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Toward understanding the cumulative impacts of roads in upland agricultural watersheds of northern Thailand

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Abstract

This paper describes the interactions of various physical processes that allow unpaved roads to contribute disproportionately to basin-wide runoff and stream sediment in the 93.7 ha Pang Khum Experimental Watershed (PKEW) in northern Thailand. Many road sections in PKEW are constant sources of sediment entering the stream during most rain events because: (1) Horton overland flow is generated on the compacted surfaces after small depths of rainfall; (2) surface preparation processes, including vehicle detachment and maintenance activities, renew the supply of easily transportable surface sediment on inter- and intra-storm time scales; (3) erosion of the road surface is accelerated in locations where slopes are steep, overland flow distances are long, and/or vehicle usage is high; (4) surface runoff typically exits from the road directly into the stream. Owing to these collective processes, sediment delivery rate on PKEW roads is more than an order of magnitude higher than that on adjacent fields (≈120 Mg ha^{-1} per year versus 9 Mg ha^{-1} per year). Thus, unpaved roads appear to be on the same order of importance as agricultural lands in contributing sediment to the stream network, despite occupying a fraction of the total surface area in the basin (≈0.5% versus 12%). A more thorough assessment of linkages between all hillslope runoff/sediment sources and the stream network, however, is still needed to fully evaluate the relative impacts of roads versus those of agriculture practices in PKEW.

Keywords: Unpaved roads; Erosion; SE Asia; Land degradation; Tropical hydrology/geomorphology

1. Introduction

Extensive forest removal and intensification of agriculture on steep slopes in the highlands of northern Thailand during the last several decades have been linked to changes in hydrologic phenomena and sedimentation; however, the detection of these impacts across varying scales has not always been conclusive (cf. Tangtham and Sutthipibul, 1989; Anecksamphant and Boonchee, 1992; Alford, 1992, 1994; Wilk et al., 2001). Concern about the long-term implications of unsustainable activities in the Thai highlands fostered

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the initiation of both domestic and international conservation projects (e.g. Hurni, 1982; IBSRAM, 2000; www.forestandpeople.org, 2002). Much research has focused on improving the agriculture practices of ethnic minorities, whose traditional short-term shifting systems have been evolving perforce to more permanent systems—but implemented frequently on the same steep slopes (Schmidt-Vogt, 1999). While unsustainable cultivation likely contributes to downstream environmental impacts, the expansion of the rural road network almost certainly plays a substantial part as well.

