 cm^{-3}. The coefficient of determination for a quadratic relation between q_D and θ_i was lowest for the <0.063 mm and 0.063-0.125 mm size classes (R^2 = 0.16 and 0.15, respectively), increased to 0.81 for the 2-4 mm size class, and decreased for 4-8 mm and 8-16 mm. The actual relation between q_D and θ_i is probably more complex than a simple quadratic relation and may represent the combination of two processes: the cementing of sediment by clay particles at low θ_i and the cohesion provided by soil moisture films at high θ_i. A decrease in q_D for low θ_i (< 2 % cm^3 cm^{-3}) is supported by results published by Matsushi and Matsukura (2006), which show that cohesion/cementation (as measured by shear strength plus normal stress of undisturbed soils) increases exponentially as θ_i decreases. Fine particles would be the most susceptible to cementation and have a lower



correlation with soil moisture content. A decrease in q_D for θ_i above about 10 % cm^3 cm^{-3} probably reflects increased cohesion caused by the surface tension holding soil particles together. This is supported by measurements in a wind tunnel where the threshold shear velocity for medium sand (0.200-0.450 mm) increased as θ_i increased (Neuman and Scott, 1998). Additionally, the lack of correlation with soil moisture for the larger particles may indicate that these sizes are more often moved by animal activity.

Rainsplash Rain intensities associated with rainsplash transport were less than 7 mm h^{-1} and represent the low end of intensities reported in the literature—especially for rainfall simulation experiments. However, Morris (1986) reported similar average intensities of 6.95 and 2.35 mm h^{-1} in 1981 and 1982 for vegetated south-facing slopes in the Colorado Front Range.

Rainfall intensity, *I*, was related to raindrop median diameter, d_{50} [mm], by Laws and Parsons (1943) such that:

$$d_{50} = d_1 I^{0.182} \quad , \tag{2}$$

where d_1 = 4.0 mm$^{0.818}$ h$^{0.182}$. Using (2) gives estimated diameters < 5.5 mm for the rainsplash data in this study. Upon hitting the soil, a raindrop with density of ρ_w [kg m^{-3}] and terminal velocity, v_r [m s^{-1}], transfers the downslope component of its momentum ($m_r v_r = \rho_w \pi d_{50}^3 v_r \sin\beta / 6$, where β is the slope of the surface) to soil particles of size D_i and density, ρ_s [kg m^{-3}]. Measurements of v_r and d_{50} (Gunn and Kinzer, 1949) gave an empirical relation:

$$v_r = d_2 d_{50}^{0.45} \quad , \tag{3}$$

where d_2 = 4.6 m s^{-1} mm$^{-0.45}$ and 1 mm < d_{50} < 7 mm. The maximum momentum of one particle parallel to the hillslope is $m_s v_s = \rho_s \pi D_i^3 v_s / 6$, such that the transport velocity is then

$$V_d = (\rho_w / \rho_s)(d_{50} / D_i)^3 v_r \sin\beta \, . \tag{4}$$

The number of particles, N_i, available for transport within a unit area is proportional to the percentage per unit area, p_i, of each size class among all the surface particles, and to the resistance to detachment, R_i (Poesen and Savat, 1981) so that $N_i = p_i / R_i$ [m^{-2}]. Thus, the total rainsplash sediment mass flux, q_R [kg m^{-1} s^{-1}] across a unit width is given by:

$$q_R = N_i (\rho_s \pi D_i^3 / 6) V_d \, . \tag{5}$$

Substituting equations (2)-(4) into equation (5) gives:

$$q_R = (d_3 / R_i) \sin\beta \cdot p_i I^{0.63} , \tag{6}$$

where d_3 is a constant equal to $\rho_w \pi \cdot d_2 d_1^{3.45} / 6$. By using equation (1) for p_i and the slope (β = 0.27), which are specific to this study, then (6) has the form

$$q_R = (d_4 / R_i) D_i I^{0.63} , \tag{7}$$

where d_4 is a constant equal to 7.8 x 10^9 kg m^{-4} mm$^{1.37}$ h$^{-0.37}$ (the awkward units are a result of using empirical equations). More importantly, q_R should be proportional to $D_i I^{0.63}$.

