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Simulation of runoff and erosion on mountainous roads in northern Thailand: a first look

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Abstract Field measurements are used as input to a physically based runoff/erosion model to quantify hydrological and erosional changes associated with road expansion and conversion of closed-canopy forest into swidden-based agricultural lands in one watershed in northern Thailand. Simulation of the seven largest storm events within the rainfall collection period indicate that, depending on location and soil physical and hydrological properties, roads might contribute more to hydrological and erosional impacts in this area than conversion to agriculture. These results have implications for the future management of conservation activities within mountainous tropical watersheds undergoing road expansion.

INTRODUCTION

Roads play a significant role in altering near-surface hydrological response and subsequently accelerating soil erosion in mountainous areas of Southeast Asia. However, it is not clearly understood how these road impacts compare to those resulting from other human activities, such as vegetation removal for agriculture. Although erosion and sedimentation in highland areas of northern Thailand have been accelerated by extensive deforestation and changes in agricultural patterns that have taken place over the last several decades, much of the sediment delivered to stream systems may be due to expansion of road networks. For example, Pransutjarit (1983) reported that road length was the most important variable in increasing amounts of runoff and suspended sediment in the Mae Taeng watershed in northern Thailand. Nevertheless, most conservation programs tend to focus predominantly on agricultural practices, ignoring what may be equally or more disruptive processes: the building, maintenance, and usage of rural roads.

In this paper, for one watershed in northern Thailand, we quantify changes in overland flow response and sediment transport associated with (a) the transition from closed-canopy forest to a mosaic of swidden agriculture lands, and (b) road expansion. We then compare the changes induced by each activity to determine the respective hydrological and geomorphological impacts. The objective of this research is to ascertain the importance of rural roads, compared to agricultural lands, in altering the hydrological response of watersheds in mountainous Southeast Asia.

BACKGROUND

Impacts of roads: previous studies

Previous research has identified at least three distinct road features that can alter storm flow response in temperate mountainous watersheds: (a) highly compacted road surfaces and disturbed roadside margins reduce infiltration of rain water, increasing the likelihood of overland flow generation; (b) cutbanks can intercept subsurface flow, re-routing it as overland flow (Harr *et al.*, 1975; King & Tennyson, 1984; Wright, 1990); and (c) ditches and culverts capture both subsurface flow and surface runoff, and channel it more rapidly to streams (cf. Burroughs *et al.*, 1972; Megahan, 1983). To this list we add erosional gullies, which once developed, act similarly to ditches in capturing and re-routing surface water. All of these features effectively extend the channel network and tend to produce a more rapid delivery of storm water to streams, which may produce faster flow peaks and slightly higher total discharges (Harr *et al.*, 1975; Jones & Grant, 1996). Although less work has been conducted on roads in the tropics, we expect these same road features also to be of great significance in modifying hydrologic response in tropical mountainous watersheds.

The erosional importance of roads in tropical watersheds has been described by Rijsdijk & Bruijnzeel (1991). In the Konto catchment in East Java, they estimated that rural roads, comprising about 3% of a basin area, contributed disproportionately to the basin sediment yield. Similar findings were reported by Dunne & Dietrich (1982) and Harden (1992) in Africa and South America, respectively. Several studies within temperate regions have shown the importance of road location, geometry, and usage on sediment transport (e.g. Reid & Dunne, 1984; Bilby, 1985; Coker *et al.*, 1993). Additional studies have identified several sediment source areas associated with unpaved roads (e.g. side cast material from construction, maintenance or mass wasting on adjacent hillslopes) that provide unstable material which is easily transported into streams during overland flow events (e.g. Wald, 1975; Beschta, 1978; Anderson & Potts, 1987; Grayson *et al.*, 1993).

Importance of Hortonian overland flow on mountainous roads

Hortonian overland flow (HOF) is generally thought to be rare in fully vegetated, undisturbed areas where infiltration rates are high. However, in areas where infiltration has been reduced by vegetation removal, compaction, or paving, the Hortonian mechanism can be a dominant pathway of water movement to stream channels. Highly compacted, largely bare, unpaved road surfaces are likely source areas for HOF. While roads may also enhance runoff by intercepting subsurface flow (Jones & Grant, 1996), HOF alone may explain most of the increased runoff and subsequent soil erosion associated with roads in many tropical watersheds if the road infiltration rates are sufficiently low. For example, in several studies undertaken in the tropics, rural roads and paths were found to be active runoff-generating components owing solely to their low infiltration capacities (Dunne & Dietrich, 1982; Harden, 1992; Malmer & Grip, 1990; Van der Plas & Bruijnzeel, 1993). In addition, we earlier reported evidence of a HOF-dominated runoff regime in the northern Thailand watershed investigated in this paper (Ziegler & Giambelluca, in press).

