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# Hydrologic Change and Accelerated Erosion in Northern Thailand

## Simulating the Impacts of Rural Roads and Agriculture

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### Introduction

Roads play a significant role in altering near-surface hydrologic response and subsequently accelerating soil erosion in mountainous areas of Southeast Asia;[1] however, it is not clearly understood how the hydrological and geomorphological impacts of roads 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,[2] much of the sediment delivered to stream systems may be due to expansion of road networks. For example, Pransutjarit 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.[3] 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 small sub-basin in northern Thailand, we simulate changes in overland flow response and sediment transport associated with

- the transition from closed-canopy forest to a mosaic of swidden agriculture lands
- road expansion

We then compare the changes induced by each activity to determine the respective potential hydrological and geomorphological impacts. The objective of this research is to ascertain the importance of rural roads, compared to agricultural lands, in altering hydrologic watershed function 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:

- highly compacted road surfaces and disturbed roadside margins reduce infiltration of rainwater, increasing the likelihood of overland flow generation

- cutbanks can intercept subsurface flow, rerouting it as overland flow; [4]

- ditches and culverts capture both subsurface flow and surface runoff, and channel it more rapidly to streams.[5]

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 stormwater to streams, which may produce faster flow peaks and slightly higher total discharges.[6] Although less work has been conducted on roads in the tropics,we expect these same road features to also 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.[7] 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[8] and Harden[9] in Africa and South America, respectively. Several studies within temperate regions have shown the importance of road location, geometry, and usage on sediment transport.[10] Additional studies have identified several sediment source areas associated with unpaved roads (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.[11]

### Importance of Horton overland flow on mountainous roads

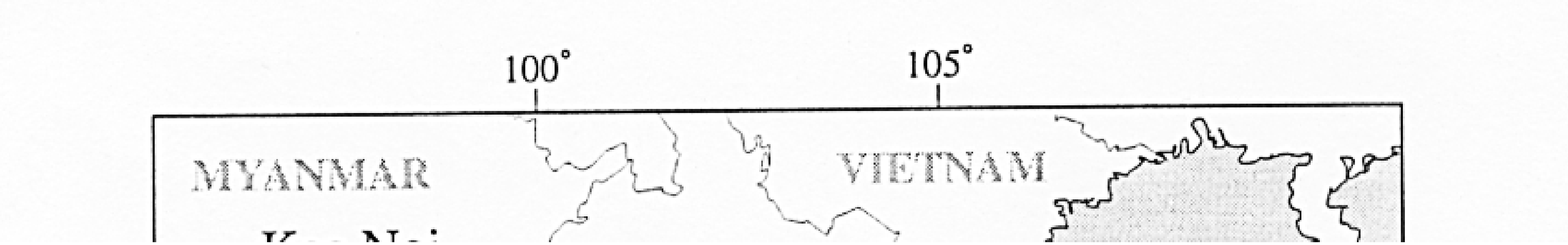
Horton overland flow (HOF) is thought to be rare in fully vegetated, undisturbed areas where infiltration rates are high. However, in areas where infiltration has been reduced by human activities, such as vegetation removal or compaction, the Horton mechanism can be a dominant pathway of water movement to stream channels. In this respect, highly compacted, largely bare, unpaved road surfaces are likely source areas for HOF in mountainous watersheds. While roads may also enhance runoff by intercepting subsurface flow,[12] 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 conducted in the tropics, rural roads, tracks, and paths were found to be active runoff-generating components owing solely to their low infiltration capacities.[13]

We found support for a HOF-dominated runoff regime on mountainous roads during a preliminary pilot study conducted recently in northern Thailand.[14] Field measurements and simulations of excess rainfall (rainfall - infiltration) showed the following regarding the importance of unpaved roads in generating HOF:

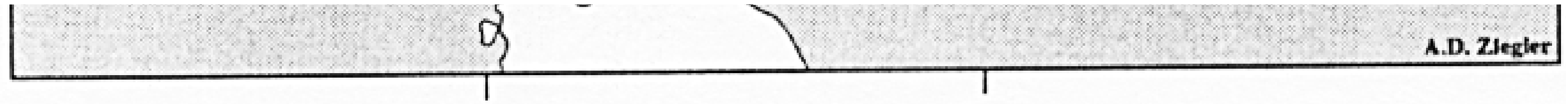
1. saturated hydraulic conductivities were approximately one order of magnitude lower on unpaved road surfaces than on any other land-surface type;
2. during the rainfall collection period, rainfall intensities never exceeded the median saturated hydraulic conductivity of any landuse except road surfaces and highly disturbed roadside margins;
3. during most storms, a significant portion of rain falling on roads does not infiltrate;
4. compared to non-road surfaces, predicted excess rainfall was generated sooner during a rain event on an unpaved road surface-and on nearly all of its area; and
5. for frequently occurring, small rainfall events, road-related surfaces contribute a large portion of simulated basin-total excess rainfall despite their relatively small areal extent (< 0.5% of basin area).

