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INTERSTORM SURFACE PREPARATION AND SEDIMENT DETACHMENT BY VEHICLE TRAFFIC ON UNPAVED MOUNTAIN ROADS

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ABSTRACT

Road survey and field rainfall simulation experiments have shown that the erodibility of a road surface is dynamic. In the absence of extreme runoff events, dynamic erodibility results from the generation and removal of easily entrained surface material by human road surface maintenance activities, vehicular detachment and overland flow events. Maintenance activities introduce easily transportable material to the road surface where it can be entrained by overland flow. Traffic in dry conditions detaches material that is quickly removed during subsequent overland flow events. The pre-storm erodibility of a road is therefore largely a function of maintenance and vehicle activity since the last overland flow event. During rainstorms, vehicle passes increase sediment production by detaching/redistributing surface material and creating efficient overland flow pathways for sediment transport. However, if incision of tracks by overland flow does not occur, post-pass sediment transport quickly returns to pre-pass rates. Field rainfall simulation data suggest that sediment transport resulting from during-storm vehicle passes is greatly influenced by the presence of existing loose material, which again is a function of prior road usage and maintenance activities. Incorporation of vehicular effects into physically based road erosion models may be possible by parameterizing both during-storm and inter-storm changes in the supply of loose surface material as changes in surface erodibility. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: road erosion modelling; hydrologic impacts; motorcycle and truck traffic; dynamic erodibility; northern Thailand

INTRODUCTION

Compacted unpaved road surfaces generally have low infiltration rates, thereby generating Horton overland flow (HOF) after small rainfall depths (Ziegler and Giambelluca, 1997). Furthermore, because roads often act as linearly connected systems, large volumes of high velocity overland flow may travel downslope toward the stream network. Roads are therefore potentially susceptible to hydraulic erosion processes, and may contribute substantially to stream sedimentation, even during low magnitude rainfall events. However, because of consolidation, unpaved road surfaces are somewhat resistant to sediment detachment forces (excluding extreme events and gullying), especially those of raindrop impact and overland flow resulting from typical storm events. Why then, if roads are resistant to detachment, is sediment production on unpaved roads such an important environmental concern throughout the world?

Prior research indicates vehicular traffic and road maintenance activities enhance sediment production by generating surface material that can be easily transported during overland flow events. For example, Reid and Dunne (1984) reported that routine road maintenance, including grading and filling of ruts/gullies, while necessary to maintain road usability, often generates easily erodible surface material (cf. Grayson *et al.*, 1993). Black and Luce (1999) found graded roads to have sediment production rates higher than background

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levels for the first year after disturbance. With respect to traffic, Reid *et al.* (1981) found sediment production on heavily used logging roads (more than four loaded logging trucks per day) in the Clearwater Basin of Washington (USA) to be more than seven times greater than on any other category of roads receiving less use. Reid and Dunne (1984) later showed that a heavily used road segment generated two orders of magnitude more sediment than an abandoned one, and that sediment production on heavily used roads decreased rapidly following the cessation of traffic. Similar correlation between traffic usage and sediment production have been reported in forestry-related papers (e.g. Burroughs *et al.*, 1984; Bilby *et al.*, 1989; R. B. Foltz, paper presented at FAO seminar on Environmentally Sound Forest Road and Wood Transport, Sinaia, Romania, 1996).

Our on-going research in northern Thailand suggests that maintenance and vehicle usage boost sediment production on unpaved roads by affecting the erodibility of the road surface. A road surface at any given time is a composite of materials of different erodibilities. These materials include: (1) the 'true' road surface, which is usually highly compacted *in situ* soil, and may contain saprolite, regolith, or bedrock; (2) a surfacing material, such as rock or a resilient soil, often applied to the road to reduce erosion or improve traction; (3) fill material used to repair road ruts/gullies, and may originate from the road prism or be imported from other areas; (4) side-cast material generated during road construction or maintenance; and (5) depositional material left behind during previous runoff events, generated during small mass wasting events, or detached from the *in situ* surface by some mechanism, often human-induced. The erodibility of these surface materials depends largely on their inherent physico-chemical properties (i.e. texture, clay mineralogy, oxide composition, organic matter content, exchangeable sodium content, shear strength and bulk density). Holding particle size and particle density constant, loose material is more erodible than consolidated material. Road erodibility is therefore controlled by both the erodibility of the underlying compacted road surface, and that of the loose surface material. The supply of the latter is constantly altered by overland flow events that move it downslope, traffic that redistributes it on the road surface, crushing/churning forces that alter its aggregate size distribution, and detachment processes that generate more from the consolidated road surface or roadside margin. Hence, the erodibility of a road surface is truly dynamic: sometimes it is quite high, such as after a long dry period where traffic has created a layer of loose material, and at other times quite low, such as following a large overland flow event that removed most easily entrained loose material.

The contemporary goal of physically modelling sediment production from unpaved roads is challenging in part because of difficulties in explicitly representing time-varying changes in surface erodibility. Additionally, the impact of vehicle detachment of sediment is a function of numerous variables related to the vehicle, the road surface, the rain event and topography. In this work we use rainfall simulation to investigate sediment production associated with one common maintenance practice in northern Thailand, and to study sediment detachment by motorcycles and pickup trucks on unpaved roads. Additionally we incorporate physical property measurements, road usage information and simulation results to determine links between sediment production on roads and interstorm preparation. Although road sediment production is very high following construction, during extreme events when gullying occurs, and during instances of slope failure and mass wasting events, we do not investigate these phenomena herein. Rather, we focus on processes that determine sediment production during typical seasonal storms.

RESEARCH SITE

All work was performed in the 93·7 ha Pang Khum Experimental Watershed (PKEW), which is near Pang Khum village (19°3′N, 98°39′E), within Samoeng District of Chiang Mai Province, approximately 60 km NNW of Chiang Mai, Thailand (Figure 1). The area has a monsoon rainfall regime with a rainy season extending from mid-May to October, during which about 90 per cent of an annual 1200–1300 mm rainfall occurs. PKEW is part of the larger Rim River Basin, which drains into the Ping River, which in turn empties into the Chao Praya River. Bedrock is Triassic granite (field observation; Hess and Koch, 1979). PKEW soils are Ultisols, Alfisols and Inceptisols (field survey). Roads, access paths and dwelling sites each comprise <1 per cent of the PKEW area. Approximately 12 per cent of the basin area is agricultural land (cultivated,

