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Reduction of Stream Sediment Concentration by a Riparian Buffer: Filtering of Road Runoff in Disturbed Headwater Basins of Montane Mainland Southeast Asia

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ABSTRACT

We determined the extent that a riparian buffer reduces stream suspended sediment concentrations by filtering road runoff during 18 rain events in a 2.5-ha, multi-use watershed in northern Thailand. The dominant buffer species was the perennial sedge *Fimbristylis aphylla* Zoll. ex Steud. (Cyperaceae). We monitored stream sediment concentration for situations where road runoff either flowed into the riparian buffer or was diverted directly into the stream (buffer and no buffer scenarios). These data were used to develop the following relationships between instantaneous stream sediment concentration (C_i) and discharge (Q_i): $C_i = 28.329Q_i^{0.851}$ (buffer scenario) and $C_i = 22.265Q_i^{1.579}$ (no buffer scenario). Using these functions to calculate total event suspended concentrations, we determined that the buffer reduced suspended sediment concentration by 34 to 87%, for the range of events monitored. Removal of sediment from runoff generated on a 2.4-m-wide, 165-m-long unpaved road section was achieved principally via ponding, which reduced the transport capacity as flow entered the relatively flat, saturated buffer. Sediment deposition occurred primarily within the first 10 m of the buffer. Some sediment was also deposited on the fillslope leading to the buffer. Maximum road sediment concentration during the largest buffer event approached 100 000 mg L^{-1}. Meanwhile, the corresponding maximum stream suspended sediment concentration was <4000 mg L^{-1}. In contrast, maximum stream concentrations when flow bypassed the buffer during smaller events were commonly 4000 to 7000 mg L^{-1}. Naturally occurring buffers represent an economical means of mitigating road-related impacts in upland basins in Southeast Asia, particularly if combined with measures limiting sediment and runoff production on contributing road sections.

Soil eroded from road surfaces, cut banks, and fillslopes during storms represents a chronic supply of sediment to streams worldwide (e.g., Megahan and Kidd, 1972; Dunne and Dietrich, 1982; Reid and Dunne, 1984; Grayson et al., 1993; Ziegler et al., 2000; Motha et al., 2004). Roads cut into hillsides in steep terrain exacerbate landslide erosion by oversteepening cut and fill slopes, removing support at road cuts, overloading fillslopes, and diverting concentrated overland flow onto unstable hillslopes (Dyrness, 1967; Sidle et al., 1985; Wemple et al., 2001). Landslide sediment contributions to streams are episodic, as material may be deposited on the hillslope or the road before reaching the stream (Arnaez-Vadillo and Larrea, 1994; Skaugset et al., 1996; Wemple et al., 2001; Sidle et al., 2006). Road sediment entering streams increases turbidity, damages aquatic habitat, interferes with biological processes, contributes to sedimentation in downstream water bodies, and potentially introduces environmentally harmful contaminants into the stream system (Graynoth, 1979; Reid 1993; Gucinski et al., 2000; Henley et al., 2000; Sutherland, 2000; Trombulak and Frissell, 2000). These impacts are prevalent in locations where road runoff drains directly into the stream (e.g., at temporary bridges, fords, and culverts), and where efficient road-to-stream connections have formed on adjacent hillslopes via gullying or discharge nodes (see Van Lear et al., 1995; Taylor et al., 1999; Croke and Mockler, 2001; Lane and Sheridan, 2002; Sidle et al., 2004).

Buffers of various types and sizes have been recognized for their ability to reduce sediment and other pollutant inputs to streams from disturbed surfaces (see Norris, 1993; Gilliam, 1994; Barling and Moore, 1994; Castelle et al., 1994). In particular, studies have shown buffers to be effective in mitigating the impacts of runoff from both managed agriculture and forest lands (e.g., Corbett et al., 1978; Borg et al., 1988; Davies and Nelson, 1994; Daniels and Gilliam, 1996). Although the importance of placing buffers between roads and streams to preserve water quality was first recognized several decades ago (e.g., Hornbeck and Reinhart, 1964; Haupt and Kidd, 1965; Packer, 1967; Ohlander, 1976), studies providing direct evidence of filtering road-generated sediment by buffers are rare (e.g., Trimble and Sartz, 1957; Haupt, 1959; Bren and Leitch, 1985). Little research has been conducted on the application of buffers in environmentally sensitive areas within developing countries, where conservation measures are seldom used to mitigate road impacts. In this paper, we determine the degree that a naturally occurring riparian buffer in a tropical headwater basin in northern Thailand reduces stream sediment concentration by filtering road runoff.

STUDY SITE

We conducted the work in the Pang Khum Experimental Watershed (PKEW) in northern Thailand (19°3′ N, 98°39′ E). Pang Khum is located on the boundary of Samoeng and Mae Taeng Districts in Chiang Mai Province, approximately 60 km north-northwest of Chiang Mai (Fig. 1). The 93.7-ha PKEW (Fig. 2) is a headwater drainage within the Mae Taeng River basin, which

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Abbreviations: PKEW, Pang Khum Experimental Watershed.

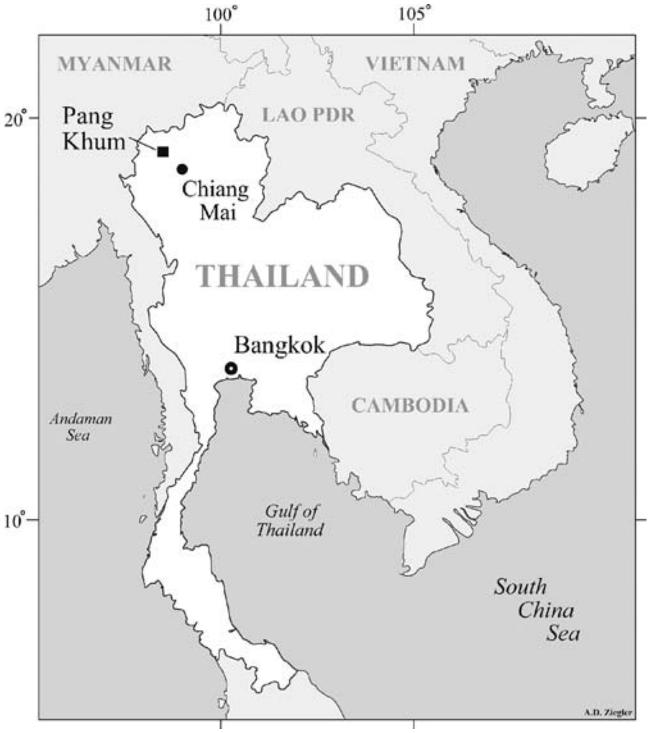

Fig. 1. Location of the Pang Khum experiment site in northern Thailand.

discharges into the Ping River, the major tributary to Thailand's largest river, the Chao Praya. Bedrock is largely muscovite granite, with gneiss also being present. Soils are predominantly Ultisols of the udic moisture regime or Inceptisols occurring on the steep upper slopes. The area has a monsoon rainy season that extends from mid-May through October. This five- to six-month period accounts for approximately 80 to 90% of the annual rainfall (1200–2000 mm; data from Station 401, Fig. 2); annual stream flow (280–825 mm; Station 405, Fig. 2) is roughly 20 to 40% of the precipitation total. Roads comprise 0.5% of the area in PKEW; 70 to 80% of the total road length drains directly into the stream, typically at intersections between the road and stream channel network (Ziegler et al., 2004; Fig. 2, 3a, and 4).