## Study Area

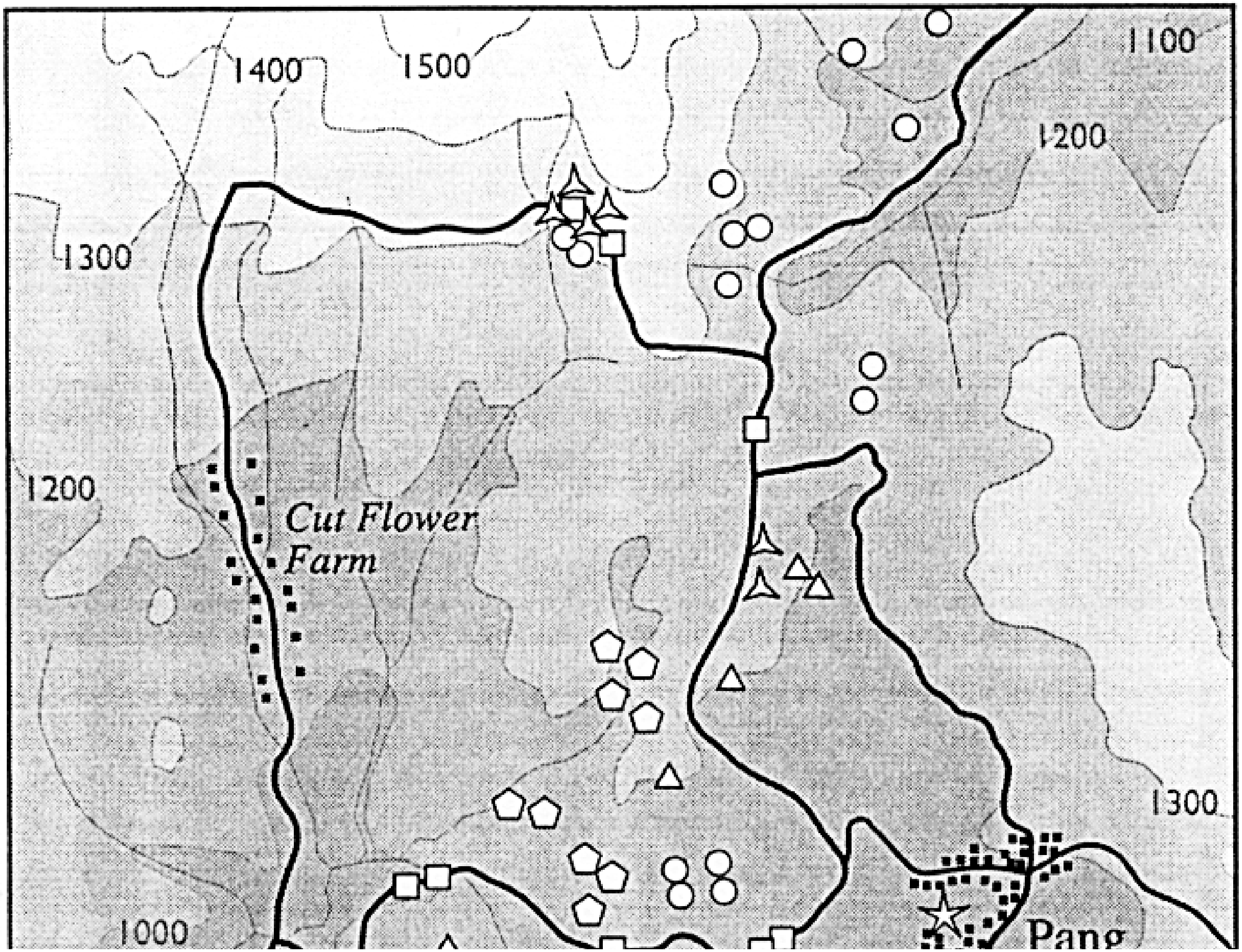
Our study site is the area surrounding Ban (village) Pang Khum (19 deg. 3 min., 98 deg. 39 min. E), within the Samoeng District of Chiang Mai Province, NNW of Chiang Mai, Thailand