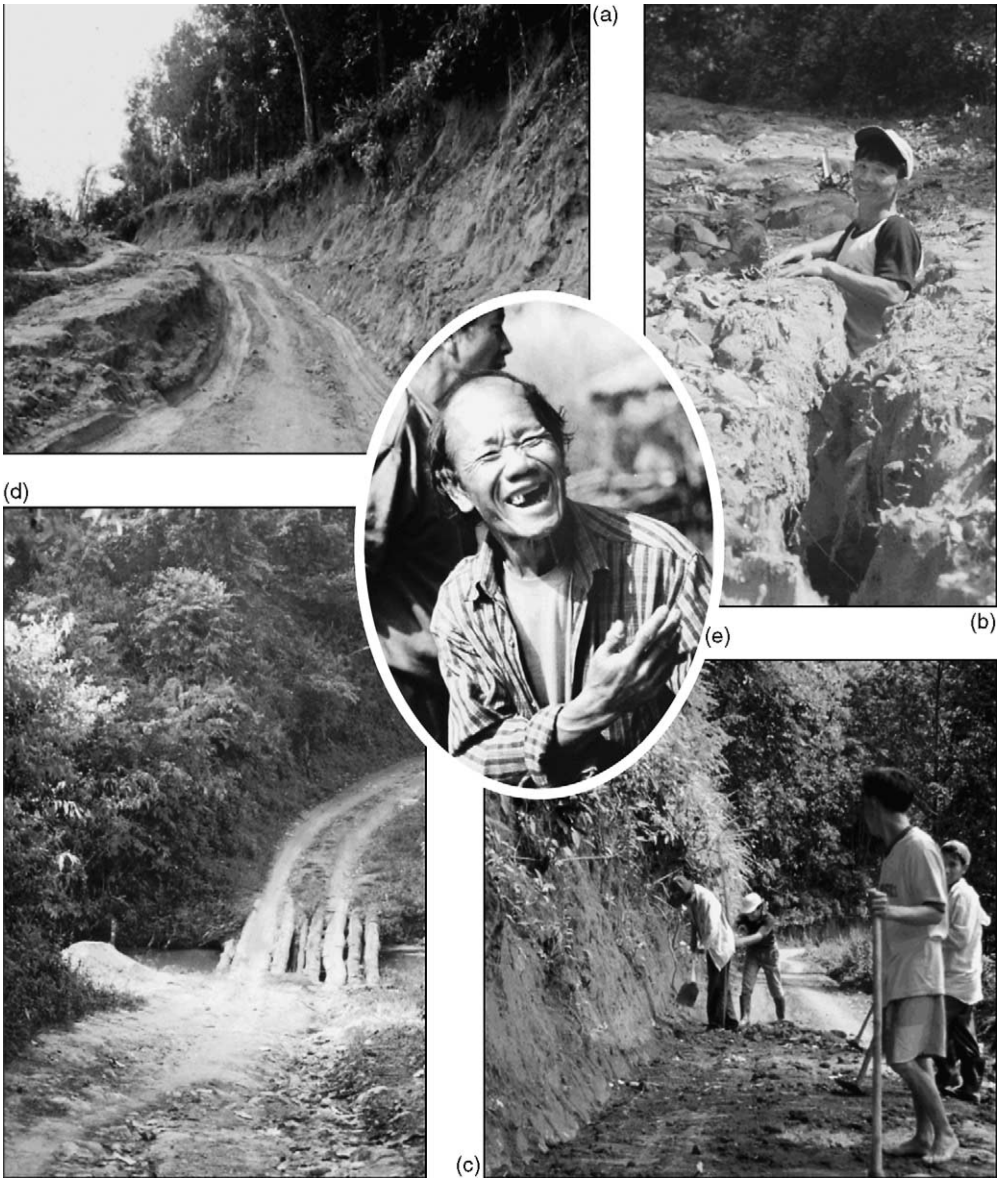

Fig. 1. Road features in northern Thailand: (a) unpaved mountain road near Pang Khum, an annual source of sediment to the stream system; (b) deep incision on the upper PKEW road (ca. 1998); (c) Pang Khum villagers repairing road ruts by filling with material taken from the cutslope; (d) typical low-water bridge where road runoff and sediment enters the stream; (e) Lisu man acknowledging that road impacts are no laughing matter.

Mountain roads in northern Thailand stand out at almost any scale as sources of sediment entering streams (Fig. 1a). Road runoff empties frequently into stream channels at low-water bridges or via culverts/gullies (Fig. 1d). During prior research in Thailand, we determined that the contribution of basin-wide excess rainfall during frequently occurring, small rainfall events was disproportionate to their area extent, compared with other common land surfaces (Ziegler and Giambelluca, 1997). Rijsdijk and Bruijnzeel (1991) showed similarly that roads in east Java (Indonesia), comprising roughly 3% of the catchment, contributed a disproportionate sediment volume to the basin yield. Studies in upland temperate basins have also shown road-related impacts can be greater than or equal to those of other disruptive activities (e.g. Megahan and Kidd, 1972; Grayson et al., 1993; Megahan and Ketcheson, 1996). One study, conducted in Chiang Mai Province of Thailand, determined forest 'destruction' to be less significant than road construction in increasing annual runoff yields (Pransutjarit, 1983).

Rural roads are important for the development of the northern highlands of Thailand. For example, they provide access to agricultural watersheds, allowing the transport of crops to markets. Mountain roads are vital to national security, especially in border areas; and they facilitate policing of drug trafficking. Because of the necessity of accessing remote mountain basins, road-associated environmental impacts are typically accepted by local inhabitants and governing officials alike. Lack of attention to road impacts may also reflect the paradigm of forest removal and unstable agricultural practices as the major disruptive activities in the region. On the other hand, it may also represent a lack of understanding, both in the nature of, and solution to, the problem. Another critical issue is determining who pays for improved road design and routine maintenance.

The literature reflects an increasing awareness of the need to address road-related impacts (e.g. Harr et al., 1975; Megahan and Clayton, 1983; King and Tennyson, 1984; Reid and Dunne, 1984; Anderson and Potts, 1987; Bilby et al., 1989; Fahey and Croker, 1989; Luce and Cundy, 1994; Montgomery, 1994; Jones and Grant, 1996; Wemple et al., 1996; Foltz and Elliot, 1997; Thomas and Megahan, 1998; Croke et al., 1999; Luce and Black, 1999; Croke and Mockler, 2001; La Marche and Lettenmaier, 2001). Only a few of these studies, however, have been conducted in SE Asia, where surface erosion on unpaved mountain roads can be severe during heavy rains of the annual monsoon rain seasons (e.g. Pransutjarit, 1983; Kamaruzaman and Nik, 1986; Malmer and Grip, 1990; Rijsdijk and Bruijnzeel, 1991; Van der Plas and Bruijnzeel, 1993; Ziegler et al., 2000b). In fairness, watershed managers in even the most developed countries in the world have yet to solve many of their road-associated environmental problems (cf. Gucinski et al., 2001).

In 1997, we began the Thailand Roads Project (TRP), a study of hydrological and geomorphologic impacts of unpaved mountain roads in northern Thailand. One object of TRP is ascertaining the relative impacts of roads versus agriculture practices in the highlands of northern Thailand. Although conducted in Thailand, results of the work contribute to understanding the environmental consequences of road-associated impacts in any geographical region. In this paper, we summarize the principal findings of TRP Phase I, which ended in May 2000.

2. Site description

The study area is near Pang Khum village (19°3′N, 98°39′E), which is located within the Samoeng district of Chiang Mai Province, approximately 60 km NNW of Chiang Mai in the eastern range of the Thanon Thongchai Mountains (Fig. 2a). Most work has been conducted in the adjacent 93.7 ha Pang Khum Experimental Watershed (PKEW; Fig. 2b), which is located in Mae Taeng District. PKEW is, therefore, part of the larger Mae Taeng River Basin, which drains into the Ping River, the major tributary to the Chao Praya (Thailand's largest river). Bedrock is largely granite. Soils are predominantly Ultisols of the Udic moisture regime. The area has a monsoon rainfall regime: the rainy season extends from mid-May through October, accounting for ≈90% of an annual total of 1200–1300 mm. Roads comprise 0.5% of the PKEW area; dwelling sites and paths another 0.5%. Approximately 12% of the basin area is agricultural land (cultivated, upland fields, and <1.5-year-old abandoned); 13%, fallow land (not used for 1.5–4 years); 31 and 12% are young (4–10 years) and advanced secondary