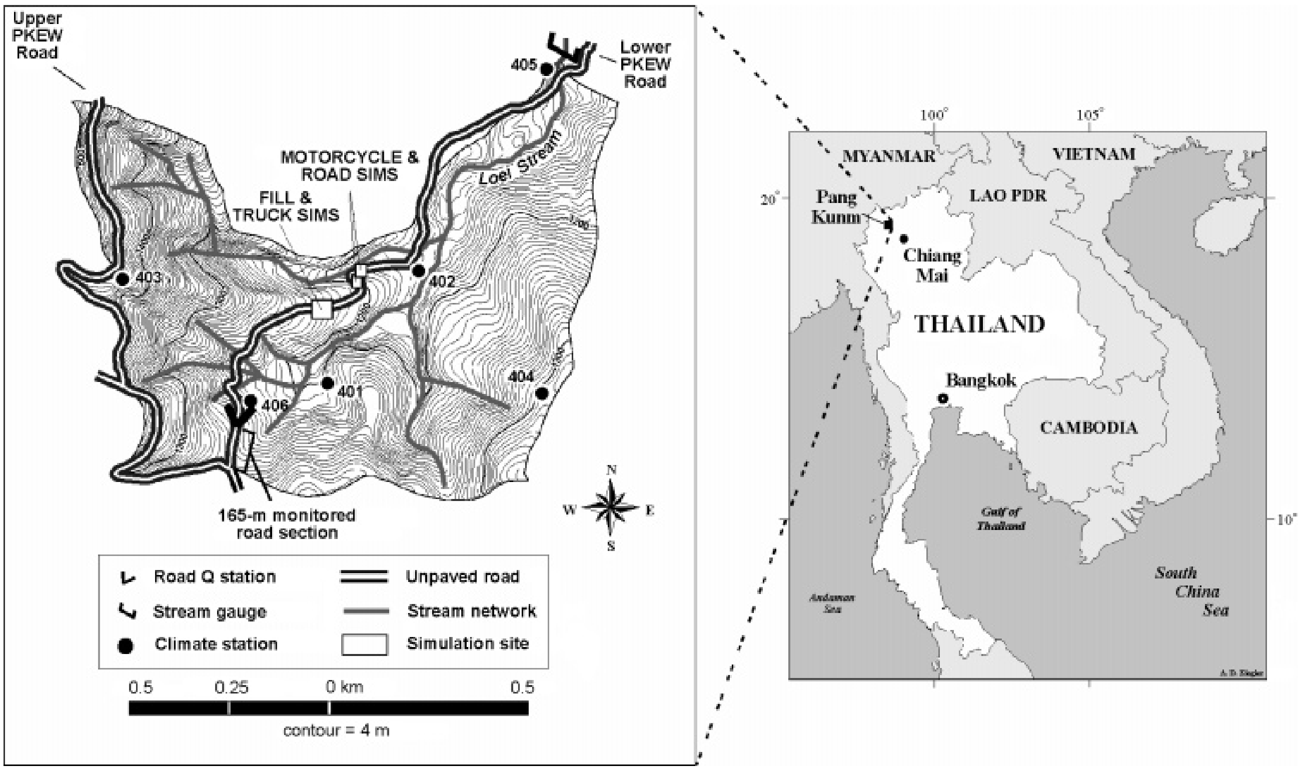

Figure 1. The 93·7 ha Pang Khum Experimental Watershed (PKEW) in northern Thailand. Experiments were performed on the 1650 m section of the Lower PKEW Road bisecting the watershed

upland fields and <1·5 year-old abandoned); 13 per cent fallow lands (not used for 1·5–4 years); 31 and 12 per cent are young (4–10 years) and advanced secondary vegetation, respectively; and 31 per cent is disturbed, old growth forest. PKEW is described in more detail elsewhere (Ziegler, 2000).

PKEW is the site of our on-going investigation of the impacts of unpaved roads in upland watershed in montane mainland SE Asia (Ziegler and Giambelluca, 1997; Ziegler *et al.*, 2000, in press). Ultimately, we hope to obtain detailed understanding of erosion processes operating on and adjacent to road surfaces and, in doing so, to quantify the contribution of roads to hydrologic change and accelerated erosion in upland watersheds. Thus far we have determined that: (1) runoff generation and sediment transport processes are unique on roads, paths and agricultural land surfaces in PKEW; (2) the dominant overland flow mechanism on PKEW roads is HOF; overland flow caused by the interception of subsurface stormflow by road cuts is rare in the basin, except where the road crosses stream channels; and (3) roads, owing to low saturated hydraulic conductivity and high connectivity of road sections, are capable of contributing disproportionately to basin runoff hydrographs. Current work is focusing on determining the importance of interstorm surface preparation and simulating road sediment transport with a physically based model.

METHODS

Survey of vehicle usage and surface physical characteristics

On the Lower PKEW Road the following were completed: (a) a survey of vehicle usage; (b) measurements of cross-sectional physical characteristics; (c) an inventory of sediment sources; and (d) a survey of exit points for road runoff. The traffic survey was conducted for 225 h on 44 days between July 1998 and February 1999. During each survey session (usually 4 to 5 h beginning at an arbitrary time of day), each vehicle pass was recorded, noting the type of vehicle, road and weather conditions, and presence/absence of tire chains. Session values were converted to values of passes per 12-h work day using a simple weighting function. A total of 32 cross-sections were established 50 m apart, beginning 25 m inside the watershed boundary. One suite of cross-sectional measurements was conducted in the dry season, March, 1998; a second, 7 months later near the end of the wet season.

At each cross-section, numerous physical phenomena were recorded, including road width, surface condition (e.g., track vs. nontrack), two-dimensional slope, lowering estimates, rut/gully dimensions, and availability of loose surface material. Area-based volumetric and gravimetric estimates of surface material availability were determined by collecting surface sediment from a 0·10 m swath across the road surface at each cross-section. The loose material was collected with a brush and a trowel, taking care not to detach new material from the road surface. Also along the road, a detailed survey was made of sediment sources, preferential overland flow pathways, and runoff entry/exit points.

Rainfall simulation experiments

Three rainfall simulation experiments were conducted, including one investigating sediment transport on fill material used to repair the road surface (referred to herein as FILL). Two other experiments investigated sediment detachment during motorcycle (MOTORCYCLE) and truck passes (TRUCK). Experimental designs for each simulation are as follows.

(I) The FILL simulations were performed in February 1999 on 1·3 m (W) $\times$ 3·75 m (L) plots on the steepest road section in PKEW (median slope = 0·18 m m^{-1}). For each of four FILL simulations, a large surface rut (median dimensions = 0·45 m (W) $\times$ 0·13 m (D)) running lengthwise down the slope was filled with material taken directly from the roadside margin. The material was excavated and applied with a hand-held hoe by Lisu farmers in a manner consistent with typical road maintenance in PKEW (Figure 2a). The fill material was compacted by stomping. Rainfall was applied for 45 min following time to runoff (TTRO).

(II) The MOTORCYCLE simulations were performed in February 1998 on a relatively new detour route bypassing a steep hillslope. Approximately five years ago local farmers altered the original road using hand tools. Maximum slope on this new road stretch is approximately 0·19 m m^{-1}. On the steepest sections, ruts created from vehicle tracks incise the surface to depths of about 0·10 to 0·15 m. The MOTORCYCLE simulations were performed on the same plots of a prior study (ROAD; Ziegler *et al.*, 2000) one day following the ROAD experiments. Initial soil moisture was relatively high (0·22 vs. 0·12 g g^{-1}) and loose surface sediment was reduced from what normally would be expected during the dry season. Simulated rain was applied to eight pairs of 0·85 m (W) $\times$ 3·75 m (L) subplots for 10 min after TTRO. After rain cessation, a 100 cc Honda motorcycle (street tyres = 5 cm wide, mass = 85 kg) was twice driven up and down through each plot. Each wave of motorcycle activity consisted of four passes through the plot. After a 15 min delay to complete the passes, rainfall was applied for another 10 min period, followed by a second identical wave of motorcycle passes and a further 15 min delay. A final 30 min of simulated rainfall was then applied.

