Partitioning total erosion on unpaved roads into splash and hydraulic components: The roles of interstorm surface preparation and dynamic erodibility

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Abstract. Field rainfall simulation experiments at two sites are used to partition sediment transport on unpaved roads into splash and hydraulic erosion components. Rain splash processes contributed 38–45% of total sediment output, with instantaneous contributions being variable throughout 60-min high-energy events. For low- and medium-magnitude rainstorms, splash erosion on roads is initially controlled by the removal of easily erodible material, followed by a dramatic reduction in sediment output associated with limited detachment from the resistant, highly compacted road surface. A conceptual model explaining temporal variations in splash and hydraulic erosion as functions of prestorm surface preparation (via traffic, maintenance, and mass wasting processes) is presented. For situations where loose sediment is readily available, rain splash energy is less important to sediment detachment. If the loose layer is diminished (e.g., following an overland flow event) or protected by a surface crust, splash energy is needed to detach material from the road surface. Equations in most physically based erosion models do not predict temporal variations in road sediment transport that result from the removal of a loose surface layer of finite depth. A strategy that successfully treats this removal as changes in road erodibility is introduced.

1. Introduction

Although the geomorphological importance of unpaved roads has been recognized for almost a century [*Gilbert*, 1917], intensive field research did not begin until the mid-1970s [e.g., *Anderson*, 1975; *Hafley*, 1975; *Megahan*, 1975; *Wald*, 1975]. To date, researchers have not successfully incorporated roads into watershed runoff and erosion models. The need to model road phenomena is made evident by field studies showing roads to be important source areas for rapid runoff and suspended sediment entering streams [e.g., *Reid and Dunne*, 1984; *Grayson et al.*, 1993; *Ziegler and Giambelluca*, 1997a]. Early attempts at modeling road-related erosion include the Road Sediment model (RoSED) [*Simons et al.*, 1977] and subsequent modifications [e.g., *Simons et al.*, 1978; *Ward and Seiger*, 1983]. Recent attempts to physically model road erosion include building road features into the topology of versatile, physically based models, such as the Water Erosion Prediction Project (WEPP) [*Elliot et al.*, 1995] and the Kinematic Erosion model (KINEROS or KINEROS2) [e.g., *Ziegler and Giambelluca*, 1997b; *Ziegler et al.*, 2000a].

Simulating road erosion with available physically based models requires the assumption that model equations accurately "describe" fundamental hydrological and geomorphological processes (e.g., infiltration, sediment detachment by rain splash, or surface flow subprocesses), which for roads are likely different than for agricultural or rangelands where model equations were developed. Simulation also requires deriving important model parameters for infiltration and sediment detachment equations. While prior studies have attempted to derive such road-related parameters [e.g., *Simons et al.*, 1982; *Ward and Seiger*, 1983; *Flerchinger and Watts*, 1987; *Luce and Cundy*, 1994; *Elliot et al.*, 1995; *Ulman and Lopes*, 1995], sediment detachment on roads is still not clearly understood. Nor is it evident whether typical model equations accurately describe these processes. In this work, we use rainfall simulation on two roads to partition total erosion into splash and hydraulic components. The objective of the study was to (1) provide a physical basis for parameterizing erosion equations for model sediment transport on unpaved roads; (2) identify temporal variations in erosion subprocesses and the underlying mechanisms causing variations; and (3) assess the ability of model equations to describe splash and hydraulic erosion processes on roads.

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2. Methodology

2.1. Research Sites

Rainfall simulation was performed on two roads, one in Thailand and the other in Hawaii, United States of America. The Thailand site was in the Pang Khum Experimental Watershed (PKEW) (described by *Ziegler et al.* [2000a]), approximately 60 km NNW of Chiang Mai, Thailand. The monsoon rainy season extends from mid-May through October, during which about 90% of an annual 1200- to 1300-mm rainfall occurs. Rain events large enough to produce road surface runoff rarely occur in the dry season. Bedrock material in PKEW is Triassic granite; soils are Ultisols, Alfisols, and Inceptisols. Maximum slope on the 100-m test road section was about 0.20 m m^{-1}. Ruts created from vehicle wheels incise the surface to depths of 0.10–0.15 m. Estimated lowering from compaction and erosion processes is 0.1 m yr^{-1}. Daily traffic includes approximately four motorcycle and two truck passes and an occasional passing water buffalo.