We conducted this experiment in a 2.5-ha subbasin referred to herein as PKEW Noi (Fig. 2 and 4). The main access road in PKEW bisects PKEW Noi near the center of the basin. Physicochemical properties of the road surface are listed in Table 1. Although the road section bisecting the subbasin is relatively short (<40 m), the total length of road contributing runoff and sediment to the stream is 165 m. Runoff is generated entirely by the Horton overland flow mechanism; interception of subsurface flow by the road cutbank does not occur (Ziegler et al., 2001a). Runoff exiting the road surface travels down the fillslope in a well-defined gully, and then passes through the fringe of a banana patch before entering the riparian wetland, which is formed where a ground water seep occurs at an abrupt change in hillslope gradient (Fig. 4).

The dominant species in the wetland is *Fimbristylis aphylla* Zoll. ex Steud. (Cyperaceae), a perennial sedge that grows to 0.5 to 1.0 m. In addition to *Fimbristylis aphylla*—and several invasive weeds—other obligate members include *Cyperus exalatus* Retz. (Cyperaceae), *Cyperus pilosus* Vahl (Cyperaceae), *Cyperus brevifolius* (Rottb.) Hassk. (Cyperaceae), *Panicum brevifolium* L. (Gramineae), *Lindernia anagallis* (Burm. f.) Penn. (Scrophulariaceae), *Digitaria violascens* Link (Gramineae), *Echinochloa crusgalli* (L.) P. Beauv. var. *breviseta* (Doell) Neilr. (Gramineae), *Ludwigia hyssopifolia* (G. Don) Exell (Onagraceae), *Polygonum flaccidum* Meissn. (Polygonaceae), *Hedyotis lindleyana* Hk. ex Wight & Arn. (Rubiaceae), *Oenanthe javanica* (Bl.) DC. (Umbelliferae), and *Pogostemon auricularius* (L.) Hassk. (Labiatae). Collectively, all the wetland species form a dense vegetative mat between the road and stream.

Although daily traffic is light, surface erosion on the road is substantial, particularly on one 60-m subsection where the slope exceeds 0.20 m m^{-1} (Fig. 3b). The lowering rate on this section can exceed 0.10 m yr^{-1} because wheel ruts are incised by flowing water and the road surface is continuously reworked by traffic. Sediment production is also elevated by inputs of material originating from the following: (i) maintenance, which includes the filling of the ruts with material excavated by hand from adjacent non-eroded road surface and the roadside margin (Ziegler et al., 2001b); and (ii) minor bank sloughing along the road cut that deposits sediment onto the road surface. Mean width of the road is 2.4 m; sediment production on the 60-m subsection alone is therefore about 16 to 22 Mg yr^{-1} (1100–1500 Mg ha^{-1} yr^{-1}). Most of this material is discharged directly into the riparian buffer in PKEW Noi during runoff events.

MATERIALS AND METHODS

During the period 16 July–13 Sept. 2002, we measured discharge and sediment concentration during runoff events at both the stream outlet in PKEW Noi and at the base of the 165-m road section (Fig. 3e and 4). These measurement locations are labeled "S" and "R", respectively, in Fig. 4. During eight events, road runoff was allowed to drain freely to the riparian buffer (i.e., this is the typical flow pathway for road runoff in PKEW Noi). During another 10 events, we forced the runoff to bypass the riparian buffer via a 7.08-cm PVC pipe (Fig. 3f and 4). These two arrangements are referred to as BUFFER and NO BUFFER treatments, respectively. For the NO BUFFER treatments, we emptied the runoff water directly into the stream channel head where water flowing from the lower boundary of the buffer typically enters the stream (Fig. 3d). The overland flow pathway for the BUFFER treatments was the following (Fig. 4): road (165-m long × 2.4-m wide) → fillslope (length = 8 m; slope = 0.75 m m^{-1}) → banana patch (2 m; 0.1 m m^{-1}) → riparian buffer (30 m; 0.1 m m^{-1}). Our analyses focused on determining the extent that this sequence of land covers reduced stream suspended sediment concentrations during monitored rainfall events.

We established a temporary gauging station near the natural basin outlet for PKEW Noi in a location where the stream channel banks and bottom had been stable during the previous 5 yr of fieldwork (Location S, Fig. 4). A Druck (New Fairfield, CT) pressure transducer and Campbell (Logan, UT) CR 500 data logger were used to record stage at incremental changes of ±0.1 cm. To estimate discharge during events, a