(III) The TRUCK simulations were conducted on the FILL simulation plots (described above) on the following morning, approximately 18 h after the FILL simulations ended. Rainfall was initially applied for 20 min. The research vehicle (1993 Isuzu Rodeo; street tyres = 20 cm wide, mass = 1700 kg) was then driven once up and then back down through the test plot. Each plot was wide enough to allow only two of the four wheels to pass over the simulation surface; therefore, each pass phase experienced detachment by four tyres. After a 20 min delay to complete the passes, rainfall was applied for 25 min. In all, four TRUCK simulations were conducted.

Data from the prior ROAD simulations (Ziegler *et al.*, 2000) are used as a road control surface. During the ROAD experiments, eight simulations were performed on 0·85 m (W) $\times$ 3·75 m (L) plots for 60 min after

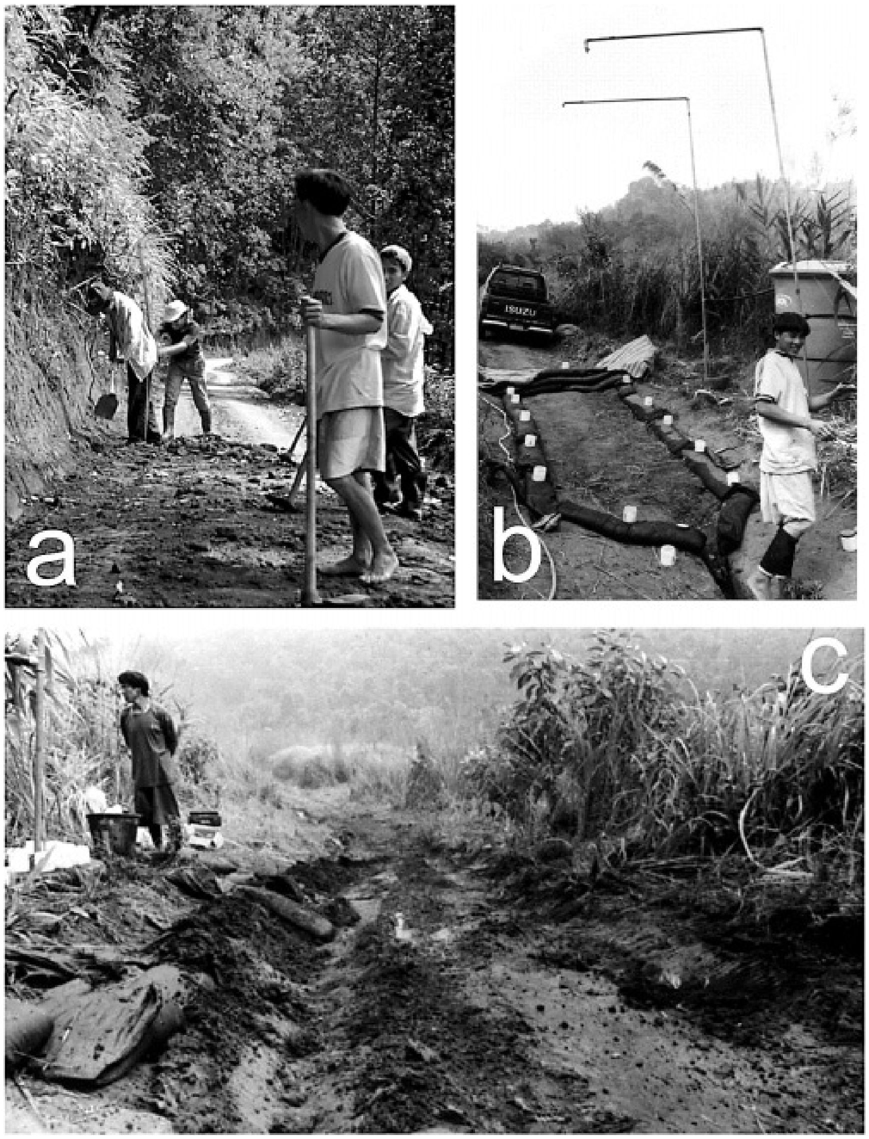

Figure 2. (a) Karen villagers repairing ruts on the road to Pang Khum by removing material from the cutslope; (b) Lisu man, Asuh, standing in front of the FILL plots and rainfall simulator; (c) Lisu man, Asam, standing beside a section of the Lower PKEW Road following the TRUCK simulations

TTRO. In the prior study, ROAD data were used to compare runoff generation on roads with that of other landuse surfaces in PKEW. The ROAD experiments indicated that sediment transport response on unpaved roads was characterized by an initial flush of loose surface material, which was abundant because the simulations were performed in the dry season, several weeks after the previous overland flow event. Following the flush, sediment output decreased to a lower rate, dependent on the detachment of material from the compacted road surface.

Rainfall simulator and plot design

The rainfall simulator 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 (EFD) of 1650–2040 J m^{-2} h^{-1} (100–120 mm h^{-1}), approximating energy sustained for

Table I. Mean slope, soil mass wetness and rainfall variables for all simulation experiments*

Treatment	n	Slope (m m^{-1})	w (g g^{-1})	r (mm h^{-1})	EFD (J m^{-2} h^{-1})
FILL	4	$0{\cdot}20 \pm 0{\cdot}06$	$0{\cdot}10 \pm 0{\cdot}05$	98 ± 11	1654 ± 188
ROAD†	8	$0{\cdot}15 \pm 0{\cdot}02$	$0{\cdot}12 \pm 0{\cdot}03$	110 ± 12	1836 ± 209
MOTORCYCLE					
Pre-pass	8	$0{\cdot}15 \pm 0{\cdot}02$	$0{\cdot}22 \pm 0{\cdot}01$	109 ± 12	1853 ± 198
Post-pass 1	8	$0{\cdot}15 \pm 0{\cdot}02$	-	108 ± 16	1826 ± 269
Post-pass 2	8	$0{\cdot}15 \pm 0{\cdot}02$	-	109 ± 16	1838 ± 262
TRUCK					
Pre-pass	4	$0{\cdot}20 \pm 0{\cdot}06$	$0{\cdot}28 \pm 0{\cdot}01$	104 ± 13	1665 ± 362
Post-pass	4	$0{\cdot}20 \pm 0{\cdot}06$	-	120 ± 17	2037 ± 294

* w is pre-simulation mass wetness, r is rainfall rate, EFD is energy flux density; values are means $\pm$ one standard dev.
† ROAD data are from Ziegler *et al.* (2000)

10–20 min during the largest annual PKEW storms (based on preliminary analysis of two years of rainfall data). Rainfall rate was measured during each event with several manual gauges placed on the plot borders. Cylindrical, sand-filled, low permeability geotextile bags ($3{\cdot}0 \times 0{\cdot}2 \times 0{\cdot}1$ m) were arranged to form two side-by-side rectangular subplots. At the base of each subplot, geotextile bags were arranged to funnel runoff into a shallow drainage trench dug into the surface. A V-shaped trough constructed from aluminium flashing was inserted into the vertical wall of the trench to allow event-based sampling. The simulator design is shown in Figure 2b. Mean values of plot slope, pre-simulation soil wetness, rainfall intensity and EFD for all simulation experiments are shown in Table I.