Table 1. Physical Properties of the Unpaved Road Surface at the Thailand and Hawaii Research Sites

Descriptor/Property[a]	Units	Hawaii	Thailand	Tied P Value
ρ_b (0–5 cm)	Mg m^{-3}	1.32 ± 0.02[b]	1.42 ± 0.02	0.0008 (36, 48)
ρ_b (5–10 cm)	Mg m^{-3}	1.09 ± 0.06	1.36 ± 0.03	0.0004 (7, 16)
ρ_b (10–15 cm)	Mg m^{-3}	1.05 ± 0.05	1.36 ± 0.03	0.0004 (7, 16)
PR	MPa	5.8 ± 0.1	6.4 ± 0.0	<0.0001 (61, 160)
K_s	mm h^{-1}	28.4 ± 4.5	13.6 ± 2.1	0.0051 (12, 12)

[a]Here ρ_b is bulk density at indicated depth; PR is penetration resistance; and K_s is saturated hydraulic conductivity. Measurement techniques are described by *Ziegler et al*. [2000b]; values are means ± standard error.

[b]Tied P values are the results of statistical testing with the nonparametric Mann-Whitney U test; values in parentheses indicate the sample number for Hawaii and Thailand, respectively.

The Hawaiian study site is located at the base of the Waianae Mountain Range on Schofield Barracks (U.S. Army) in central west Oahu Island, Hawaii. Rainfall is seasonal, with about 75% of the annual 1000–1100 mm occurring from October to April. Unlike the Thailand site, there is typically no prolonged period without rainfall events large enough to generate surface runoff. Road surface material is a composite of Kolekole Oxisol, Helemano Inceptisol, weathered oxidic ash, and exposed regolith/bedrock [*Soil Conservation Service*, 1981]. Slope on the experiment road varies from about 0.05 to 0.35 m m^{-1}. The simulations were performed on an 80-m road section, for which the road surface lies 1–4 m below the adjacent roadside margin. Enhanced surface lowering results predominately from erosional and maintenance activities. Visible tracks and ruts are present on the road surface; however, traffic is now infrequent, as the section has been closed since slope failure below the experimental site in early 1997.

2.2. Rainfall Simulation Experiments

In August 1997, six rainfall simulation experiments were performed at the Hawaii site. Eight simulations were performed in PKEW in February 1998. Each simulation run was a true replication, usually performed 6–10 m above the previous simulation plot. The simulator used at both sites consisted of two vertical 4.3-m risers, each directing one 60° axial full cone nozzle (70-μm orifice diameter) toward the surface. The operating pressure of 172 kPa (25 psi) produced rainfall energy flux densities of 1700–1900 J m^{-2} h^{-1} (100–115 mm h^{-1}), approximating energy sustained for 10–20 min during the largest annual PKEW storms (based on preliminary analysis of 2 years of rainfall data). Cylindrical, sand-filled, low-permeability geotextile bags (3.0 × 0.2 × 0.1 m) were arranged to form two side-by-side rectangular subplots. For each simulation, one subplot was designated as a rain splash treatment (referred to herein as "Splash"); the other was covered with 2-mm wire screen suspended 0.1 m above the road surface to retard raindrop energy ("No splash"). The design is similar to *Hudson*'s [1957] mosquito gauze treatments of experiment 3 in Rhodesia. Sediment output from the "No splash" treatment is assumed to result entirely from hydraulic erosion processes, and the difference between "Splash" (rain splash plus hydraulic erosion) and "No splash" (only hydraulic erosion) treatments represents the sediment contributed by rain splash, that is, detachment and rain-affected flow. Subplot dimensions for Schofield simulations were 3.50 (length) × 0.75 (width) m; the Thailand plots were slightly larger, 3.75 (length) × 0.85 (width) m. At the base of each subplot, geotextile bags were arranged to funnel runoff into a shallow drainage trench dug into the road surface. A V-shaped trough constructed from aluminum flashing was inserted into the vertical wall of the trench to allow event-based sampling. The face of the drainage trench and the triangular area below the main plot were treated with a 5:1 mixture of water and Soil Sement™ (an acrylic vinyl acetate polymer from Midwest Industrial Supply, Inc., Canton, Ohio) to prevent sediment detachment on these nonplot areas. The sealed triangular area (an additional plot length of 0.5 m) contributed only runoff to the plot output, and discharge values were corrected accordingly. Rainfall was measured during each event with 12 manual gauges placed on the plot borders. Table 1 shows physical properties associated with the road surfaces at the two sites. Mean values of plot slope, antecedent mass soil wetness, and simulation rainfall intensity are shown in Table 2.

