

Elephant Trail Runoff and Sediment Dynamics in Northern Thailand

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Although elephants may exert various impacts on the environment, no data are available on the effects of elephant trails on runoff, soil erosion, and sediment transport to streams during storms. We monitored water and sediment fluxes from an elephant trail in northern Thailand during seven monsoon storms representing a wide range of rainfall energies. Runoff varied from trivial amounts to 353 mm and increased rapidly in tandem with expanding contributing areas once a threshold of wetting occurred. Runoff coefficients during the two largest storms were much higher than could be generated from the trail itself, implying a 4.5- to 7.9-fold increase in the drainage areas contributing to storm runoff. Clockwise hysteresis patterns of suspended sediment observed during most storms was amplified by a “first flush” of sediment early on the hydrograph in which easily entrained sediment was transported. As runoff areas expanded during the latter part of large storms, discharge increased but sediment concentrations declined. Thus, sediment flux was better correlated to kinetic energy of rainfall on the falling limbs of most storm hydrographs compared to rising limbs. Based on a power function relationship between sediment flux and storm kinetic energy, the estimated annual sediment yield from the trail for 135 storms in 2005 was 308 to 375 Mg ha⁻¹ yr⁻¹, higher than from most disturbed land surfaces in the tropics. The eight largest storms (30% of total storm energy) in 2005 transported half of the total annual sediment. These measurements together with site investigations reveal that highly interconnected elephant trails, together with other source areas, directly link runoff and sediment to streams.

BECAUSE OF THEIR SIZE, longevity, range of travel, and dietary and water requirements, elephants exert stresses on their environment that exceed those of most other animals (e.g., Laws, 1970). Contentions that elephant disturbances may modify plant communities in ways that provide habitat for different ranges of animal species (e.g., Herremans, 1995; Maisels et al., 2001; Gillson and Lindsay, 2003) need to be balanced against documented landscape impacts associated with high population densities or confinement of elephants within limited areas. Such impacts are complex and involve biodiversity (Lombard et al., 2001; Levick and Rogers, 2008), invertebrate fauna (Pullan, 1979; Botes et al., 2006), extirpation of important plant species (Anderson and Walker, 1974; O'Connor et al., 2007; Landman et al., 2008), decreased site productivity (Pamo and Tchamba, 2001), disturbances associated with accessing water and food sources (e.g., Blake and Inkamba-Nkulu, 2004; de Beer et al., 2006; Fernando et al., 2008), and conversion of woodland into grassland or scrubland (Laws, 1970; Tafangenyasha, 2001; Skarpe et al., 2004). In view of these long- and short-term impacts, the management of elephant populations and domesticated use of elephants in both Africa and Asia have proven both difficult and controversial. Despite the decline in the overall Asian elephant population (e.g., Hedges et al., 2005), large numbers of elephants are concentrated in recreational areas of northern Thailand where they are used in trekking camps (Lair, 2008), exerting substantial pressures on the ecosystems in which they traverse, feed, bathe, and bed.

Studies in Southeast Asia have shown that trails and footpaths alter local site hydrology by decreasing infiltration capacity of the path surface, redirecting incoming rainfall and inflowing water from upslope sources as infiltration-excess (Hortonian) overland flow, and concentrating this erosion-producing surface runoff onto a limited number of slope segments (e.g., Ziegler et al., 2001a; Sidle et al., 2006). Occasionally, footpaths on hillslopes can intercept subsurface water during storms, although such mechanisms of overland flow generation are not as common as Hortonian overland flow from compacted surfaces because paths are typically not cut deeply into the soils (Ziegler et al., 2001a). Trails are linear or curvilinear landscape features that facilitate

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Abbreviations: API₃, 3-d antecedent precipitation index; ROC, runoff coefficient; TSS, total suspended solids.

the transport of sediment to headwater streams (Croke et al., 2001; Sidle et al., 2004; Clarke and Walsh, 2006). Although it is recognized that unpaved roads and trails in tropical mountain catchments can produce considerable runoff and sediment (Dunne, 1979; Ziegler et al., 2000; Sidle et al., 2006; Rijdsdijk et al., 2007; Negishi et al., 2008), the specific effects of large animal trails on soil erosion and storm runoff have been essentially ignored.

Reviews of cattle grazing and horse riding emphasize the importance of large animal traffic on soil erosion, but few studies were cited that actually measured erosion rates from trails during storm events (Trimble and Mendel, 1995; Pickering et al., 2010). Most of the relevant research that has actually measured sediment production has focused on plot-scale (e.g., Warren et al., 1986; Butler et al., 2006) or catchment-scale (e.g., Johnson and Smith, 1978; McDowell, 2007) results that may include effects of animal trails along with a wide array of other disturbances on sediment production. Many other studies have used proxies to link grazing and animal use pressures to sediment production (e.g., Anderson, 1974; Trimble and Mendel, 1995; Foster et al., 2007). As such, results from such investigations span the gamut from relatively insignificant to major effects of animal usage on sediment production due in part to issues of scale, inability to isolate specific impacts (e.g., trails), and differences in connectivity between sediment sources and measurement locations. The somewhat counterintuitive findings (i.e., no relation between grazing pressure and sediment production) of several studies may be related to such factors (Phippen and Wohl, 2003; Onda et al., 2007).

If large animal trails are located within forests, their influence on sedimentation may be small because runoff is buffered by downslope vegetation; however, if located in converted plantations or open areas, paths may capture sediment-laden runoff from adjacent fields and clearings and redirect it to streams or divert overland flow onto these adjacent areas, where it may move to streams as surface runoff (Sidle et al., 2006). Furthermore, run-on from adjacent areas may enhance hydraulic erosion on paths. Sediment delivery to the stream also depends on the position of the trail relative to the stream network, downslope vegetative buffers, and terrain features (e.g., gullies, diversions) that allow surface flow to bypass potential buffers (Dunne, 1979; Ziegler et al., 2001a, 2006; Sidle et al., 2004, 2006). As such, the location and orientation of trails are important for determining whether surface runoff will exacerbate surface erosion, sediment delivery to streams, and peak flows.

To our knowledge, soil erosion in areas affected by elephants has not been quantified, although it has been alluded to in a few studies (e.g., Pullan, 1979; Höft and Höft, 1995; Carruthers, 2006). Given the paucity of data on this erosion source, our study focused on quantifying runoff and sediment fluxes from elephant trails in northern Thailand during several monsoon storms. Other objectives include inferring erosion and runoff mechanisms from real-time measurements and observations during storms, estimating annual sediment delivery from the trail to the stream system, and comparing our elephant trail erosion rates with those from other highly disturbed lands in Southeast Asia.