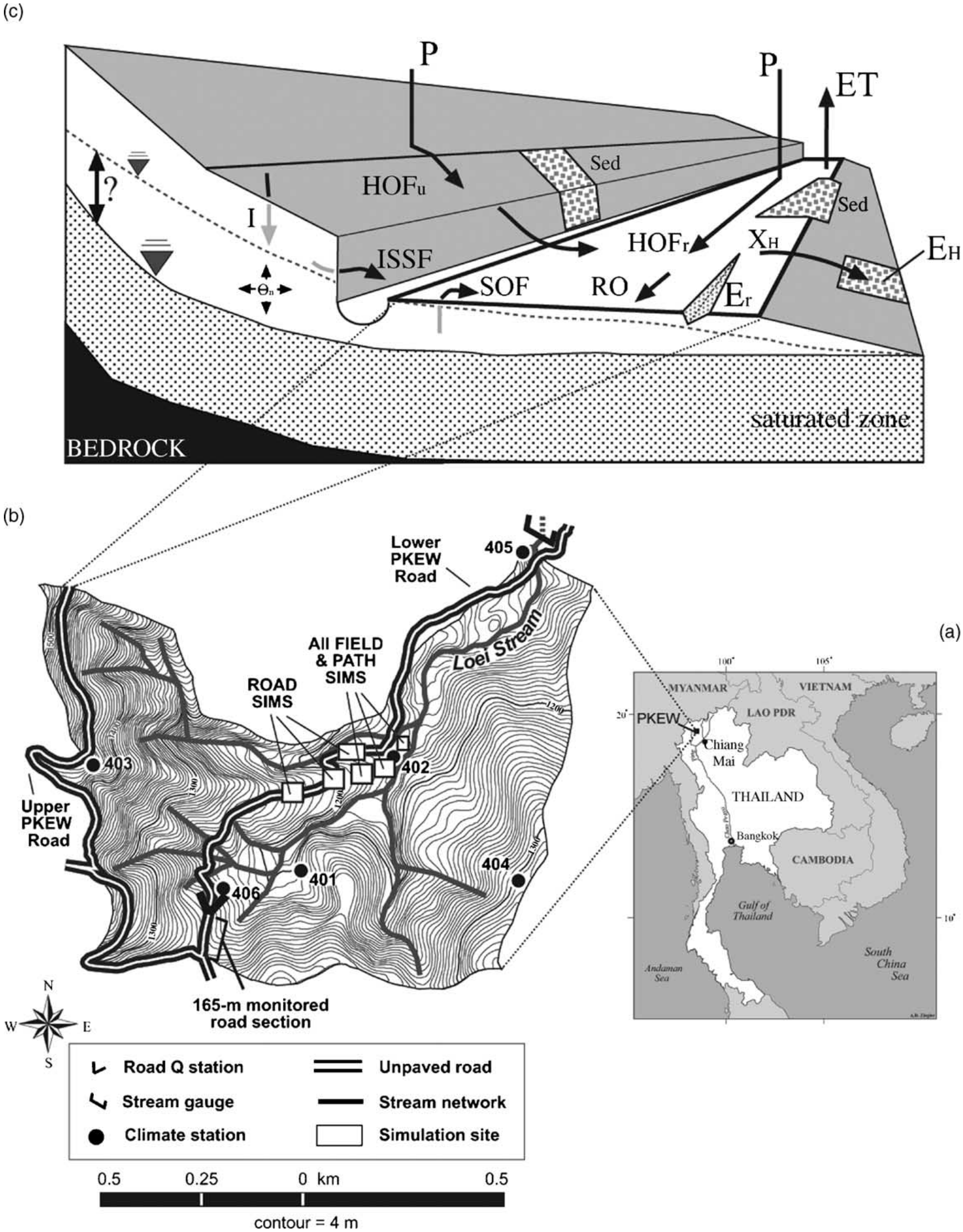

Fig. 2. (a) Pang Khum Experimental Watershed (PKEW) in northern Thailand; (b) experiment locations in the 93.7 ha PKEW; the climate network and simulation sites are explained briefly in Sections 4.2 and 4.3; (c) conceptualization of important processes operating on the three-dimensional road prism. Abbreviations are defined in Section 3.

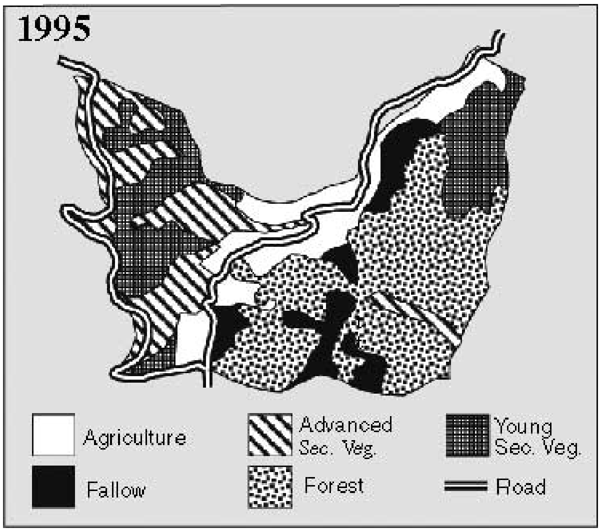

Fig. 3. Landcover distribution in PKEW for 1995 (based on 1:50,000 airphoto).

vegetation, respectively; and 31% is disturbed primary forest. A landcover map for 1995 is shown in Fig. 3.

The original pine-dominated forest has been altered by hundreds of years of timber removal and/or swidden cultivation by Karen, Hmong, and recently, Lisu ethnic groups. Some attempts have been made to regenerate degraded hillslopes by planting *Pinus kisiya* Roy. ex Gord. Additionally, *Castanopsis diversifolia* King ex Hk. f., *Glochidion sphaerogynum* (M.-A.) Kurz, *Helicia nilagirica* Bedd., *Phyllanthus emblica* L., *Schima wallichii* (DC.) Korth, and *Styrax benzoides* Craib are found commonly in secondary regrowth forests. In the disturbed primary forests, *Castanopsis tribuloides* (Sm.) A. DC., *Lithocarpus elegans* (Bl.) Hatus. ex Soep., *Phoebe lanceolata* (Nees) Nees, *Rhus chinensis* Mill., *Saurauia roxburghii* Wall., and *Wendlandia tinctoria* (Roxb.) CD. tinctoria are present. Understory vegetation in both primary and secondary forests commonly includes *Dioscorea glabra* Roxb. var. glabra, *Flemingia sootepensis* Craib., *Microstegium vagans* (Nees ex Steud.) A. Camus, *Panicum notatum* Retz., *Rubus ble-pharoneurus* Card., *Scleria lithosperma* (L.) Sw. var. lithosperma, *Setaria palmifolia* (Koen.) Stapf var. palmifolia, *Thelypteris subelata* (Bak.) K. Iw., and *Thunbergia similis* Craib.

