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Horton overland flow contribution to runoff on unpaved mountain roads: A case study in northern Thailand

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Abstract

Two indirect methods are used to detect evidence of intercepted subsurface flow (ISSF) by the road prism in the Pang Khum Experimental Watershed (PKEW) in northern Thailand. During the 12-month study period we failed to observe a soil moisture change that corresponds with ISSF being generated by the water table rising above the road surface. In support of the soil moisture data, δ^{18}O signatures of rain water, road runoff, and stream water (a proxy for soil water) suggest Horton overland flow (HOF) generated on the road surface, not ISSF, is the dominant source of observed road runoff during typical rainfall events in the study area. This finding, which is contrary to the ISSF-dominant road runoff regime found typically on unpaved mountain roads in the US Pacific NW, suggests that the use of a HOF-based model to simulate runoff and sediment transport on unpaved roads in PKEW provides not only lower bound estimates of these processes, but realistic approximations for typical events. Copyright © 2001 John Wiley & Sons, Ltd.

Introduction

Mountain roads constructed on shallow soils are known to intercept subsurface flow (SSF, Megahan, 1983; Megahan and Clayton, 1983; Reid and Dunne, 1984; Jones and Grant, 1996; Jones, 2000). As shown in Figure 1A, SSF travelling downslope above the soil–bedrock/regolith interface can exfiltrate from the cutbank onto the road surface. Exfiltrated water, referred to herein as intercepted subsurface flow (ISSF), can be transported overland to the stream system—possibly at a more rapid rate than SSF. Megahan (1983) reported ISSF in the US Pacific NW to be 7–18 times greater than Horton overland flow (HOF) generated by rain falling directly on the compacted road surface. In areas with deep soils, ISSF may be rare because the soil–bedrock/regolith interface is often situated below the cutbank and road surface. For this 'deep-soil' scenario ISSF can be generated if a local water table rises above the road surface (depicted in Figure 1B).

In the Pang Khum Experimental Watershed (PKEW) in northern Thailand (Figure 2), where soil depth exceeds 2 m, we are using the quasi-physics-based, HOF-based KINEROS2 model (Smith *et al*., 1995a, b) to quantify hydrological and erosional impacts of unpaved mountain roads. During three years of fieldwork we have yet to observe ISSF, a road runoff component that cannot be modelled explicitly with KINEROS2. Absence of this end member suggests that the KINEROS2 simulations,

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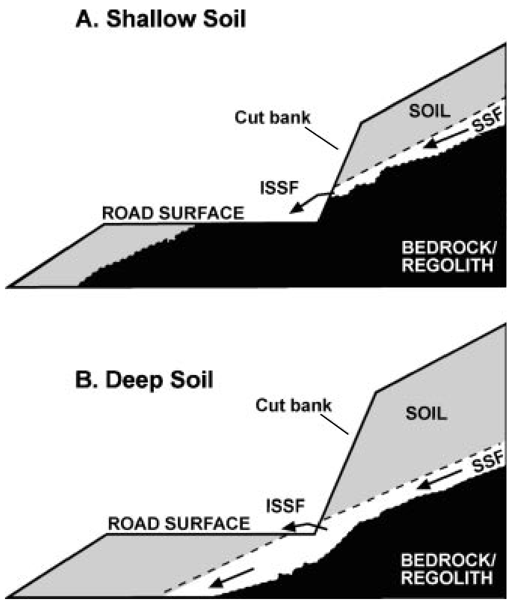

Figure 1. Two end members of the intercepted subsurface flow (ISSF) system, for which subsurface flow (SSF) exfiltrates onto the road surface: (A) *for shallow soils*, SSF travelling above the bedrock/regolith interface can exfiltrate at a road cut becoming ISSF; (B) *for deeper soils*, ISSF can occur if the water table rises above the road surface

which from one point of view provide lower-bound estimates, produce reasonable estimates of road runoff and sediment transport during typical storm events in PKEW. This briefing reports on the use of automated soil moisture measurements and oxygen isotope analysis to detect evidence of ISSF as a dominant flow path on PKEW roads. The existence of ISSF would necessitate our use of a more sophisticated model that is capable of simulating ISSF.