Site Description

The field study was conducted in Chiang Mai Province, Thailand, in the foothills of the Thanon Thongchai Mountains. Elephant trail runoff and related sediment fluxes were monitored during two campaigns in the August monsoon seasons of 2005 and 2007; the complete elephant trail network was mapped in August–September 2009 (Fig. 1). The area receives about 1600 mm of annual rainfall. In the 3-yr period from 2005 to 2007, annual rainfall varied from 1412 to 1810 mm with about 72% of the total rainfall occurring from June through October when monsoon storms dominate. Monsoon storms often occur in the afternoon and are characterized by short durations (usually <2

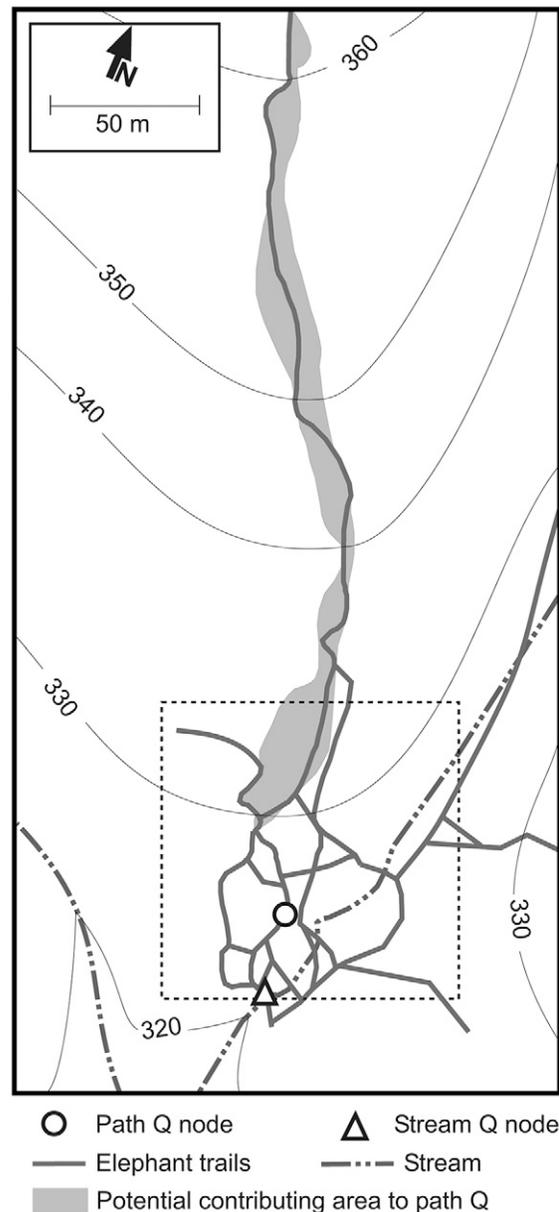


Fig. 1. Map of the study area in northern Thailand (contour intervals are 10 m) prepared by field surveys in 2009. Heavily used elephant trails within the area are noted as is the shaded drainage “catchment” defined by the upper trail network. Note that the monitored trail section is located in the lower portion of the catchment and is not directly connected to the longest elephant path. A 1-ha area (stippled box) used for calculating path density is illustrated in the lower catchment region. Q refers to either path or stream discharge.

h) with periods of high intensity (2-min intensities sometimes $>100 \text{ mm h}^{-1}$).

The study site occupies a lower hill-slope–riparian zone complex where three to five elephants cross a small stream daily on their way to and from trekking areas. Soils are primarily Ultisols formed above medium to coarse crystalline, muscovite-biotite granite and gneiss. Vegetation is disturbed lowland dipterocarp forest with large openings (Fig. 2a). Elephant trails and heavily trampled areas occupied about 10% of the 1-ha area upstream of the channel crossing (stippled box in Fig. 1) in 2008. Trail gradients throughout the area averaged $13.4 \pm 6.3\%$ (1 SD), including some steeper and gentler sections of limited extent. Trail density changed somewhat among all observation years (2005, 2007, 2008, and 2009) because elephants selected new routes when steeper trail sections became extremely muddy during the monsoon season (Fig. 1). Most of the storm runoff from these trails drains directly into the small stream at five stream crossing locations (Fig. 1 and 2b,c). Each morning the mahouts (elephant handlers) bring the elephants from a bedding–feeding area to a nearby trekking camp, returning them by mid-to-late afternoon (Fig. 2d). Sometimes the return trip coincides with an afternoon storm (see results for the 25 Aug. 2005 storm).

The actively used trail section monitored in August 2005 was 7.5 m long with an average width of 1.48 m and an average gradient of 25% (Fig. 3a). By 2007, the trail section had widened but was used less frequently. Because of this reconfiguration, in 2007 we isolated a longer (12 m) trail section with a mean width of 1.99 m and gradient of 21%. Runoff and sediment samples were collected at the same runoff node in both observation years (Fig. 3b).

Materials and Methods

A tipping bucket rain gauge was installed in an open area about 200 m from the monitored path to record rainfall at 1-min intervals. Runoff from the elephant path segment was measured manually throughout seven monsoon storms—two in late August 2005 and five in August 2007 (Table 1). The monitored path segment was isolated from upslope path runoff contributions by excavating a small ditch at the upper boundary to prevent water from entering from the upslope portions of the path.



Fig. 2. (a) The open meadow with degraded forest in the lower study area where the elephants traversed each day and often grazed and bedded. (b) The main elephant trail through the study area. (c) The outlet of the elephant trail into a small tributary. (d) An elephant being returned to its feeding area along the study trail. (e) Deep elephant footprints on the trail acted as an initial storage reservoir for runoff during the early portion of storms preceded by dry conditions.

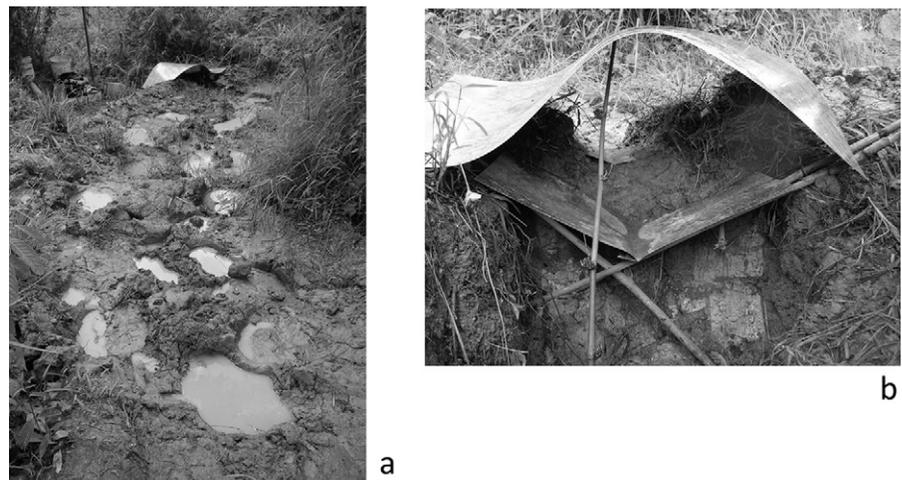


Fig. 3. (a) The monitored section of the elephant trail and (b) the outlet where runoff was measured and sediment samples were collected.