Most lower basin slopes are cultivated by Lisu villagers who migrated to Pang Khum from Mae Hong Son Province 20–30 years ago. The farming system now resembles a long-term cultivation system with short fallow periods, as opposed to the traditional Lisu long-fallow system (Schmidt-Vogt, 1998). Annual swidden and permanent cultivation activities are similar to those of many groups in northern Thailand (Schmidt-Vogt, 1999). Opium was a prevalent crop before government eradication began in the 1980s. Upland rice and corn are important swidden-based crops; cabbage, cauliflower, onions, garlic, and flowers are representative cultivated crops.

3. Conceptual framework: the road prism

In Fig. 2c, we conceptualize the three-dimensional road prism. One common source of road runoff (RO) is Horton overland flow (HOF, rainfall rate in excess of infiltration rate and ponding, Horton, 1933). Horton flow can be prevalent on road surfaces (HOF_r) when compaction reduces the rate of infiltration (I). Saturated hydraulic conductivity (K_s) is often used as an index of infiltrability. In some instances, Horton flow entering from upslope surfaces (HOR_u) may increase total on-road overland flow. Compacted roadside margins are often common sources of HOF_u. Antecedent soil moisture (Θ_n) influences HOF generation, e.g. during wet versus dry conditions, a smaller depth of rainfall is required before the occurrence of saturation, then ponding. Road surface Θ_n is influenced, in part, by rainfall (P) and evaporation rate (ET).

Water table depth also affects Θ_n, and can, therefore, play a role in overland flow generation. For example, saturation overland flow (SOF) occurs when the water table rises above the road surface, such that additional inputs of rain water flow across the saturated surface. The broken line and double arrow in the figure signify variation in the water table height. Water may also exfiltrate onto the road surface when subsurface flow (SSF) paths are 'intercepted' by the cutbank (ISSF). This process is most common where soils are shallow. In the case of deep soils, ISSF may be rare because the soil–bedrock interface can occur well below the road surface, even when cutbanks are deep.

With respect to road erosion, sediment detachment/transport is controlled to some extent by rill and interrill erosion processes that operate on agriculture lands. In the absence of gully formation and mass wasting, these processes are functions of (i) dynamic storm-related phenomena, including precipitation rate and overland flow conditions (e.g. flow depth and velocity); (ii) soil surface erodibility. In general, the compacted road surface is somewhat resilient to sediment detachment by rain splash and flowing water. With respect to the latter, as downslope travel distance increases hydraulic erosion becomes more likely as overland flow depth and velocity increases. After exceeding some critical threshold of soil shear strength, the flowing water erodes the compacted road surface (E_r)—incision is often initiated in existing ruts or tire tracks (Fig. 1b). In addition, sediment concentration in road runoff is enhanced by the transport of loose material originating from on- and off-road sediment sources (Sed). Road runoff may exit the road at locations where the road and stream intersect, representing a direct linkage between the two (Fig. 1d). At locations where runoff exits onto the adjacent hillslope (X_H), the flowing water will infiltrate, initiate incision (E_H), or a combination of both. In severe cases of incision, gullies may extend to the stream channel, forming a partial or direct linkage between road and stream.

4. Methods

4.1. Field data

To gather information needed to quantify road- and agriculture-associated impacts in PKEW, we performed the following:

1. Hydrological and physical measurements, such as saturated hydraulic conductivity (via disk permeameters), bulk density (BD), penetration resistance (PR), and texture at several locations on PKEW roads and all other important land covers.
2. Bedload and suspended sediment measurements in Loei stream at the basin outlet (Station 405, Fig. 2b).
3. Assessments of cross-sectional physical characteristics at 50 m intervals on the upper and lower PKEW roads; measurements during both wet and dry seasons included road width, surface condition (e.g. track versus non-track), two-dimensional slope, lowering estimates, rut/gully dimensions, and available sediment depth.
4. Inventories of road sediment sources, overland flow pathways, and overland flow entry/exit points on all PKEW roads.
5. Usage survey (225 h spanning 44 days), during which vehicle passes were recorded, noting the type of vehicle, road and weather conditions, and presence/absence of tire chains.

4.2. Climatological network

We installed a climatological network consisting of six stations (Fig. 2b) that allow estimation of the basin water balance variables with a high degree of spatial detail. Stations 401 and 402 record meteorological data required to model latent and sensible heat fluxes over heterogeneous land surfaces. Station 401 sensors are installed above the canopy of 20 m degraded primary forest stand (Fig. 4b); station 402 is within an upland swidden field (Fig. 4a). Instruments at stations 403 and 404 measure rainfall and soil moisture on secondary vegetation landcovers. Station 405 monitors streamflow (by recording stage behind a 3 m wide broad-crested weir) and rainfall at the basin outlet. Station 406, situated across the road near the entrance of the watershed (Fig. 2b), is designed to monitor rainfall and road surface soil moisture, thereby allowing us to prescribe pre-event soil wetness for modeling.