Simulation data collection and calculations

During each experiment, instantaneous discharge and sediment output were recorded at time to runoff (TTRO), then again at 1·0, 2·5 or 5·0 min intervals until the end of simulation or until a scheduled break to conduct vehicle passes. Discharge volume was reduced to account for presence of sediment in the samples. Instantaneous discharge and sediment output values were adjusted to rates per unit area by dividing by filling time and plot area. The rates were then divided by energy flux density (EFD) values of the simulated rainfall (calculation of EFD is described by Ziegler *et al.*, 2000). Normalized instantaneous discharge (Q_t) and sediment output (S_t) therefore have units m^3 J^{-1} and kg J^{-1}, respectively. Total normalized event discharge and sediment output, Q_{event} and S_{event}, were calculated as event total values divided by total event EFD. Runoff coefficients (ROCs) were calculated at each sampling time as the fraction of rainfall leaving the plot as discharge. Final event steady-state infiltration rates (f_{ss}) were estimated from the event rainfall intensity (r) and the final event runoff coefficient (ROC$_{final}$, determined over the last 15 min of simulation time) as:

$$f_{ss} = (100\% - \mathrm{ROC}_{final})r \tag{1}$$

This approximation assumes surface storage depressions are full, and thus the difference in rainfall and discharge rate is the f_{ss}.

Statistical analysis

For comparing FILL with ROAD data, slope, antecedent soil wetness (w), r, event energy flux density (EFD), TTRO, Q_{event}, ROC, f_{ss}, S_{event} and C_{event} data were analysed using the non-parametric Mann–Whitney U-test (M-W U). For the MOTORCYCLE simulations, the data were log$_{10}$-transformed then analysed using one-way analysis of variance (ANOVA); multiple comparison testing was then conducted with the Fisher's protected least-squares difference test (PLSD) when the F-values were significant at $\alpha = 0{\cdot}05$ (Gagnon *et al.*, 1989). For comparison of MOTORCYCLE pre-pass S_t values with ROAD simulation data, repeated

Figure 3. Surface lowering on the main road to Pang Khum. The >0·5 m elevated bench on the left was the original road surface before the rainy season began four to six months earlier

measures (RM) ANOVA was performed on $\log_{10}$-transformed data. The pre-pass and post-pass TRUCK simulation data were analysed with M-W U.

RESULTS

Road survey

The traffic survey revealed that the Lower PKEW Road receives $4{\cdot}1 \pm 0{\cdot}5$ (standard error) motorcycle and $1{\cdot}8 \pm 0{\cdot}3$ truck passes per 12 h work day. Daily motorcycle traffic is from farmers going to and from their fields. Truck traffic is generally from small pickups taking crops to the village or market; few villagers who utilize PKEW own a truck. Occasionally a caravan of one to four trekking jeeps will pass through. An army personnel transport truck (six wheels, mass >4400 kg) passes through once or twice a year carrying troops conducting opium eradication. Well-defined tyre tracks/ruts exist throughout the entire 1·65 km length; in some areas a centre motorcycle track parallels existing truck ruts. On steep sections, incised tracks provide a rough, exhilarating driving challenge during both wet and dry periods. Surface lowering, of $\leq 0{\cdot}10$ m a^{-1}, is detectable mainly on steep sections ($\geq 0{\cdot}15$ m m^{-1}), which occupy <30 per cent of the total road length. This lowering value is based on one-year and five-year estimates made on the new detour section where the FILL simulations were conducted. In comparison, on one steep (>0·20 m m^{-1}) section of the main artery leading to Pang Khum, we observed lowering in excess of 0·75 m during the 1996 rainy season (Figure 3).

Road cross-section measurements conducted in the 1998 dry season revealed 8·59 Mg (2·17 kg m^{-2}) of loose surface material on the Lower PKEW Road (1650 m (L) × 2·4 m (W) = 3960 m^2) Cross-sectional measurements taken during the rainy season verify significantly less (M-W U, tied-P value <0·0001) loose road material (3·13 Mg, 0·79 kg m^{-2}). The texture of this material (58 per cent sand, 19 per cent silt, 23 per cent clay) is indistinguishable from that of the compacted road surface and adjacent fields. Some locations with the greatest sediment depth were found on and immediately below the steepest roads sections, but no significant correlation existed between sediment depth and slope. Most surface material present during the survey is road material detached by vehicle traffic. Other non-road sediment sources include: (1) material removed from the roadside margin for repair; (2) infrequent bank failures (e.g. at entry points to upslope fields) and side slope slumping; (3) localized excavation sites for harvesting plants, insects, etc. Some of the wet-season material includes sediment deposited during prior overland flow events. The wet-season value, which is one-third that of the dry-season value, may be higher than what typically exists during the wettest part of the rainy season (June–August), for the survey was conducted during an extended dry period.

Conveyance efficiency (CE) of road runoff to the stream network varies spatially and temporally. For any given road section, erosion processes, maintenance and mass wasting change the overland flow pathways and runoff exit points. During large storms, overland flow may bypass typical flow channels, thereby altering the conveyance efficiency. In PKEW, a total of 1263 m of the lower road terminates at the stream network. Assuming that runoff exiting elsewhere infiltrates on the hillside (supported by field observations) and that no evaporation or surface storage occurs, the maximum CE estimate for the Lower PKEW Road is 76 per cent. During large storms, some overland flow leaves the road surface at ephemeral exit points, where it again infiltrates into the hillside. Factoring in these losses, the minimum CE estimate is 56 per cent. For most storms, including STORM discussed below, estimated CE for the lower PKEW road is about 70 per cent (field observation).

FILL simulations

Data in Table II show both hydrological and geomorphological differences between the FILL and ROAD simulations. For example, TTRO was much slower on the repaired/filled surface; additionally, total event discharge (Q_{event}) and event ROC were lower for FILL compared with the ROAD control. Bulk density of the fill surface was 1·05 Mg m^{-3} (taken *it situ* after the repair), significantly lower (M-W U, $\alpha = 0{\cdot}05$, $n = 12$) than the 1·42 Mg m^{-3} of the road surface. ROAD and FILL steady-state infiltration rates were statistically indistinguishable, implying that ending ROCs (thus final discharge) were similar. Total event sediment output for the FILL simulations was about 40 per cent higher than for the ROAD simulations. Instantaneous sediment transport for the two simulation surfaces was very similar for the first 15 min, but then separated for the final 30 min, as FILL S_t remained relatively high, and ROAD S_t diminished (Figure 4a). Total sediment concentration was 2 times higher for the FILL versus the ROAD simulations (Table II). Figure 4b shows FILL instantaneous sediment concentrations (C_t) to be consistently higher than those for ROAD. The maximum C_t during the FILL simulation was almost twice as high as that for ROAD (320 vs. 170 g l^{-1}).

