

Thailand Roads Project: Overview and Initial Findings

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Abstract: Through fieldwork in northern Thailand we have been working toward a realistic assessment of hydrological and geomorphological impacts of roads in mountainous tropical watersheds. Findings from field rainfall simulations, surveys of road and traffic phenomena, and computer simulations are presented. Because roads generate Horton overland flow (HOF) during most rain events, they transport sediment into the stream system throughout the rainy season. The linking road sections via rut and gully systems allow them to transport runoff generated in one watershed into adjacent basins, where it may contribute to hydrological and erosional impacts. Footpaths, like roads, accelerate runoff, and may enhance in-field erosion by acting as source areas for surface runoff. Vehicle detachment and maintenance activities during interstorm periods increase the volume of loose material that can be removed by overland flow during subsequent rainstorms. Road sediment transport is simulated best when the surface layer of loose sediment is explicitly modeled. This research serves as a foundation for future work aimed at quantifying road and agricultural contributions to cumulative watershed effects in SE Asia.

Keywords: unpaved roads, erosion modeling, Thailand, land degradation, tropical hydrology/geomorphology

1. Introduction

Intensification of swidden agriculture in mountainous northern Thailand over the last few decades has contributed to hydrologic change and sedimentation in major river systems, including the Chao Praya. In response, domestic and international conservation projects have often focused on improving perceived detrimental agricultural practices of ethnic minority (hilltribe) groups living in highland watersheds. This attention has helped foster a general perception that unwise agricultural practices of ethnic minorities are the predominant cause of lowland water shortages, more frequent flooding, and excessive sedimentation. While improper cultivation techniques on steep slopes are certainly responsible for serious downstream effects in some areas, expansion of the rural road network may be equally or more important. Studies in the North American Pacific Northwest region and Australia have demonstrated that road-related impacts can be greater than those of other known disruptive watershed activities (e.g., Megahan and Kidd, 1972; Grayson et al., 1993; Megahan and Ketcheson, 1996).

In northern Thailand, where road systems have been rapidly expanding over the last 20 years, road-related environmental impacts have generally been overlooked by conservation projects. Lack of attention may simply reflect the paradigm of agricultural practices as the major disruptive activities. While, recent studies have advanced understanding of road impacts in temperate regions (e.g., Megahan, 1974; Reid and Dunne, 1984; Jones and Grant, 1996, Megahan and Ketcheson, 1996; Bowling and Lettenmaier, 1997; Foltz and Elliot, 1997; La Marche and Lettenmaier, 1998; Thomas and

Megahan, 1998; Wemple, 1998; Black and Luce, 1999; Ketcheson et al., 1999; Luce and Black, 1999), comparatively few studies have addressed this issue in SE Asia (e.g., Pransutjarit, 1983; Malmer and Grip, 1990; Rijdsdijk and Bruijnzeel, 1991; Van der Plas and Bruijnzeel, 1993). Our prior research in northern Thailand showed that unpaved rural roads can be disproportionately disruptive to watershed hydrological response, compared with other lands (Ziegler and Giambelluca, 1997a, b). Our current research involves both field work and physically based computer model simulations geared toward quantifying hydrological and erosional impacts resulting from the expansion of road networks. In this paper, we describe the research and report initial findings.

2. Background

2.1 The Thailand Roads Project

In 1997 we began conducting the Thailand Roads Project (TRP), a study of hydrological and geomorphological impacts of unpaved roads, near Pang Khum village (19°3'N, 98°39'E) in northern Thailand (Figure 1A). Pang Khum is located within the Samoeng District of Chiang Mai Province, about 60 km NNW of Chiang Mai, Thailand in the eastern range of the Thanon Thongchai Mountains. Objectives of TRP were to (1) obtain a detailed understanding of erosion processes operating on and adjacent to road surfaces; (2) quantify erosional and hydrologic impacts associated with the expansion of road networks; and (3) evaluate the conservation value of several road management-related scenarios.