4.3. Rainfall-runoff simulation experiments

During the 1998 and 1999 dry seasons we conducted five suites of rainfall simulations (a total of more than 100 events) to determine: (1) runoff generation and sediment transport responses for roads, paths, and several agricultural land surfaces (e.g. active and fallow fields); (2) how to partition total erosion into splash and hydraulic components; (3) the contribution of vehicular activity and road maintenance to sediment production on roads. Simulation locations are shown in Fig. 2b. Rainfall simulations were conducted for 45–60 min on small-scale plots (ranging from 3.0 to 3.4 m^2). Simulations had rainfall energy flux densities (EFDs) of 1650–2050 $J\,m^{-2}\,h^{-1}$, approximating energies sustained for 10–20 min during the largest annual PKEW storms. The rainfall simulator and a typical plot design are shown in Fig. 4d; they

Fig. 4. (a) Climate station 402, in an upland rice field (see Fig. 2b for station location); (b) climate station 401, above the canopy of a 20 m disturbed primary forest; (c) flume at the road collection station near Station 406; (d) rainfall simulator and plot layout on an upland field, ca. 1998; (e) Lisu girl collecting water.

are described in detail elsewhere (e.g. Ziegler et al., 2000a,b, 2001a,b). To understand differences between processes observed during small-scale rainfall simulations and hillslope-scale phenomena during natural events, we constructed a road runoff collection station at the foot of a 165 m sloping road near Station 406 (Fig. 4c).

5. Results

Unpaved roads in PKEW are on the same order of importance as agricultural surfaces in contributing surface runoff and sediment to the stream. The relative contributions of road and agricultural fields to basin-wide HOF during the largest observed storm

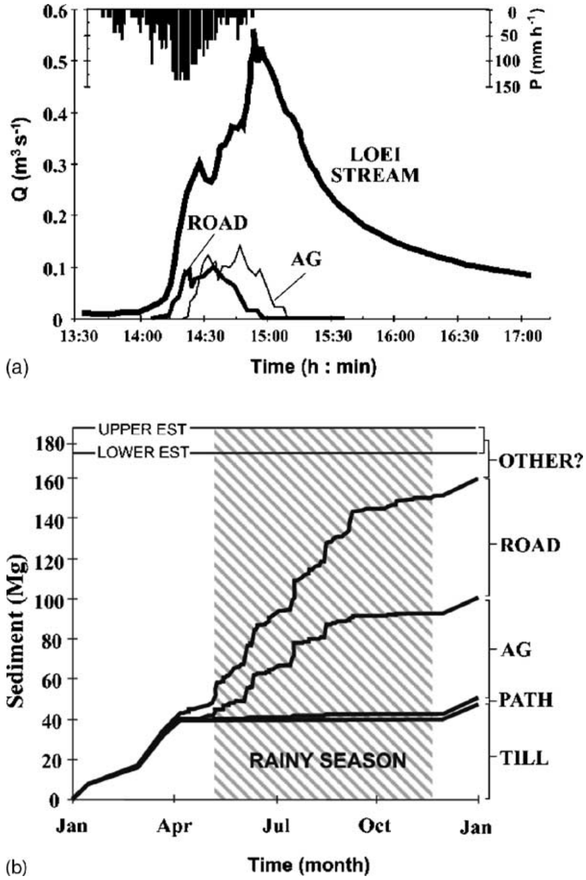

Fig. 5. (a) The contribution of HOF from PKEW roads and agricultural fields to the Loei Stream storm hydrograph during the largest storm of 1998; (b) the 1998 partial sediment budget for sediment entering the stream via HOF from roads (ROAD), agricultural fields (AG), and path/dwelling sites (PATH). TILL represents the contribution from dry-season tillage erosion. Stream bank and channel erosion contribute to the OTHER? category. The values are cumulative over the dry and rainy seasons; and the contribution from each source is represented as the distance between any two curves. The estimated total for Loei Stream is 175–190 Mg (upper and lower estimates are shown).

can be seen in Fig. 5a. Total rainfall is about 58 mm, with most falling during the first 30 min after runoff initiation on the road. Mean 1 min rainfall intensity during this period is 89 mm h^{-1}; the maximum 1 min intensity is 137 mm h^{-1}. During the first 1–2 h following runoff initiation, HOF from the road alone comprises approximately 10% of the stormflow hydrograph. While the response from the roads occurs sooner than that of agricultural lands, the magnitude is similar despite roads occupying a very small fraction of the area (≈0.5% versus 12%). This finding is in agreement with our prior work in Kae Noi, Thailand, and the general area surrounding PKEW (Ziegler and Giambelluca, 1997).

With respect to sediment delivery to the stream, the partial budget in Fig. 5b shows nearly equivalent contributions coming from roads and agricultural fields via HOF during rainstorms (59 and 50 Mg, respectively). We estimate that a third nearly equivalent proportion enters the stream via dry mechanical/tillage erosion (47 Mg; ADZ, unpublished data), and that a small HOF-related portion originates on basin access paths and dwelling sites (<5 Mg). Our total estimated annual sediment volume is 175–190 Mg, for which the residual portion contributed by stream channel/bank erosion is approximately 15–30 Mg. These estimates are for the year 1998; and they are revised from those reported in Ziegler et al. (2002a). In agreement with the runoff data (for which the response in Fig. 5a is just one example), roads contribute sediment to the stream at a rate that is disproportionate to their surfaces area. The cumulative values shown in Fig. 5b equate to sediment delivery rates of roughly 120 and 9 Mg ha^{-1} per year for roads and agricultural fields (HOF + tillage erosion), respectively.

In the following sections, we describe some of the various phenomena that allow roads to contribute disproportionately to runoff and sediment delivery to the stream.

