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Case Study 28

Estimation of basin sediment flux in the Pang Khum Experimental Watershed in Northern Thailand: the contributions of roads and agricultural lands

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ABSTRACT

Stream sediment load and sediment contributions from roads, paths, and agricultural lands are estimated for a one-year period in an upland watershed in northern Thailand. Total road sediment input to the stream was only slightly higher than that from agricultural lands (30-41 versus 25-40 Mg), but corresponding erosion rates were substantially greater (65-88 versus 2-4 Mg ha^{-1} y^{-1}). The results emphasize that basin sediment yield is not a reliable indicator of the existence of severe erosion within a watershed. Rather, sediment budgeting approaches are needed to uncover important sediment sources that occupy small percentages of the total basin area (e.g., roads). Finally, the trend of focusing solely on erosional impacts of agricultural practices, ignoring impacts associated with unpaved roads, is not a sustainable conservation strategy for managing upland watersheds in SE Asia.

INTRODUCTION

In many areas of montane mainland SE Asia conservation efforts directed at reducing (1) human-induced alterations to stream hydrologic response and (2) sediment inputs to stream systems often focus on improving agricultural practices in upland watersheds, but ignore the associated impacts of mountain roads. In the Pang Khum Experimental Watershed (PKEW) in northern Thailand, we currently believe road-related impacts are on the same order of importance as those of agricultural lands, owing largely to the high frequency of Horton overland flow (HOF) generated on roads, the high conveyance efficiency of road runoff to the stream channel, and the constant renewal of entrainable road surface sediment by traffic. Figure 1 shows the estimated road surface runoff contribution to the stream system during the largest storm of the 1998 rainy season to be nearly equivalent to that associated with agricultural lands, despite roads occupying about 0.5% versus 12% of the land area (Ziegler et al., in review). In this paper, we use data from rainfall simulation experiments, recorded rainfall, and stream sediment measurements to estimate the sediment contributions from roads and other PKEW landuse types for a one-year period to determine the relative impact of roads versus agricultural lands in the basin

THAILAND ROADS PROJECT (TRP) & PKEW

In 1997 we began a study of hydrological and geomorphological impacts of unpaved roads near Pang Khum Village (19°3'N, 98°39'E), roughly 60 km NNW of Chiang Mai, Thailand (Figure 2). One objective is to determine the role of roads in initiating hydrologic change and contributing to erosion processes. Field work conducted mostly in the 93.7-ha PKEW included (1) establishing a network of six climatological stations to record variables needed for estimating basin water balance, and to provide data for numerical model simulations; (2) conducting rainfall simulations on roads and other basin landuse types to understand runoff generation and erosion processes, and to parameterize model variables; and (3) conducting detailed surveys of basin landcover/landuse and road-related phenomema (usage, sediment sources, and runoff exit points). Results from TRP are summarized elsewhere (Ziegler et al., in press; webdata.soc.hawaii.edu/hydrology).

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 comprise about 1% of the PKEW area. Based on 1995 airphotos and recent ground cover surveys, 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. PKEW is described in detail elsewhere (Ziegler et al., 2000). Approximately 70% of all road runoff in PKEW directly enters the stream network at intersections of the road and stream channel (Ziegler and Giambelluca, 1997; Ziegler et al., in press). Despite light traffic, the Upper and Lower PKEW Roads are noticeable sediment sources for material entering the stream channel network.

METHODS

During the one-year period extending from 15 Aug 1998 to 14 Aug 1999, a tipping bucket rain gauge (0.254-mm threshold) and datalogger were used to measure 1-min rainfall intensities (Station 406, Figure 2). Storm events were defined as precipitation events accumulating at least 12.7 mm without a 6-h rain-free period, or events having 6.4 mm within a 15-min period (based on Wischmeier and Smith, 1978). During the study period, 46 storms were recorded out of 178 total precipitation events. Stream flow was recorded at a V-notch weir constructed at the basin mouth in Loei Stream, the principal stream in PKEW (Station 405, Figure 2). In the dry seasons of 1998 and 1999 several replications of rainfall simulation experiments were performed on agricultural lands (hoed fields, upland fields, fallow fields, and field furrows), roads, and footpaths (Ziegler et al., 2000, in review).