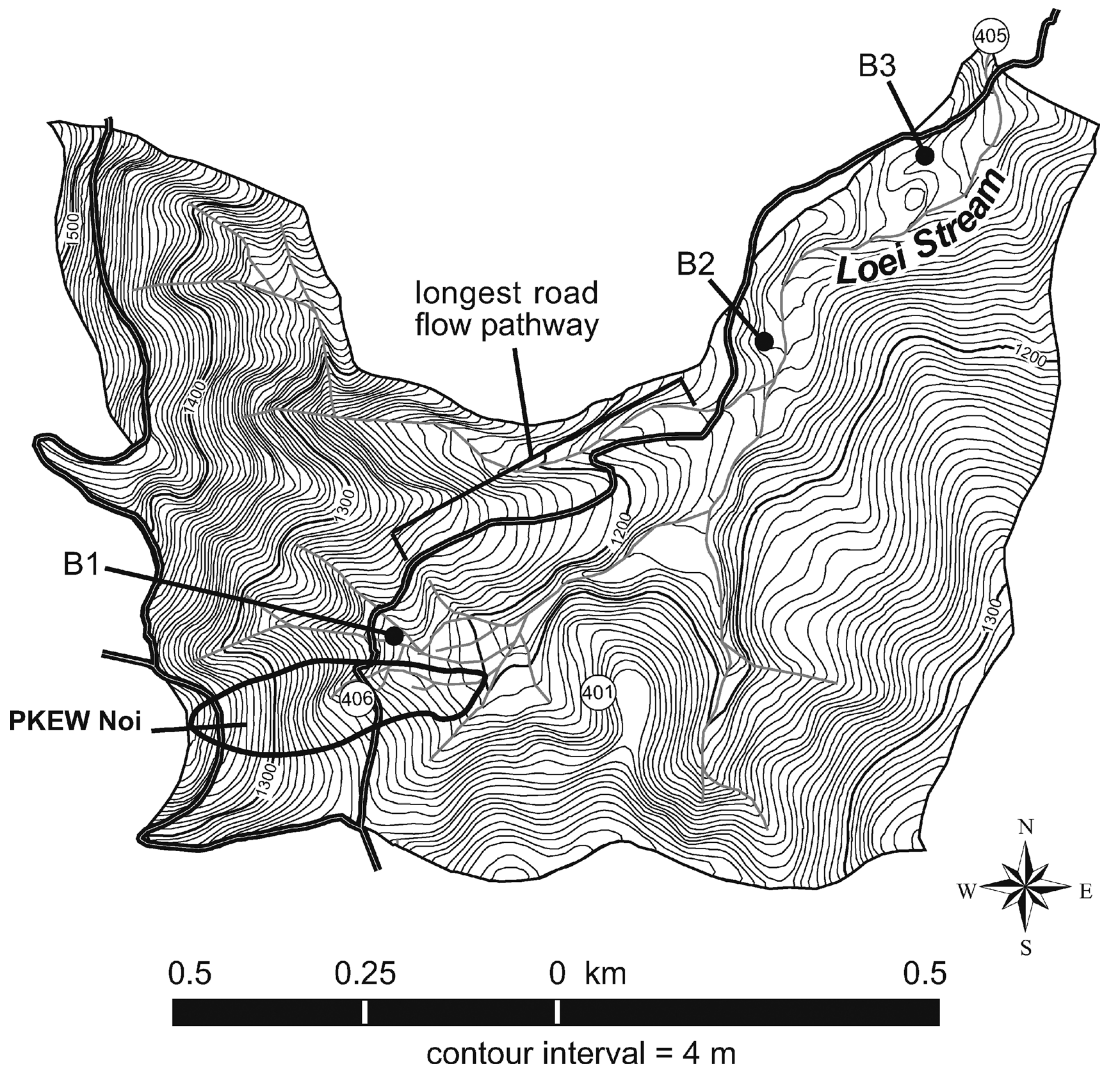

Fig. 2. The 93.7-ha Pang Khum Experimental Watershed (PKEW) and location of the 2.5-ha PKEW Noi subbasin. Long-term rainfall data are collected at Station 401; Station 405 is where PKEW discharge is measured at a v-notch weir in Loei Stream. B1, B2, and B3 represent additional locations where road runoff could be directed into riparian buffers.

stage-discharge rating curve was developed from about 100 measurements. Stream velocity was measured at several points along a transect with a USGS pygmy-type current meter (Model 6205) at 0.6 depth from the water surface (note, stage never exceeded 0.4 m). We determined flow area by measuring channel geometry at 1-cm incremental heights above the channel bottom. These measurements were repeated at the beginning, middle, and end of the measurement period to account for cross-sectional changes.

We recorded rainfall with a 20.3-cm-diameter Met-One (Grants Pass, OR) tipping bucket rain gauge and an Onset (Pocasset, MA) Hobo logger located near the road runoff collection station (Fig. 4c). Total event stream discharge was calculated as the flow volume between the onset of rainfall and the time when discharge returned to baseflow, minus the baseflow component. Discharge was converted to a depth by dividing by the area of PKEW Noi (2.5 ha).

Bulk suspended sediment samples (250-mL plastic bottles) were collected in the stream at irregular time intervals during runoff events to obtain representative samples during the rising limb, peak, and receding limb of the storm hydrograph. Suspended sediment concentrations were determined by filtering samples (0.2–0.5 L) through pre-weighed, pre-ashed, 0.7-μm Whatman (Maidstone, UK) glass filters (4.7-cm diameter) using a 60-psi vacuum pump and Nalgene polysulfone filter holders (Nalge Nunc International, Rochester, NY). After drying at 105°C for 24 h, we weighed the filters to determine the mass of total suspended material. The volume of the water sample was corrected by subtracting the mass of the material (usually negligible). Stream sediment concentration is simply the mass of the material divided by the corrected water volume of the sample. This value represents suspended material only; the bedload component was not measured.

At the base of the monitored road section, we constructed a concrete-lined drainage ditch to direct road runoff into a portable flume to measure road discharge and sediment concentration (Fig. 3c and 3e, and R in Fig. 4). The ditch is located approximately 10 m upslope from where the runoff exiting the road would naturally enter the buffer after flowing down the fillslope and through the banana patch. Discharge measurements were made every 1 to 5 min by recording the time to fill plastic containers, which ranged in volume from 0.5 to 25 L, depending on the volume of road runoff at the time of measurement. The mass of sediment transported was determined from separate 0.5-L grab samples. This material

Fig. 3. (a) On-road runoff draining directly into the stream at a low-water bridge in the Pang Khum Experimental Watershed (PKEW). (b) The steep, 60-m subsection of the observed road where severe erosion is perpetual. (c) Road runoff exiting the measurement flume at the base of the monitored section; flow rate exceeds 8 L s^{-1}. (d) Exit point at the channel head for water diverted directly past the riparian buffer. (e) Flume and drainage ditch constructed at the base of the 165-m monitored road section. (f) The PVC pipe used to direct runoff past the 30-m riparian buffer during the NO BUFFER events.