5.1. Propensity for generating HOF

Compared with agricultural surfaces, HOF generation on unpaved roads in PKEW is accelerated because of reduced K_s (Table 1). Road K_s is low because compaction reduces total porosity (particularly macro-porosity) and alters pore connectivity for several centimeters below the surface. Road surfaces can additionally form a low-permeability seal through the filling of pores and subsequent packing during subsequent vehicle passes. Bulk density and penetration resistance, indices of compaction and sealing, are shown in Fig. 6 to be correlated negatively with time to runoff (TTRO) generation during the rainfall simulations. In general, highly compacted surfaces and surfaces with detectable 'seals' generate HOF faster than adjacent surfaces that are not disturbed as such.

Table 1
Mean compaction- and infiltration-related variables for the six simulation surfaces

Treatment	TTRO (min)	BD ($Mg\,m^{-3}$)	PR (MPa)	K_s ($mm\,h^{-1}$)
Road	1.1 ± 0.3 (8) a	1.45 ± 0.13 (74) b	6.4 ± 0.4 (160) d	15 ± 9 (26) a
Access path	12.1 ± 3.5 (3) b	1.40 ± 0.11 (21) b	6.4 ± 0.7 (90) d	8 ± 5 (6) a
Field path	34.1 ± 12.8 (4) c	1.24 ± 0.11 (22) a	2.8 ± 1.1 (40) b	244 ± 88 (10) b
Upland field	26.5 ± 4.4 (4) c	1.20 ± 0.09 (36) a	4.7 ± 1.4 (98) c	133 ± 77 (6) b
Hoed field	>57.8 (4)*	1.19 ± 0.06 (22) a	1.8 ± 1.2 (40) a	316 ± 129 (10) b
Fallow field	>60 (4)*	1.11 ± 0.05 (6) a	1.7 ± 0.9 (60) a	129 ± 38 (6) b

TTRO: time to runoff; BD: bulk density; PR: penetration resistance; K_s: saturated hydraulic conductivity; values are ±1 S.D.; values in parentheses are simulation replications or sample sizes; values in each column with the same letter are not statistically different (one-way analysis of variance (ANOVA) on $\log_{10}$-transformed data, followed by post hoc multiple comparison testing with the Bonferroni/Dunn test (B–D) when the F-values were significant at 0.05).

* Only one of four Hoed field events produced runoff; none of the four simulations on advanced fallow fields produced runoff.

Also shown in Fig. 6 is the positive association between K_s and TTRO, i.e. the higher the K_s, the more water that is infiltrated before runoff generation.

Owing to reduced K_s on roads, HOF can be initiated for low rainfall intensities and small depths. For example, during the 1998 rainy season, 41% of the 2 min rainfall intensities exceeded the road K_s value of 15 $mm\,h^{-1}$, demonstrating the high frequency of potential HOF-producing rainfall. During the wet season when surface soil moisture is relatively high, HOF is generated typically within a few minutes of the onset of a rain shower. In contrast, runoff initiation on agriculture lands is slower, in part because of higher K_s, but also because surface roughness allows a greater ponding depth. The propensity of roads to generate HOF is apparent in the runoff response patterns during rainfall simulation (Fig. 7a). In contrast with agricultural fields that can infiltrate large rainfall depths, HOF is initiated on roads early in an event. Thus, event runoff coefficients (ROC, the percentage of rainfall that becomes runoff) are high (≥80%).

We believe HOF is the principal runoff generation mechanism on PKEW roads (Ziegler et al., 2001c). Small contributions of SOF may occur near locations where the road intersects the stream (e.g. below Station 406, Fig. 2b), but this type of road-associated overland flow quickly exits before contributing to surface erosion. To date, we have not observed ISSF, despite conducting complementary hydrometric (e.g. piezometers and arrays of moisture probes) and tracer tests (e.g. $\delta^{18}O$) to verify its existence. Non-existence of ISSF means that HOF alone is capable of creating the hydrological and geomorphologic impacts (change in storm flow response, road surface erosion,

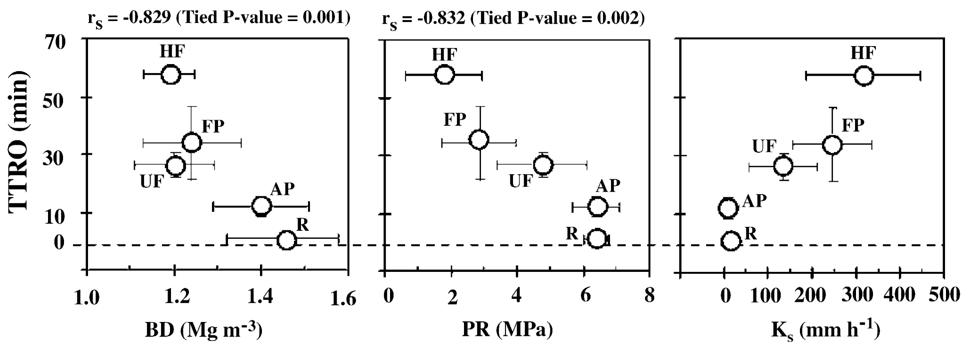

Fig. 6. Relationship between time to runoff (TTRO) during rainfall simulation experiments and bulk density (BD), penetration resistance (PR), and saturated hydraulic conductivity (K_s). Open circles are means; error bars are ±1 S.D. The Spearman rank correlation coefficient (r_s) is determined for variables measured inside the simulation plots; r_s is not available for K_s, which was measured in the general vicinity of the experiments. R, AP, UF, FP, and HF refer to road, access path, upland field, field path, and hoed field surfaces, respectively. Data are from Ziegler et al. (2000b).