Thailand Roads Project and 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 of this work is to determine the role of roads in initiating hydrologic change and contributing to erosion processes in tropical highlands of montane mainland southeast Asia. Field work conducted mostly in the 93·7-ha PKEW has included: (1) establishing a network of six climatological stations (Figure 2) 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 land-use types to understand runoff generation and erosion processes, and to parameterize model variables; and (3) conducting detailed surveys of basin landcover/land-use and road-related phenomena (usage, sediment sources, and runoff exit points). Results from this work are presented elsewhere (Ziegler *et al*., 2000a, b; 2001a, b).

PKEW is part of the larger Rim River Basin that eventually drains into the Ping River, which empties into the Chao Praya River. Bedrock in PKEW is Triassic granite; deep (>2·5 m) soils include ultisols, alfisols, and inceptisols (field survey at stations 401–4, Figure 2). Roads, access paths, and dwelling sites comprise about 1% of the PKEW area. Approximately 12% of the basin area is active agricultural land; 13% is fallow land; 31 and 12% are young (4–10 years) and advanced (>10 years) secondary vegetation, respectively; and 31% is disturbed, old-growth forest. The road in PKEW was created by hilltribe farmers using handtools. Approximately 70% of all road runoff in PKEW directly enters the stream network at intersections of the road and stream channel (Ziegler *et al*., 2001b). Despite light traffic, the Upper and Lower PKEW Roads are important sediment sources for material entering the stream channel network.

Methods

During the period extending from 1 Aug 1998 through 14 Aug 1999, road runoff was measured periodically during rain events at a collection station constructed at the footslope of a 165-m road section near the watershed entrance (Road Q Station near Station 406 in Figure 2; described by Ziegler *et al*., 2000b). A tipping bucket rain gauge (0·254-mm threshold) and datalogger were used to measure 1-min rainfall intensities (Station 406, Figure 2). To detect a rise in the water table, we monitored the soil moisture at three depths relative to the road surface. Approximately 2 m downslope of the road runoff collection station, we installed three Campbell CS-615 soil moisture probes horizontally into the face of the road cutbank at depths 0, 0·2, and 0·4 m below the road surface (depicted in Figure 3). Probe-measured values of soil moisture were calibrated against those determined from gravimetric samples taken at the time

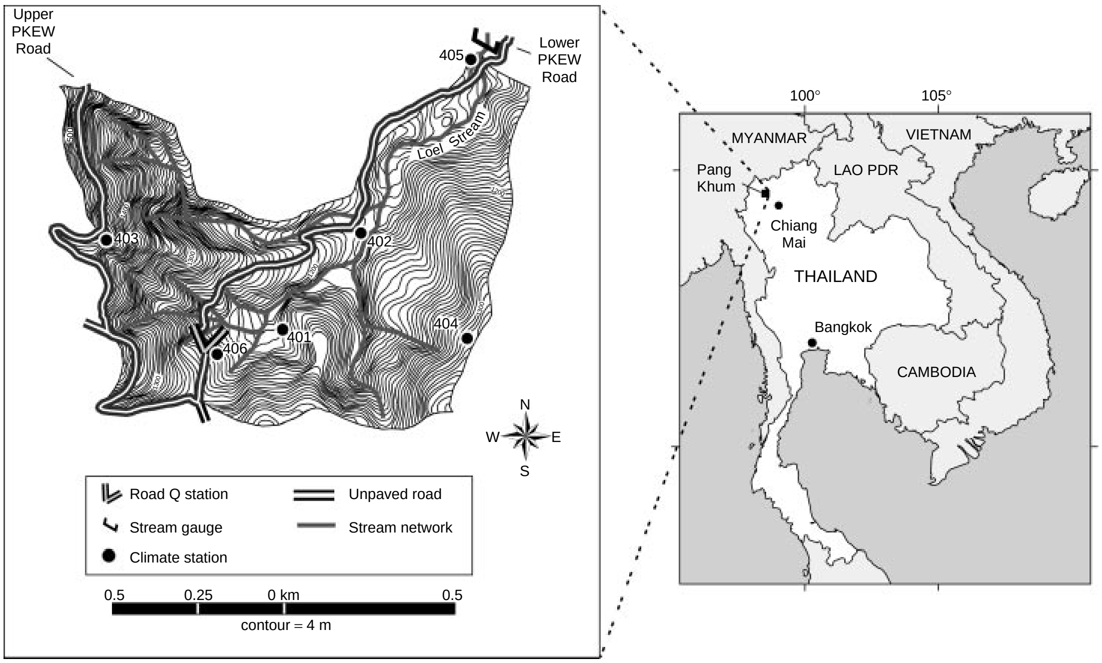

Figure 2. The Pang Khum Experimental Watershed in northern Thailand. Experiments were performed at the base of a 165-m road section originating at the watershed entrance; measurement locations are located adjacent to the road discharge (Q) collection station and station 406 (details are shown in Figure 3)