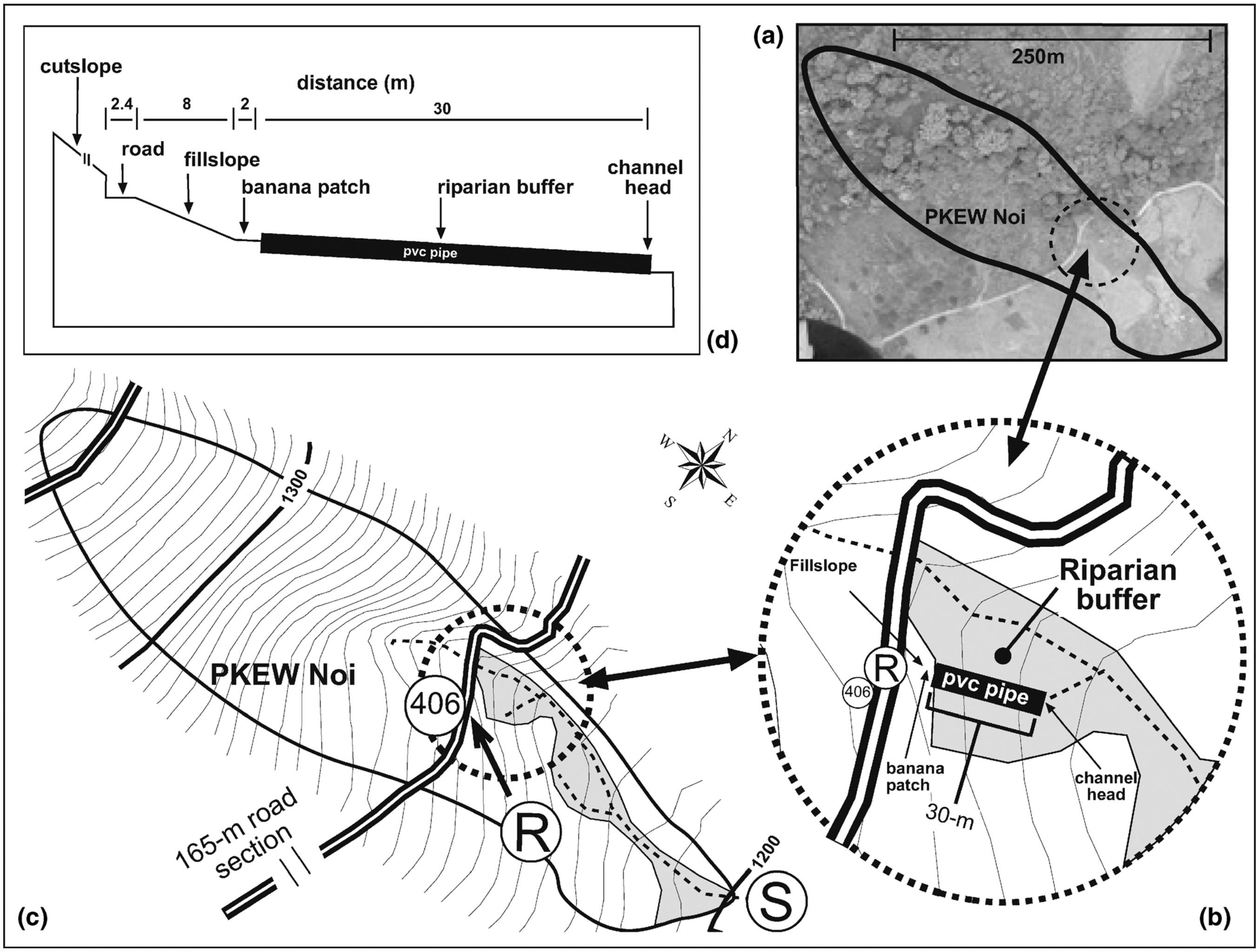

Fig. 4. Experimental setup in the 2.5-ha Pang Khum Experimental Watershed (PKEW) Noi. (a) The photograph was taken in 2002 from light aircraft at 500 m above the surface. (b) Exploded view of principal road measurement area shown in (c), including locations of the road, fillslope, banana patch, riparian buffer, and channel head. (c) Circles labeled "R" and "S" refer to discharge and sediment measurement locations at the base of the 165-m road section and in the stream channel, respectively; the tipping bucket rain gauge is located at Station 406. (d) Transect shows the flow path sequence from the road, down the fillslope, through the banana patch, into either the riparian buffer (BUFFER treatments) or through the PVC pipe (NO BUFFER), and into the stream channel. Note: only panel (a) is to scale.

includes both suspended sediment and sediment moved by saltation (i.e., bedload). After settling, the supernatant in these samples was decanted; the samples were then dried at 105°C until a constant mass was achieved. Sample discharge volumes were corrected to account for the presence of sediment. Instantaneous road sediment concentration values are calculated as the mass of the sediment divided by the corrected water volume of the sample.

Table 1. Selected road-related properties.

Variable†	Mean	Range	n
	Road surface		
K_s, mm h^{-1}	10.7 ± 6.0	1–16	6
ρ_b, Mg m^{-3}	1.61 ± 0.11	1.51–1.80	6
PR, MPa	6.7	6.7	6
	Road sediment		
Sand, g kg^{-1}	670 ± 90	510–800	14‡
Silt, g kg^{-1}	160 ± 40	90–230	14‡
Clay, g kg^{-1}	170 ± 70	40–280	14‡
OC, g kg^{-1}	19 ± 11	9–33	5
TN, g kg^{-1}	1.3 ± 0.8	0.7–2.5	5

† K_s, saturated hydraulic conductivity (determined with disk permeameter); ρ_b, bulk density (90-cm^3 cores); PR, normal penetration resistance (determined in dry season with Lang penetrometer); OC, organic carbon; TN, total nitrogen. Road sediment values determined from grab samples; means are ±1 standard deviation.

‡ Determined for the entire Pang Khum Experimental Watershed (PKEW) road.

RESULTS

Experimental Data

We define runoff-producing rainfall events as periods of sustained or intermittent rainfall that produced overland flow on the monitored road section. Rainfall depth (RF) for 18 monitored events ranged from 0.8 to 30.5 mm (Table 2). All events were included in the analysis because substantial road sediment was generated even for the smallest: for example, during an 0.8-mm storm (27 min, Event 2), approximately 1 kg of soil was transported from the monitored road section. The largest storm (30.5 mm, 56 min, Event 7), which occurred during BUFFER experiments, generated over 700 kg

Table 2. Runoff and sediment concentration data for Pang Khum Experimental Watershed (PKEW) Noi and the instrumented road section during monitored storm events.†

Sampled storms				PKEW Noi					165-m Road					
No.	Date	RF	D	Q_s	S_s	C_s‡	C_s^{max}	n_s	Q_r	Q_r^{max}	S_r	C_r‡	C_r^{max}	n_r
		mm	h:min	m^3	kg	mg L^{-1}			m^3	L s^{-1}	kg	mg L^{-1}		
						BUFFER events								
1	16 July	2.6	1:23	5	1	42	140	6	0.6	1.3	15	25400	56600	14
2	16 July	0.8	0:27	1	0.2	39	70	2	0.2	0.3	1	550	6600	2
3	16 July	3.3	0:26	15	2	81	2960	8	1.3	2.7	32	25600	49600	8
4	17 July	1.0	0:12	1	0.1	17	5	2	0.1	0.4	3	24700	44500	6
5	24 Aug.	2.3	0:17	6	3	98	340	7	0.6	0.6	9	15300	20200	4
6	24 Aug.	2.8	2:22	9	2	31	43	5	0.6	0.4	3	5500	9200	14
7	25 Aug.	30.5	0:56	151	140	581	3970	12	15.8	17.6	736	46600	96800	35
8	29 Aug.	2.3	0:41	9	2	60	120	8	1.2	1.9	11	9100	20000	15
						NO BUFFER events								
9	26 Aug.	3.9	0:29	12	4	198	750	7	1.3	1.8	11	8800	13800	19
10	26 Aug.	24.0	1:50	71	119	1004	1950	17	9.0	8.5	98	11000	35100	36
11	28 Aug.	1.0	0:13	2	2	94	200	8	0.2	0.2	2	7000	10500	8
12	29 Aug.	2.1	1:13	7	3	105	490	2	0.5	1.1	4	8600	13100	12
13	8 Sept.	8.7	1:16	31	54	687	4470	18	4.5	4.4	62	14000	25000	29
14	10 Sept.	4.6	0:56	10	3	147	1660	11	2.1	4.3	20	9500	17900	23
15	10 Sept.	13.6	2:01	54	212	2302	4540	14	7.1	8.4	164	23000	50200	30
16	11 Sept.	3.9	0:28	10	5	145	5470	11	1.7	5.0	28	16700	22300	8
17	13 Sept.	2.8	0:12	9	3	197	730	4	1.4	4.2	17	12200	18800	11
18	13 Sept.	12.6	0:36	38	110	1309	7020	9	5.7	8.6	131	22900	35600	23

† No., event number; RF, event rainfall depth; D, event duration; Q_s, total event stream discharge; S_s, total stream sediment; C_s, total mean stream concentration; C_s^{max}, maximum measured stream concentration; n_s, number of stream sediment samples collected; Q_r, total event runoff on the road; Q_r^{max}, maximum road discharge; S_r, total sediment transport on the road; C_r, event mean sediment concentration on the road; C_r^{max}, maximum measured sediment concentration on the road; n_r, number of road sediment samples collected.