Additionally, a small berm was constructed around the bottom of the path segment to direct all runoff into a flexible sheet-metal trough inserted into the soil where runoff exited the trail (Fig. 3b). Sand bags were placed around the outlet to capture all of the path runoff during storms. A large umbrella covered the runoff outlet to remove effects of incident rainfall on the

Table 1. Characteristics of the seven storms in 2005 and 2007 and the respective runoff and sediment that was monitored on the elephant trail.

Storm date	Total rainfall	Storm duration	Avg. rainfall intensity	Max. 2-min intensity	API ₃ †	Runoff lag time	Total path runoff	Total sediment flux	Kinetic energy	Runoff coefficient
	mm	min	— mm h ⁻¹ —		mm	min	mm	Mg ha ⁻¹	J m ⁻²	
25 Aug. 2005	11.8	88	8.85	42.6	0.54	33	6.5	1.04	248.6	0.55
26 Aug. 2005	44.5	80	33.38	170.2	12.90	2	353.0	23.35	1188	7.93
21 Aug. 2007	0.55	65	0.51	2.3	13.09	7	0.058	0.002	6.0	0.105
22 Aug. 2007	3.83	81	2.84	26.3	13.90	6	0.12	0.042	71.5	0.032
23 Aug. 2007, #1	0.57	19	1.80	2.3	29.24	6	0.17	0.005	8.4	0.29
23 Aug. 2007, #2	38.4	140	16.46	127.7	28.97	2	172.0	15.74	976	4.48
26 Aug. 2007	2.06	24	5.15	24.8	49.21	7	2.4	0.24	42.6	1.15

† API₃, 3-d antecedent precipitation index.

collection trough. No borders were placed along the sides of the path segment so that runoff could drain freely onto the path from the adjacent field and vice versa (i.e., natural conditions; Fig. 3a).

During sampled storms, runoff was measured manually using either a 250- or 500-mL graduated cylinder during low flows, a 2-L container at moderate flows, and a 8.2-L calibrated bucket at high flows; the respective filling times were monitored with a stopwatch. The estimated errors for low, moderate, and high flow measurements were ±2, ±2, and ±3%, respectively, based on field testing. During many of the manual discharge measurements, a sample of runoff was collected in a 500-mL plastic bottle for later sediment measurement. This manual monitoring during storms allowed us to assess the dynamic storm runoff processes and greatly enhanced our interpretation of the collected field data. The samples collected for sediment analysis were transported back to the laboratory in Chiang Mai on the same day. Sediment masses for water samples with very high sediment concentrations were determined gravimetrically after drying at 105°C. Samples with lower sediment concentrations were filtered through 47-mm diameter, 0.7 μm (pore size) Whatman pre-weighed fiberglass filters, dried at 105°C, and then weighed. The measured dry mass of sediment (and any included organic matter) divided by the corrected sample volume yielded the sediment concentrations. Sampling error for sediment is expected to be in the same range as for flow measurements.

Hydrographs of individual storms were constructed by estimating flow rates at 2-min intervals based on measured runoff. Sediment concentrations from the nearest sample time were applied to respective discharge values in each 2-min period. The resultant value was divided by the path area to calculate sediment flux (Mg ha⁻¹). For time intervals at the midpoint of successive sediment samples, the sediment concentrations were weighted appropriately. Based on these data, calculated sediment graphs and hydrographs from the elephant trail were plotted along with 2-min rainfall intensities for each storm. Soil moisture condition on the trails before each storm was assessed as the cumulative precipitation in the 3-d period before the event—i.e., 3-d antecedent precipitation index (API₃). This short-term index reflected soil moisture conditions affecting path runoff during the study. Runoff coefficients (ROCs) were calculated for each sampled storm by dividing the total depth of storm runoff on the trail by total rainfall depth. Because ROC was calculated based on the actual trail area, when runoff

from adjacent areas flowed onto the trail during larger storms, values of ROCs were sometimes >1.

Kinetic energy of incident rainfall was estimated for all storms by an exponential relationship between rainfall intensity and energy (Kinnell, 1980)

$$e_K = e_{\max} [1 - a \exp(-bI)] \quad [1]$$

where e_K is the kinetic energy per unit depth of rainfall associated with a particular drop size distribution (J m⁻² mm⁻¹), e_{\max} is the maximum kinetic energy content, I is rainfall intensity (mm h⁻¹), and a and b are empirical constants. Coefficient a together with e_{\max} determines the minimum kinetic energy, while b defines the general shape of the curve. For our study, KE (J m⁻²) was calculated in 2-min intervals using the empirical values for e_{\max} , a , and b derived by van Dijk et al. (2002) from 21 extensive data-sets worldwide (including the tropics):

$$KE_2 = 28.3[1 - 0.52 \exp(-0.042I_2)](I_2 / 30) \quad [2]$$

where KE_2 is the kinetic energy for a 2-min interval of rainfall (J m⁻²) and I_2 is the rainfall intensity in the 2-min interval (mm h⁻¹). The term on the right side of Eq. [2] ($I_2/30$) is used to express KE values in 2-min intervals (KE_2 in J m⁻²). Total event kinetic energy (KE_{storm}) was then calculated as the sum of all KE_2 values for a given storm. Equation [2] has been shown to estimate rainfall energy within ~10% of measured or locally predicted kinetic energy (van Dijk et al., 2002). Annual sediment yield was calculated for 2005, a typical rainfall year with 1570 mm of total precipitation (range in annual precipitation from 2005–2007 was 1412–1810 mm). We calculated KE_{storm} for each of the 135 storms during 2005 with $KE_{\text{storm}} > 10$ J m⁻² and applied these values to a power function relationship between total sediment flux and KE_{storm} developed for the seven monitored storms. Then annual sediment yield was calculated as the sum of these 135 sediment flux estimates.

A map of the elephant trail network was prepared by first surveying the area around the main elephant trail that drained to the stream just downslope of the monitored discharge node (Fig. 1). Thereafter, all side trails that drained onto the main trail or into the stream were mapped. The area adjacent to the upper path that contributed to discharge (see shaded area in Fig. 1) was mapped in the field at more than 100 documented coordinates by estimating the width of likely run-on to the main trail; wider areas included multiple parallel trails. All of

these trails drain to a common stream discharge point (triangle in Fig. 1).

Results

Storm Runoff and Sediment Transport Dynamics

The seven complete storms sampled represent a wide range of monsoon storms in northern Thailand. All storms initiated in the afternoon, between 1330 and 1630, and all but the two smallest storms had periods of high intensity. Except for two short storms (23 and 26 Aug. 2007), duration ranged from 65 to 140 min (Table 1). Two large storms had much higher total rainfall and kinetic energies compared with the other events: 26 Aug. 2005 (44.5 mm of rainfall, 1188 J m^{-2}) and 23 Aug. 2007 #2 (38.4 mm, 976 J m^{-2}). Soil moisture conditions on the trail ranged from moist to very wet before all storms (API_3 ranged from 13 to 49 mm), except for the first event (25 Aug. 2005) when API_3 was $<1 \text{ mm}$ (Table 1).