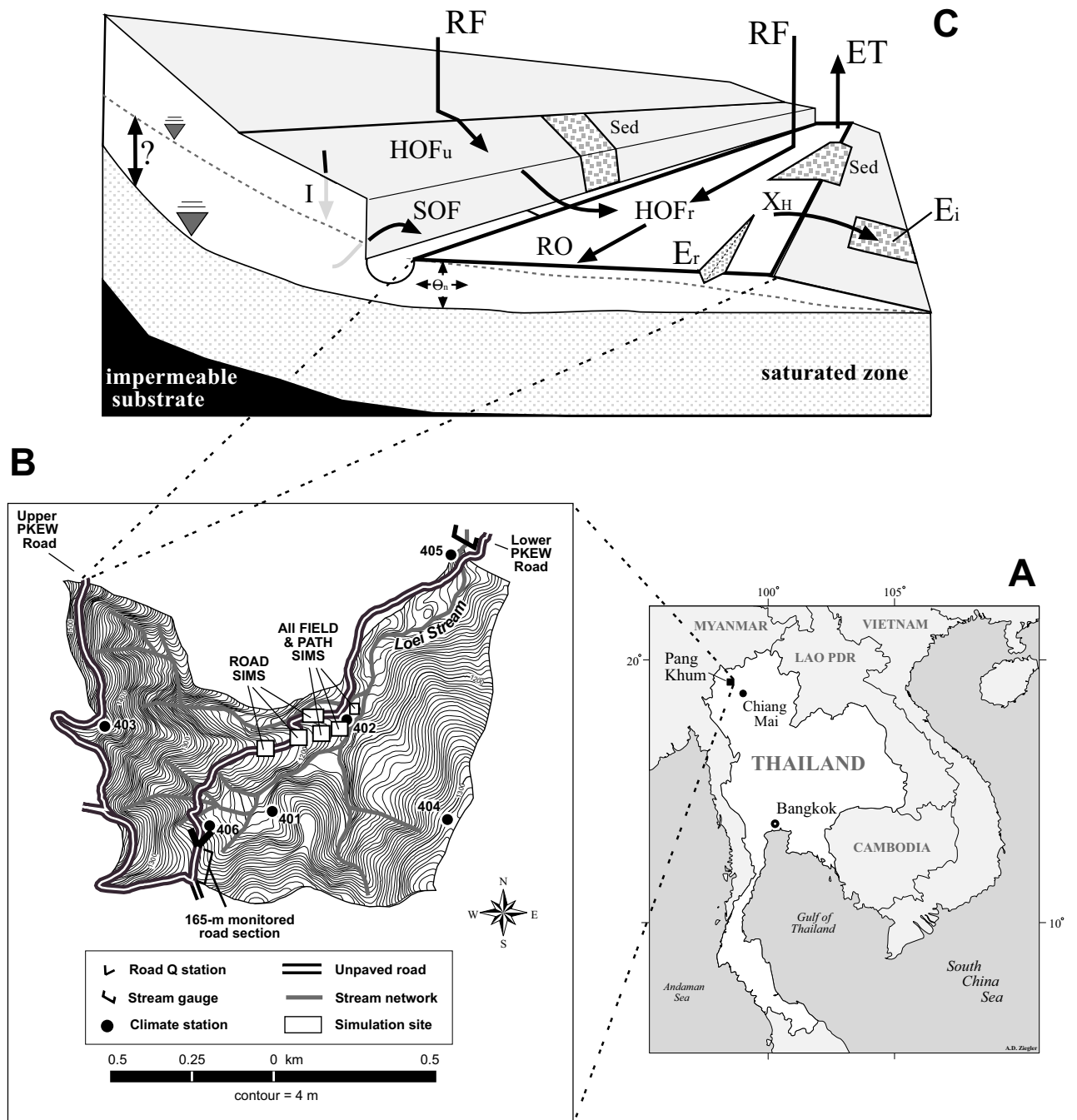


Figure 1. (A) Research site near Pang Khum Village in northern Thailand; (B) the 93.7-ha Pang Khum Experimental Watershed (PKEW); (C) hydrological and erosional processes operating on the 3-dimensional road prism.

2.2 Pang Khum Experimental Watershed

Most TRP field work has been conducted in the 93.7-ha Pang Khum Experimental Watershed (PKEW; Figure 1B). PKEW is part of the larger Khan River Basin that drains into the Ping River, which in turn empties into the Chao Praya River. Bedrock in PKEW is Triassic granite; soils include ultisols, alfisols, and inceptisols (field survey). Roads, access paths, and dwelling sites each comprise < 1% of the PKEW area. Approximately 12% of the basin area is agricultural land (cultivated and upland fields; and < 1.5 year-old abandoned fields); 13% is fallow land (i.e., not used for 1.5-4 years); 31 and 12% are young (4-10 years) and advanced (>10 years) secondary vegetation, respectively; and 31% is disturbed, primary forest.

The original pine-dominated forest has been altered by hundreds of years of swidden cultivation by Karen, Hmong, and, recently, Lisu ethnic groups. Some attempts have been made to regenerate deforested areas by planting *Pinus kisiya* Roy. ex Gord. A more complete vegetation description is given elsewhere (Ziegler, 2000). Most lower basin slopes are cultivated by Lisu villagers who migrated to Pang Khum from Mae Hong Son Province 20-25 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). Upland rice and corn are important swidden crops; cabbage, cauliflower, onions, garlic, and flowers comprise the cultivated crops. Opium was a prevalent crop before government eradication began about 15 years ago.

3. Methods

3.1 Traffic survey and physical property measurements

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

1. A 225-h survey of vehicle usage was conducted over 44 days. During each survey session (usually 4 to 5 h beginning at an arbitrary time of day), vehicle passes were recorded, noting the type of vehicle, road and weather conditions, and presence/absence of tire chains.
2. Assessments of cross-sectional physical characteristics were made 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 vs. nontrack), two-dimensional slope, lowering estimates, rut/gully dimensions, and available sediment.
3. An inventory of road sediment sources, overland flow pathways, and overland flow entry/exit points was taken on all PKEW roads (Figure 2B,D,E).

4. Hydrological and physical measurements, such as saturated hydraulic conductivity (K_s), bulk density (BD), penetration resistance (PR, via Lang penetrometer), and texture, were made at several locations on PKEW roads and other land-use types (Ziegler et al., 2000).

3.2 Climatological network in PKEW

In 1997 we installed a network of six climatological stations (Figure 1B) that allow monitoring of basin water balance with a high degree of spatial detail and provide data for calibrating, validating, and forcing the physically based KINEROS2 model (Smith et al., 1999) for simulating road runoff and erosion. Stations 401 and 402 record detailed meteorological data required to model latent and sensible heat fluxes over heterogeneous land surfaces. Station 401 sensors are installed above the canopy of 17-m degraded primary forest stand; station 402 is over an upland swidden field (Figure 2C). Stations 403 and 404 measure rainfall and soil moisture. Station 405 monitors streamflow (by recording stage behind a 3-m-wide broad-crested weir) and rainfall at the mouth of the watershed. Station 406, situated across the road near the entrance of the watershed, is designed to monitor rainfall and road surface soil moisture, thereby allowing us to prescribe pre-event soil wetness for modeling.