‡ Calculated based on estimates of instantaneous sediment concentrations using Eq. [1] and [2]; all other values are based on field measurements.

of sediment on the road section. The largest NO BUFFER storm was 24.0 mm (110 min, Event 10); this event produced roughly 100 kg of sediment on the road section.

The relationships between instantaneous stream discharge (Q_i) and suspended sediment concentration (C_i) for the BUFFER and NO BUFFER treatments are plotted on log-log scales in Fig. 5a and 5b because both Q_i and C_i vary over a few orders of magnitude. Because of limited data for the BUFFER treatments, we included data from one event collected during a prior study in 2002 (not listed in Table 2). The fitted curves describing the relationship between Q_i and C_i for the two treatments are the respective power functions:

$$C_i = 28.329 Q_i^{0.851} \; \{\text{BUFFER}; p < 0.001, \; r^2_{adj} = 0.3, n = 59\} \quad [1]$$

$$C_i = 22.265 Q_i^{1.579} \; \{\text{NO BUFFER}; p < 0.001, \; r^2_{adj} = 0.4, n = 101\} \quad [2]$$

Because of limited sediment concentration data for low discharges, we combined the BUFFER and NO BUFFER baseflow data during the regression analyses ("+" symbols in Fig. 5). Comparison of medians and 95% confidence intervals via box-plots indicated no significant differences in concentration between BUFFER and NO BUFFER baseflow values (not shown). There are only 14 baseflow values, owing to sample contamination and runoff events initiating before our collection of baseflow samples.

To calculate total event suspended sediment loads, Eq. [1] and [2] were used to first estimate the suspended sediment concentrations at each recorded discharge value during the 18 events. To prevent overestimating suspended sediment concentrations for high discharge values, we restricted the maximum calculated suspended concentration to be the observed maximum value (7020 mg L^{-1}, Event 18, Table 2). To prevent overestimation of low flow concentrations, Eq. [2] was used to calculate C_i for all discharge values of <1 L s^{-1}. Total event stream concentrations ranged from about 20 to 600 mg L^{-1} for the BUFFER events, compared with 90 to 2300 mg L^{-1} for the NO BUFFER events (Table 2). The corresponding sediment totals were similarly lower for the BUFFER versus NO BUFFER treatments (Table 2). We believe the high maximum suspended sediment concentration observed during Event 3 results from our research activities in the riparian area immediately before the storm (installation of piezometers).

Road sediment concentration values are two to three orders of magnitude higher than corresponding stream suspended sediment values for both the BUFFER and NO BUFFER treatments. The highest mean concentration of road sediment was 46 600 mg L^{-1}, and the maximum observed concentration during this event was almost 100 000 mg L^{-1}. The elevated road values reflect the entrainment of comparatively high concentrations of coarse and fine material (670, 160, and 170 g kg^{-1} sand, silt, and clay, Table 1). The source of this material is principally the Bt and Bw horizons that comprise the road surface and cutbank along the monitored road section (Table 3).

Owing to a paucity of similar-sized storms for the two treatments, it is not possible to draw conclusions about the effect of the buffer on the timing of sediment delivery to the stream. Regardless, interpretation of timing differences between the two treatments would be difficult because we routed the road sediment directly (and

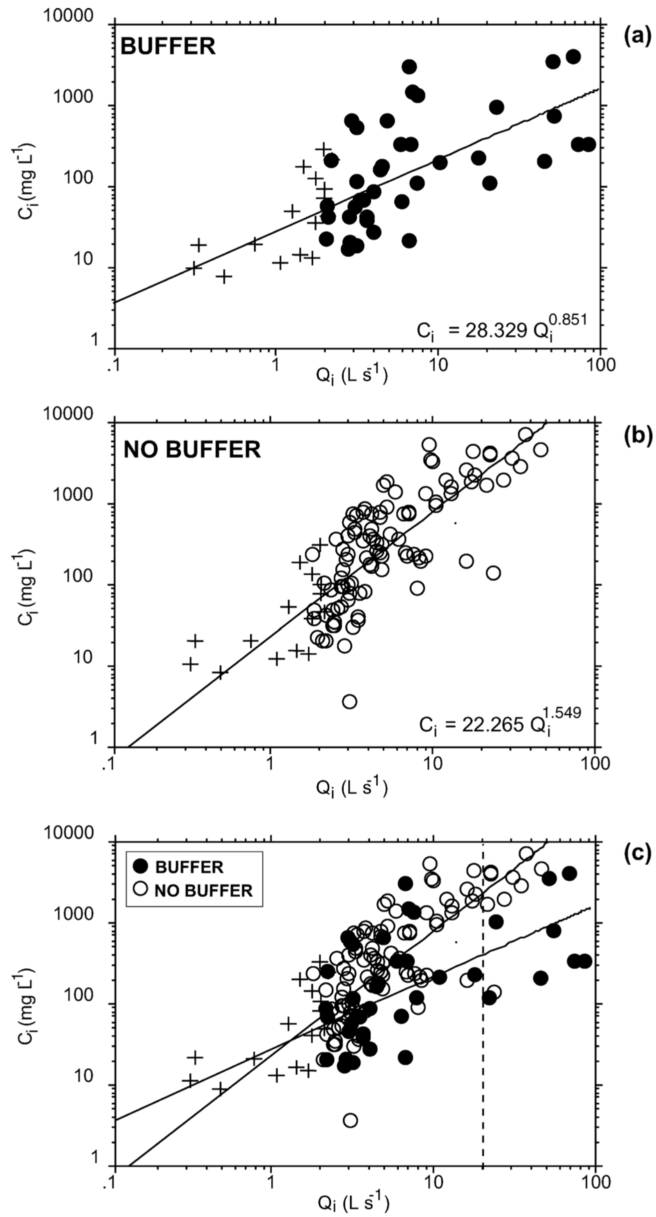

Fig. 5. Discharge (Q_i) versus suspended sediment concentration (C_i) for (a) BUFFER events (closed circles); (b) NO BUFFER events (open circles); and (c) both BUFFER (closed circles) and NO BUFFER events (open circles) superimposed on one graph. The fitted lines are the power regression curves of Eq. [1] ($p < 0.001$, $r^2_{adj} = 0.3$, $n = 59$) and Eq. [2] ($p < 0.001$, $r^2_{adj} = 0.4$, $n = 101$), which are listed in the lower right corner of panels (a) and (b). The "+" symbols signify baseflow values.

unnaturally quickly) into the stream via a pipe during the NO BUFFER events.