Runoff varied from a trivial amount during the smallest event to 353 mm during the largest event (calculated relative to the area of the monitored trail). The two large storms produced runoff well in excess of contributions that could be derived from the trail surface alone. Runoff coefficients (ROC = total depth of storm runoff divided by total rainfall depth) were 7.9 and 4.5 for the two largest events (Table 1). The other five storms produced about two orders of magnitude less runoff.

In contrast to the two large storms, which had very short (2 min) lag times from the onset of rainfall to runoff initiation, the first storm (25 Aug. 2005) had a long lag time (33 min) before runoff reached the plot outlet, despite 4 min of relatively high intensity rainfall ($>40 \text{ mm h}^{-1}$) early in the event (Fig. 4a). Before this storm, the trail was dry ($\text{API}_3 < 1 \text{ mm}$) and many deep (up to 25 cm) elephant footprints were void of water (Fig. 2e). Thus, much of the initial overland flow was ponded either on the rough trail surface or in footprint depressions before discharge occurred at the outlet node. Following runoff initiation, overland flow persisted throughout the second part of the storm, although it nearly ceased once rainfall intensity declined to $<5 \text{ mm h}^{-1}$. The runoff coefficient for this entire storm was 0.55; however, during the latter half of the event, the ROC was slightly above 1.0. This result combined with our field observations confirms that the entire trail surface contributed to runoff once the deficit storage was met. A notable third peak in sediment flux (from 15:32 to 15:35) with very high sediment concentrations (24 g L^{-1}) coincided with passing of three elephants that were returning to the grazing area upslope (Fig. 4a and 5a). Of the five largest storms sampled, this was the only one in which sediment fluxes were higher on the falling limb of the hydrograph than the rising limb (Fig. 6a). This counter-clockwise hysteresis effect was likely caused by elephant traffic on the path during the storm.

The four small storms ($<4 \text{ mm}$ total rainfall) sampled in 2007 produced highly variable runoff, and of these, only the

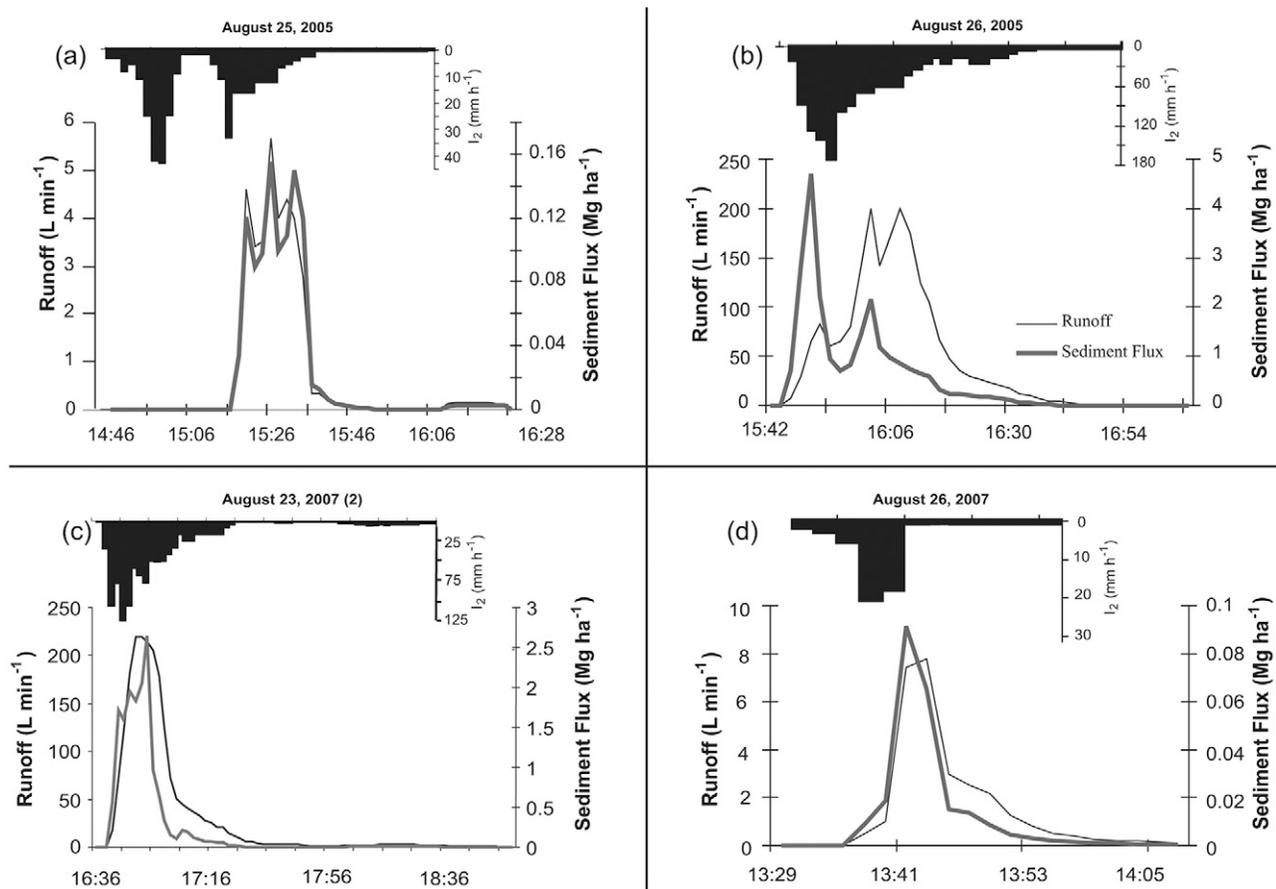


Fig. 4. Hydrographs of trail runoff and graphs of sediment flux for the following storms: (a) 25 Aug. 2005; (b) 26 Aug. 2005; (c) 23 Aug. 2007 (second storm of the day); and (d) 26 Aug. 2007. I_2 is the 2-min rainfall intensity.