Motorcycle and Truck simulations

Runoff and sediment transport data from the MOTORCYCLE and TRUCK simulations are shown in Table II. For both types of simulations, post-pass phases had higher event discharge and ROCs. These increases may

Table II. Mean runoff and sediment transport data for all simulations*

Treatment	TTRO (min)	Q_{event} (l J^{-1})	ROC (%)	f_{ss} (mm h^{-1})	S_{event} (g J^{-1})	C_{event} (g l^{-1})
FILL†	6·1 ± 3·4 a	0·043 ± 0·01 a	60 ± 14 a	12·0 ± 11·3 a	1·7 ± 0·6 a	44 ± 9 b
ROAD†	1·1 ± 0·3 b	0·053 ± 0·01 a	82 ± 4 b	6·2 ± 4·1 a	1·2 ± 0·6 a	21 ± 9 a
MOTORCYCLE‡						
Pre-pass	0·6 ± 0·3 b	0·044 ± 0·01 a	69 ± 10 a	16·4 ± 9·6 a	0·79 ± 0·4 a	17 ± 9 ab
Post-pass 1	0·4 ± 0·2 a	0·045 ± 0·01 a	75 ± 8 b	12·1 ± 8·4 a	1·15 ± 0·6 a	22 ± 10 b
Post-pass 2	0·3 ± 0·1 a	0·054 ± 0·01 b	86 ± 5 c	9·8 ± 5·1 a	0·89 ± 0·4 ab	15 ± 6 a
TRUCK§						
Pre-pass	0·8 ± 0·2 b	0·043 ± 0·01 a	73 ± 12 a	12·1 ± 11·8 a	1·2 ± 0·3 a	25 ± 7 a
Post-pass	0·5 ± 0·2 a	0·051 ± 0·01 a	86 ± 7 a	7·0 ± 6·6 a	3·8 ± 0·6 b	68 ± 8 b

* TTRO is time to runoff, Q_{event} is total normalized event discharge, ROC is the total event runoff coefficient (total runoff/total rainfall), f_{ss} is estimated steady-state infiltration rate (from Equation 1), S_{event} is normalized event sediment output, C_{event} is total event concentration; values are means ± one standard deviation

† ROAD and FILL data in each column with the same letter were *not* statistically different at $\alpha = 0{\cdot}05$, non-parametric Mann-Whitney U-test; ROAD data are from Ziegler *et al.* (2000)

‡ MOTORCYCLE simulation data in each column with the same letter were *not* statistically distinguishable at $\alpha = 0{\cdot}05$, ANOVA followed by Fisher's PLSD post hoc testing on $\log_{10}$-transformed data

§ TRUCK simulation data in each column with the same letter were *not* statistically different at $\alpha = 0{\cdot}05$, non-parametric Mann-Whitney U-test

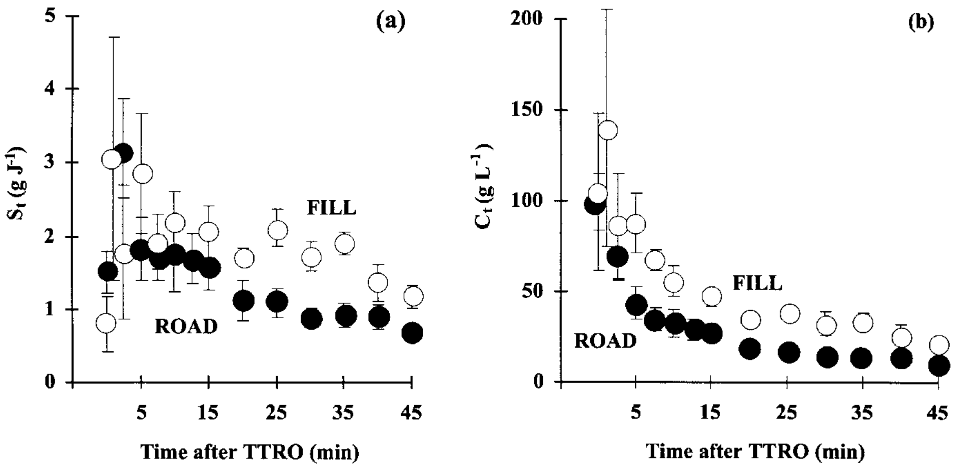

Figure 4. (a) Normalized instantaneous sediment output (S_t) and (b) instantaneous sediment concentration (C_t) for the FILL and ROAD simulations. Values are means ± one standard error

result from the creation of well-defined flow channels by the vehicle tyres, but may also be artifacts of the post-pass phases having higher soil moisture values than the previous phases. The truck passes initiated significant increases in total event sediment output and concentration. The motorcycle passes increased sediment transport without causing the doubling in event sediment concentration that was present in the TRUCK simulations. Figures 5 and 6 show sharp increases in instantaneous sediment transport and concentration occurring immediately following truck and motorcycle passes. These spikes were soon followed by sharp declines to pre-pass values within 10–30 min.

DISCUSSION

Interstorm surface preparation

Although traffic in PKEW is light (based on definitions of Reid and Dunne, 1984), the roads are important sediment sources for material, particularly loose surface sediment, entering the stream channel network. Abundance of loose road surface material at any given time is a function of vehicle traffic and other surface preparation processes occurring since the last overland flow event. Surface preparation refers to any phenomenon that contributes to the availability, erodibility/detachability, or transport of material (cf. Bryan, 1996). Interstorm preparation in PKEW is extensive during the four to five month dry season. During the wet season, the supply of loose material generated before each storm is diminished because the interstorm period is shortened. Importance in the length of the interstorm preparation period is illustrated in Figure 7a, where sediment transport on a road section during simulated rainfall after a long dry period (DRY) is compared with that on the same section one day following an approximately 80 mm rainfall event (WET, all data based on the ROAD and MOTORCYCLE simulations discussed below). Instantaneous sediment transport (S_t) for the DRY condition is significantly greater (RM ANOVA, $\alpha = 0{\cdot}05$) than for WET at all time periods during the short, high-intensity (mean = 110 mm h^{-1}) event. Absent from the WET time series is the large initial flush of loose material that was present during the DRY time series. The material constituting this flush was generated by truck and motorcycle passes that occur for many weeks prior to the rainfall event. In the case of the WET simulation, the overland flow event on the previous day removed most loose surface material.

When interstorm sediment preparation is great, relatively small overland flow volumes can transport significant sediment loads. Figure 7b shows that one-third of the total sediment for the DRY road simulation is removed within the first 10 min of the 45 min event, when ROCs were far below event maximum values.