DISCUSSION

Filtering Capacity

The filtering capacity of the riparian buffer can be seen in Fig. 6a and 6b, where total stream sediment and maximum stream concentration are plotted against total road runoff. Over the range of runoff discharges we encountered, the total stream sediment and maximum stream concentration values were typically higher for the NO BUFFER versus the BUFFER treatment. Measured BUFFER and NO BUFFER sediment concentration data and respective rating curves are superimposed in Fig. 5c. The low r^2_{adj} values result from large scatter at high discharges. Because of limited data, we were unable to treat the rising and falling limbs separately to account for any hysteresis effect in the discharge–concentration relationship (see Sidle and Campbell, 1985; Williams, 1989; Asselman, 1999; Bronsdon and Naden, 2000). Nevertheless, the curves allow a first-order approximation of the influence of the riparian buffer on suspended sediment concentrations over a wide range of flow conditions. For discharges of $\geq$20 L s^{-1} (dotted line, Fig. 5c), predicted sediment concentration values for the NO BUFFER treatment are elevated by an order of magnitude or more over those of the BUFFER treatment.

In Table 4, mean-weighted sediment concentration values for the 10 NO BUFFER events have been recalculated using Eq. [1]. This recalculation represents a simplified simulation of event-specific road runoff passing through the riparian buffer, rather than flowing directly into the stream. Each value represents the estimated reduction in sediment concentration attributed to the presence of the riparian buffer. The buffer reduces suspended sediment concentration on average by 61%—although variability is high (Table 4).

The general tendency for this range of event sizes is for greater reductions to occur for larger events. After some unknown threshold in storm size, however, the filtering effects offered by the buffer should diminish. In fact, during the BUFFER events, the effect of the buffer on total stream sediment and maximum suspended sediment concentration does tend to decrease with increasing depth of road runoff (Fig. 6c and 6d). The estimations in Table 4 are therefore coarse, given the moderate fit of Eq. [1] and [2], but they are reasonable because there is no extrapolation involved.

Table 3. Soil horizon properties determined at soil pit near Station 406 in Pang Khum Experimental Watershed (PKEW) Noi.†

Horizon	Depth	ρ_b	Sand	Silt	Clay	pH	OC	TN	SOB	CEC	B_{sat}
	cm	Mg m^{-3}	g kg^{-1}				g kg^{-1}		cmol$_{(+)}$ kg^{-1}		%
A	0–10	1.09	494	198	308	4.6	27.3	2.6	12	14	83
BA	10–25	1.21	479	163	359	4.1	14.2	1.4	6	11	53
Bt1	25–50	1.23	492	154	352	4.0	10.9	1.0	5	10	54
Bt2	50–125	1.29	492	151	357	4.1	5.1	0.7	4	9	51
Bw3	125–175	1.52	587	104	309	4.1	3.8	0.4	3	6	42
BC	175–205	1.44	614	244	142	4.1	2.2	0.1	2	5	30
Cr	205–225	1.56	685	232	83	4.2	1.8	0.1	1	4	31

† ρ_b, Bulk density (90-cm^3 cores); pH was determined with KCL; OC, organic carbon; TN, total nitrogen; SOB, sum of bases, CEC, cation exchange capacity; B_{sat}, base saturation. Particle density is 2.5 Mg m^{-3} for all horizons except for BC (2.3 Mg m^{-3}).

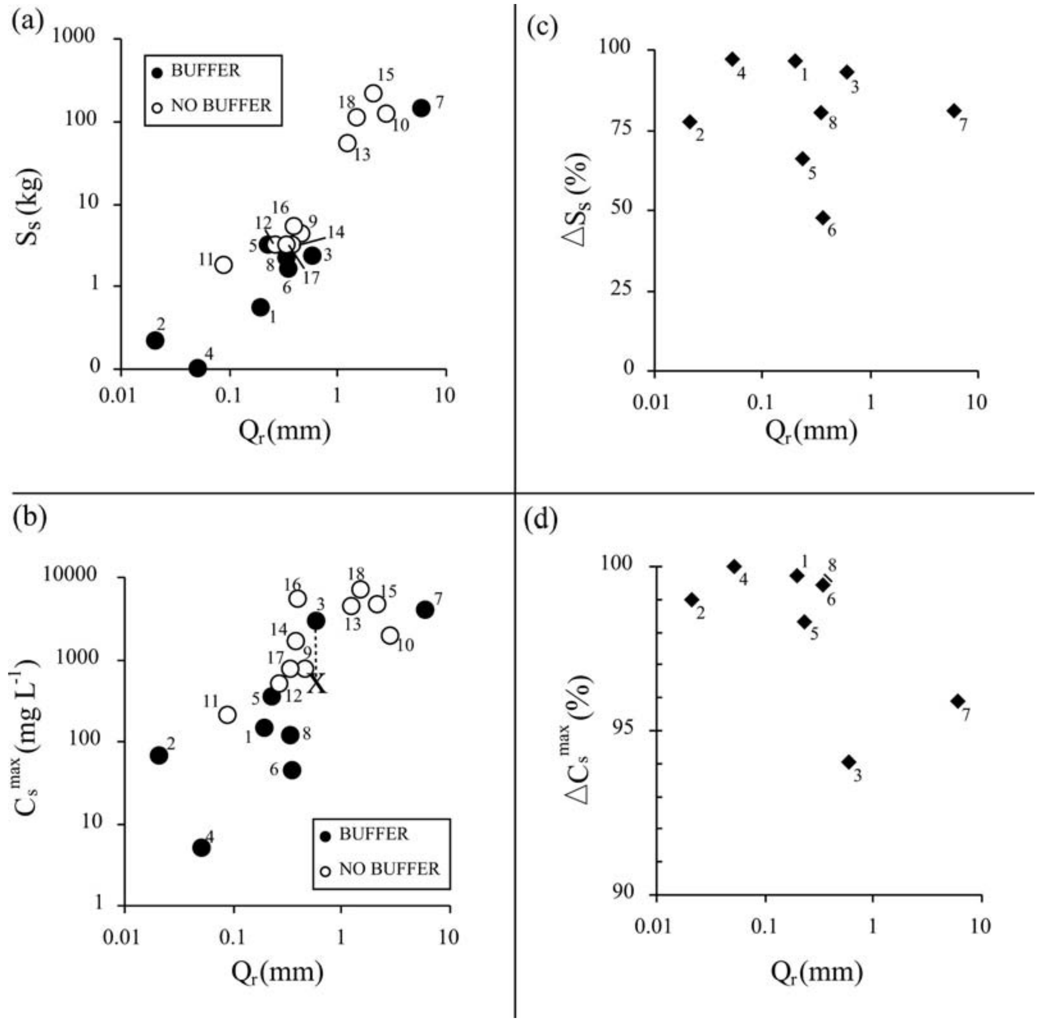

Fig. 6. For BUFFER and NO BUFFER events, the following: (a) comparison of total stream sediment (S_s) with total road runoff (Q_r) and (b) comparison of maximum measured stream concentration (C_s^{max}) and road runoff. The "x" in panel (b) is an estimation of maximum concentration for Event 3, had we not disturbed the wetland before the rainfall event (determined via regression). For various magnitudes of road runoff during the BUFFER events only, the following: (c) the reduction of total stream sediment (ΔS_s) versus that of road runoff, calculated as $\Delta S_s = (S_r - S_s)/S_r \times 100\%$; and (d) the reduction in maximum stream concentration (ΔC_s^{max}) versus that of road runoff, calculated as $\Delta C_s^{max} = (C_r^{max} - C_s^{max})/C_r^{max}) \times 100\%$. Abbreviations are explained in Table 2. Numbers in all panels refer to the storms listed in Table 2.