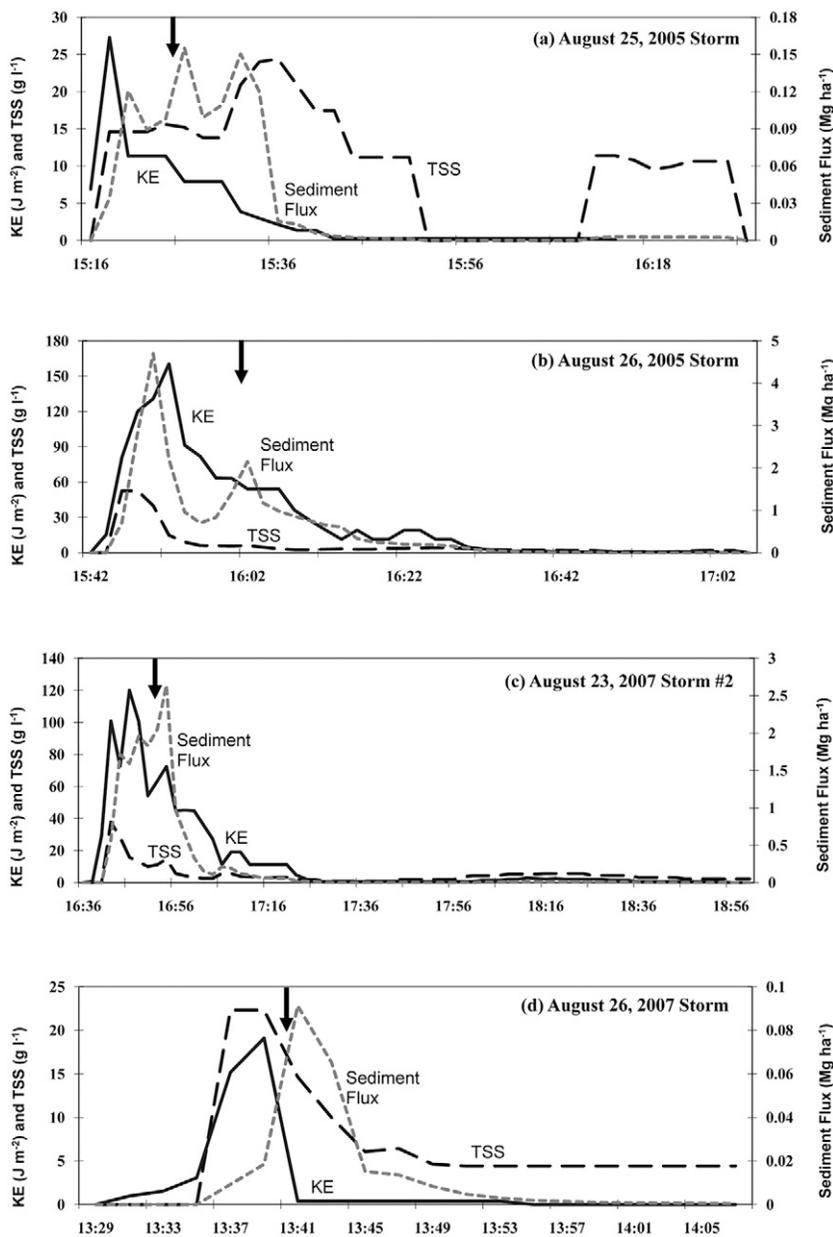


Fig. 5. Changes in total suspended solids (TSS), kinetic energy (KE) of rainfall (calculated based on Eq. [2]), and sediment flux during the following storms: (a) 25 Aug. 2005; (b) 26 Aug. 2005; (c) 23 Aug. 2007 (second storm of the day); and (d) 26 Aug. 2007. Vertical arrows mark the peak of each storm runoff hydrograph shown in Fig. 4.

26 August event generated substantial sediment (Table 1). The small storm on 22 Aug. 2007 (3.8 mm; duration 88 min), with a total kinetic energy of 71 J m^{-2} , produced only 0.042 Mg ha^{-1} of sediment due to the small runoff depth (0.12 mm) despite having high suspended sediment concentrations on the rising limb of the hydrograph (up to 43.1 g L^{-1}). In contrast, the shorter duration and smaller (2.1 mm) storm on 26 Aug. 2007 with less kinetic energy (43 J m^{-2}) produced five times more sediment (0.24 Mg ha^{-1}) with the highest concentrations of sediment (22.3 g L^{-1}) occurring early on the rising limb (Fig. 4d and 5d). Differences between these storms can be attributed in part to the high storm runoff coefficient (1.15) of the latter. This finding together with field observations during the 26 Aug. 2007 storm indicates that both the trail and adjacent areas contributed to discharge and sediment production. Furthermore,

the elevated sediment flux could have been exacerbated by very wet antecedent conditions ($\text{API}_3 = 49.2 \text{ mm}$) and re-entrainment of sediment stored temporarily during previous events (Ziegler et al., 2001b). The two storms that produced the least sediment and had the lowest peak sediment concentrations ($4.6\text{--}6.3 \text{ g L}^{-1}$) were the smallest of the seven events ($<0.6 \text{ mm}$ of rainfall; ROCs ranged from 0.11 to 0.29). In all four of the small 2007 storms, sediment flux corresponded closely with runoff. The two larger of these storms (22 and 26 Aug. 2007) exhibited clockwise hysteresis in runoff–sediment flux relationships (not shown). The lag time from peak rainfall intensity to peak runoff at the path discharge node was only 4 min for both of these somewhat larger events, whereas longer lag times occurred (16–18 min) during the two smallest storms.

Both of the large, high-intensity storms (26 Aug. 2005 and 23 Aug. 2007, #2) exhibited a distinct first flush phenomenon (e.g., Horowitz et al., 2008) in which suspended solids were very high during the very early stages of runoff (Fig. 5b and c, Table 2). During the 26 August storm, the initial (and largest) rain intensity peak produced the highest 2-min sediment flux (4.7 Mg ha^{-1}), which occurred 2 min earlier than peak rainfall during a relatively small (83 L min^{-1}) runoff peak (Fig. 4b). Later and much larger runoff during the storm produced only 0.6 to 2.1 Mg ha^{-1} of sediment in 2-min intervals. The very high ROC (7.93) during this event combined with field observations confirms that a large adjacent and upslope area contributed to runoff measured at the path discharge node, especially during the second half of the storm. In comparison, the 23 Aug. 2007 (#2) event was longer (140 min), but not as intense, and run-on from adjacent trail areas was significant, but less (ROC = 4.48) (Fig. 4c). Sediment concentrations peaked (37.9 g L^{-1}) during the first flush and declined to $\leq 10 \text{ g L}^{-1}$ shortly thereafter (Fig. 5c). Runoff from

both large storms exhibited distinct clockwise hysteresis effects (Fig. 6b,c). The effect was strongest during the 23 Aug. 2007 event, likely because runoff during the rising limb originated predominantly from the sediment-rich trail surface. In comparison, during the 26 Aug. 2005 event, runoff containing less sediment from adjacent grassy areas may have diluted sediment fluxes before peak discharge.

Comparison of Erosion Rates with Kinetic Energy of Rainfall

To examine the relationships between sediment export from the trail and rainfall energy, both sediment fluxes and total suspended solids (TSS) concentrations were correlated with kinetic energy of rainfall for 2-min intervals (KE_2) through-

out the five largest events. Both sediment flux and TSS were lagged by 0, 2, 4, and 6 min in correlation analyses with KE_2 to compensate for any delay in sediment transport with respect to rainfall inputs. The maximum correlation coefficients and respective lag times are presented for both sediment flux and TSS versus KE_2 during the rising limb, the falling limb, and the entire hydrograph in Table 2. To check for possible serial correlations, KE_2 data were correlated with sediment flux and TSS on both the rising and falling limbs of the five storms using a 6-min moving average for all variables. No evidence of serial correlations with either sediment flux or TSS and KE_2 was found on the falling limbs of hydrographs; most of the correlation coefficients for the 6-min moving averages were lower compared with the values reported in Table 2. For the rising limbs of storms, nearly the same number of storms experienced increased and decreased correlations between KE_2 and sediment flux (compared with values in Table 2); thus there was no strong basis to support serial correlation of the KE_2 data.