For the above-mentioned one-year period we estimated (1) stream sediment contributions originating from major landuse types via HOF, and (2) total stream sediment load. The first calculation uses storm event sediment transport rates (normalized by area and rainfall energy) that were determined during the rainfall simulation experiments. Specifically, for each of 46 storms and nine major landuse types--degraded forest, advanced secondary, young secondary, three types of agricultural fields (upland rice field, hoed field, hoed field with furrows), dwelling sites and access paths, and roads (Table 1)--we calculate the sediment input to the stream from a particular landuse type (Sj) as:

$$S_j = \sum_{i=1}^{46} \sum_{j=1}^{9} Storm\ EFD_i * Area_j * CE_j * Sed_j \qquad (1)$$

where i and j refer to the storms and nine landuse types, respectively; *Storm EFD* [J m^{-2}] is the energy flux density over the course of a storm event (calculated from rainfall data using equations in Ziegler et al., 2000); *Area*, *CE*, and *Sed* are the area, conveyance efficiency, and normalized sediment delivery rate for the nine landcover types (from Ziegler et al, in review). Road *CE* was based on a field survey; a range of realistic *CE* values were chosen for the other landuse types. *Sed* [g J^{-1}] values are unique for wet and dry antecedent moisture conditions (wet defined as > 0.25 g cm^{-3}). Landcover-specific values for Eq. 1 calculations are shown in Table 1. Note, sediment transport associated with overland flow resulting from non-HOF mechanisms is not represented by the *Sed* values determined from rainfall simulation.

Table 1. Area, conveyance efficiency, and sediment delivery values for nine landuse types used in the calculation of stream sediment inputs (via Eq. 1).

Landcover Type*	*Area* (ha)	*CE* (-)	Sed_{dry} (g J^{-1})	Sed_{wet} (g J^{-1})
FOREST	29.0	0.1-0.2	-	-
ADVANCED SEC	11.2	0.1-0.2	-	-
YOUNG SEC	29.0	0.1-0.2	-	-
FALLOW FIELD	9.4	0.3-0.4	0.00	0.00
UPLAND FIELD	2.1	0.3-0.4	0.04	0.13
HOED FIELD	6.0	0.3-0.4	0.00	0.02
FIELD & FURROWS	6.0	0.3-0.4	0.02	0.07
DWELLINGS & PATHS	0.5	0.2-0.3	0.06	0.11
ROAD	0.5	0.7	1.23	0.74

*Data and landuse types are described in Ziegler et al., in review; "-" indicates no data were available from the rainfall simulation experiments; therefore, the values are assumed to be equal to those of FALLOW (i.e., *Sed* = 0).

To estimate stream sediment load (S_{load}), measurements of sediment trapped behind the weir (trapped load, $S_{trapped}$) and suspended sediment flowing through the weir (free load, S_{free}) are used. To do so, we establish a relationship between discharge (Q_i) and the two types of loads. For $S_{trapped}$, the relationship is determined from data collected before the volume of trapped material exceeded 25% of the weir capacity, after which the trapping efficiency greatly changed. Using discharge relationships, we calculate S_{load} for each of 46 storm intervals (defined as extending from the beginning of one storm event until the start of the next) as follows:

$$S_{load} = \sum_{i=1}^{46} S_{trapped}(Q_i) + S_{free}(Q_i) \tag{2}$$

RESULTS

Estimations of sediment contributions from PKEW landuse types to Loei stream are shown in Figure 3A. Predicted surface runoff via the HOF mechanism occurred only on roads, paths, dwelling sites, and some agricultural surfaces (recently abandoned fields and fields containing footpaths), but not on fallow, secondary vegetation, and forest lands (Ziegler et al., in review). Corresponding predicted sediment input is approximately 56 Mg, for which the road contribution comprises 54%. Also shown is a higher estimate (B), calculated by (1) using higher CE values (Table 1) and (2) allowing non-storm events to produce runoff if total rainfall is greater than the depth required to produce HOF (based on rainfall simulation experiment data). For this estimate, the total sediment delivered to the stream is 83 Mg, with 50% coming from roads; 2%, from paths and dwelling sites.