Table 4. Reduction of predicted mean sediment concentration if road runoff were to pass through the riparian buffer before entering the stream.

Event	No buffer, C_s†	Simulated buffe, $\hat{C}_s$‡	Reduction in concentration, ΔC_s§
	mg L^{-1}		
9	198	87	0.56
10	1004	201	0.80
11	94	62	0.34
12	105	65	0.38
13	687	158	0.77
14	147	78	0.47
15	2302	299	0.87
16	145	69	0.52
17	197	87	0.56
18	1309	201	0.85

† C_s, total mean stream concentration from Table 2, calculated via Eq. [2].
‡ Determined using Eq. [1] instead of Eq. [2].
§ Determined as $\Delta C_s = (C_s - \hat{C}_s)/C_s$.

Filtering Mechanisms

The literature provides insight for defining the minimum buffer dimensions needed to reduce environmental impacts in disturbed watersheds (e.g., Corbett et al., 1978; Bren and Turner, 1980; Borg et al., 1988; Davies and Nelson, 1994; Ziegler et al., 2006). Clinnick's (1985) review concluded that the most commonly recommended slope length for stream buffers was 30 m, which by chance is the slope length occupied by the buffer we investigated in PKEW Noi. The concept of buffering has different meanings depending on the type of filtering functions needed (e.g., sediments, chemicals, nutrients, bacteria) and the water body to be protected (Norris, 1993; Barling and Moore, 1994; Schmitt et al., 1999; Lee et al., 2004). In this study, we were concerned with the capacity to reduce stream suspended sediment during typical monsoon storms by filtering sediment in road runoff. For the range of events we encountered, the 30-m buffer greatly reduced suspended sediment concentrations, compared with not having a buffer (Fig. 6b).

Other works elucidate the mechanisms by which filtering occurs (e.g., Dabney et al., 1995; Meyer et al., 1995; Pearce et al., 1997; Herron and Hairsine, 1998; Lee et al., 2000). Primarily, particle deposition occurs once the velocity of the conveying water falls below the velocity initially required to induce sediment movement (i.e., via Stokes Law). Actual filtering by the vegetation is typically much less important (see Fiener and Auerswald, 2003), although vegetation does act to retard the resuspension of already-trapped sediments (Braskerud, 2001). Reduction in flow velocity can result from several inter-related phenomena acting on the inflowing water: for example, infiltration, ponding, change in slope gradient, and encountering increased surface roughness. In the buffer we investigated, ponding occurred immediately as runoff encountered the comparatively flat slope of both the banana patch and the saturated riparian wetland vegetation. Additionally, sediment deposition occurred in the gully of the fillslope because of high surface roughness. Because the buffer was located at a natural seep, the soil was saturated for the duration of our study. Infiltration was therefore not a key factor in filtering sediment (see McKergow et al., 2004a).

Prior studies have shown that more than 95% of the sediment deposition may occur within buffers less than 6 to 8 m wide, with most coarse fractions being retained in the first 1 to 3 m (see Tollner et al., 1976; Dabney et al., 1995; Daniels and Gilliam, 1996; Robinson et al., 1996; Pearce et al., 1998; Schmitt et al., 1999; Hook, 2003; McKergow et al., 2004b). We also found a predominance of sand-dominated material (>70 g kg^{-1} sand; 90-cm^3 cores; $n = 6$) within the first 10 m of the riparian buffer. Coarse depositional material was not detected farther downslope near the stream channel. This observation in itself suggests that a 10-m riparian buffer would be effective for removing the coarse sediment component from the road runoff (here, we are also recognizing the supporting role of the fillslope gully and banana patch in trapping sediment). Assuming that all coarse material in the road runoff was retained by the buffer, then the average estimated reduction in total sediment produced by the buffer was 80% (Fig. 6c).

Large Events

The high sediment concentration values in BUFFER Event 7 are undoubtedly related to the highest road sediment inputs we recorded during all experiments (Table 2). Maximum road discharge entering the buffer was 17.6 L s^{-1}; total discharge was 16 m^3 for this event. Basin runoff was additionally an order of magnitude higher than for any other BUFFER event (equivalent to a runoff coefficient of 20%). The vertical dashed line in Fig. 7 demarcates the approximate time when road discharge into the buffer exceeded a threshold rate of 10 to 13 L s^{-1}, after which stream suspended sediment concentrations rose above 1000 mg L^{-1}. Road sediment concentrations of >50 000 mg L^{-1} were sustained for 20 min, even after road discharge dropped below this threshold.

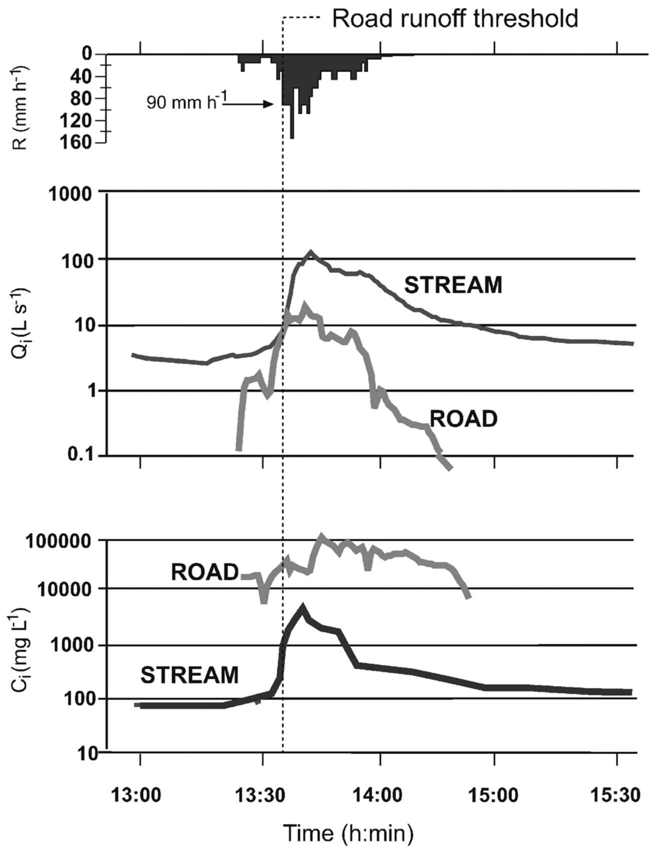

Fig. 7. The following data were measured during Event 7: (top) 1-min rainfall intensities; (middle) discharge rates for road and stream runoff; and (bottom) suspended sediment concentrations for road and stream runoff. Measurement locations for road and stream runoff are shown in Fig. 4. The dashed line highlights the threshold road runoff volume (10–13 L s^{-1}) for which the filtering effect of the riparian buffer is compromised.