This relation was tested by using the data from the 1-m^2 plots. Data were sorted by particle size into eight, I_{30}^{max} intervals (0.5, 1.3, 1.5, 2.0, 2.5, 3.2, 4.3, and 6.6 mm h^{-1}), and $D_i I^{0.63}$ in (7) was plotted against the measured q_R (fig. 4). The 4-8 mm and 8-16 mm size classes were not included because of the high probability that they represent dry ravel as others have found particles larger than 8 mm are only indirectly affected by rainsplash (Carson and Kirkby, 1972; Morris, 1986). Agreement between predicted and measured q_R appears best for mid-size particles and less for the larger (> 2 mm) and smaller sizes (<0.125 mm). The 2-4 mm size probably has a higher fraction that can be attributed to dry ravel than the other sizes as mentioned above. Smaller sizes have been shown to have the largest resistance to detachment by Poesen and Savat (1981), who measured the kinetic energy per kilogram of detached soil using 4.1-mm-diameter raindrops with an intensity of 35.8 mm h^{-1}. Their laboratory results showed a maximum kinetic energy of about 1200 J (value is quite variable) for 0.030-mm particles, a decrease to a minimum of 225 J (minimal variability) for 0.125-mm particles, and a slight increase to 460 J (more variable) for 0.610-mm particles. The increased scatter for the smaller sizes probably reflects the increased variability in resistance to detachment. Using the slope (0.22 g $m^{-1}mm^{-1.63}$ $h^{-0.37}$) of a linear regression through the data in figure 4 and the constant value of d_4, the resistance to detachment, R_i, is 3.6 x 10^4. Using only the three smaller size classes (<0.063, 0.063-0.125, and 0.125-0.250 mm) gives a slightly greater value of R_i = 4.4 x 10^4. These are similar to values of R_i (1.0 x 10^4 to 5.3 x 10^4) recomputed from field data for bare loamy and sandy soils published by Poesen (1986) as the ratio of rainfall kinetic energy to the potential energy at the maximum height of particle trajectory into a splash cup.

Resistance to detachment was shown by Poesen and Savat (1981) in the laboratory to depend on θ_i. For the data described in this paper, the I_{30} interval equal to 1.5 mm h^{-1} had the largest number of samples (N=7) and was used to investigate the dependence of q_R on θ_i for each particle size. Plots of q_R versus θ_i were similar to those shown in figure 3, but R^2 values only ranged from 0.27 to 0.37. This suggests that rainsplash is only weakly dependent on θ_i and secondary to the dependence on rainfall intensity.

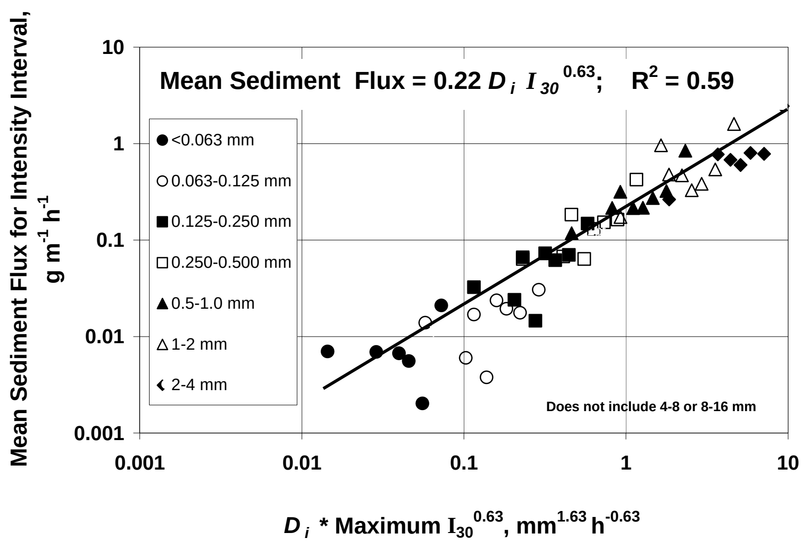


Figure 4 Rainsplash transport from 1-m2 plots as a function of particle diameter and rainfall intensity.

Rainflow Most sediment transport equations have been developed for perennial streams and rivers with small relative roughness (D_i/h << 1), which justifiably assumes transport by saltation. However, with shallow flows ($h \leq 2$ mm) on hillslopes sliding and especially rolling may play a more important role.