STUDY AREA

Our study site was near Ban (village) Pang Khum (19°3′N, 98°39′E), within the Samoeng District of Chiang Mai Province, NNW of Chiang Mai, Thailand. This

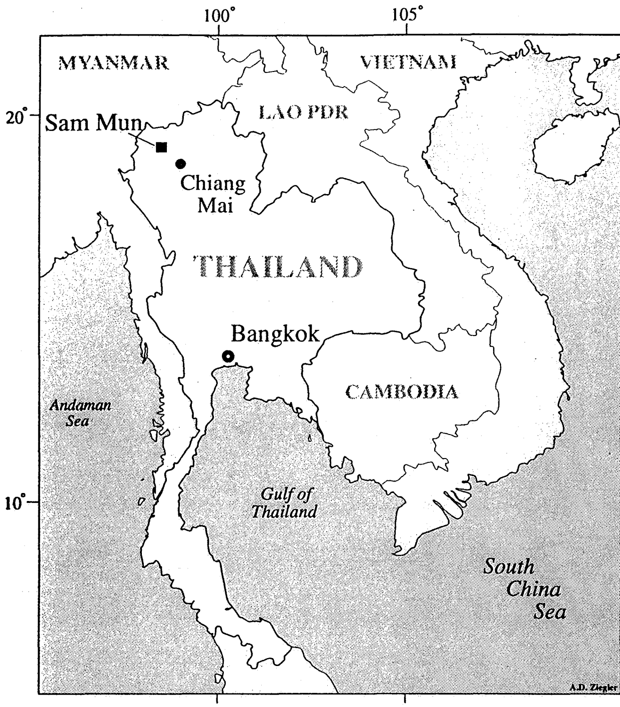

Fig. 1 The Sam Mun study area in northern Thailand.

area is referred to herein as Sam Mun (Fig. 1), and described in detail in Ziegler & Giambelluca (in press). Sam Mun ranges in elevation from 750 to 1850 m a.s.l. The area has a monsoon rainfall regime with a rainy season extending from mid-May through October or early November, during which approximately 90% of the 1000-1200 mm annual rainfall occurs.

Roads in Sam Mun comprise only 0.22% of the study area (0.56 km km^{-2}). In contrast, forest, agriculture, initial secondary vegetation, and paddy fields comprise 72.3, 20.4, 4.6, and 2.1% of the area, respectively (Fox *et al.*, 1995). It is our belief that roads are responsible for a significant proportion of the increased erosion and sedimentation that is attributed to the expansion of agriculture activities in Sam Mun. This erosion results from the interaction of soil, slope (up to 18°), road usage, and road maintenance variables. Furthermore, variations in sediment yield are related to annual cycles in both climate and the supply of erodible sediment on road surfaces. At the beginning of the wet season, the thick layer of fine sediment that accumulates on the road surfaces during the dry season is initially flushed by surface flow during the first few rainstorms. Thereafter, daily traffic, although light, detaches sediment and creates ruts where gullies often form. Road maintenance, especially the filling of gullies with unconsolidated material, is another source of erodible material. Because HOF is generated on roads during almost every rainstorm (Ziegler & Giambelluca, in press), surface runoff continually transports the easily entrainable sediment and causes further incision of concentrated flow channels. Hence, erosion occurs throughout the rainy season; and because many road sections terminate at the stream, sedimentation is often substantial.

SIMULATION OF EROSION AND RUNOFF

In this study, we use the KINEROS runoff/erosion model (Woolhiser *et al.*, 1990) to simulate overland flow and sediment transport during seven rainstorms for three land-use scenarios (21 total simulations). KINEROS is a distributed, event-oriented, physically based model that can simulate Hortonian runoff and sediment transport from complex watersheds or hillslopes. Detailed description of KINEROS equations and modelling approach can be found in the work by Woolhiser *et al.* (1990).