Instantaneous discharge (Q_t), sediment output (S_t), and concentration (C_t) were measured at time to runoff (TTRO) and then at 2.5- or 5-min intervals. Discharge volume was reduced to account for presence of sediment in the samples.

Table 2. Mean Runoff-Related and Sediment Transport-Related Data for the Hawaii and Thailand Simulations

	Slope, m m^{-1}	w,[a] g g^{-1}	r, mm h^{-1}	TTRO, min	ROC, %	f, mm h^{-1}	S_{event}, g m^{-2} mm^{-1}	C_{event}, kg m^{-3}
Thailand (n = 8)								
Splash	0.15ab[b]	0.12a	105a	1.1a	84b	6.2a	19.0b	19.3b
No splash	0.15b	0.12a	111ab	1.5ab	75b	17.7b	11.5ab	13.3ab
Hawaii (n = 6)								
Splash	0.13ab	0.21b	113ab	1.5ab	75b	17.6b	19.7b	21.3b
No splash	0.12a	0.21b	129b	2.4b	62a	36.6c	8.4a	10.3a

[a]Here w is antecedent soil mass wetness, r is rainfall rate, TTRO is time to runoff, ROC is the total event runoff coefficient (total runoff/total rainfall), f is steady state infiltration rate, S_{event} is event sediment output (normalized by event rainfall depth), and C_{event} is total event concentration.

[b]Values in each column with the same letters are not statistically different at $p = 0.05$; analysis of variance is followed by Fisher's protected least significant difference post hoc testing on $\log_{10}$-transformed data.

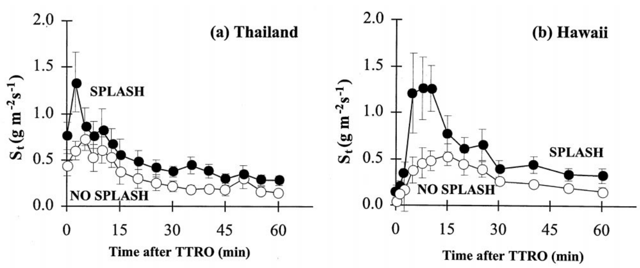

Figure 1. Temporal variation in mean sediment output for "Splash" and "No splash" treatments on (a) Thailand ($n = 8$) and (b) Hawaii ($n = 6$) unpaved road sites. Error bars represent ±1 standard error; TTRO represents time to runoff. Under the assumptions of the investigation, "No splash" values result from hydraulic erosion processes, and "Splash" values combine splash and hydraulic erosion processes.

Values of Q_t and S_t were adjusted to rates per unit area by dividing by filling time and plot area. The runoff coefficient (ROC) was calculated at each sampling time as discharge rate per rainfall rate multiplied by 100%. Final event steady state infiltration rate (f) was estimated as the difference in rainfall rate and discharge rate over the last 30 min of each simulation. This approximation assumes surface storage depressions are full, and thus the differences in rainfall and discharge rates are due to infiltration.

3. Results

3.1. Runoff Data

Table 2 contains mean runoff and sediment transport data for the Hawaii and Thailand simulations. At both sites, "Splash" treatments produce runoff sooner and have higher ROCs (i.e., greater discharge) than the "No splash" treatments. Final steady state infiltration values are lower for "Splash" than for "No splash" treatments. These data collectively show that, even on highly compacted road surfaces, raindrop impact enhances runoff generation in a manner similar to that often occurring on cultivated soils [*Flanagan et al.*, 1988; *Römkens et al.*, 1990; *Gimenez et al.*, 1992]. In this respect the main effect of rain splash is to produce sealing of the surface by redistributing already-detached material, rather than causing aggregate breakdown.

3.2. Sediment Output Data

Total sediment transport (S_{event}) and sediment concentration (C_{event}) at both sites is higher for the "Splash" treatments, compared with "No splash" (Table 2). "Splash" sediment output is characterized by an initial flush of material, followed by a sharp decline, and then a stabilization in output toward the end of the 60-min simulations (Figure 1). "No splash" output is typically less than "Splash," and in the Hawaii experiment output fluctuations are damped. In Figures 2c and 2d, total erosion (e_T) is partitioned into splash (e_s) and hydraulic erosion (e_h) components. Figures 2a and 2b show percent contributions of e_s and e_h to total erosion. At the Thailand site, e_h dominates e_T at the beginning of the simulation but is only slightly greater than e_s after 60 min. In contrast, e_s at the Hawaii site is greater than hydraulic erosion for the first 20 min, after which e_h predominates. Total splash contribution to e_T at the Thailand and Hawaii sites is 37 and 48%, respectively. In comparison, *Ulman and Lopes* [1995] reported the e_s contribution to e_T to range from 44 to 60% for sites in Idaho and Colorado.