Some material that was deposited in the buffer during smaller prior events was likely re-entrained as flow depth and velocity increased during this large event. In addition, bank channel erosion and the liberation of sediment stored at relatively high channel locations may have contributed to the high sediment load. Elevated stream concentration, however, fell sharply soon after road runoff volume dropped below 10 L s^{-1}, lending support that concentrated flow from the road was the principal factor in boosting stream suspended sediment.

In the general case, rainfall intensities in the range of 90 to 150 mm h^{-1}—even if sustained for only a few minutes—can initiate these flow magnitudes on the monitored road section via the Hortonian overland flow mechanism alone (i.e., Fig. 7; see Ziegler et al., 2004). However, less than 1% of the recorded 1-min rainfall intensity values in PKEW exceed this rate (based on data for 1 Aug. 1997 to 31 Dec. 2003). This represents only 4% of the annual rainfall total, occurring typically during two to three storms. Events producing the type of flow required to elevate stream concentration values into the range observed during BUFFER Event 7 are therefore infrequent. In contrast, similarly high concentrations occur frequently when road runoff is dispersed directly into the stream (e.g., 4 of 10 NO BUFFER events).

Toward Sustainable Buffers in Upland Basins of Southeast Asia

Earlier research in PKEW showed that the amounts of runoff and sediment entering streams from roads are disproportionately high compared with other lands (Ziegler and Giambelluca, 1997; Ziegler et al., 2004). In other areas of tropical Southeast Asia the importance of various road-related sediment sources has also been recognized (e.g., Rijsdijk and Bruijnzeel, 1991; Douglas, 1999; Chappell et al., 2004; Sidle et al., 2004). Riparian buffers, such as the one investigated here, therefore represent an affordable means of reducing road impacts in upland basins in developing regions where funding is scarce.

The 1.65-km road in PKEW crosses the stream in five locations; three in one 50-m stretch near PKEW Noi (Fig. 2). This road, as is the case for many mountain roads in northern Thailand, originated from a footpath. The buffer opportunity we investigated in PKEW Noi is the result of the original walking path crossing immediately above the wetland seep. In total, three additional locations exist in PKEW where road runoff could be directed into riparian buffers. One occurs in the immediate vicinity of PKEW Noi, in essentially the same wetland (B1, Fig. 2). The other two locations are currently used for agriculture—irrigated crops (B2) and rice paddy (B3) in Fig. 2. The longest road section (> 400 m), which is the source of substantial sediment volumes entering the stream each year (Ziegler et al., 2004), drains directly into the stream channel (Fig. 2 and 3a). Reducing sediment delivery from this road section via buffering would require substantial rerouting of surface runoff to downstream locations B2 or B3. The affected agriculture lands would also have to be converted to buffers, and some type of compensation made to the local farmer.

The general situation in PKEW highlights two important issues confounding the mitigation of cumulative watershed effects as related to road erosion in the highlands of northern Thailand: (i) many roads were built without considering design criteria to address watershed conservation (see Furniss et al., 1991; Carling et al., 2001; Sidle et al., 2004); and (ii) funding is not available to perform appropriate types of road maintenance at appropriate times of the year. Naturally occurring buffers, therefore, represent an economically feasible strategy for reducing sediment inputs to streams from roads and other surfaces in disturbed upland basins in Southeast Asia. Here we are referring to surfaces that were not intentionally created for the purpose of buffering road runoff, such as the riparian wetland investigated in PKEW Noi. To ensure best success, buffers should be used together with other complementary conservation practices: for example, avoid building roads on steep slopes, minimize disturbance in sensitive watershed areas (e.g., channel head locations and hollows), and limit distances over which surface runoff can travel (Sidle et al., 2004; Chappell et al., 2006; MacNamara et al., 2006). With respect to the latter, the maximum length for road sections draining into buffers similar to the one in PKEW Noi is probably on the order of 50 to 100 m—particularly if interception of subsurface flow at road cuts contributes additional surface flow.

Finally, long-term effectiveness of a buffer requires management by local and regional entities. This point is emphasized by the contemporary situation in PKEW Noi. One year following our experiment, water buffalo were permitted in the riparian zone for several months in the dry season. Trampling and creation of wallows destroyed much of the continuity of the riparian vegetation and created new sediment sources. The sediment retention benefit afforded by the buffer in prior years was obviated by this disturbance. Thus, protection of buffer zones, once established, is a critical management concern that would have to be addressed before riparian buffers could be viable conservation options in the highland areas.

CONCLUSIONS

Using a full-scale field experiment that altered the path of road runoff to the stream channel, we gained direct evidence that a riparian buffer reduced stream suspended sediment by filtering road-generated sediment. Our preliminary data indicated that deposition on the approaching fillslope and within the 30-m riparian buffer reduced stream suspended sediment load by 34 to 87% during typical monsoon rain events. Filtering in the riparian buffer was achieved principally by sediment deposition related to ponding or velocity reduction in the saturated, relatively flat buffer, for which the sedge *Fimbristylis aphylla* was the dominant species. Deposition of the coarse sediment load occurred within the first 10 m after entering of the buffer. Some deposition also occurred in a fillslope gully and at the base of the fillslope before entering the buffer.

The contributing area of the 165- × 2.4-m monitored road section was probably near the threshold for which this buffer can effectively filter road-generated sediments during large runoff events that occur one to three times a year. Short bursts of high-rainfall intensity (90–150 mm h^{-1}) during one such observed storm produced concentrated Hortonian overland flow on the road that had a maximum total sediment concentration of nearly 100 000 mg L^{-1}. Stream suspended sediment concentrations during this event rose above 4000 mg L^{-1}, despite the presence of the buffer.

Naturally occurring riparian wetlands, such as the one investigated herein, represent an affordable means of reducing road-generated sediment in upland areas of northern Thailand, but complementary conservation practices and buffer management and protection are required to ensure long-term functionality. Ensuring buffer effectiveness for larger flow volumes would require partitioning road runoff into isolated buffers and/or converting concentrated flow pathways into shallow unconcentrated overland flow. In general, restricting flow path distances to approximately 50 to 100 m on steep sections would be beneficial in reducing the velocity and total volume of flow into the buffer. All these measures would facilitate a reduction in road-generated sediment entering the riparian area and stream.

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