of installation. A datalogger recorded instantaneous changes in the volumetric soil moisture. If ISSF were to occur anywhere in PKEW, the measurement site is one of the most likely locations, because (1) the measurement position is at the base of a long hillslope and near the confluence of three first-order streams, and (2) the road surface is incised about 1 m into the landscape surface. Because the soil–bedrock/regolith interface is well below the road surface in PKEW, if ISSF were to occur, it would be by the mechanism depicted in scenario B of Figure 1.

As an exploratory approach to detect the presence of ISSF in road runoff, we compared $^{18}O/^{16}O$ signatures (expressed as $\delta^{18}O$) of stream water (SW) with rain water (RW) and road runoff (RR) during natural events. $\delta^{18}O$ was analysed at the Environmental Isotope Laboratory of the University of Waterloo; values are reported in parts per thousand(‰), relative to VSMOW. Samples (10–50 ml) of RR and RW were collected at the road discharge station; SW samples were collected in the nearby stream (Figures 2 and 3). Sample times for all three variables were 0, 10 and 20 min after runoff generation. We assume the source for prestorm SW is ‘old water’, such that the $\delta^{18}O$ signatures for SW, soil water and ground water are similar; and hypothesize that SW and RW signatures are different (Genereux and Hooper, 1998). Based on the above assumption, if RR is predominantly Hortonian in origin, then RR and RW $\delta^{18}O$ signatures should be similar over the course of a storm. Signature differences between RR and RW, and/or similarity of RR and SW signatures, support the occurrence of ISSF.

Soil Moisture Change

Figure 4 shows 1-min rainfall values and corresponding temporal changes in soil moisture at three depths below the road surface. As an example of a period favourable to raising the water table above the road surface, 6–10 Sept was selected. More than 200 mm of persistent, low-intensity rainfall (almost 12% of the total rainfall for the 12-month study period) occurred during these 5 days. Corresponding depth-specific soil moisture response for this 5-day period