Although flow depth was not measured directly, an order of magnitude estimate can be made using the kinematic wave theory for overland flow (Moore and Foster, 1990) and steady rainfall intensity of I_{30}. Depth estimates assuming laminar flow (h ~ 0.13-0.18 mm) were similar to estimates assuming turbulent flow using a Manning's type resistance (h ~ 0.14-0.26 mm). These depths are decidedly shallow and probably are limited by the short length (1 m) of the plot. Using depths of 1-2 mm and a velocity of 0.30-0.50 m s^{-1} gives a Reynolds number on the order of 300-1200, which is within the range of laminar flow, and therefore laminar flow was assumed. Without measurements of water depth, the boundary shear stress could not be calculated so a stream power approach was used. Stream power was given by Bagnold (1966) as:

$$\omega = \rho g q S \ \text{[J m}^{-2}\text{ s}^{-1}\text{ or N m}^{-1}\text{ s}^{-1}\text{]}, \tag{8}$$

where ρ =1000 [kg m^{-3}] is the density of water, g=9.8 [m s^{-2}] is the acceleration of gravity, q [m^2 s^{-1}] is water discharge per unit width, and S is the slope. The actual cumulative width, λ, is needed to calculate $q = V/\lambda\Delta t$, where V is the volume of runoff and Δt is the duration of the rain. Even though λ was unknown and uniform sheet flow across the entire 1 m width of the plot is unrealistic, $\lambda = 1$ m was used. While this value underestimates ω and q_B, the form of the relation between ω and q_B, which is of primary interest, will be unaffected (for example, if λ were 0.1 m, then ω and q_B would simply be multiplied by 10).

Sediment flux, q_B, is the product of the number, N_i, which is the combined weight of moving particles per unit area times the particle velocity (Bridge and Dominic, 1984). This gives

$$q_B = N_i V_p; \tag{9}$$

however, V_p for rolling particles in shallow, laminar flow has a complex dependence on particle diameter, D_i. At present, no unified theory predicts bedload motion by rolling in shallow flows where three different conditions are possible: (1) particles are completely submerged ($D_i/h << 1$), (2) particles are just under the water surface ($0.75 < D_i/h < 1$) where they generate surface waves, which alter V_p, or (3) particles protrude through the flow ($D_i/h > 1$) and generate bow waves and wakes that reduce V_p. Velocities also will depend on D_i through the mean fluid velocity acting on the particles and thus the drag force on the particle, and through the rotational inertia and angular acceleration. Parsons (1972) measured V_p for laminar flow on a “smooth cement mortar bed” with depths ranging from 0.60-2.84 mm in which all three conditions were present. Reanalysis of Parsons’ data produces an empirical equation based on ω:

$$V_p = a_1 D_i (1 - a_2 D_i)(\omega - \omega_{cr}) \qquad R^2 = 0.79, \tag{10}$$

where a_1 = 2474 s^2 kg^{-1}, a_2 = 413.5 m^{-1}, and ω_{cr} ~0. Zero value of ω_{cr} may be caused by the smooth bed. This is a quadratic equation with maximum V_p at ~ $1/2a_2$ = 1.2 mm, and thus q_B increased for D_i/h < 0.80 (mean h ~ 1.5 mm for Parsons’ data) and decreased for D_i/h > 0.80. Parsons used only a single smooth surface, but q_B should also depend on the friction or bed roughness scale, D_i/k_s, where k_s [m] is the median diameter of the surface roughness elements. Govers (1989) made measurement of V_p for different values of D_i/k_s. Analysis of his data digitized from published figures indicate that the critical shear velocity decreases nonlinearly with D_i/k_s and that V_p increases nonlinearly with D_i/k_s. This indicates that q_B of larger particles will increase because they are rolling over a relatively smooth bed, whereas particles with diameters ~ k_s may be trapped more often in pockets and q_B would decrease.

Linear regressions of q_B and ω were computed separately for each particle size class and the slopes of the regression lines were found to be a function of D_i. This dependence was then combined into a single equation. Analysis of the rainflow transport did not include I_{30} < 7 mm h^{-1}, which was the domain of the rainsplash transport and may have affected the results. Sediment flux was found to be a function of D_i and ω with the form:

$$q_B = b_1 (D_i (1 - b_2 D_i) + b_3)(\omega - \omega_{cr}) \qquad R^2 = 0.87, \tag{11}$$