3.3 Rainfall simulation experiments

In 1998 and 1999 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-surface types; (2) how to partition total erosion into splash and hydraulic components, which are needed to model road erosion with KINEROS2; and (3) the contribution of vehicular activity and road maintenance to sediment production on roads. Rainfall simulations were conducted for 45-60 min on small-scale plots (ranging from 3.0-3.4 m²). Simulations had rainfall energy flux densities (EFDs) of 1650 to 2050 J m⁻² h⁻¹, approximating energies sustained for 10-20 min during the largest annual PKEW storms (based on preliminary analysis of 2 years of rainfall data). The rainfall simulator and plot design are shown in Figure 2A and are described elsewhere (Ziegler et al., 2000; in press a,b,c). To compare ROAD simulation data with discharge and sediment transport data from natural runoff events on PKEW road sections, we constructed a discharge collection station at the foot of a 165-m sloping road near station 406 (described in Ziegler et al., 2000).

4. Results

4.1 The road prism

Observations have led us to focus on the entire three-dimensional “road prism”, because runoff generation, and

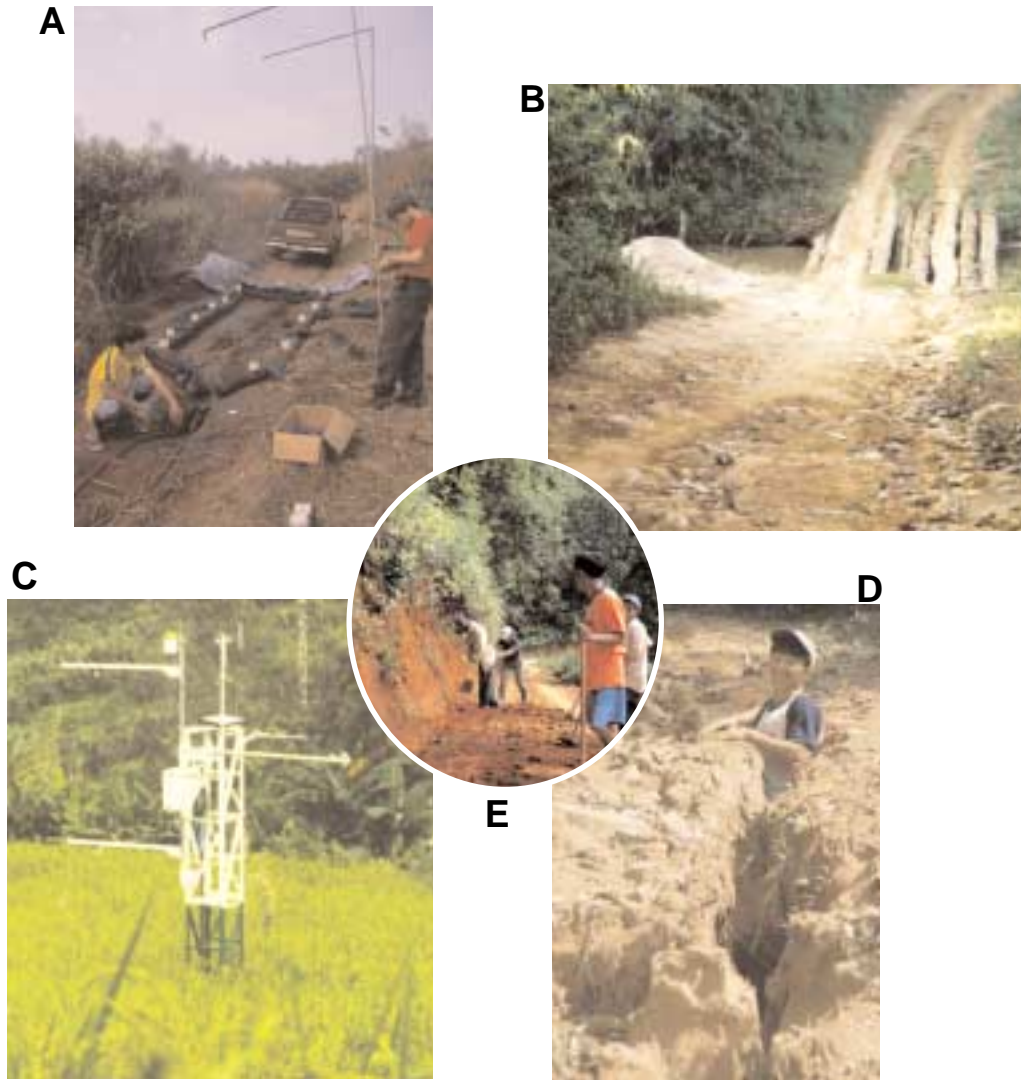


Figure 2. (A) the rainfall simulator and plot during one of the road rainfall simulations, 1998; (B) termination of a road section at a stream crossing; (C) climate station 402 within an upland rice field in PKEW; (D) a deep gully on the upper PKEW road; (E) road maintenance during inter-storm periods is one source of loose surface material.

subsequently, sediment transport, are affected by both surface and subsurface processes. Figure 1C gives a diagram of the road prism that serves as the basis for the following definitions. One common source of road surface runoff (RO) is Horton overland flow. Because road surface infiltration rates are usually very low (owing to compaction), Horton flow is generated quickly on road surfaces (HOF_r) even during relatively low-magnitude rainfall events (Ziegler and Giambelluca., 1997a). In some instances, Horton flow generated on adjacent surfaces (HOR_n) may flow onto the road, increasing total on-road overland flow. Antecedent soil moisture content (Θ_n) also

governs HOF generation: e.g., time to runoff (TTRO) is shorter on a wet road compared with the same road under dry conditions. Road surface Θ_n is affected by rainfall (RF), the evaporation rate (ET), and by the depth of the underlying water table—the latter may also play an important role in overland flow generation. For example, saturation overland flow (SOF) occurs when the water table rises above the road surface and the ground water exfiltrates onto the road. The broken line and double arrow in Figure 1C signify variation in the height of the rising water table. SOF can also occur at road cuts where subsurface storm flow is intercepted and the water emerges.