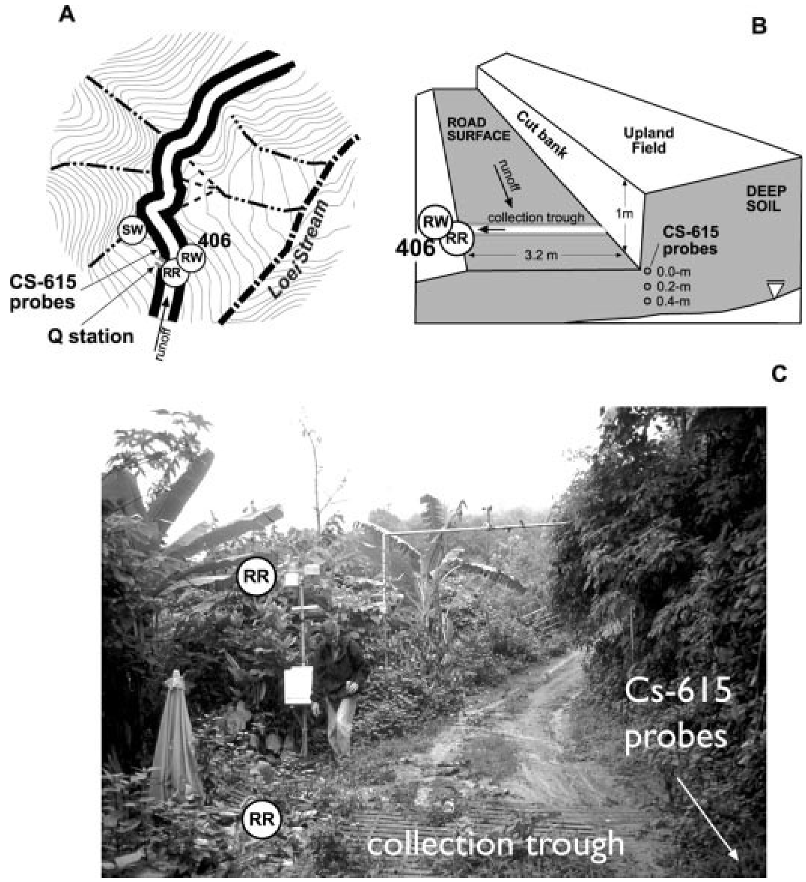

Figure 3. (A) Enlargement of the road section where samples of rain water (RW), soil water (SW), and road runoff (RR) were collected for $\delta^{18}O$ analysis. (B) Schematic showing the location of the CS-615 soil moisture probes relative to the locations where RR and RW samples were collected. To show the probe location relative to the cutback, the schematic is drawn from the opposite perspective as the map in A. The collection trough channels RR to the discharge (Q) collection station (described in detail by Ziegler *et al*., 2000a, b). The triangle refers to the general location of the local water table below the natural (soil) road surface (e.g. the deep soil scenario depicted in Figure 1B). (C) Monitored road section and data collection locations

is shown in Figure 5. Soil moisture increases first at the 0-m probe. An increase is finally detectable at the deeper probes several minutes later. To improve clarity the 0·2-m probe response, which is practically indistinguishable from that of the deepest probe, is not shown. This ordering in depth-specific soil moisture response indicates that soil moisture changes are caused by water infiltrating downward in the soil profile, rather than rising up from below, as would be the case if the saturated zone had expanded upward, intersecting the road surface. This general relationship in soil moisture change was observed for all events during the measurement period, providing no support for a rise in the water table that would permit ISSF to occur. Finally, at no time during the study period did soil moisture at any of the three depths rise above estimated minimum soil porosity (i.e. saturation of the near-surface profile below the road did not occur; Figure 4).

$\delta^{18}O$ Data

Figure 6 shows temporal change of RW, SW and RR $\delta^{18}O$ for two events. From Figure 6 it is clear that there are both intra- and inter-storm variations in the $\delta^{18}O$ of rain water at the field site. The initial

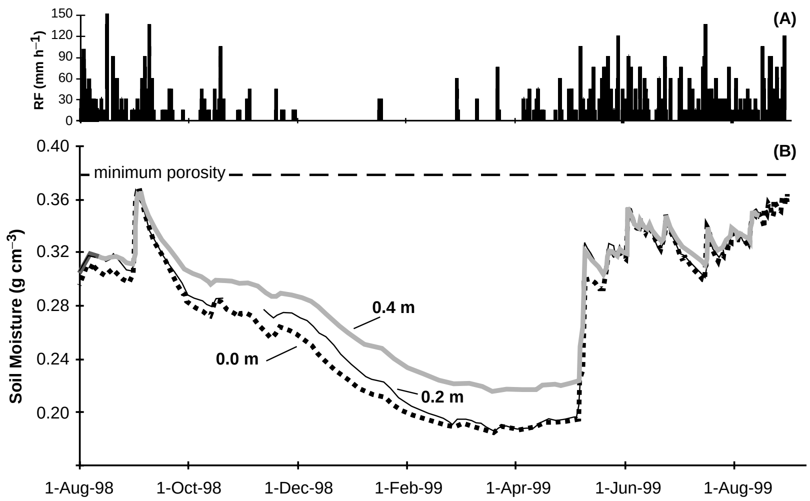

Figure 4. (A) Rainfall and (B) temporal change in volumetric soil moisture at three depths below the road surface during the study period. Estimated porosity ranges from 0·38 to 0·45 over the monitored depths