where b_1 =2.15 m^{-1}, b_2 = 134 m^{-1}, and b_3 = 0.00014 (fig. 5). The constant b_3 is small such that (11) has the form of (10) if ω_{cr} ~ 0. Values of ω_{cr} for each D_i were ~ 0 with some negative values, which was probably a result of the large uncertainty in estimating ω_{cr} (mean = 1.1 x 10^{-4} J m^{-2} s^{-1} with coefficient of variation of 1.1). Additionally, it is possible that rainsplash preceding the runoff, loosened soil particles, and was a surrogate for ω_{cr} . A linear regression gives more weight to the greater values of q_B (upper right end of the regression line in fig. 5) and therefore does not appear to 'fit' the remaining data (lower left), which are highly variable. This variability may be the result of dry ravel or rainsplash transport that would represent a larger proportion (and therefore error) of the smaller values of q_B than it would represent for the greater values of q_B If the data are log transformed, then each value of q_B is weighted equally and the regression 'appears' to fit the data better (slope =1.01; R^2=0.64). This version might be preferable for predicting contaminate transport, which is usually associated with the finer fractions of the soil. The quadratic expression in (11) has a maximum for D_i equal to 3.7 mm. This is greater than the maximum for Parsons' data and may reflect the differences in k_s. However, a maximum q_B for larger particles (1-3 mm) was also observed by Asadi et al. (2007) during rainfall simulations on natural soil and attributed to transport by rolling. Based on (10), the quadratic expression in (11) is part of V_p and so the constant b_1 for individual size classes can be interpreted as N_i . N_i as a function of D_i had a minimum for the 0.250-0.500 mm size class. This minimum in the number of moving particles may be a result of this size being more frequently trapped among pockets formed by the surface roughness. The number of moving particles, finer than this size, may be

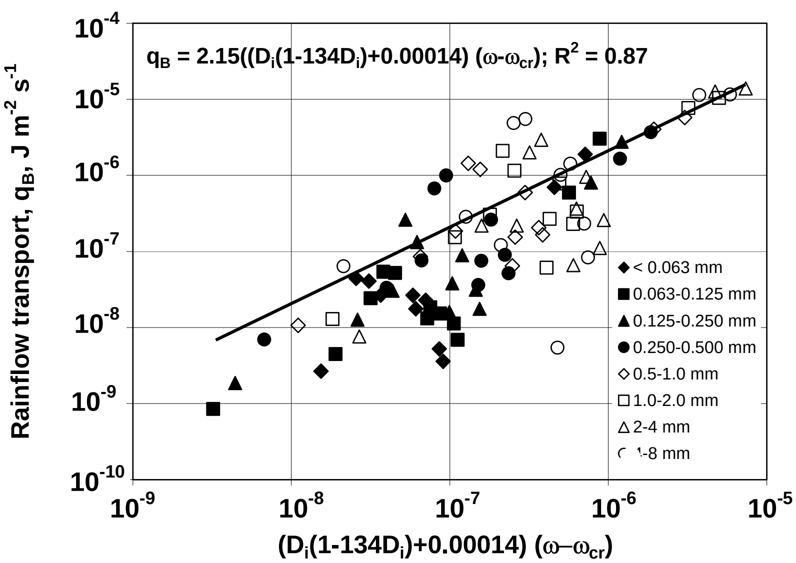


Figure 5 Rainflow transport from 1-m^2 plots as a function of D_i and stream power.

greater because, even in shallow flows, they are saltating and being trapped less frequently. The number of moving particles, coarser than this size, may be greater because they roll easily over a relatively smooth bed and are rarely trapped. However, the sediment flux of the larger particles is less because V_p decreases as a result of the particles projecting out of the shallow flow, which likely creates waves that reduce V_p.

SUMMARY AND CONCLUSIONS

For dry ravel transport, there is a non-linear relation between particle size and θ_i that has a maximum between 5-9 % cm^3 cm^{-3}. At low θ_i, cohesion may increase as a result of cementation, which prevents soil particles from being detached. At high θ_i, cohesion may increase with increased surface tension. The effects of animal activity are probably episodic and appear to preferentially affect larger soil particles; however, while the flux calculated using the episodic time interval may be large, the flux averaged over a longer time interval is small. Rainsplash transport (for I_{30}^{max} 1-7 mm h^{-1}) on bare soils had a downslope advective component, was proportional to *Di*, varied as $(I_{30}^{max})^{0.63}$, and varied inversely with a resistance to detachment (ratio of the kinetic energy of the rainfall to the potential energy of ejected particles). This rainsplash dependence on I_{30}^{max} may need to be considered in landscape erosion models especially in the light of possible changes in rainfall variability associated with climate change. Rainflow transport (I_{30}^{max} > 7 mm h^{-1}) was most likely by rolling in shallow flows (h < 2 mm), but fine particles (< 0.250 mm) may still have a saltation component. Rainflow transport had a quadratic dependence on D_i with a maximum sediment flux in the 2-4 mm size class. Sediment flux also depended on $\omega - \omega_{cr}$, but ω_{cr} ~ 0, which indicated that rainfall preceding runoff may serve as a surrogate for ω_{cr}.

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