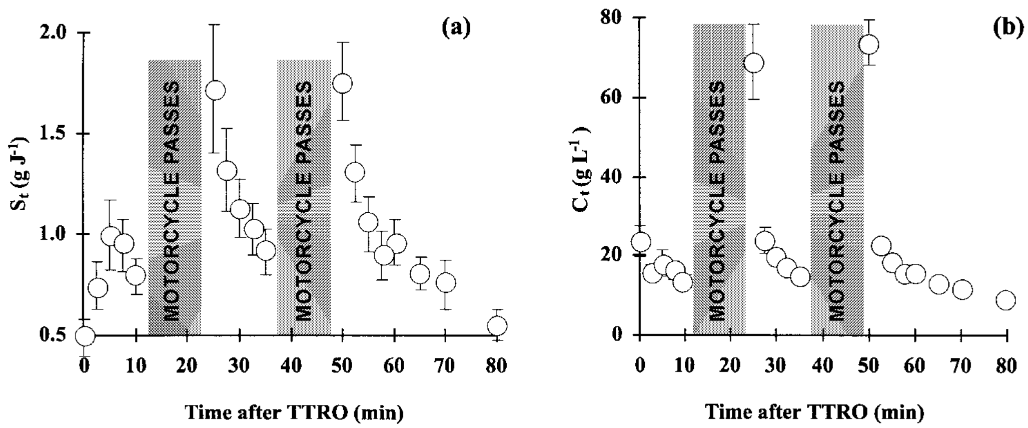

Figure 5. (a) Normalized instantaneous sediment output (S_t) and (b) instantaneous sediment concentration (C_t) for the pre-pass and two post-pass phases of the MOTORCYCLE simulations. Rainfall was stopped for 15 min to make the motorcycle passes. Each phase time series begins when runoff was generated. Values are means ± one standard error

Furthermore, nearly two-thirds of the material was removed before the mid-point of the storm (22·5 min). For shorter storm events, larger percentages of total event material will be removed early. For example, if the event lasts only 15 min, approximately 40 per cent of the total sediment output will occur in the first 5 min. Figure 7a and b collectively indicates that; if loose material is available, much will be transported soon after overland flow generation; even low-magnitude events are capable of entraining sediment on the road surface. Because of a high conveyance efficiency for the PKEW network, most of this material goes directly into the stream system.

Hydrological and geomorphological consequences of maintenance activities

Road maintenance is another interstorm preparation activity affecting sediment availability. In PKEW, less than 10 per cent of the road requires some type of repair during or following the rainy season (field survey). Many attempts by villagers to make the road passable by filling gullies with cutslope material are quick-fix solutions (Figure 2a), where much of the fill is quickly eroded during subsequent large storm events. The FILL simulations demonstrate the vulnerability of this type of repair. The fill material, being significantly

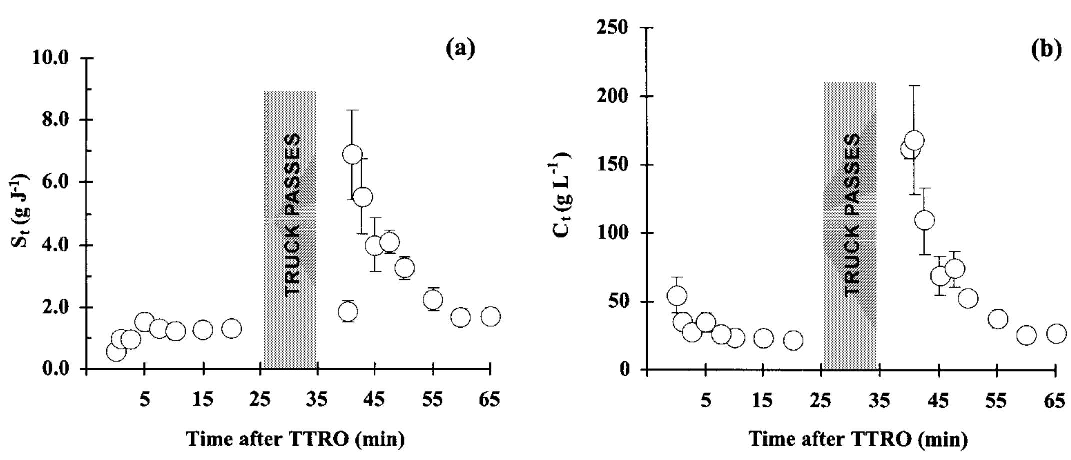

Figure 6. (a) Normalized instantaneous sediment output (S_t) and (b) instantaneous sediment concentration (C_t) for the pre-pass and post-pass phases of the TRUCK simulations. Rainfall was stopped for 10 min to make the truck passes. Each phase time series begins when runoff was generated. Values are means ± one standard error

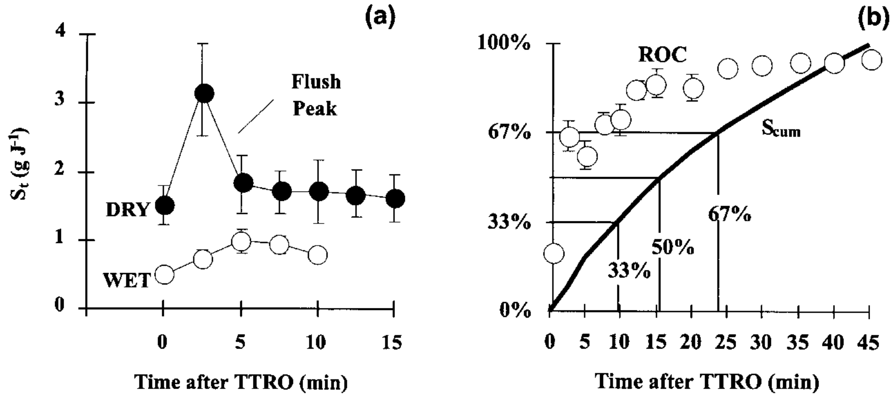

Figure 7. (a) Comparison of instantaneous sediment transport (S_t) on a road surface during DRY conditions with S_t one day after an 80 mm rainfall simulation event (WET). Values are means ± one standard error. (b) Cumulative sediment transport (S_{cum}) as a percentage of total output plotted with instantaneous runoff coefficients (ROC, dots) for the DRY road simulations shown in (a). Values are means ± one standard error. One-third of the total sediment output was transported within the first 10 min when ROC values were well below maximums. By the event mid-point (22·5 min) almost two-thirds of the event total output had been transported

less compacted than the road surface, infiltrated more rain water, delaying runoff generation by 5 min (Table II). Throughout the simulation, the fill material temporarily stored rainwater that otherwise would have become HOF on the compacted road surface. During later stages of the simulation, subsurface stormflow exited the fill as return flow near the bottom of the plot. Post-event runoff from the ROAD simulation plots subsided within 1 min. In comparison, runoff continued on the FILL plots for several minutes after rainfall was discontinued. Although the fill had a higher infiltrability, water storage was limited, and the long-term infiltration rate was governed by that of the underlying, compact road surface. Thus, the repair represents a non-consolidated layer resting atop a less permeable surface that is subject to failure by two mechanisms: (1) sliding on the underlying compacted surface where infiltrated water flows laterally on steep road sections; and (2) surface erosion and incision by overland flow generated on upslope road sections.

With respect to surface erosion, both FILL and ROAD surfaces experienced an initial flush of easily removed surface material during rainfall simulation (Figure 3a). Again, much of the total event sediment for ROAD was removed in the first few minutes following runoff generation. In contrast, only a little more than half the total FILL output was transported after 25 min. Fluctuations in the FILL S_t data (e.g. 15 to 35 min) result from the creation and destruction of surface microdams (observed), processes that are common on bare, rough agricultural surfaces. FILL sediment response resembles a hybrid of that found on road and agricultural surfaces. To date, the FILL surface is the most erodible surface complex we have identified in PKEW, eclipsed perhaps only by field erosion resulting from HOF generated on agricultural maintenance paths. We use the term ‘complex’ because it is the juxtaposition of an erodible material with a compact surface capable of generating sufficient HOF that produces high sediment output. Because the erodibility of this type of repaired surface is different from that of non-repaired road sections, it is important to discriminate between the two surface types when modelling.