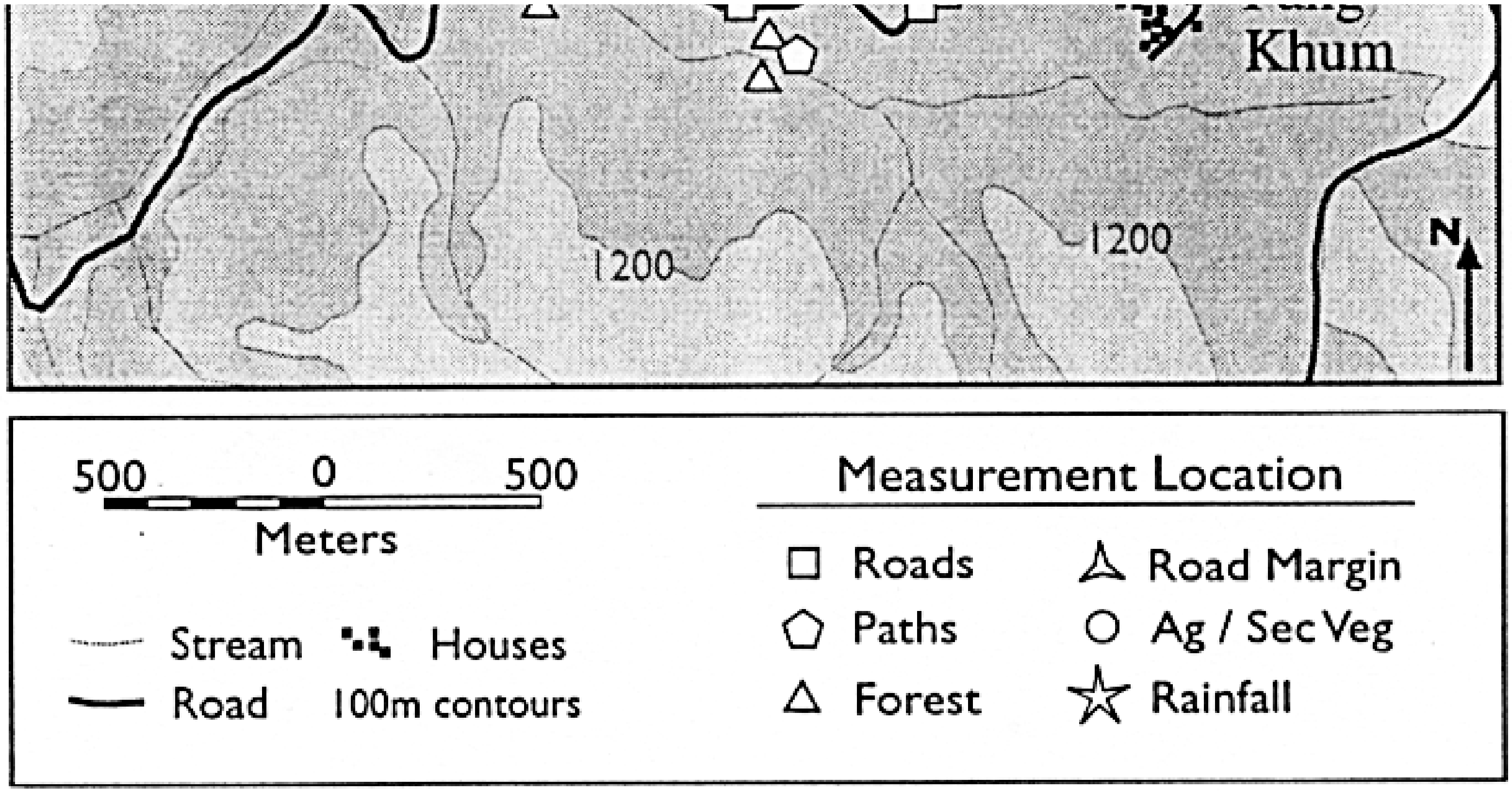



Kae Noi
20°
Sam Mun
Chiang Mai
LAO PDR
THAILAND
Bangkok
CAMBODIA
Andaman Sea
Gulf of Thailand
10°
South China Sea



(Figure 1) and the





inset.