The three model scenarios (Fig. 2; Panel I) represent the evolution in land use practices that has taken place in this area over the last several decades. Scenario 1 is a relatively undisturbed basin of closed-canopy forest, with small, undetectable patches of swidden agriculture. Scenario 2 incorporates intensified land use resulting in approximately 25% of the area being in various stages of swidden agriculture, including cultivation, fallow, or secondary vegetation regrowth. Scenario 3 represents Scenario 2 with a road constructed through a small lowland portion ($\approx$0.25%) of the area. Each scenario is simulated for the same basin of approximately 112 ha. All information to build the basin flow planes are based on field observations and measurements, or derived from a land use map (Department Geography, Chiang Mai University). Scenarios A and B were modelled with 13 overland flow planes, and Scenario C, with 17 planes. Dry season baseflow for each of the two main streams is ≈ 0.02 m^2 s^{-1}.

Most model inputs are derived from soil physical and hydrological properties measured near Pang Khum (Table 1). Rainfall was measured at 10-min. intervals from March to August, 1993 and June to August, 1995. Seven of the largest storms in terms of total precipitation were used in these simulations. The estimated return period for these storms is less than 2 years. Total rainfall, maximum rainfall intensity, and event durations are detailed in Table 2. In Fig. 3, these storms are plotted against median values of saturated hydraulic conductivity (K_s) for road surfaces and agriculture/secondary vegetation lands. Periods where rainfall intensity exceed K_s are first order indicators that HOF may occur. All other input variables were estimated based on literature values, or derived from equations and tables in the KINEROS manual (Woolhiser *et al.*, 1990). Each simulated event is independent, i.e. soil moisture was initialized each time to approximately field capacity.

RESULTS AND DISCUSSION

The results of the 21 simulations are summarized in Table 2. Peak flow rate, time to peak flow rate, total basin runoff, runoff coefficient (total runoff/(rainfall – interception)*100), and total sediment yield from the overland flow planes are presented for all events during which overland flow was predicted. The following can be noted regarding the simulations:

(a) *Scenario A*. No overland flow was produced from the all-forest landscape because infiltration rates are greater than maximum rainfall intensities.

(b) *Scenario B*. Only one (#2) of the seven storms produced HOF despite three storms having rainfall intensities greater than K_s on secondary vegetation and