Once generated, surface runoff tends to remain on the road for tens to hundreds of meters until it exits at a stream crossing (X_S , Figure 6) or onto the side of a hill-slope (X_H). High connectivity of the road ensures that a large percentage of the RO is delivered to the stream network. In locations where runoff flows from the road onto a hillside, water may either infiltrate (I) or incise the hill-slope (E_i), developing flow paths that may eventually terminate in the stream network. Relatively small volumes of overland flow can entrain loose surface material and small rocks lying on the road surface. As runoff water continues down the road network, depth and velocity increase. At some critical distance, runoff erodes the compacted road surface (E_r)—incision is often initiated in existing ruts or tire tracks. In the absence of gullying and mass wasting, road erosion is controlled by the same rill and interrill erosion sub-processes that operate on agricultural and range lands. These processes are functions of (i) dynamic storm-related phenomena, including rainfall, infiltration, surface water flow conditions (especially depth); and (ii) soil surface erodibility properties, including shear strength. But, as will be shown below, road erosion is a unique process.

3.2 Runoff generation on roads

Figure 3A shows runoff responses associated with roads and other landuse types during high-energy simulated rainfall experiments ($\approx 100\text{--}110\text{ mm h}^{-1}$), under dry antecedent soil moisture conditions ($0.04\text{--}0.12\text{ g g}^{-1}$). HOF generation on non-road surfaces requires large rainfall depths. In contrast, road HOF is generated early in an event, and road runoff coefficients (ROC, the percentage of rainfall that becomes runoff) are high. During the 1998 rainy season, 41% of the 2-min rainfall intensities recorded at station 406 exceeded the road K_s value, demonstrating the high frequency of potential HOF-producing rainfall. During the wet season when surface soil moisture is relatively high, only a few minutes of rainfall with intensities exceeding K_s are needed to generate HOF. Frequent occurrence of HOF on road surfaces is a function of low infiltration rates. K_s , a controlling variable for infiltration, is approximately an order of magnitude lower on PKEW roads and paths than on other surfaces (Table 1). Road K_s is low because compaction reduces total porosity (particularly macro-porosity) and alters pore connectivity for several cm below the road surface. Road surfaces may additionally have a low-permeability surface crust/seal, created by the drying of fine surface material that is dispersed during rainfall. Bulk density and penetration resistance, indices of compaction and surface sealing, are shown in Figure 4 to be negatively correlated with time to runoff (TTRO) during rainfall simulation (Spearman correlation coefficients, $r_s = -0.829$ and -0.832 , respectively). Also shown, is the general relationship between K_s and TTRO.

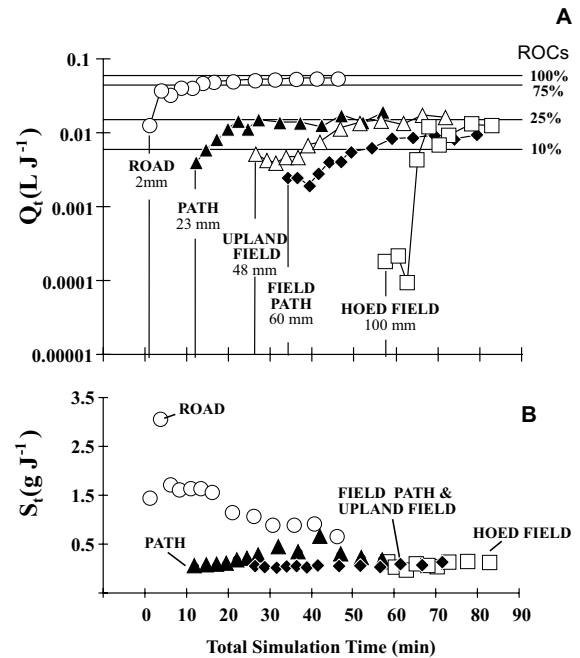


Figure 3. (A) Energy-normalized instantaneous discharge (Q_i), runoff coefficients (ROCs, %), and rainfall depth (mm) before runoff generation for several land-use types in PKEW during rainfall simulations; (B) normalized sediment output (S_i). Data from Ziegler et al. (2000).

As demonstrated by Figures 3A&B, footpaths, like roads, accelerate HOF generation. They, therefore, may enhance in-field surface erosion by acting as source areas for surface runoff on agricultural lands where HOF is otherwise rare (Ziegler et al., 2000). Runoff occurred on the basin access path after about 12 min of 100 mm h^{-1} rainfall; HOF on the newly created field maintenance paths required almost twice as much rainfall. In comparison, hoed and fallow field surfaces required greater rainfall depths to generate runoff; and ROCs were much lower, at about 25%. The hoed surface required approximately 100 mm of rainfall to initiate HOF during the lone runoff-producing simulation event—three other simulation events failed to produce runoff after 90 min (roughly 150 mm), demonstrating the low probability of this surface contributing to HOF. Similarly, runoff was not generated after 60 min rainfall during four simulations on the fallow surface.

4.3 Watershed runoff delivery

The delivery pathway of surface or subsurface water to the stream network determines the timing and contribution of event water to the storm hydrograph and controls the extent of erosion during a storm event. Conveyance efficiency (CE) of road runoff to the stream network varies spatially and temporally. Erosion processes, maintenance, and mass wasting can change the overland flow pathways and runoff exit points. We have estimated CE for the lower PKEW road to be about 70% for most

Table 1. Mean compaction- and infiltration-related variables for the 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 is time to runoff (TTRO); BD is bulk density; PR is penetration resistance, and K_s is saturated hydraulic conductivity; values are ± one standard deviation; 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 log₁₀-transformed data, followed by post-hoc multiple comparison testing with the Bonferroni/Dunn test (B-D) when the F-values were significant at α = 0.05).