This area, described in detail by Ziegler and Giambelluca,[15] ranges in elevation from 750 to 1850 m asl. It 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. This area is representative of other mountainous regions throughout tropical montane Southeast Asia in that it is undergoing active rural development with an expanding network of unpaved roads.

Pang Khum is a part of the larger Sam Mun study area in which roads comprise less than 0.25% of the total 9600 ha (0.56 km km-2). In contrast, forest (mostly exploited), agriculture, initial secondary vegetation, and paddy fields comprise approximately 72.3, 20.4, 4.6, and 2.1% of Sam Mun, respectively.[16]

It is our belief that roads are responsible for a significant proportion of the increased erosion and sedimentation that is often attributed to agriculture activities in Sam Mun. This erosion results from the interaction of soil, slope (up to 18 deg), 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. For example, at the beginning of the wet season, the thick layer of fine sediment that accumulates on the road surfaces throughout 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 most rainstorms, [17] surface runoff continually transports the easily entrainable sediment and further incises concentrated flow channels. Hence, erosion occurs throughout the rainy season; and because many road sections terminate at the stream, sedimentation is often substantial.

## Methods

### Simulation of Erosion and runoff with KINEROS

We used the KINEROS runoff/erosion model to simulate overland flow and sediment transport during seven rainstorms for three landuse scenarios (21 total simulations).[18] KINEROS is a distributed, event-oriented, physically based model that can simulate Hortonian runoff and sediment transport from complex watersheds or hillslopes. Application and testing of KINEROS is well-documented. [19] Detailed description of the KINEROS equations and modeling approach can be found in the works by Woolhiser et al. and Smith, Goodrich et al. from which the following description is adapted:[20]

- Simulating Runoff in KINEROS utilizes the kinematic wave method to solve the dynamic water balance equation:

  $$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q(x,t) \tag{1}$$

  where $A$ is cross sectional area, $t$ is time, $Q$ is discharge per unit width, $x$ is distance, and $q(x,t)$ is the local source or loss rate. In KINEROS, Equation (1) can be applied to plane, rill, or channel elements, provided a rating relationship can be developed between $Q$ and $A$ for each. The solution of Equation (1) requires an estimate of excess rainfall:

  $$q(x,t) = r(x,t) - f(x,t) \tag{2}$$

  where $r$ and $f$ are time- and space-dependent rainfall intensity and infiltration capacity respectively. The infiltration scheme, which incorporates initial soil moisture and rainfall intensity, is based on the model of Smith & Parlange.[21] A simple microtopography model links runoff and infiltration.

- Simulating Erosion involves the dynamic sediment balance equation:

$$\frac{\partial(AC_s)}{\partial t}+\frac{\partial(QC_s)}{\partial x}-e(x,t)=q(x,t) \quad (3)$$

where *A*, *Q*, *t*, and *x* are as above, *Cs* is local sediment concentration, *e(x,t)* is erosion/deposition rate, and *q(x,t)* is inflow of water containing sediment. The *e* term encompasses both rainsplash and hydraulic erosion detachment processes:

$$e=e_s+e_h \quad (4)$$

where *es* is rainsplash erosion, a function of rainfall intensity *r* and water depth *h*; and *eh* is net hydraulic erosion due to surface water flow, the difference between hydraulic soil particle detachment (dependent on velocity, slope, and depth) and deposition. Sediment transport capacity relations describe concentration (*Cmx*) in terms of hydraulic variables, particle size, and particle density. Hydraulic erosion rate is estimated as being linearly dependent on the difference between the equilibrium concentration and the current local sediment concentration *(Cs = Cs(x,t)):*

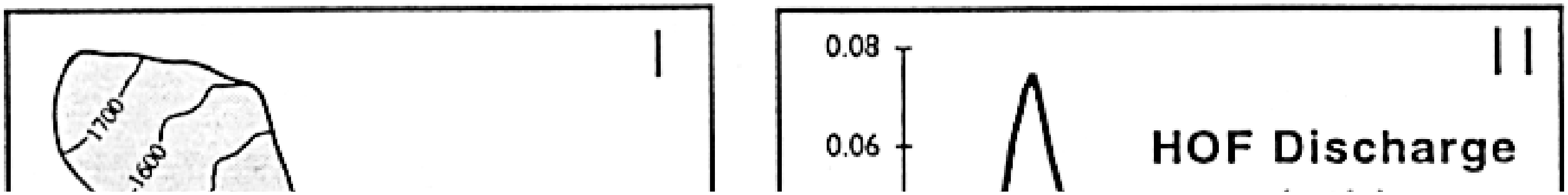
$$e_h=c_g\left(C_{mx}-C_s\right)A \quad (5)$$