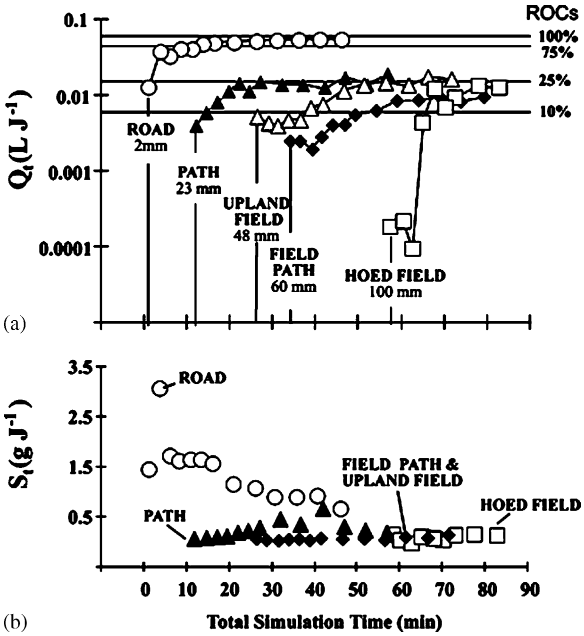

Fig. 7. (a) Energy-normalized instantaneous discharge (Q_t), runoff coefficients (ROCs,%), and rainfall depth (mm) before runoff generation for several land-use types in PKEW during rainfall simulations; (b) normalized sediment output (S_t) during the same simulations. Data and simulation experiments are described in detail elsewhere (Ziegler et al., 2000b).

sediment delivery to the stream) that we are observing in PKEW. If ISSF were to occur, we would expect the road-related impacts to be more pronounced.

5.2. Removal of loose surface material

Road surface sediment is mobilized by overland flow during most rain events. On simulation plots, road sediment transport is characterized by an initial flush occurring soon after runoff initiation (Ziegler et al., 2000a, 2002b). This response is shown in the data from the rainfall simulations (Fig. 7b). The gradual decline in material transported following the flush results because easily entrained material is depleted quickly. Thereafter, sediment transport is limited by the detachment of new material, which is a function of the erodibility of the compacted road surface. If rill incision occurs, sediment transport will again increase. In the absence of incision, however, sediment output will typically remain low because the compacted road surface is resilient to both raindrop detachment and hydraulic erosion (compared with the loose layer of surface material). Sediment output on agricultural plots under similar experimental conditions is usually different, principally because surface erodibility on agriculture surfaces is much higher than that for compacted roads. Thus, rain splash and hydraulic erosion (once overland flow is generated) are capable of detaching new material throughout the duration of a long, high-energy event. A flushing effect is possible, but sediment output is likely to build over time, rather than decrease, as is the case on unpaved roads after the initial flush.

At the hillslope-scale and during natural rainfall, the observed sediment output response on roads may appear different than that seen on erosion plots. It is our belief, however, that the same processes are operating. For example, loose surface material is mobilized early in an event. The flushing effect and gradual decline may not be obvious because of several inter-related phenomena: (1) in contrast with controlled rainfall simulation experiments, rainfall intensity varies throughout a natural event; (2) there is an inherent lag in travel time of runoff and sediment down the hillslope—such that the lowest slope areas are depleted of loose material first; (3) the rainfall event may end before all loose material is transported downslope; (4) during large storms, rill incision is likely to occur (again before all loose material is removed), masking the fact that the loose material was removed initially. What is observed typically is a series of flushes of material, initiated in response to bursts of rainfall and the arrival of waves of runoff from upslope. The only detectable decline in sediment output may be related to a decline in precipitation, which causes overland flow to decrease. As the volume of runoff decreases, the transport capacity of flowing water decreases. Entrained sediment is subsequently deposited into surface depressions, where it becomes part of the supply of loose, easily eroded sediment during the next storm.

The physical nature of the road surface tends to favor the movement of detached material. For example, smooth sections offer little resistance to facilitate particle settling. At the other extreme, incised channels concentrate runoff, acting as conduits to funnel water and sediment efficiently downslope. In some instances, sediment settles in surface depressions down slope of knickpoints; however, these stores can be flushed during large seasonal events. The key point here is that regardless of the physical nature of a road surface, some depth of loose sediment is mobilized during nearly all rainfall events.

5.3. Continual sediment preparation

The supply of the loose material on the road surface is refreshed constantly by many phenomena, including traffic, road repairs, cut-bank failure, and overland flow (Ziegler et al., 2001b). Thus, sediment production is dynamic, varying both on inter- and intra-storm scales. For example, sediment production is correlated positively with traffic volume. Vehicle passes between storms detach road surface material, much of which is deposited on the road surface where it can be entrained by overland flow. Within rainfall events, vehicle passes generate large sediment volumes under the following circumstances: (1) great effort is required to ascend steep hills when roads are wet/slippery; (2) tire chains are used; (3) the vehicles are heavy (e.g. 4–6 Mg dump trucks); (4) tire depressions/tracks are incised immediately by overland flow (e.g. during very wet conditions). Even on relatively flat surfaces, vehicle passes during storms can accelerate sediment transport for several minutes (as shown in Fig. 8).

During the rainy season, road repairs in PKEW are typically geared toward filling ruts to allow immediate passage. At the end of the rainy season, villagers will typically make a more comprehensive repair—one that will make the road usable for several months. Both temporary and seasonal repairs involve filling ruts with material taken from the cutslope (Fig. 1c). Nearly all repairs are made with hand tools; compaction of the fill material occurs with subsequent vehicle passes. In many cases, the fill material remains on the road surface only until the next overland flow event. The cutslope is also an important source of sediment to the road surface: e.g. as small-scale creep, dry ravel, or when the cutslope is disturbed by other activities, such as cattle trampling or digging by local people gathering plants and insects. Finally, overland flow itself plays a crucial role in a continual process of mobilizing, depositing, and remobilizing surface material until it exits the road.