In general, the relationship between KE_2 and sediment flux was stronger than between KE_2 and TSS for all parts of the storm hydrograph (i.e., entire storm, rising limb, and falling limb). The first flush of sediment generated high TSS levels early in most storms even in cases where discharge was not so high; thus, correlations between KE_2 and TSS on the rising limb tended to be low (Table 2). An exception was the 26 Aug. 2007 storm during which TSS closely followed rainfall KE_2 up through the hydrograph peak. Given the short duration of this storm (most of the rainfall within the first 10 min) and the very high antecedent moisture, the rising and falling limbs of the hydrograph were very steep and likely the first flush response occurred throughout the short-duration rising limb due to active transport of detached sediment during this period of highest rainfall intensity. Just after the peak rainfall intensity (maximum KE_2), TSS declined substantially.

Sediment flux was generally more highly correlated with KE_2 on the falling limbs of hydrographs than on rising limbs (Table 2). For most of the storms with slightly longer recession limbs, sediment flux declined together with decreasing KE_2 in the latter portion of the event (Fig. 5 and 6). This correlated response may more reflect the effects of hydraulic erosion as opposed to raindrop detachment as runoff depth was at a maximum and runoff sources were most widespread at the onset of the falling limb.

Annual Sediment Yield from the Elephant Trail

To estimate sediment yield from the monitored elephant trail segment, the following power function relationship ($R^2 = 0.96$) between total sediment flux (S ; $Mg\ ha^{-1}$) and storm kinetic energy (KE_{storm}) was developed for the seven monitored events (Fig. 7):

$$S = \begin{cases} 0.000113KE_{storm}^{1.700913} & KE_{storm} \geq 10\ J\ m^{-2} \\ 0 & KE_{storm} < 10\ J\ m^{-2} \end{cases} \quad [3]$$

KE_{storm} values are based on a summation of KE_2 values derived from Eq. [2]. Then, Eq. [3] was used to calculate sediment yields from all storms in a typical rain year (2005) with KE_{storm} values $>10\ J\ m^{-2}$ (135 storms total). While the relationship

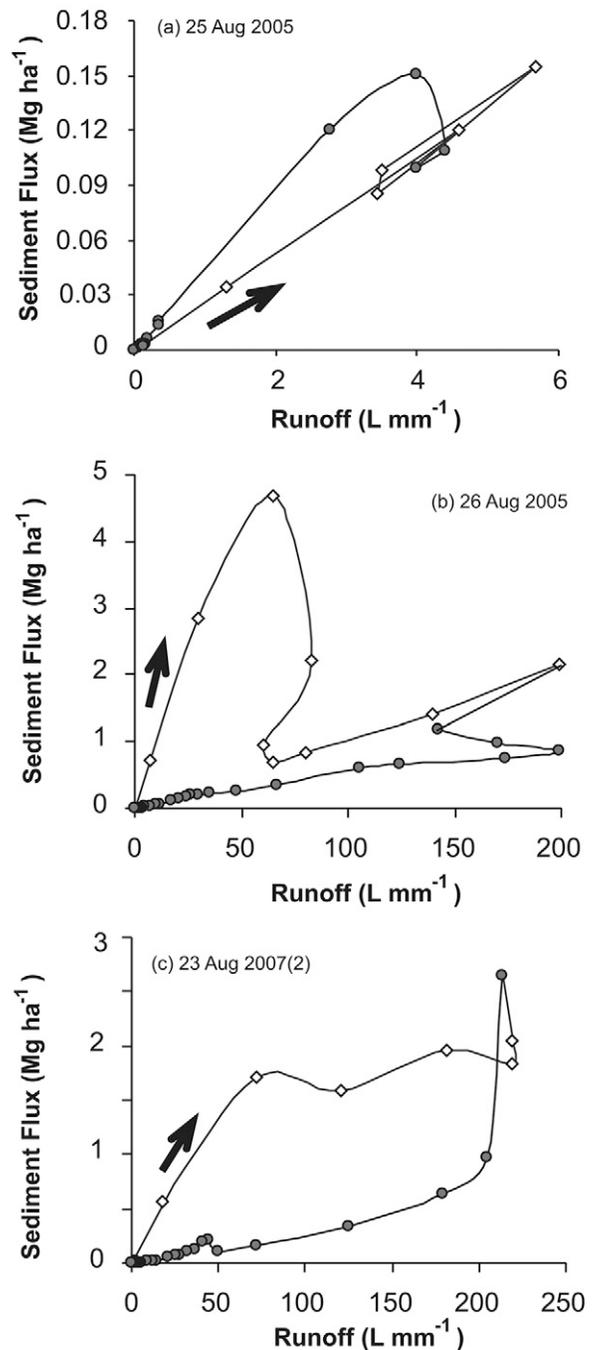


Fig. 6. Plots of sediment flux versus storm runoff showing sediment hysteresis effects for the following storms: (a) 25 Aug. 2005 (only storm exhibiting reverse hysteresis effects); (b) 26 Aug. 2005; and (c) 23 Aug. 2007 (second storm of the day). Arrows indicate the onset of the storm and trajectory of fluxes; open symbols are points on the rising limb of the hydrograph and solid circles are samples from the falling limb.

shown for storms with KE_{storm} values $\geq 10\ J\ m^{-2}$ (first part of Eq. [3]) was derived from all seven data points shown in Fig. 7, because of the very low values of sediment transported in storms with KE_{storm} values $<10\ J\ m^{-2}$, sediment yield was deemed negligible for these small events. The KE_{storm} of the sampled events and the respective sediment fluxes covered representative ranges of these values experienced during 2005 (Fig. 7). A plot of cumulative sediment flux versus cumulative KE_{storm} for the 135 storms sorted from largest to smallest storms on the x axis shows that half of the sediment flux was

Table 2. Correlation coefficients between kinetic energy of rainfall (KE_2 calculated for 2-min intervals based on Eq. [2]) for various portions of the seven storms and either sediment flux ($Mg\ ha^{-1}$) or total suspended solids ($g\ L^{-1}$).

Storm date	Parameters correlated with KE_2					
	Sediment flux			Total suspended solids		
	Entire	Rising	Falling	Entire	Rising	Falling
25 Aug. 2005	0.701 (2 min)	0.385 (2 min)	0.936 (4 min)	0.078 (4 min)	0.196 (2 min)	0.805 (0 min)
26 Aug. 2005	0.850 (0 min)	0.690 (0 min)	0.965 (6 min)	0.693 (0 min)	0.542 (0 min)	0.659 (0 min)
22 Aug. 2007	0.935 (0 min)	0.931 (0 min)	0.993 (0 min)	0.497 (0 min)	negative	0.987 (0 min)
23 Aug. 2007, #2	0.883 (2 min)	0.899 (6 min)	0.834 (0 min)	0.776 (0 min)	0.291 (0 min)	0.537 (0 min)
26 Aug. 2007	0.935 (4 min)	0.896 (4 min)	0.653 (6 min)	0.888 (0 min)	0.937 (0 min)	0.561 (6 min)

generated by the eight largest events which constituted 30% of the total storm energy in 2005 (Fig. 8). All eight storms had $KE_{storm} > 970\ J\ m^{-2}$, including the sampled event on 26 Aug. 2005. The maximum estimated individual storm sediment flux among the 135 events was $22.4\ Mg\ ha^{-1}$. Total sediment flux for the 135 storms represents an annual sediment yield of $308\ Mg\ ha^{-1}\ yr^{-1}$ for the monitored trail. This is a conservative estimate because the largest monitored storm was within the four largest of the year (and these were separated by only $\sim 100\ J\ m^{-2}$) and produced more sediment than the predicted flux for the largest event of 2005 ($KE = 1301\ J\ m^{-2}$). An alternative function to Eq. [3] ($S = 0.000150KE_{event}^{1.687874}$), in which the 22 Aug. 2007 event with the very weak relationship between total sediment flux (S) and KE_{event} was omitted, predicts an annual sediment yield of $375\ Mg\ ha^{-1}\ yr^{-1}$ for the trail.