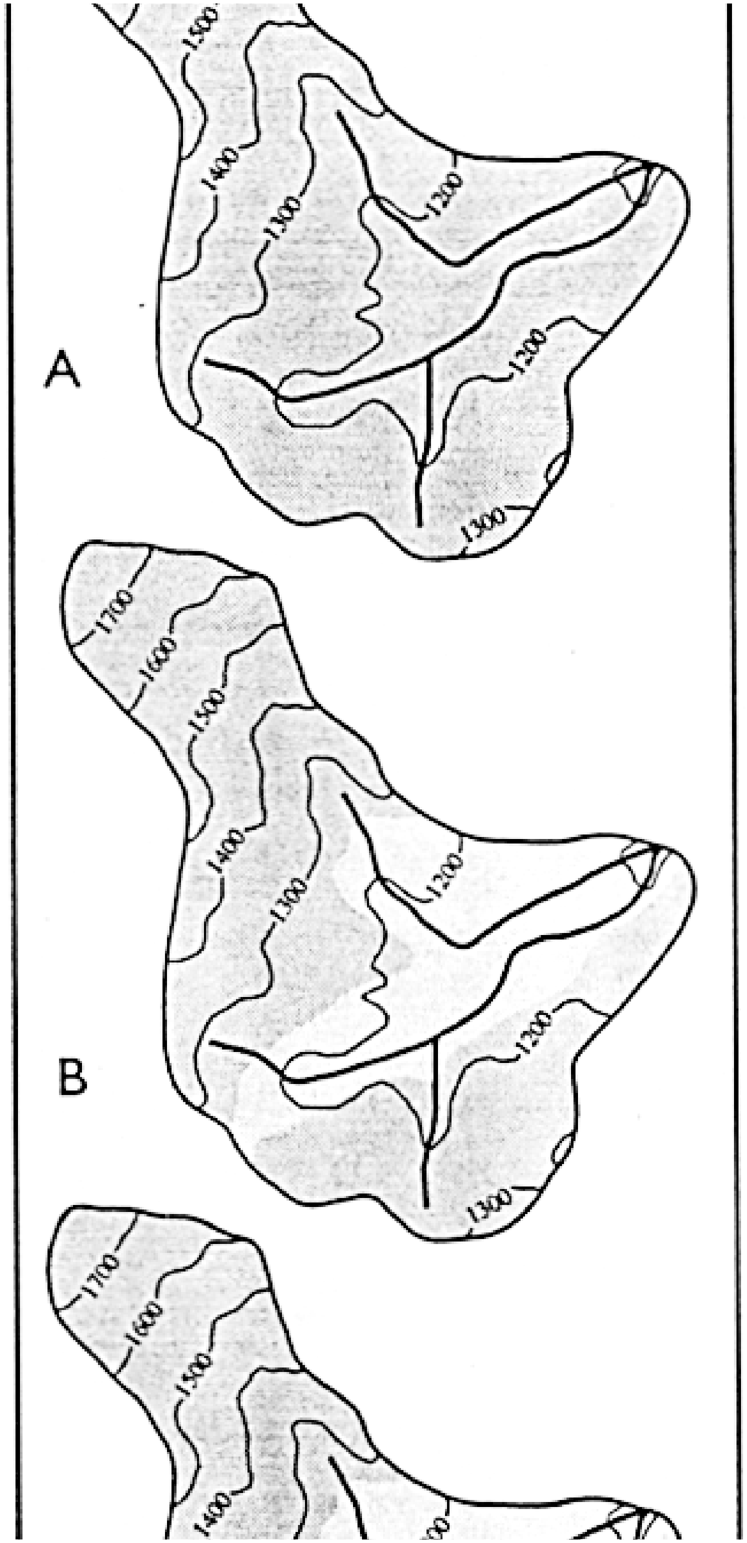
where *cg* is the transfer rate coefficient, a function of particle settling velocity and hydraulic depth. KINEROS does not explicitly separate interrill and rill erosion processes; therefore, these processes must be parameterized by adjusting the two terms in Equation 4.

- Drainage basin representation in KINEROS is accomplished by treating the catchment as a cascading network of elements representing runoff surfaces, channels, and ponds. Channels may receive flow from surfaces on either side of their length or from other channels. Surfaces are rectangular, but may be cascaded or arranged in parallel to represent complex topography or erosion features. For example, gullies can be represented by subdividing a surface into parallel flow planes. Each element is characterized by assigning parameter values that control its runoff and erosion responses.