*Only one of four Hoed field events produced runoff; none of the four Fallow field simulations produced runoff.

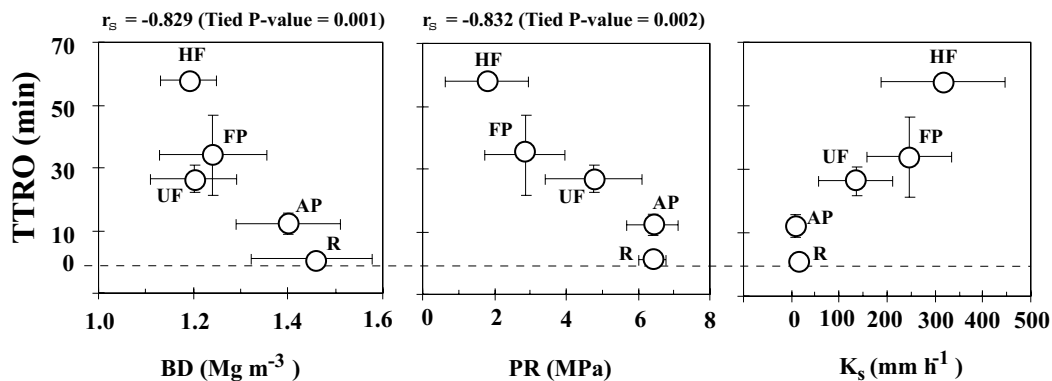


Figure 4. Relationship between time to runoff (TTRO) during rainfall simulation experiments and bulk density (BD), penetration resistance (PR), and saturated hydraulic conductivity (K_s). Open circles are means; error bars are ± one standard deviation. r_s is the Spearman rank correlation coefficient determined for paired data (not available for K_s). Identifiers R, AP, UF, FP, and HF refer to road, access path, upland field, field path, and hoed field surfaces, respectively.

storms. Figure 5 shows the road network contribution to the basin storm hydrograph during the largest event of 1998 (STORM). Total rainfall was 51.5 mm, with most falling during the first 30 min after runoff initiation. Mean 1-min rainfall intensity during this period was 89 mm h⁻¹; the maximum 1-min intensity was 154 mm h⁻¹. During the first 1-2 h following runoff initiation, HOF from the road alone comprised an estimated 10% of the stormflow hydrograph.

The distance and direction that on-road HOF travels is primarily determined by geomorphological variables associated with basin road location, i.e. topography, ridge vs. valley location, slope, and distance to stream. Because road sections are linked via rill and gully systems, the hydrologic boundary for road surface runoff can transcend the natural watershed boundary. Therefore, surface water generated on roads in one basin can contribute to stormflow response and/or erosional

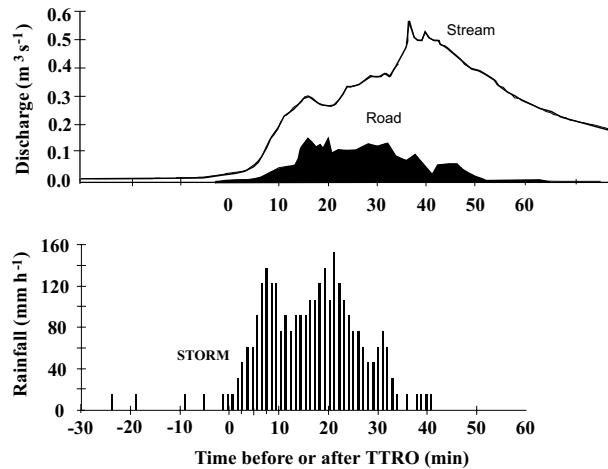


Figure 5. Road runoff contribution to basin storm hydrograph for the rain event on 15 August, 1998, the largest event of the year (STORM).

impacts in adjacent basins. For example, the 130-m section of Lower PKEW Road (section B-C, Circle 1, Figure 6) imports surface runoff from the adjacent watershed. Runoff follows the incised road into PKEW, flowing into the stream network at the log bridge (Figure 7-1). If this road captures runoff generated upslope on non-road surfaces, the contributing area to PKEW hydrological response is further increased. Similarly, section D-E (Circle 2, Figure 6) is also physically outside PKEW (Figure 7-2), but has one runoff exit point within the basin (Point E).

The influence of the Upper PKEW Road on basin hydrologic response varies depending on storm intensity and road surface conditions. Surface water originating on section F-G converges, exiting into an upper ephemeral tributary of the Loei Stream network. Water generated below G flows out of the basin. At the first switchback (H), runoff is partitioned into pathways that determine if it will re-enter PKEW (Figure 7-3). For low volume flows, runoff follows a rut system down the road, exiting the basin. If discharge surpasses a threshold of about $0.7 \pm 0.3 \text{ m}^3 \text{ s}^{-1}$ (field estimates August 1998), runoff crosses into an incised ditch (roughly 1.3 m (W) x 0.4 m (D)) on the inside of the road that channels the runoff to a hillslope exit point (I) within PKEW (Figure 7-3). The 'crossover' to this ditch is an ephemeral feature, changing in response to vehicle traffic (creating ruts) and maintenance activities (repairing of ruts). The contribution of any road section to basin stormflow is therefore a function of interstorm phenomena, as well as during-storm processes/characteristics, such as gullyng and storm intensity (e.g., determines flow depth and velocity).