Discussion

General Runoff and Sediment Trends

Runoff from the elephant trail rapidly increased in tandem with the expanding contributing areas once sufficient wetting occurred. Runoff expansion first occurred on the trail itself

and then progressed to adjacent fields and upslope areas, most of which were compacted by elephant grazing. This phenomenon was observed during the two largest storms (26 Aug. 2005 and 23 Aug. 2007, #2) that produced much more runoff than could be derived from the trail surface alone. A more abrupt (albeit delayed) runoff response during the 25 Aug. 2005 storm following a relatively dry period can be attributed to the time necessary for rainfall to fill the deep footprints on the elephant path as observed during field sampling (Fig. 2b). Once this initial abstraction was met, the entire wet trail and portions of the areas adjacent to the path contributed

to runoff. During three of the four smaller storms, runoff was restricted to only a small portion of the path; the exception (26 Aug. 2007 storm; $ROC = 1.15$) had the wettest antecedent conditions of all storms monitored.

A distinct clockwise hysteresis effect in runoff–sediment flux relationships occurred for most events (e.g., Fig. 6c). This clockwise pattern generally reflects (i) depletion of easily detached and entrained sediment by concentrated flow during early stages of runoff; (ii) dilution of sediment concentrations as runoff eventually entered the monitored node from longer upslope path distances and less-erodible adjacent areas; and (iii) protection of some portions of the path from splash detachment after the development of a thick film of overland flow. In particular, hysteresis was accentuated by the first flush of loose sediment from the trail surface that was either detached by elephant traffic (both between and during storms) or temporarily deposited during prior runoff events (e.g., Fig. 6b).

The stronger relationship between KE_2 and sediment flux on the falling limb compared with the rising limb of most storm runoff hydrographs reflects nonlinearities attributed to the first flush sediment phenomena and the interrelated higher sedi-

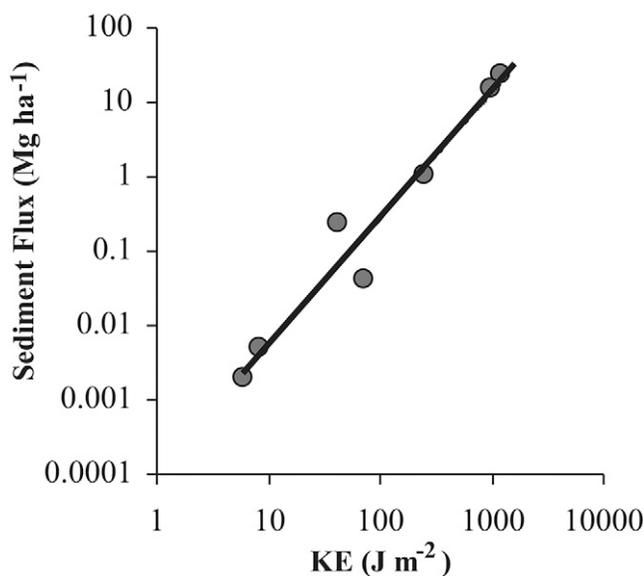


Fig. 7. Power function relationship between kinetic energy (KE) of rainfall for each of the seven monitored storms (calculated by summing values from Eq. [2]) and sediment flux.

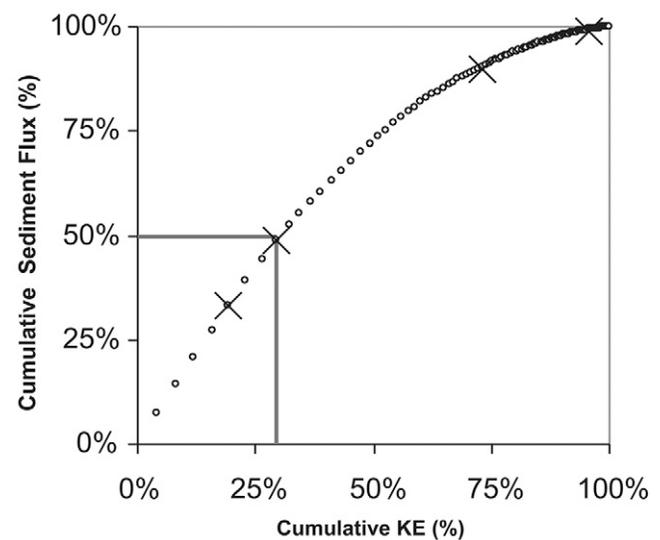


Fig. 8. Cumulative sediment flux calculated based on Eq. [3] for 135 storm events in 2005 versus cumulative kinetic energy (KE) of the storms (based on Eq. [2]). The four largest storms sampled in our study period are superimposed on this relationship as X's.

ment availability and more active sediment source areas during the early portion of runoff. During smaller storms, antecedent moisture appeared to influence the extent of the trail that contributed to runoff (Table 1). Nevertheless, considering the full spectrum of storm kinetic energies, it was possible to develop a reasonable relationship between event-based kinetic energy and total sediment flux (Eq. [3]).

Sediment Connectivity: Source-to-Stream Linkages

The concept of catchment-scale sediment connectivity is supported by stream sediment samples collected at the end of two successive storms in August 2005. The first of these storms (25 August) was a moderate-sized event preceded by dry conditions; the second was a large storm with wet antecedent conditions. At the end of the 25 Aug. 2005 storm, very high sediment concentrations (1.66 g L^{-1}) were detected in the stream below the elephant path, but above the paths the concentration was very low (0.01 g L^{-1}). This difference indicates that the trail network contributed most of the sediment to the stream during this moderate storm and that other sediment sources within the catchment were not activated due to a combination of storm size and dry antecedent conditions. The much larger storm on the next day (nearly five times the kinetic energy) yielded high sediment concentrations in both the stream below the elephant trails (0.95 g L^{-1} , but only 57% of the values measured on 25 August), and above the trails ($0.61\text{--}0.73 \text{ g L}^{-1}$). These increases in sediment levels upstream of the concentrated network of elephant trails (Fig. 1) reflect the greater connectivity of upslope sediment sources (e.g., compacted grazing areas, unpaved roads, motorbike and foot trails) facilitated by wetter antecedent conditions and expanded source areas of flow during this larger event. The lower sediment concentrations in the downstream sampling site in the 26 August event reflect the dilution of sediment at higher flows.