Total stream sediment load, estimated from Eq. 2, is 87 Mg (S_{load}, Figure 3). For the free load estimate, which comprises 70% of the total, we were unable to determine a significant relationship between discharge and concentration; therefore, we use the mean sediment concentration value (0.18 g L^{-1}; n = 48) for all 46 storm intervals in the calculation. For 13 trapped load measurements and corresponding Q_i, the following power function best described the data:

$$S_{trapped} = 0.00000182\, Q_i^{1.524} \tag{3}$$

for which the P-values of the two coefficients are both < 0.0001; the fit for Eq. 3 is shown in Figure 4.

DISCUSSION

The higher value for S_{load}, compared with the estimated inputs from basin landuse types (Figure 3), is logical because stream sediment load is composed of not only storm-related inputs (i.e., those estimated by Eq. 1), but also redistributed material that entered the stream channel during prior events, and sediment resulting from stream bank/bed erosion and/or mass wasting. The S_{load} estimate is likely low because we were unable to collect data allowing calculation of sediment flushes that may occur within short intervals during the largest annual storm events (e.g., that in Figure 1). The agricultural sediment input estimate may be elevated because we intentionally use a relatively high range of CE values (Table 1). Conversely, cumulative S_j could be underestimated, for we assume secondary vegetation and forest landuse types have the same sediment delivery values as that for fallow (i.e., *Sed* = 0, Table 1). Furthermore, S_j estimates are probably low because we do not include sediment transport associated with non-HOF mechanisms. Despite the above errors, agreement between S_{load} and total sediment inputs (Figure 3) suggests the estimates are reasonable for PKEW.

These estimates suggest PKEW sediment yield is probably about 1.0 Mg ha^{-1} y^{-1}, a rate not greatly different than that expected for soil formation. Estimated agricultural, road, and path/dwelling contributions, however, range from 2-4, 65-88, and 2-5 Mg ha^{-1} y^{-1}, respectively. The agricultural estimate is similar to recent data from the International Board for Soil Research and Management (IBSCRAM) and Swiss Development Cooperation (SDC) experiment site at Huay Luek (Chiang Dao), Thailand, where typical farmer-practice erosion rates for slopes similar to those in PKEW were < 6 Mg ha^{-1} y^{-1} (mean of 6 years; unpublished data). Although estimated annual road sediment input to the PKEW stream system is similar to that from agricultural sources, the erosion rate is 20-30 times higher. Therefore, although the sediment yield estimate does not indicate the occurrence of substantial erosion in the basin, the partial budget identifies roads as an important sediment source. In PKEW, significant road lowering (0.10-0.15 m y^{-1}) occurs only on the steepest sections (0.15-0.30 m m^{-1}), which comprise only 20-30% of the total basin road length. In other basins having a greater total road length, roads built on steeper slopes, and/or a major road artery (which PKEW does not), road-related sediment transport to the stream may be even more substantial.

CONCLUSION

This work indicates that road-related sediment inputs to a stream system can be on the same order of importance as those coming from agricultural lands, which have much larger contributing areas. Erosion assessments based solely on basin sediment yield measurements may fail to identify basins where road-related erosion is substantial. Only through sediment budgeting will the relative sediment contributions from all important sediment sources be uncovered. Finally, the data acknowledge that three keys to minimizing road-related sediment inputs to the stream system in upland watersheds in the study area are (1) limiting total road length; (2) minimizing road building on steep slopes; and (3) reducing conveyance efficiencies of road overland flow to the stream network.

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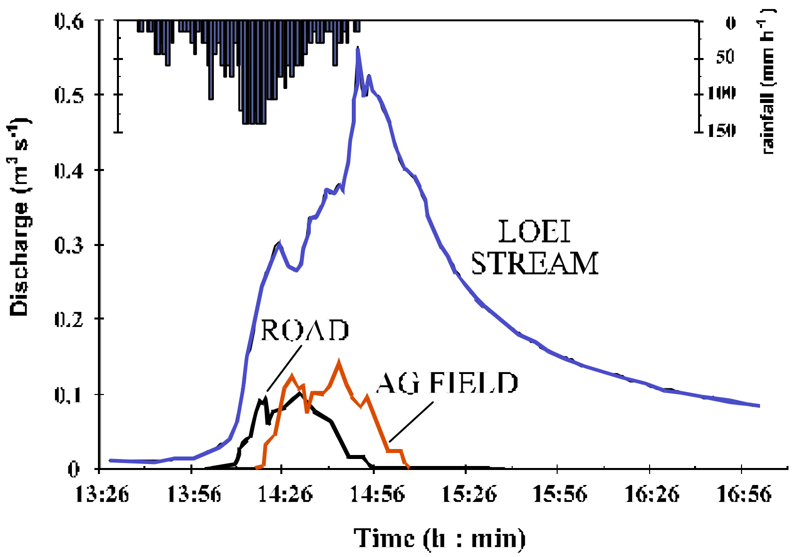