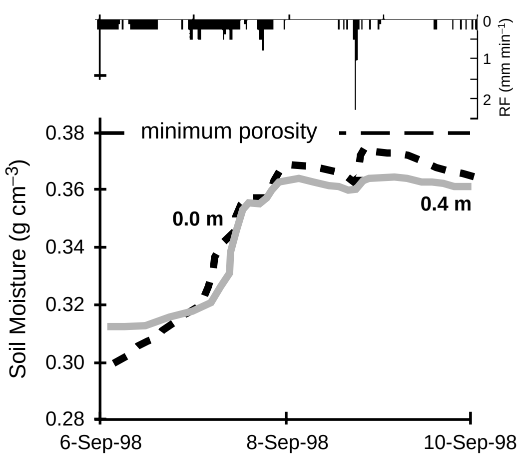

Figure 5. Change in depth-specific soil moisture in response to persistent, low-intensity rainfall. Estimated porosity ranges from 0·38 to 0·45 over the monitored depths. See Figure 4 for comparison

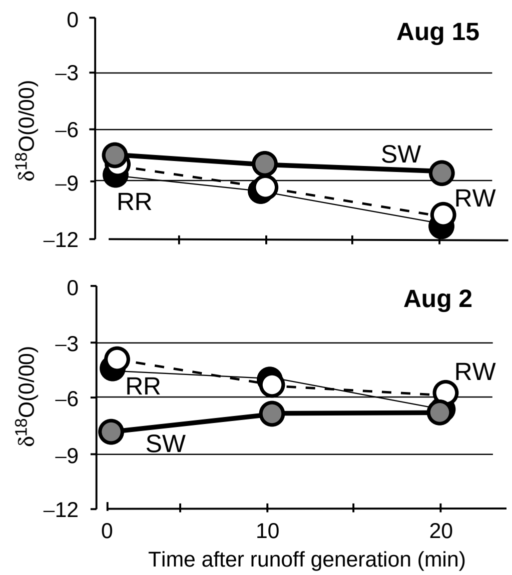

Figure 6. Comparison of δ^{18}O signatures for pre-event stream water (SW, grey circles), rain water (RW, open circles), and road runoff (RR, black circles) over the course of two storms. Storm total, maximum intensity, and duration for the 2 Aug 1998 event are 16·5 mm, 30 mm h^{-1}, and 80 min, respectively; for the 15 Aug, 1998 event, 51·3 mm, 152 mm h^{-1}, and 56 min, respectively

δ^{18}O value for the Aug 15 event was −8·4‰, compared with −4·3‰ for the Aug 2 event; and during both events, δ^{18}O values decreased at each successive measurement time. Isotopic variations in rainfall at intra- and inter-storm time scales are well documented for high latitude sites (Pionke and DeWalle, 1992; Ingraham, 1998). For example, Pionke and DeWalle (1992) found mean δ^{18}O to range from about −3·5 to −15·4‰ for 10 storms during a 7-month period in central Pennsylvania. In contrast to the variable RW δ^{18}O values in the PKEW data, initial SW δ^{18}O values were nearly identical for the two storms in

PKEW (−7·7 vs −7·8‰). These values changed only slightly over time, becoming more like the RW signature, as rain falling directly into the stream mixed with the 'older' SW. Importantly for this analysis, RR and RW δ^{18}O are indistinguishable on both intra- and inter-storm time scales, suggesting that the source of RR is predominantly RW, not SW, which would be the case if significant ISSF were occurring. Additionally, the patterns shown in Figure 6—particularly the variability in RW δ^{18}O for this tropical site—suggest that a more extensive isotopic study could be used to separate the RR hydrographs into RW (event water) and ISSF (pre-event water) constituents in watersheds where ISSF is a dominant end member.

Conclusion

Using two independent methods, we failed to find evidence that interception of subsurface flow by the road prism contributes substantially to road runoff in the study area. Although the δ^{18}O data are limited in number and detailed hydrologic measurements are confined to one location, they suggest that focusing on the HOF mechanism is appropriate for studying road runoff generation and erosion in PKEW. The dominance of the HOF component over an ISSF component in PKEW, which is contrary to the findings typically reported for mountain roads (e.g. in the US Pacific NW), likely does not apply to all watersheds in northern Thailand either; we have witnessed ISSF by roads in basins very near PKEW. Even in the absence of ISSF, HOF alone may be sufficient to put road-related hydrological and erosional impacts in PKEW on the same level of importance as those caused by current steep-slope agricultural practices, which in general are blamed for much downstream sedimentation in Thailand. As a final point, preliminary analysis of δ^{18}O at this tropical location suggests that conservative tracer analyses, when thoroughly applied, could be useful for partitioning stream storm hydrographs into constituent sources.

Acknowledgements

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