4.4 Saturation overland flow

We believe HOF is the principal overland flow mechanism on PKEW roads; and SOF is rare except near the stream network. In the Pacific Northwest (USA), interception of subsurface flow by road cuts has been identified as the dominant source of overland flow on unpaved mountainous road surfaces (Megahan, 1983). Figure 6 (Circle 4) shows the principal location in PKEW where SOF occurs regularly. Here, three ephemeral stream channels converge (Figure 7-4). The center channel is typically dammed to provide a small reservoir for irrigation. Throughout the rainy season the area is saturated and surface water is pooled between channels and in road ruts. During rainfall, this pooled water flows across the road into the stream network immediately downslope. The distance this additional road surface flow travels is not sufficient to increase erosional impacts significantly. However, if this type of SOF were to occur upslope of a long road section, surface erosion would be exacerbated. Although we have found SOF to be rare in PKEW, it may be more common in other watersheds in the region, and therefore is should not be totally discounted.

4.5 Road erosion

ROAD S_t is characterized by an output peak within the first few minutes after TTRO, followed by a gradual decline throughout the remainder of the simulation (Figure 3B). The response peak is related to flushing of easily transported, loose surface material that is generated during interstorm periods. Once the superficial layer is depleted, sediment output is limited by detachment of new material from the compacted road surface. At any given time, the road surface consists of a compacted, resilient surface underlying a layer of loose material of finite depth. The volume of the loose material is constantly altered by overland flow events, traffic, maintenance, and mass wasting. Because the availability of road surface sediment is dynamic, sediment transport response on the road varies both during and among events. In general, roads receiving high traffic volumes will have high sediment production rates (cf., Reid and Dunne, 1984). In contrast, sediment transport on roads can be low, such as during a storm that follows closely after a large overland flow event has removed most loose material.

Figure 8A shows the contributions of splash and hydraulic erosion to total road erosion during 60-min rainfall simulation events (Ziegler et al., press b). This information allows us to prescribe splash and hydraulic erosion parameters for modeling road erosion with KINEROS2. Figure 8B shows observed and KINEROS2-predicted discharge, sediment transport, and sediment concentration for five rainfall simulation events on unpaved roads (Ziegler et al., in press a). Temporal response in sediment transport on unpaved PKEW roads

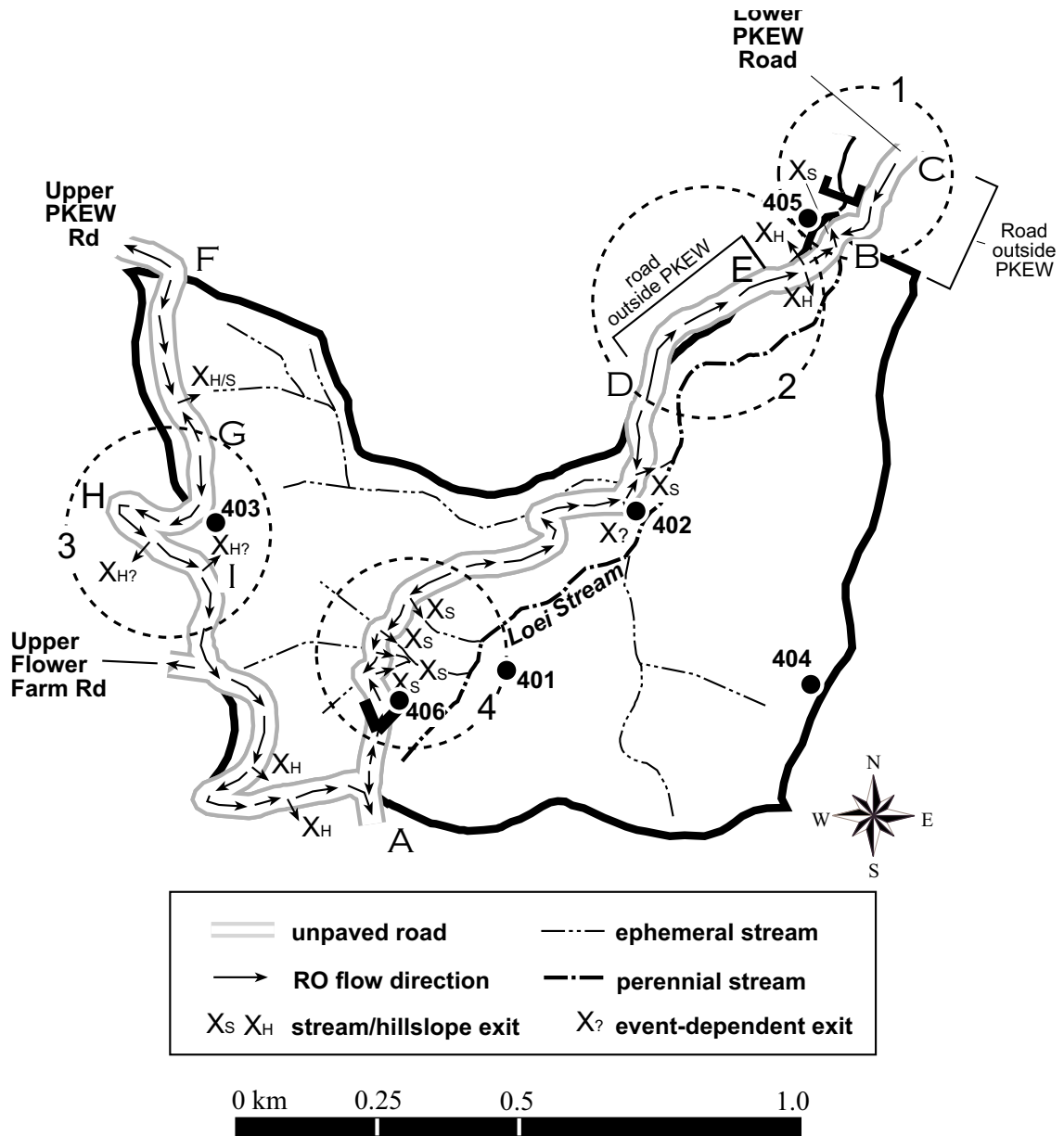


Figure 6. Road surface water flow paths and locations of several road-related geomorphological features affecting hydrological response in PKEW (letters A through H). Detail within dotted circles (1-4) are shown in Figure 7.