### Model landuse scenarios for Pang Khum

The three model scenarios investigated herein





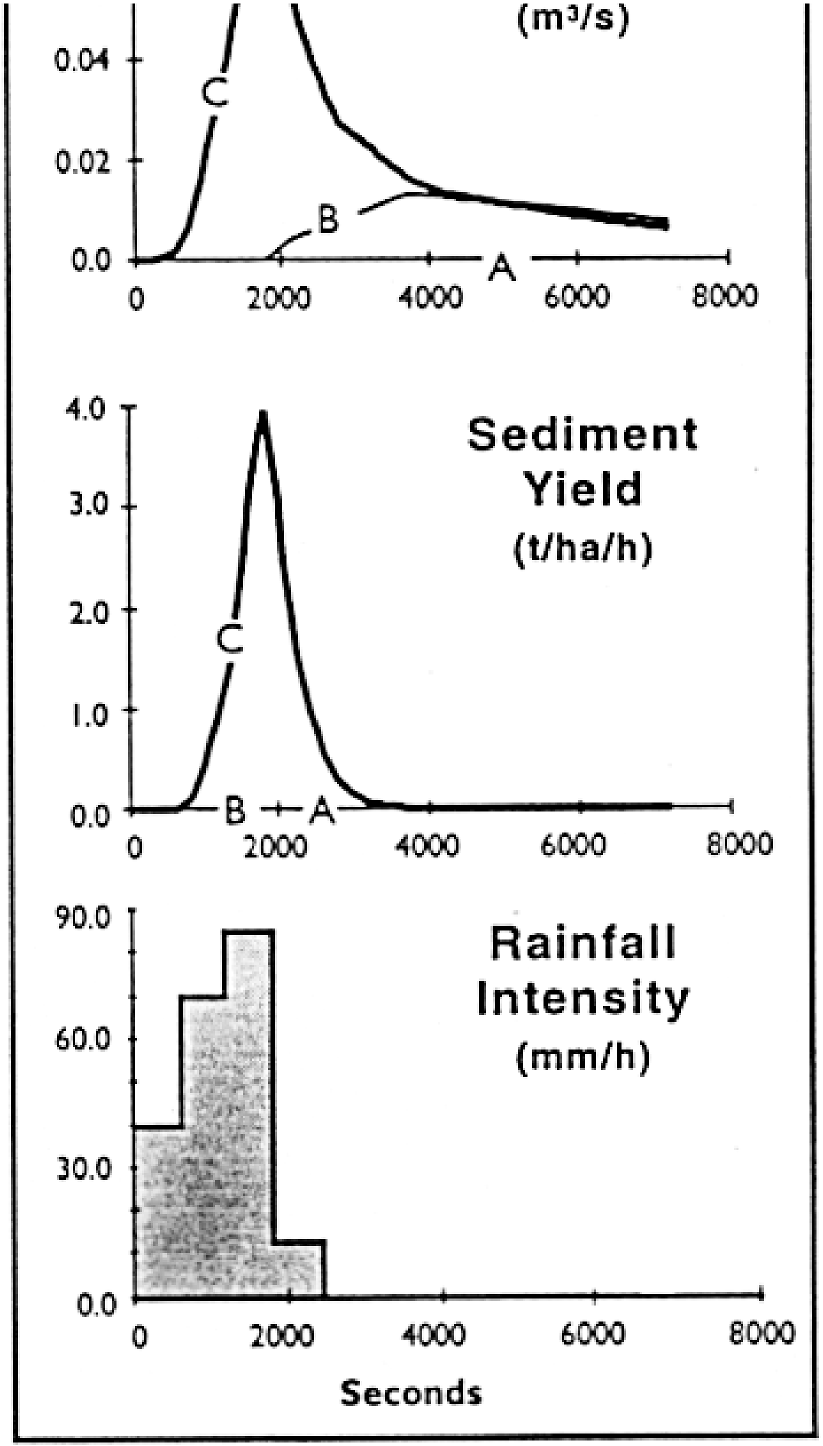
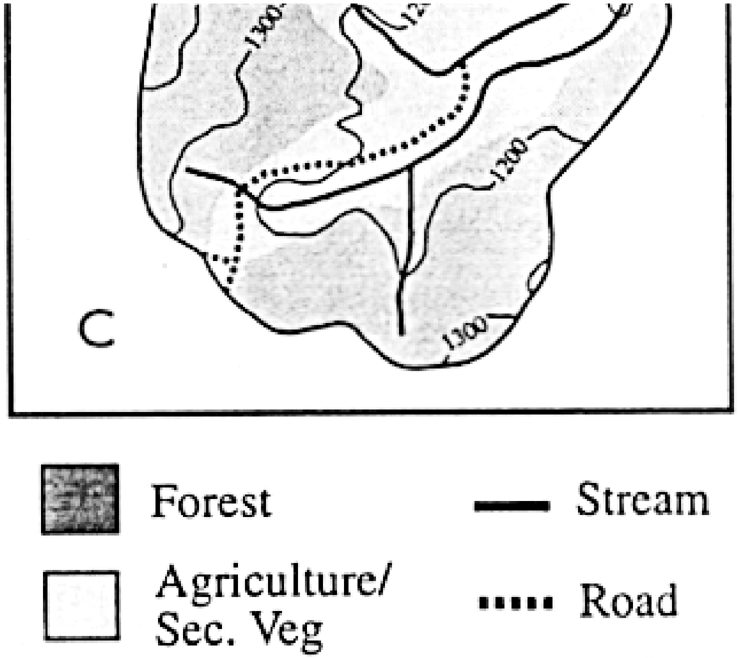