Figure 1. Estimated road and agricultural field contributions to the storm hydrograph in PKEW during the largest storm of 1998 (Ziegler et al., in review).

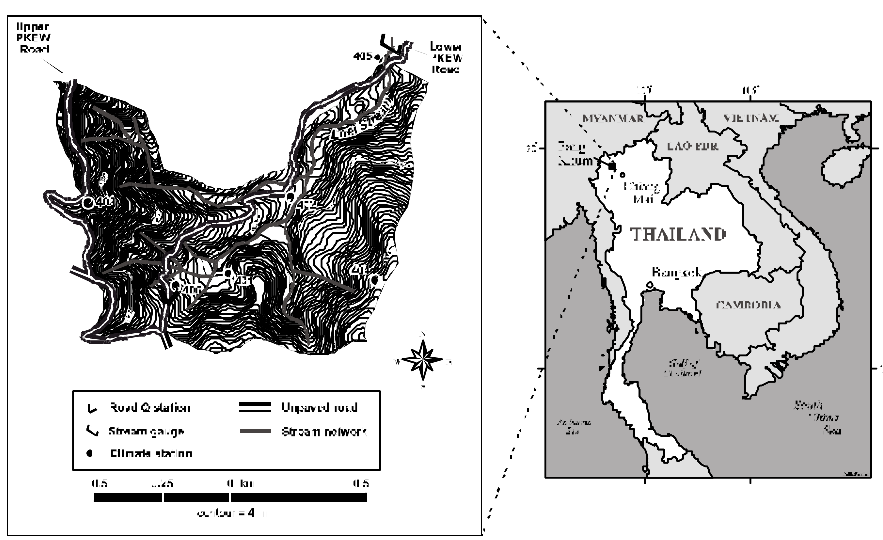

Figure 2. The Pang Khum Experimental Watershed in northern Thailand. Experiments were performed near Station 406.

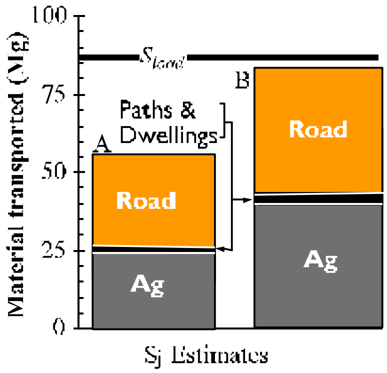

Figure 3. Two estimates of contributions from roads, agricultural fields, and path/dwelling sites (via Eq. 1 & Table 1 values) to annual total stream sediment load (S_{load}, from Eq. 2). Estimated values for the three landuse groupings are respectively: (A) 30, 25, and 1; and (B) 41, 40, and 2 Mg.

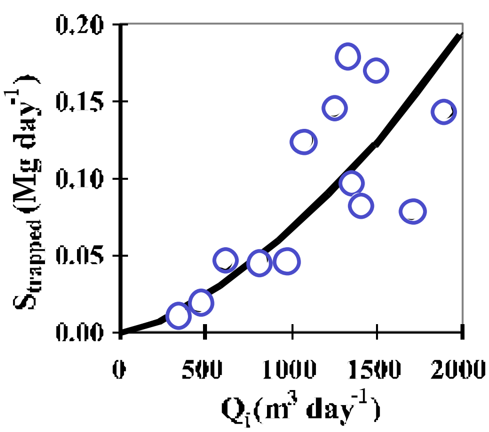

Figure 4. Relationship between discharge (Q_i) and sediment trapped by the weir; the fitted line for $S_{trapped}$ is that of Eq. 3.