Sediment detachment by vehicles

The MOTORCYCLE simulations demonstrate the role of vehicular traffic in enhancing sediment transport on unpaved roads during rain events (Figure 5, Table II). Sediment transport during these experiments was relatively low because the simulation plots were used the preceding day for the ROAD simulations. The pre-pass simulation stage (0 to 10 min) demonstrates a supply-limited situation in which little loose surface material was present; most sediment output, therefore, was material detached from the road surface by raindrop impact and rain-affected flow processes. By the end of this 10 min phase, S_t was probably approaching a baseline rate. Following the first wave of motorcycle passes, sediment output immediately doubled. Over the next 10 min S_t declined, but remained higher than the final pre-pass rate. Following the second set of motorcycle passes, S_t nearly doubled from the preceding value. Once again S_t declined during the remainder of the simulation. After about 15 min, S_t values were lower than those at the end of the pre-pass phase, indicating that the motorcycle passes detached a limited supply of material that was removed in 10 to 15 min.

Although the passes created visible tyre tracks, overland flow did not incise them: incision would have produced protracted, high S_t values. Nevertheless, the first motorcycle passes doubled total sediment production from what would have been expected without the disturbance (calculations based on S_t data from the 10 min post-pass phase). Similarly, the second motorcycle passes increased total sediment production by about 60 per cent in the final simulation phase. Sediment concentrations increased significantly following each wave of the passes (Figure 5b). Concentration was significantly higher only at the initial post-pass sampling time when ROCs were still relatively low (about 40 per cent). Just 2·5 min later when ROCs increased to about 80 per cent, C_t values dropped to approximately their pre-pass values. This 'elastic' response in C_t results from the detached material being stored temporarily within or near the well-defined tyre tracks, where it could be removed quickly by channellized flow.

The S_t and C_t responses to truck passes were generally similar to those of the MOTORCYCLE simulations (Figure 6), with an exception being the magnitude of the sediment output spike following truck passes. TRUCK S_t increased to more than five times the pre-pass value, as compared with an approximate doubling of S_t following motorcycle passes. The greater TRUCK response results from two conditions: (1) the TRUCK simulations were performed on a more erodible surface (the FILL simulation plots discussed above) – in fact, nearly all pre-pass TRUCK S_t values were more than or equal to the maximum MOTORCYCLE pre-pass S_t value; and (2) the heavier trucks (1700 vs. 85 kg) with wider tyres (20 cm vs. 5 cm) detached more material than did the motorcycles. Following the truck passes, S_t peaked immediately, then declined over time. The final output value, however, remained higher than the final pre-pass value, indicating that the new material detached by the truck passes was not completely removed during the final 25 min of simulation. It may also indicate that incision of the newly formed truck tracks by overland flow was contributing substantially to sediment transport (incision on the fill was observed during some experiments). The truck passes generated 2·5 times more sediment output than would have been expected without the passes; this value is slightly higher than the doubling response witnessed during the first set of motorcycle passes. Initial post-pass sediment concentration (approximately 165 g l^{-1}) increased almost eight times over the ending pre-pass values. Somewhat different from the MOTORCYCLE concentration response, post-pass TRUCK C_t remained high for several minutes. Unfortunately, because the TRUCK and MOTORCYCLE simulation methodologies were different, it is not possible to estimate reliably how much more sediment was detached by the truck versus the motorcycle passes.

Vehicle detachment in a prior study: a comparison

Similar to our study, Coker *et al.* (1993) found elevated sediment concentrations following truck passes (two passes of a 3000 kg, six-wheel dump truck) on a wet road during simulated rainfall (400 m^2 plot, 30 min, 38 mm h^{-1}) in the Marlborough Sounds of New Zealand. In all, five groups of two passes were made approximately 5 min apart. Immediately following dump truck passes, sediment concentrations at one site initially rose by an order of magnitude to $>$120 g l^{-1}. Within 2·5 min, C_t fell to roughly the pre-pass value. For each successive pair of truck passes, large post-pass C_t peaks were generated; however, successive peak values constantly decreased, with the final peak value only reaching about 60 g l^{-1}. In comparison, we did not find the diminishing concentration peak phenomena during the MOTORCYCLE simulations, and our post-pass TRUCK C_t values did not return to the range of pre-pass values until after about 10 to 15 min.

Apart from being related to differences in soil erodibility, differences between our simulation results and those in the Marlborough experiment are probably related to surface preparation. The Marlborough plots were raked prior to simulation to ensure the presence of a loose layer of uniformly distributed material. Most loose material on our plots was removed by prior rainfall simulation events. Therefore, most of the post-pass sediment transport during the MOTORCYCLE and TRUCK simulations was that of newly detached material. Post-pass sediment output at Marlborough was probably a combination of material detached by the truck passes and loose pre-simulation material that the dump truck passes redistributed into efficient overland flow pathways (i.e. newly formed tracks). Concentration peaks declined over time not because the passing trucks were necessarily detaching less material, but, we believe, because the supply of loose surface material became depleted over the course of the simulation. Some differences between the two studies could be related to scale, as sediment output on our small-scale plots is sensitive to sediment detachment at the bottom of the plots. Nevertheless, these two field-based studies emphasize that vehicle-induced sediment output is substantially influenced by availability of loose surface material, which is influenced by pre-event surface preparation, e.g. traffic (cf. Reid and Dunne, 1984).

Toward modelling vehicular traffic

The rainfall simulations have increased our knowledge about two specific mechanisms by which vehicular traffic influences sediment transport on unpaved roads: (1) interstorm surface preparation; and (2) detachment of new material and/or redistribution of existing material during rain storms. Both mechanisms generate new material to be flushed from the road surface either during the next overland flow event (in the case of interstorm preparation) or within the next few minutes (in the case of detachment during an overland flow-producing storm). A third mechanism, incision of tyre ruts/tracks, was not investigated.

An on-going goal in erosion research is to use physically based models to simulate sediment production on unpaved roads (Simons *et al.*, 1977, 1978; Ward, 1985; Elliot *et al.*, 1995; Ziegler *et al.* in press). This endeavor is difficult because model sediment transport equations, which are often based on agricultural or range land experiments, typically do not describe realistically the observed sediment transport response on unpaved roads (e.g. that of ROAD in Figure 4a). In a prior work, we introduced the dynamic erodibility (DE) methodology to simulate the initial flush of loose material and the ensuing decay in sediment transport by explicitly modelling the removal of a finite layer of loose material (Ziegler *et al.*, in press). The DE methodology recognizes that erodibility changes both as material is detached during the interstorm period, and during a storm as surface sediment is removed by overland flow. Initial erodibility for any given storm is a function of sediment availability; once all loose material is removed, erodibility is that of the compacted road surface.

Surfaces represented by FILL can be modelled with DE by assigning repaired road sections initial erodibility parameters that are higher than those of the surrounding compacted road surface. Eventually erodibility will decrease as the easily transported material is removed. Again, we are not considering extreme events where gullying and mass wasting occur. Other researchers have reported decreases in road erosion rates over time following grading on gravel roads (Black and Luce, 1999) and road construction (e.g. Megahan, 1974; Riley, 1988; Beschta, 1978). In most cases, the decline results, in part, from preferential depletion of fine, highly erodible fractions (others have referred to this process as armouring, e.g. Megahan, 1974; Black and Luce, 1999). With DE, one would treat preferential depletion as a shift to a less erodible material (i.e. the coarse and/or consolidated material left behind).