Figure 3. KINEROS simulation of stream dis-



charge and sediment yield changes resulting from landcover conversion within a small watershed in northern Thailand (Ziegler and Giambelluca, in press). The simulation was conducted for three landcover 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.

(Figure 2; Panel I) represent the evolution in landuse practices that has taken place within Sam Mun 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 landuse, resulting in approximately 25% of the area being in various stages of swidden agriculture, including cultivation, fallow, and secondary vegetation regrowth. Scenario 3 is Scenario 2 with a road constructed through a small lowland portion (0.25%) of the area. Each scenario is simulated for the same 112 ha sub-basin, which lies on the NE side of Doi Mon Ang Get near Pang Khum. All values to build the basin flow planes are based on field observations and measurements, or derived from a landuse map obtained from the Department of Geography, Chiang Mai University. Basin geometry for Scenarios A and B was described with 13 overland flow planes; Scenario C, 17 planes.

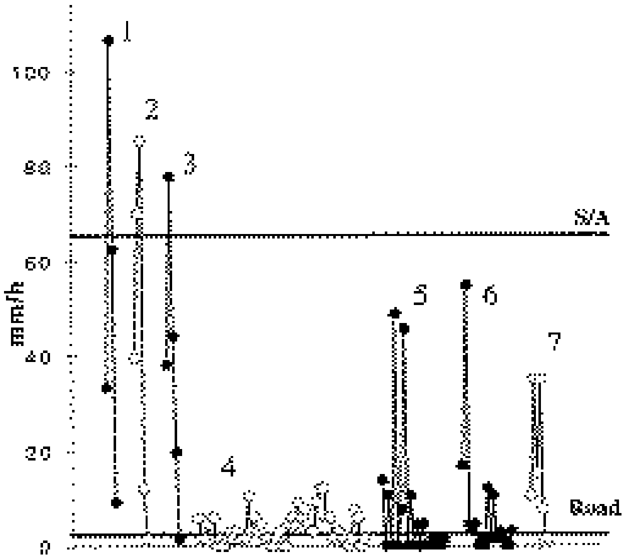
**Table 1. Parameter values used in KINEROS simulations**

| **Parameter** | **Agriculture/** | **Road** | |
|---|---|---|---|
| | **Forest** | **Secondary Veg.[a]** | **Surface** |
| Area (ha) | 83.78 | 28.0 | 0.28 |
| Saturated hydraulic conductivity (mm h-1) | 172.60 | 65.33 | 2.40 |
| 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 |
| KUSLE**[b]** | 0.24 | 0.28 | 0.41 |
| D50 (mm)**[c]** | 0.095 | 0.108 | 0.129 |
| Note: All values are based on field measurements | | | |
| **a** Values are area-weighted based on secondary vegetation lands comprising about 80% and agriculture lands comprising about 20% of the group area.[22] KUSLE and D50 values in this group are based on secondary vegetation measurements only. | | | |
| **b** The Universal Soil Loss Equation K factor was calculated from soil texture values using the Wischmeier and Smith nomograph;[23] it is used to calculate rainsplash and hydraulic erosion parameters.[24] | | | |
| **c**The soils for the three landuse types fall into the sandy loam texture class; specifically soils in the general area are paleudults, haplahumults, kandiustults, paleustalfs, and dystropepts.[25] | | | |