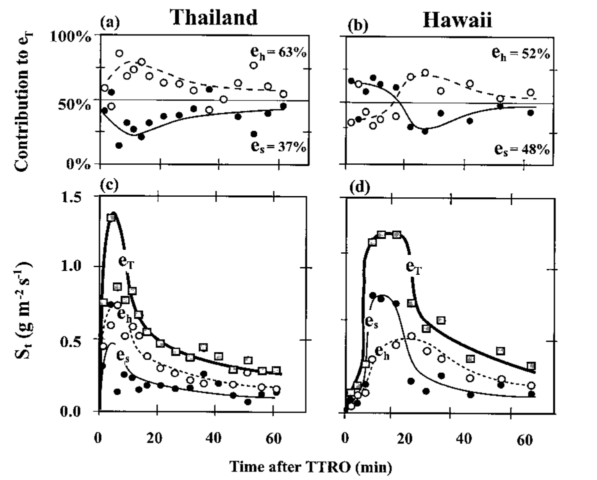

Figure 2. Time-dependent sediment contributions (percent) of splash (e_s) and hydraulic (e_h) erosion components to total sediment output (e_T) for (a) Thailand and (b) Hawaii experimental sites, and temporal variations of e_s, e_h, and e_T during 60 min of simulation for (c) Thailand and (d) Hawaii sites.

4. Discussion

4.1. Role of Surface Preparation in Road Erosion

Surface preparation results from prestorm events or processes that affect availability or transportability of sediment during storm events [cf. *Bryan*, 1996; *Ziegler et al.*, 2000b]. Sediment detachment by vehicular traffic, maintenance activities, mass wasting events, and sediment deposition/removal during prior storms are important preparation processes affecting sediment availability. Temporal and spatial variations in road sediment transport are related to prestorm surface preparation, except, possibly, for high-magnitude events. For example, the early output peak during the Thailand dry-season simulations results from the flushing of loose, easily entrained material, which was generated on the road surface by vehicle detachment since the last overland flow event several weeks before (Figure 2c). The energy of flowing water was sufficient to entrain this material, as evidenced by the early importance of e_h to e_T. After the loose material was removed, however, splash energy was needed to entrain material from interrill areas adjacent to well-defined flow paths into the rill system. By simulation's end both hydraulic and splash subprocesses were greatly contributing to net erosion. Had less loose material been available at the beginning, e_T would likely have been more equally partitioned between e_s and e_h throughout the simulation. Time since the last overland flow event dictates the initial relationship between e_s and e_h. In general, holding traffic and maintenance constant, the longer the period between storms is, the greater is the opportunity for surface preparation to occur, and the greater is the initial role of e_h in sediment transport.

Similarity in total sediment output (S_{event}, Table 2) at the Thailand and Hawaii sites suggests that the dissimilar e_s and e_h responses result largely from site-specific differences in surface preparation, as opposed to differences in soil erodibility. Because of differences in usage and rainfall seasonality, the aban-

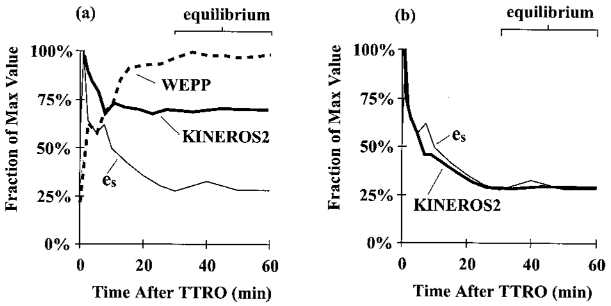

Figure 3. (a) Comparison of the measured splash component (e_s) with that predicted using KINEROS2 splash erosion equation (1) and Water Erosion Prediction Project interrill erosion equation (2). All values were derived from observed rainfall, runoff, water depth, and physical plot data from Hawaii road simulations. (b) Comparison of e_s with that predicted from KINEROS2 equation (1) using the dynamic erodibility (DE) concept. For both Figures 3a and 3b, data were normalized by dividing by the maximum value in each times series.

doned Hawaii road had received less cumulative surface disruption than had the active Thailand road. Again, while the Thailand simulations were performed during a lengthy dry period, the Hawaii experiments were performed only 2 weeks after the last overland flow event. Prior to simulation, the Hawaii road surface contained a mechanical crust, and little loose surface material was present. During simulation, limited material could be entrained by surface flow alone. Rain splash energy was important during the early simulation phase because it disrupted the crust and detached material. Had prestorm traffic been greater, more loose material would have been present, and sediment transport would likely have resembled that on the Thailand road. At simulation's end, e_h was only slightly higher than e_s, as it was in the Thailand experiment. These data indicate that the fundamental differences in sediment transport response between the two sites resulted from availability of loose material, which was controlled by differences in cumulative surface preparation since the last overland flow event.