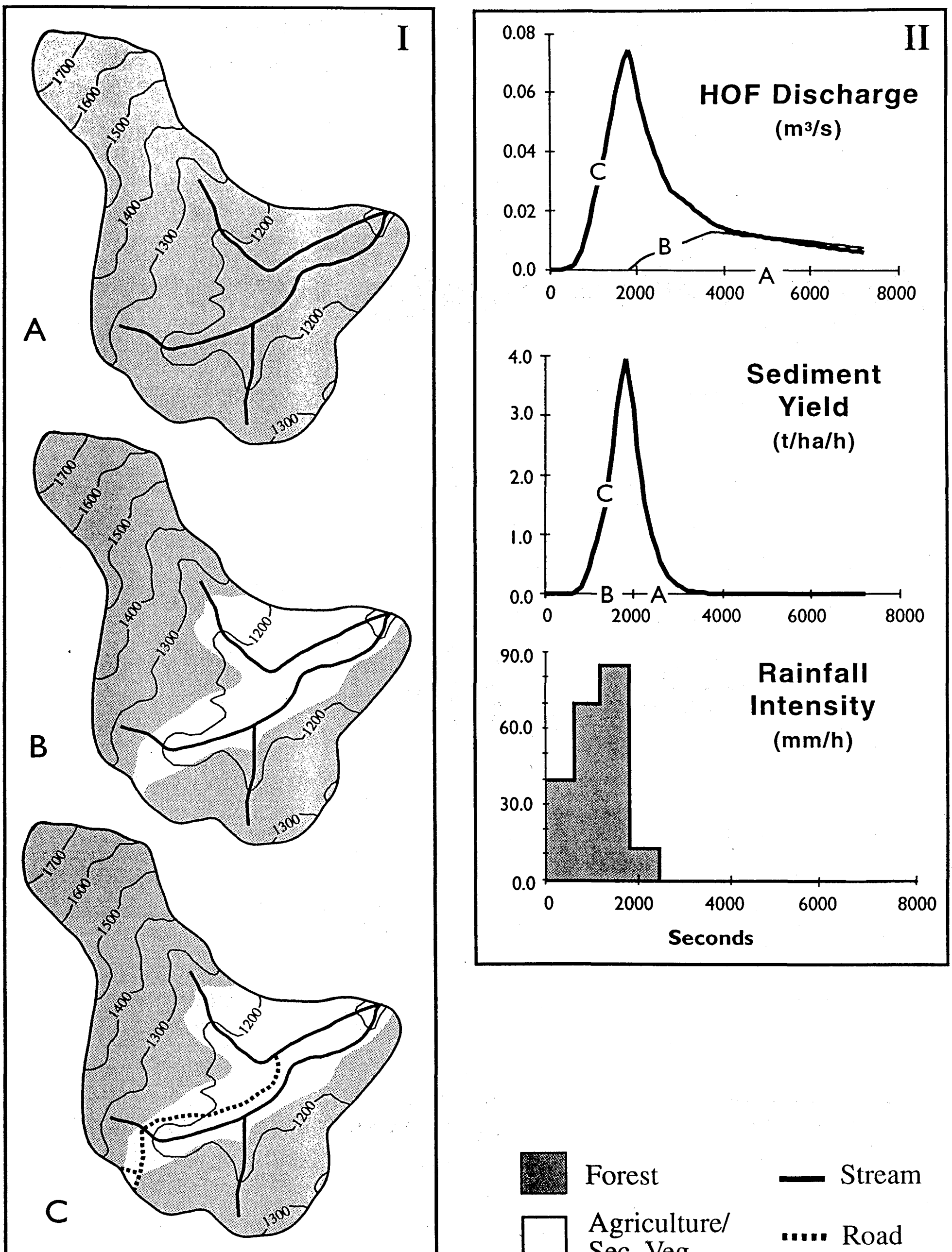

Fig. 2 KINEROS simulation of stream discharge and sediment yield changes resulting from land-cover change within a small watershed in northern Thailand. The simulation was conducted for three land-cover scenarios during a 40-min storm event (#2). Scenario A represents a hillslope covered entirely with closed-canopy forest. In Scenario B, part of the lower slope has been converted to a mix of agriculture and secondary vegetation, which is typical of the swidden agriculture system in the area. Scenario C represents the area after a road was constructed.

Table 1 Parameter values used in KINEROS simulations. All values are based on field measurements.

Parameter	Forest	Ag/Sec. Veg.[a]	Road surface
Area	83.78	28.0	0.28
Saturated hydraulic conductivity (mm h^{-1})	146.10	82.8	2.3
Bulk density (g cm^{-3})	0.89	1.10	1.40
Porosity (%)	0.62	0.56	0.48
Soil moisture at saturation (g cm^{-3})	0.46	0.37	0.39
Particle density (g cm^{-3})	2.49	2.55	2.57
[b]K_{ULSE}	0.24	0.28	0.41
[c]D_{50} (mm)	0.095	0.108	0.129

[a] Values are area-weighted based on secondary vegetation lands comprising ≈80% and agriculture lands comprising ≈20% of the group area (based on land use classification of Fox *et al.*, 1995). K_{USLE} and D_{50} values are based on secondary vegetation measurements only.

[b] The Universal Soil Loss Equation *K* factor was based on texture measurements, and is used to calculate rainsplash and hydraulic erosion parameters (cf. Woolhiser *et al.*, 1990).

[c] The soils for the three land uses fall into the sandy loam texture class; specifically soils in the general area are paleudults, haplahumults, kandiustults, paleustalfs, and dystropepts (soils map, Department of Land Development, Bangkok, n.d.).

Table 2 Summary information for simulated storms and KINEROS-predicted Horton overland flow and sediment transport values. Only events that produced overland flow are shown in the table.

Storm	Scenario	Simulated storms: TR (mm)	Max I (mm h^{-1})	D (min)	KINEROS results: PFR ($m^3 s^{-1}$)	TP (min)	RO (m^3)	ROC (%)	TS (kg)
1	C	35.3	106.7	40	0.07	27	98	0.24	2337
2	B	34.8	85.3	50	0.01	63	50	0.12	0
2	C	34.8	85.3	50	0.07	30	147	0.37	2134
3	C	30.2	77.7	50	0.05	27	79	0.24	1291
4	C	32.2	12.2	540	0.01	407	43	0.12	80
5	C	25.2	48.8	210	0.02	72	46	0.18	24
6	C	19.8	54.8	170	0.01	12	20	0.11	4
7	C	17.5	35.1	60	0.02	32	27	0.19	134

TR = total event rainfall; Max I = maximum rainfall intensity; D = event duration; PFR = peak flow rate; TP = time to peak flow rate; RO = total basin runoff; ROC = basin runoff/(total rainfall − interception)*100; TS = total sediment contributed from overland flow planes.

agricultural lands. Although HOF was generated during storm 2, predicted sediment transport from contributing flow planes was negligible.