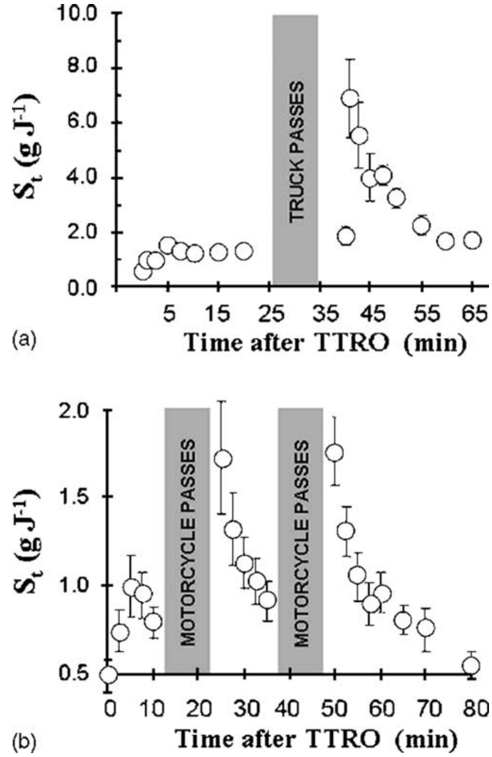

Fig. 8. Elevation in sediment output on rainfall simulation plots following the passage of 'waves' of (a) trucks (two passes of an Isuzu Rodeo, four total tires) and (b) motorcycles (total of four passes). Passes were made during a break in simulated rainfall, followed by more simulated rain. Error bars are ±1 S.D. about the mean ($n = 8$ and 4 for the motorcycle and truck simulations, respectively). Data and simulation experiments are described in detail elsewhere (Ziegler et al., 2001b).

5.4. High conveyance of runoff and sediment to the stream

A final characteristic that contributes to a disproportionate runoff and sediment response from unpaved roads is the efficient transport of overland flow to the stream. The flow pathway influences the timing and contribution of runoff to the basin storm hydrograph, the amount of surface erosion that occurs before the water exits the road, and the delivery of entrained sediment into the stream. The distance that road runoff travels is determined primarily by topography, slope, and location of exit points. With respect to the latter, exit points are not static because flowpaths are changed by erosion, maintenance (including the creation of overland flow diversions), and mass wasting events. Approximately 85% of the lower PKEW road drains directly into the stream at low-water bridges or road/stream intersections. In some instances, runoff may stay on the road surface for 100–200 m before exiting. The other 15% is partially connected with the stream, i.e. runoff exits onto hillslopes, where it flows into rice paddies, banana patches, or other wetland features that are connected to the stream system. A final consideration here is that roads convey runoff to the stream system even during small events when HOF is not initiated on other surfaces. With this in mind, we can put the storm contributions shown in Fig. 5a into perspective. During this large event, we show near-equivalent proportions of HOF coming from roads and agriculture fields. The ratio of agriculture HOF to road HOF is higher than would be expected for smaller, more frequent annual storms. In those events, the road proportion would be greater because relatively high runoff coefficients are maintained in part by the direct conveyance of runoff to the stream.

5.5. Relative importance of roads versus other land surfaces

Various non-road surfaces do indeed contribute to basin-wide hydrological and geomorphological impacts. For example, substantial soil erosion occurs on many vegetated hillslopes, including those within disturbed forests. Grazing (cattle and water buffalo) and recurrent dry season fires thin under-story vegetation, thereby exposing the soil surface to rain drop impact once the rainy season commences. Much of the sediment eroded from such grazing/fire-affected surfaces, however, is redeposited on the hillslope below, rather than transported to the stream. Compacted path surfaces, like roads, generate erosion-producing HOF during most rain events (Ziegler et al., 2001a). Both the rainfall simulation data and the runoff-compaction indices shown above reveal a similarity between roads and paths in terms of hydrologic response. This is particularly true for basin access paths, on which our measured K_s is lower than that for the road (Table 1). The total length of discernible basin paths is approximately 6100 m (2000 survey), but this value expands and contracts yearly by at least 20%, depending on the usage of remote fields. Although path and dwelling site area is equivalent to that of roads, these surfaces are typically not linked directly with the stream system. Most runoff from these surfaces exits onto the adjacent hillslope where it is infiltrated. Thus, the inherent direct linkage between road and stream networks is a key factor escalating the impact roads have on basin hydrology and geomorphology.

6. Conclusion

Compared with other land surfaces, roads contribute disproportionately to the basin runoff and sediment yield in PKEW because (1) infiltration is reduced by compaction; therefore, roads have the propensity to generate HOF during most rain events; (2) sediment production on roads is high because easily-removed material is re-supplied by inter- and intra-storm phenomena (including vehicular detachment, road repairs, and cutbank failure); (3) runoff on most road sections drains directly into the stream channel at low-water bridges or locations where the road and ephemeral channels intersect. Delivery of road-related runoff and sediment to the stream network, however, is variable because flow paths change as rut systems are created (e.g. via rill incision, mass wasting) and destroyed (e.g. via maintenance). Our results reveal several keys to minimizing road-related sediment input to the stream: (1) limiting total road length; (2) minimizing road building on steep slopes; (3) minimizing the detachment of sediment by vehicles; (4) improving repair methods; (5) reducing conveyance efficiencies of road overland flow to the stream network.

The preliminary findings reported here do not yet constitute a complete assessment of road versus agriculture impacts in PKEW. Incorporating knowledge of all forms of degradation is important to understanding the overall relevance of road-associated impacts. A complete inventory of hydrologic response and sediment loss on all basin land surfaces, disturbed and undisturbed alike, must be attempted. In this sense, a true picture cannot be drawn simply by looking at basin sediment yield and stream flow records. Substantial degradation can be occurring on some hillslopes, but the effects may not be obvious at the basin scale because of storage (e.g. eroded sediment) and buffering (e.g. runoff) within the basin. Only by investigating the underlying processes at various spatio-temporal scales can meaningful assessments be made. This is our objective in TRP Phase II.

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