A total of five trails crossed the stream channel within the study area (Fig. 1). Occasionally, elephants walked within the stream channel for several meters. The greatest trail disturbance occurred on steep segments draining directly into the stream and on saturated trail surfaces adjacent to and within the riparian zone. Even upslope trails, which tended to be less disturbed because the surfaces were not typically saturated, were highly connected to the stream because the continual elephant traffic created a distinct (albeit narrow) hydrological source area that facilitated storm drainage to fully connected stream nodes, rather than drainage onto adjacent hillslopes (Fig. 1). Given the long trail length (>300 m), relatively steep (generally 5–25%) and continuous gradients, and highly disturbed and compacted surfaces, the energy of concentrated storm runoff generated high sediment fluxes to the stream. As such, these fluxes can be attributed to both the high sediment transport capacity and hydraulic erosion.

Elephant trail density varied a bit from year to year due to deteriorating path conditions, changing grazing patterns, and access to water and shade related to tethering locations. In the 1-ha site near the stream crossings (Fig. 1), trails occupied 7 to 10% of the area during the course of the study. In 2005, elephant trails and compacted grazing sites comprised 21% of the immediate area around the runoff node (within a total area of 0.17 ha). This high density is probably typical for rugged ter-

rain near stream crossings and perhaps around tethering areas, but probably not for the general grazing area within the upper catchment. In the case of the former, such a high concentration of trails exacerbates sediment delivery because of the direct connection and close proximity of trails to the stream network.

Broader Implications of Elephant Trails in Catchments

Our sediment yield estimates from the trail segment scale to values on the order of 65 to 79 and 31 to 38 $\text{Mg ha}^{-1} \text{ yr}^{-1}$ for the intensely used hillslope–riparian complex in the lowermost part of the catchment and entire 1-ha lower catchment area, respectively. The lower erosion values associated with the entire 1-ha catchment area represents a continuum from heavy trekking to less dense transport and grazing areas for elephants. The respective ranges in sediment yields for each area reflect alternative approaches outlined for annual sediment flux calculations. These estimates likely underestimate total sediment to the stream because we did not quantify sediment flux on the 300-m trail where concentrated overland flow occurs during large events. Nevertheless, they are on the high end of values associated with agricultural land disturbances in Southeast Asia (Sidle et al. [2006] and references therein), erosion sources that receive far greater attention than animal trails.

The sediment yields we report from elephant paths also tend to be higher than most values measured for other paths and trails in Southeast Asia. For example, paths and adjacent dwelling areas in a nearby site in northern Thailand produced sediment yields of approximately $20 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, despite occupying only about 2% of the 1-km² catchment area (Ziegler et al., 2004). Rijdsdijk et al. (2007) indirectly estimated erosion from agricultural foot trails at two sites in East Java, Indonesia. Along a 1-m-wide footpath at Air Terjun (83 m long; gradient 1.7–19%), soil losses of $\sim 420 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ were estimated, while similar size trails that drained adjacent areas at Gagar contributed only $\sim 14\text{--}34 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Bons (1990) estimated sediment yields of $70 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ on field boundaries used as access trails in West Java. Baharuddin et al. (1995) measured erosion losses of 10 and $2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ from skid trails traversed by crawler tractors in Pahang, Malaysia, during the first and second years, respectively, after logging. Higher rates of erosion were estimated on mechanized skid trails in Sabah, Malaysia ($30\text{--}104 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, Hartanto et al., 2003; $77\text{--}547 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, Malmer, 1996) and Bukit Tarek catchment in Peninsular Malaysia ($275 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, Sidle et al., 2004). Our estimates of annual sediment yield from the elephant path itself based on measured fluxes ($308\text{--}375 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) are in the upper end of these reported rates in other parts of Southeast Asia, including from trails severely disturbed by heavy machinery.

Conclusions

The results of this synoptic storm sampling in northern Thailand indicate that elephant trails generate very large sediment yields ($>300 \text{ Mg ha}^{-1} \text{ yr}^{-1}$). When these trails are located on steep slopes near streams or within riparian zones, surface runoff and eroded sediment are conveyed efficiently to the channel network. The eight largest of the 135 storms in 2005 (all with $\text{KE}_{\text{storm}} > 970 \text{ J m}^{-2}$) generated half of the total estimated annual sediment flux from the monitored trail seg-

ment. While high-energy monsoon storms drive much the sediment flux from all sources in the region, the cumulative effect of large numbers of small storms is also important because of the direct connection of the entire trail network with the stream system.

Sediment transport during most storms was characterized by a clockwise hysteresis pattern in the runoff–sediment signature whereby higher sediment fluxes and concentrations occurred on the rising limbs of hydrographs compared to falling limbs. This pattern resulted from the availability of easily entrained sediment on the trail surface that was disturbed throughout the year by elephant trampling. Furthermore, the hysteresis was amplified by a first flush phenomenon, in which the initial wave of surface runoff entrained loose sediment on the trail, particularly sediment temporarily stored near the outlet of the path discharge node. Both the clockwise hysteresis and the first flush were most evident during large storms. An interesting hydrologic phenomenon observed during one storm that followed a dry period was the significant delay in runoff due to the time needed for rain water to fill the deep elephant footprints. During wetter conditions, such lag times did not occur. Elephant traffic during storms also caused abrupt increases in both sediment concentrations and fluxes.

Our observations indicate that in addition to path density, the following factors need to be considered when assessing the significance of water and sediment fluxes from elephant trails: (i) adjacent topography; (ii) proximity to the riparian zone; (iii) path-to-stream connectivity; (iv) interconnectivity among multiple trails; (v) flow-path length and gradient; (vi) extent and recentness of trafficking; and (vii) level of heavy grazing or other land uses adjacent to trails. Because of these interrelated factors, overland flow generated on adjacent areas and upslope path segments can contribute substantially to trail runoff and sediment delivery, particularly during large storms. For example, during the largest monitored storm (26 Aug. 2005), run-on water from adjacent and upslope areas increased the runoff coefficient almost eightfold above what could be produced from the path area alone and delivered nearly 8% of the annual sediment flux from this path segment to the stream.

Because of the potential for high sediment loads to streams from elephant trails during monsoon storms, our observations suggest that management of concentrated elephant populations should focus on minimizing trail density, limiting stream crossings, reducing direct disturbances in riparian zones, avoiding routes on steep slopes perpendicular to slope contours, minimizing the length of interconnected path segments that facilitate the formation of concentrated overland flow, restricting traffic during heavy storms, limiting disturbance on areas adjacent to paths, and maintaining suitable permanent paths. As with unpaved roads and skid trails, the linkages of elephant paths to streams is likely the most important factor related to high sediment yields. The appropriate placement of dedicated trails, which have low connectivity with other trails and the stream network, is a good initial strategy for minimizing sediment delivery from trails. Given the heavy disturbance on elephant trails (especially the deep footprints), several years of recovery would be needed before erosion on unused paths substantially declines.

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