(c) *Scenario C.* All seven rain events produced overland flow and sediment transport because road K_s values are very low compared to rainfall intensities. In addition, sediment transported from road segments into the stream network (TS in Table 2) is predicted to be substantial for the largest storms. These results indicate that the hydrological and erosional impacts of roads are potentially greater than those from agricultural lands-at least for storms of this general magnitude (cf. Ziegler & Giambelluca, in press). Figure 2 (Panel II) elucidates important differences in hydrologic response and sediment transport between Scenarios B and C during storm 2. In general, the discharge hydrograph suggests (a) overland flow is generated on road surfaces early in a storm event; and (b) linear road segments route overland flow to the stream channel more quickly than hillslopes, thereby

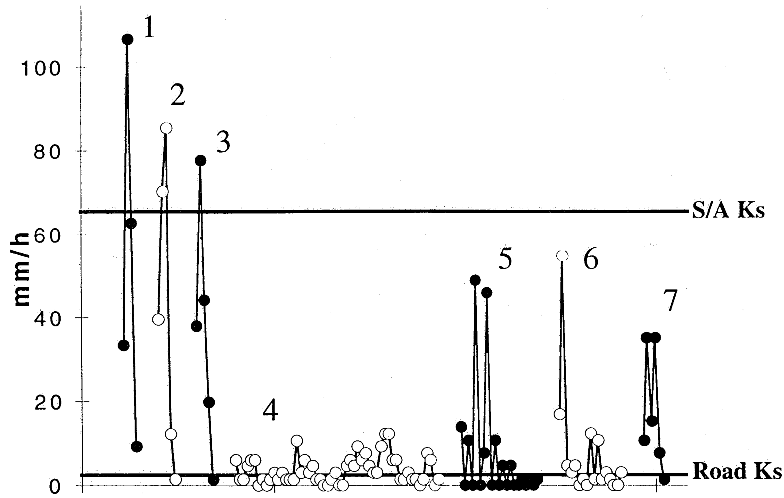

Fig. 3 The structure of the seven storms simulated in this paper are plotted against saturated hydraulic conductivity (K_s) values for roads and agriculture/secondary vegetation lands. Each dot represents a 10-min period at a given intensity. Periods when rainfall intensities > K_s represent times when Horton overland flow may be initiated.

reducing the time to peak discharge and increasing the peak flow value. This is an example of the road extending the stream channel network (cf. Jones & Grant, 1996). The sediment yield graph shows (a) that the sharp sediment pulse from the road segments (Scenario C) corresponds with the HOF hydrograph; and (b) that negligible sediment was transported from the overland flow planes for Scenario B (no roads).

Although KINEROS was forced with recorded rainfall data and field measured data for crucial hydrological and erosion-related properties, it was not calibrated or validated with measured discharge or sediment yield data. In addition, the model description of the basin does not specifically include all important landscape features that influence runoff routing (e.g. gullies, ditches, cutbanks, paths, and discharge points where HOF is directed onto the hillside). Therefore, the results only reflect relative differences in responses of HOF and sediment transport, which result from differences in soil physical and hydrological properties. We cannot yet specify confidence bands around the predicted runoff and sediment output values. For example, sediment pulses from contributing road segments appear to be quite high during the larger events (Table 2). While we believe that erosion rates on road surfaces are significant, these simulations do not account for the event-to-event changes in sediment availability, or for detachment by vehicle traffic or gullying processes.

CONCLUSIONS

This work provides insight into the relative hydrological and erosional impacts of roads *vs.* those imposed by a mosaic of agricultural, fallow, and recovering secondary vegetation lands. The simulations suggest that during large rainstorms, Horton overland flow and concomitant sediment transport on roads is greater than that from the agriculture-related lands. One explanation for this is that compared to agriculture-based hillslopes, roads are linear features, with lower infiltration rates, that channel overland flow quickly/directly to the stream channel. However, these simulations may not fully describe all hydrological and erosional processes operating in the region as a whole. For example, in other basins where agriculture is more intense and occurs on steeper slopes than in Sam Mun, the impacts of an agriculture-related landscape may be greater than predicted here. In addition, these simulations only consider the Hortonian overland flow contributing to surface runoff. Nevertheless, this work stresses the need to place greater emphasis on mitigating the impacts of road expansion in Southeast Asia, which is an inevitable consequence of rural development. If roads, as they are currently built and used, are major contributors to surface erosion and sedimentation, soil conservation efforts should include improving the routing, design, and maintenance of existing and future rural roads.

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