is best modeled when the surface layer of loose sediment is explicitly considered. This approach recognizes that roads have an initial erodibility that is related to availability of loose surface material—and sediment availability is a function of interstorm vehicular traffic and maintenance. We have recently introduced the “dynamic erodibility” (DE) technique for modeling this process (Ziegler et al., in press a). Vehicle passes during rain

events also play a role in enhancing sediment transport on roads. Figure 8C shows spikes in sediment output resulting from motorcycle passes during simulated rainfall (Ziegler et al., in review c). This mechanical stress generates a new supply of loose material to be transported by overland flow during a storm event. The DE methodology also represents a means to model this process (work in progress).

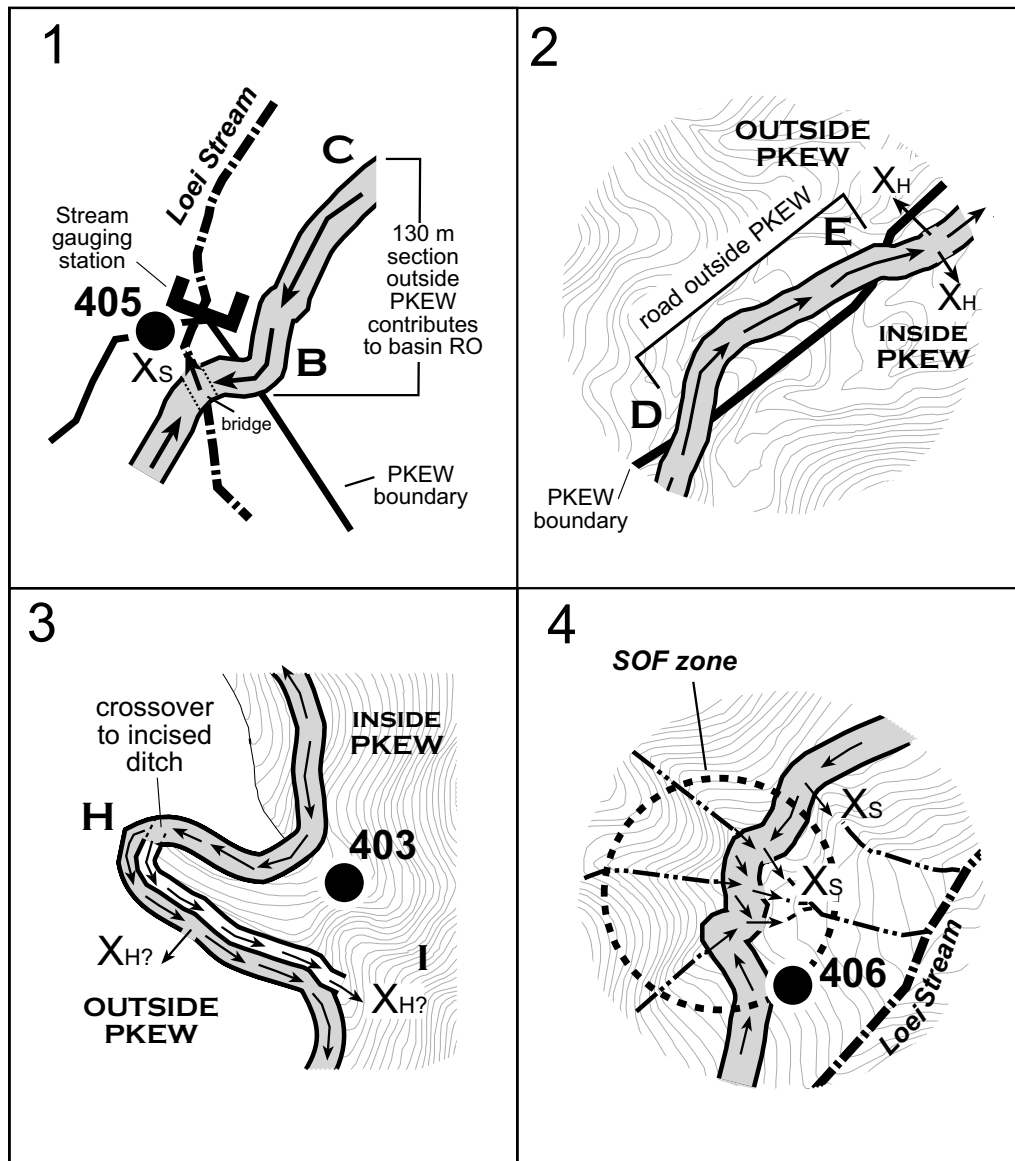


Figure 7. Topographical or geomorphological features that influence watershed delivery in PKEW. Each location is shown in Figure 6.

5. Conclusions

Because of low rates of infiltration, overland flow generation on unpaved roads is more frequent and begins earlier during rain events, compared with other watershed surfaces in the study area. Horton overland flow generation within agricultural fields is generally rare, except on path surfaces. Footpaths, like roads, accelerate runoff, and may enhance in-field erosion and redistribution of sediment. The extent of the road network contributing runoff to basin stormflow changes in response to activities/events that alter surface flow pathways on the road. Delivery of road surface water,

and hence sediment, to the stream network is variable. Because rut and ditch systems link separate overland flow source areas into continuous pathways, the hydrological boundary of a road system can transcend the topographical boundary of the watershed. Runoff generated on the road surface in one watershed can be transported to other basins, where it potentially contributes to cumulative watershed hydrological and geomorphological impacts.