4.2. Dynamic Erodibility and Implications for Modeling Road Erosion

Erosion model equations, which are based on experiments conducted on nonroad surfaces, do not predict an initial flush of loose material that we have observed on the Thailand and Hawaii test roads. This is shown in Figure 3, where the observed e_s during the Hawaii simulations is compared with that predicted by the KINEROS2 [*Smith et al.*, 1995; C. Unkrich, Agriculture Research Service, U.S. Department of Agriculture, Tuscon, Arizona, personal communication, 2000] splash erosion equation and the WEPP [*Flanagan and Nearing*, 1995] interrill erosion equation. Splash erosion in KINEROS2 is calculated by

$$e_s = \begin{cases} c_f k(h) r^2 & q > 0 \\ 0 & q < 0 \end{cases}, \tag{1}$$

where r is rainfall intensity (m s^{-1}), q is excess rainfall (m s^{-1}), $k(h)$ is a function of surface water depth that reduces splash erosion as water depth increases, and c_f is a coefficient related to soil erodibility that partially controls the rate at which rainfall produces transportable material from the soil surface. Splash detachment in WEPP is embedded (along with the rain-affected flow phenomenon) within a general expression representing sediment delivery (D_i):

$$D_i = K_i I R S_f f(c), \tag{2}$$

where D_i has units of kg m^{-2} s^{-1}, K_i is the relative erodibility parameter (kg s m^{-4}), I is rainfall intensity (m s^{-1}), R is excess runoff (m s^{-1}), S_f is a slope factor (dimensionless), and $f(c)$ is a function of canopy cover and/or surface residue [cf. *Zhang et al.*, 1998]. In Figure 3a the WEPP response increases toward a limit that is approximately the maximum value. In contrast, e_s peaks near the beginning of the simulated event then decreases (near monotonically) toward a limit that is a fraction of its maximum value. KINEROS2 splash output peaks early, falls, then stabilizes, largely in response to fluctuations in water depth. The observed e_s response is fundamentally different from the KINEROS2-predicted response in that it is controlled by the availability of entrainable material, not increasing water depth. Thus equations that do not explicitly consider the removal of a finite layer of loose material will produce a poor prediction of temporal sediment transport for conditions similar to those examined in Thailand and Hawaii.

Removal of the loose surface layer can be simulated by allowing road erodibility to change throughout the event, for example, c_f and K_i in (1) and (2), respectively. Normally, erosion is assumed to take place on a uniform soil. Erodibility values are therefore held constant throughout simulated events. Our field simulation data, however, indicate the loose material that is initially removed is more erodible than the underlying compacted surface, which is eroded once the upper layer is removed. Road erodibility is therefore dynamic, changing in response to the availability of the loose surface material. Initial erodibility is determined by surface preparation; the erodibility after the loose material has been removed is that of the true road surface. Figure 3b shows the improvement of employing dynamic erodibility (DE) in simulating splash with KINEROS2.

5. Summary and Conclusions

Rain splash enhances runoff generation and contributes greatly to sediment detachment/entrainment on unpaved roads. Even on these highly compacted surfaces, raindrop impact reduces the infiltration rate in a manner similar to that occurring on aggregated agricultural and rangeland soils. Total event splash contribution (e_s) to the total erosion process (e_T) during 60-min rainfall simulations on two road surfaces ranged from 38–45%. On the Thailand test road, e_s was less than hydraulic erosion (e_h) at all times during the simulation. On the Hawaii road, however, e_s dominated e_h for the first third of the event then became less than hydraulic erosion for the last 40 min of the simulation. On compacted roads, variability in splash and hydraulic erosion subprocesses is initially controlled by the availability of surface sediment and finally by the shear strength of the underlying road surface. Prestorm availability of loose material is a function of cumulative surface preparation since the previous overland flow event. Physically based erosion models that do not explicitly describe the removal of a loose material layer of finite depth will fail to predict road sediment transport response for roads where sediment preparation is important. If road erodibility is allowed to change during computer simulation (e.g., as in the DE methodology presented herein), removal of the loose surface layer can be simulated with conventional erosion models.

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