### Model inputs

Most model inputs (Table 1) are derived from soil physical and hydrological property measurements made in Pang Khum (Figure 1) or nearby Kae Noi during a prior study.[26] Rainfall was measured at 10-minute intervals in Pang Khum 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. Total rainfall, maximum rainfall intensity, and event durations appear in Table 2. In Figure 3,



these storms are plotted against median values of saturated hydraulic conductivity (Ks) for road surfaces and agriculture/secondary vegetation lands.

Periods where rainfall intensity exceed Ks 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.[27] Each simulated event is independent (i.e., soil moisture was initialized each time to approximately the field capacity).

**Table 2. Summary information of simulated storms and KINEROS-predicted Horton overland flow and sediment transport values**

| | | Simulated Storms | | | KINEROS Results | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Storm | Scenario | TR (mm) | Max I (mmh-1) | D (min) | PFR (m3s-1) | TP (min) | RO (m3) | ROCB % | 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 | " | " | " | 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 |

Note: Only events that produced overland flow are shown in the table.

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

## Results & Discussion

### Simulations of runoff and erosion

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

- **Scenario A.** No overland flow would be produced from this all-forest landscape because calculated infiltration rates are greater than maximum rainfall intensities.

- **Scenario B.** Only one (#2) of the seven storms would produce HOF despite three storms having rainfall intensities greater than Ks on secondary vegetation and agricultural lands. Although HOF was predicted during storm 2, predicted sediment transport from contributing flow planes was negligible.

- **Scenario C.** All seven rain events would produce overland flow and sediment transport because road Ks 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 during the three 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.28 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 that

1. overland flow is generated on road surfaces early in a storm event; and that
2. linear road segments route overland flow to the stream channel more quickly than hillslopes,

thereby reducing the time to peak discharge and increasing the peak flow value. This is an example of the road extending the stream channel network.29

The sediment yield graph shows that

1. the sharp sediment pulse generated from the road segments (Scenario C) corresponds with the peak in the HOF hydrograph; and
2. predicted sediment transport from the overland flow planes for Scenario B (no roads) was negligible.

### Limitations to the simulations

Although KINEROS was forced with recorded rainfall data and field measurement data of crucial hydrologic and erosion-related properties, it was not calibrated or validated with measured stream discharge or sediment yield data. In addition, the generalized model description of the basin does not specifically include all important landscape features that may influence runoff routing (e.g., gullies, ditches, cutbanks, paths, and discharge points where HOF is directed onto the hillside). The exclusion of paths in these simulations is an especially important limitation as we believe them to be responsible for much of the HOF initiation on steep agricultural fields;30 their absence is likely responsible for the negligible runoff on agriculture/secondary vegetation lands in these simulations. Therefore, the simulation results only reflect relative differences in responses of HOF and sediment transport resulting from differences in soil physical and hydrological properties.

We can not 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 do believe erosion on road surfaces is significant, these simulations do not account for the event-to-event changes in sediment availability, or to detachment by vehicle traffic or gullying processes. In fact, erosion parameters (*es* and *eh*) for each landuse type are computed from USLE K factor estimations (see note in Table 2), which for this general area of northern Thailand, have been difficult to determine.31

## 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, overland flow and concomitant sediment transport on roads is greater than that from the agriculture-related lands.

One explanation is that compared to swidden-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 near Pang Khum, the hydrological/ geomorphological impacts of an swidden-dominated landscape may be greater than predicted here.

Nevertheless, this work stresses the need to place greater emphasis on mitigating impacts of road expansion, an inevitable consequence of rural development in montane Southeast Asia.

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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## Notes

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**27** Woolhiser et al., *KINEROS*.

**28** *cf.* Ziegler and Giambelluca, "Importance of Rural Roads."

**29** *cf.* Jones and Grant, "Peak Flow Responses."

**30** *cf.* Ziegler and Giambelluca, "Importance of Rural Roads."

**31** *cf*. K. Vlassak, S. Ongprasert, A. Tancho, K, Van Look, F. Turkelboom and L. Ooms, *Soil Fertility Conservation Research Report 1989-1992* (Chiang Mai: SFC Project, Maejo University, 1992).