The road surface consists of a compacted, resilient surface that underlies a layer of loose material of finite depth. Because the volume of road surface sediment

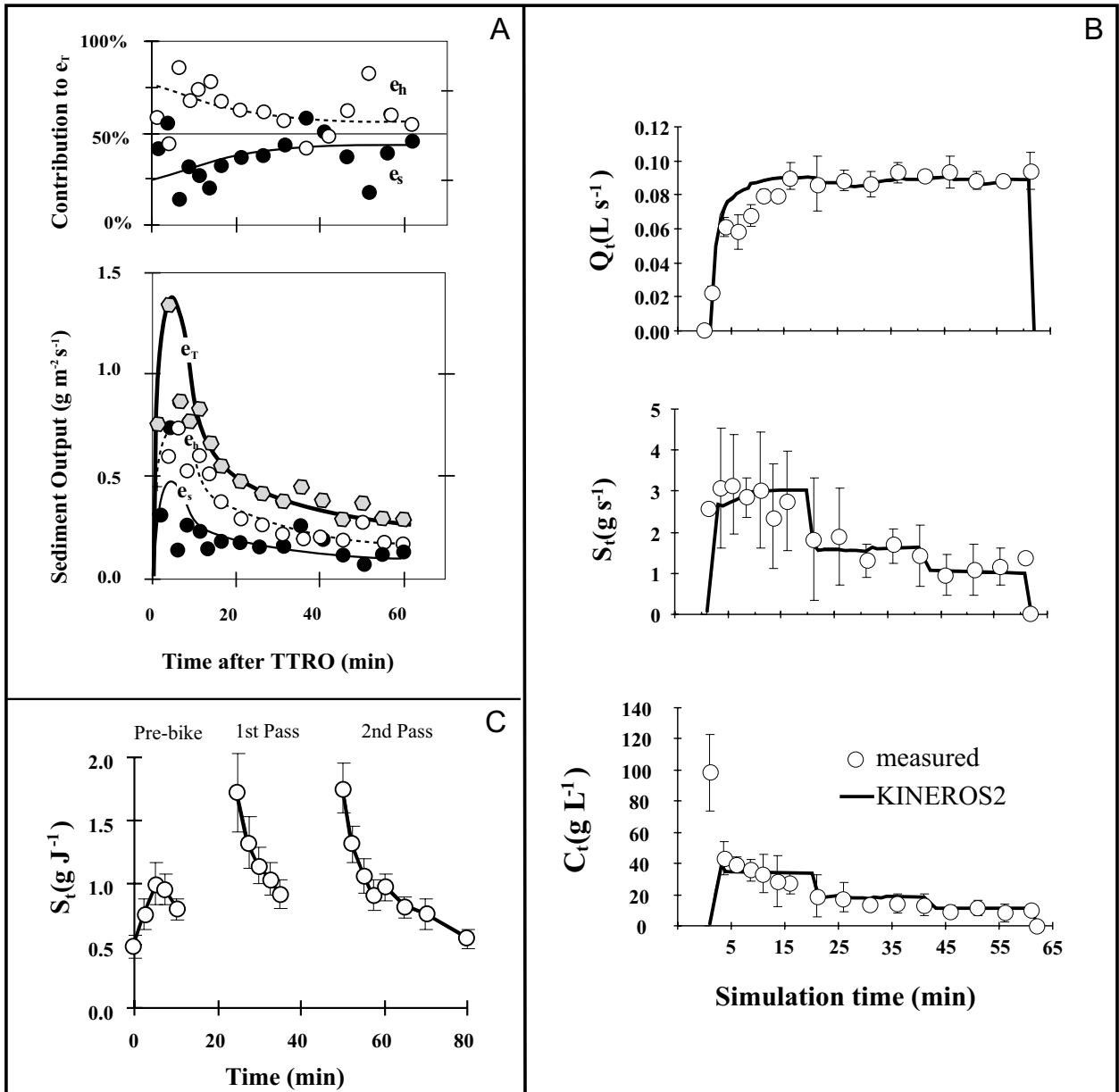


Figure 8. (A) Partitioning of total road erosion (e_r) into splash (e_s) and hydraulic (e_h) erosion components; (B) KINEROS2 predictions of field-simulated road discharge (Q_t), sediment transport (S_t), and concentration (C_t); (C) spikes in sediment output resulting from four motorcycle passes during simulated rainfall. Error bars are for (B) \pm one absolute deviation about the median (dot); and for (C) \pm one standard error about the mean (dot).

is altered by overland flow events, traffic, road maintenance, and mass wasting, sediment transport response on the road is variable, both during and between events. During a storm, and in the absence of vehicular traffic, sediment transport declines over time as the loose sediment supply diminishes. Temporal response in sediment transport on PKEW unpaved roads is best modeled with KINEROS2 when the superficial layer of loose material is explicitly considered (dynamic erodibility, DE). Collectively, because of (1) frequent HOF generation, (2)

high connectivity of road sections, and (3) the daily generation of road surface sediment, roads continually disrupt natural watershed systems throughout the course of the rainy period—potentially more than agricultural activities in some upland watersheds.

Acknowledgments

This project is funded by the NSF Award (grant no. 9614259). Alan Ziegler was supported by an EPA Star Fellowship and a Horton Hydrology Research Award (Hydrological Section, AGU).

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