Modelling vehicle detachment during storms is difficult because users must simulate the process by manipulating model splash and hydraulic erosion parameters. A plausible approach using DE is to treat vehicle-induced increases in the supply of surface material as temporary increases in road erodibility. In the case of interstorm surface preparation, erodibility is a function of sediment availability, which is related to total traffic since the last overland flow event. Modelling vehicle passes during a storm requires employing DE at a shorter time scale. Sediment transport following a vehicle pass increases because a new limited supply of material becomes available on the road surface where it can be entrained immediately by overland flow. For modelling, each pass marks the transition to a higher state of erodibility. After the new material is removed, sediment transport rate – hence erodibility – returns to that of the pre-pass state.

Figure 8 conceptualizes modelling vehicular detachment during a storm employing DE. Sediment production on the road surface (S_{Road}, from ROAD data) decreases over time as easily entrained surface

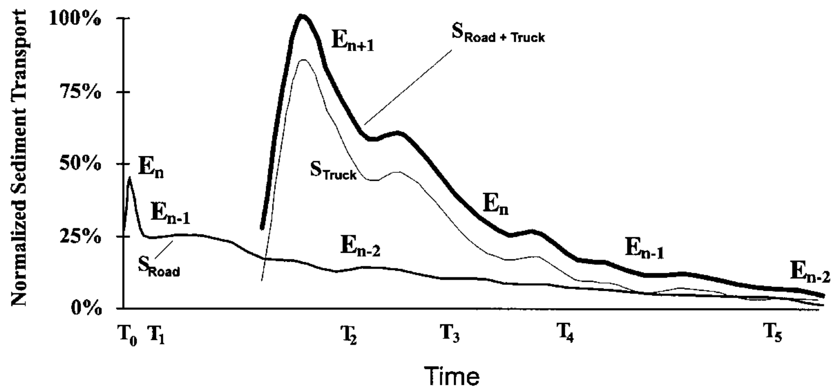

Figure 8. Conceptual methodology for modelling vehicular detachment during a storm. S_{Road} is sediment transport on the road surface. S_{Truck} is the sediment transport resulting from truck passes. $S_{Road + Truck}$ is the total sediment transport following the truck passes. All values are normalized by dividing by the maximum $S_{Road + Truck}$ value. Values of E (where $E_n > E_{n-1}$) represent the road surface erodibility, which decreases as loose material is removed and increases as vehicle passes detach new material from the compacted road. T_n values mark transitions to lower erodibility states (described in the text). The time scale is on the order of 2–3 h

material is removed. Thus, for a lengthy storm without during-event traffic a road surface passes through several states of decreasing erodibility. Initial road erodibility (E_n) is determined by sediment availability. Times T_1 and T_2 mark transitions to states of lower erodibility (i.e. $E_n > E_{n-1} > E_{n-2}$). The fine line represents the sediment output generated following a vehicle pass (based on post-pass TRUCK S_t rates minus the pre-pass equilibrium rate). The thick line is the combined sediment production from the road and that generated by the truck pass: $S_{Road + Truck} = S_{Road} + S_{Truck}$. The passing of the truck immediately produces a transition to a higher erodibility state (i.e. $E_{n+1} > E_n$). After several minutes of high sediment production, $S_{Road + Truck}$ declines, and at time T_3 the surface erodibility switches to the preceding value, E_n. As time progresses, erodibility values reduce to E_{n-1} at T_4, then E_{n-2} at T_5.

A model from a prior study (Megahan, 1974) provides a basis for assigning post-pass erosion rates:

$$\varepsilon_t = \varepsilon_n + kS_o e^{-kt} \tag{2}$$

where ε_t represents the erosion rate at a disturbed site, ε_n is the erosion rate of the site prior to disturbance, S_o is the amount of material made available by the disturbance, k is the recovery potential for the disturbed site and t is time. The Megahan model is incorporated into the conceptual model shown in Figure 9 simply by substituting E_{n+1} and E_n for ε_t and ε_n, respectively in Equation 2.

At present we have little experimental data for prescribing various S_o, k and erodibility values. The MOTORCYCLE and TRUCK simulations generally indicate that erodibility doubles following a set of passes for about 15 to 30 min (assuming relatively high, stable rainfall and overland flow). In another 'truck' study conducted in Hawaii (A. D. Ziegler, unpublished data) we found post-pass S_t values returned to approximately the pre-pass maximum values after about 20 min following two passes of a pickup truck having similar mass to the Isuzu used in Thailand (Figure 9). Total sediment output attributed to the Hawaiian truck passes was less than that determined in the TRUCK simulations, emphasizing that various states of erodibility are inherently determined by the physical properties of the road soil surface. Erodibilities will probably have to be determined experimentally for different locations. Although our knowledge base to make such prescriptions is nascent, Figure 9 represents a framework from which we are directing future research.

CONCLUSION

Knowledge of pre-storm surface preparation phenomena, especially vehicular and maintenance activities, is

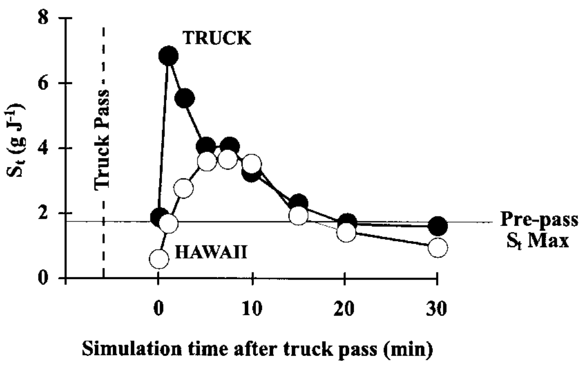

Figure 9. Comparison of post-pass instantaneous sediment transport (S_t) for the TRUCK simulations (reported herein) and a previous study in Hawaii (A. D. Ziegler, unpublished data). In both experiments, post-pass values decrease to approximately the pre-pass maximum value after about 20 min (33 and 40 mm of rainfall for the Hawaii and Thailand simulation, respectively)

crucial to understanding sediment transport on unpaved roads. During typical rainfall events where overland flow does not greatly incise the surface, much of the sediment transported on PKEW roads is loose, easily entrained material that was present prior to the event. This loose material is predominantly generated by vehicular detachment and maintenance activities during the interstorm period. In general, for any given usage level, the longer the interstorm period, the greater the supply of loose material, thus the greater the event sediment transport. Vehicular traffic during rainstorms initiates high sediment transport rates by detaching new material from the road surface and creating efficient overland flow paths. Additionally, a vehicle pass redistributes existing loose material into flow paths where it can be entrained. Sediment transport response to a vehicle pass is therefore related to interstorm surface preparation, as well as to the more obvious variables associated with the passing vehicle, *in situ* soil, and rain event. Because the supply of loose material is in constant flux, the road behaves like a surface with changing erodibility. Through adopting this concept of dynamic erodibility, one can parameterize maintenance and vehicular activities during physically based modelling of road-related erosion.

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