HYDROLOGICAL PROCESSES
Hydrol. Process. **22**, 4339–4354 (2008)
Published online 17 July 2008 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.7039

The roles of roads and agricultural land use in altering hydrological processes in Nam Mae Rim watershed, northern Thailand

Lan Cuo,[1†] Thomas W. Giambelluca,[1*] Alan D. Ziegler[1,2] and Michael A. Nullet[1]

[1] *University of Hawai'i at Mānoa, Department of Geography, 2424 Maile Way, Honolulu, Hawai'i 96822 USA*
[2] *National University of Singapore, 1 Arts Link, Kent Ridge, Singapore*

Abstract:

The distributed hydrology soil vegetation model (DHSVM) is applied in the 107 km^2 Nam Mae Rim watershed (NMRW) in northern Thailand. Simulations using land cover scenarios for 1989 and 2002, extreme deforestation, and forest, each run with and without roads, show that roads have very small effects on the mean water fluxes, but significantly increase peak flows for all land cover scenarios. The magnitude of the road effect on peak flow depends on the land cover context in which the roads are placed. Roads have the smallest effect on peaks within the extreme deforestation scenario, and affect mainly the smallest peaks in the two homogeneous land cover scenarios (forest and extreme deforestation). Roads have the largest effect on peaks within the heterogeneous landscapes of the two historical land cover scenarios (1989 and 2002). This result indicates that, by conveying surface flow quickly to the stream, roads within a fragmented landscape are especially important in converting greater amounts of overland flow into higher peak flows. Without roads, the patchy land cover pattern buffers the impacts of the scattered overland flow source areas and limits increases in peak flows.

The combined effects of land cover and roads are examined in comparison with forest. The 1989 and 2002 land cover patterns result in relatively small changes in the mean annual water balance, but with some significant changes in the seasonal distribution of fluxes. Streamflow is lower in the late wet season and higher in the dry season for the 1989 and 2002 scenarios compared with forest. Conversion from forest to any of the other land cover scenarios results in higher dry season evapotranspiration (ET) and lower wet season ET. The extreme deforestation scenario results in much lower wet season ET and much higher annual streamflow, but little change in dry season streamflow, in comparison with forest.

KEY WORDS catchment hydrology; road effects; land cover; DHSVM; south-east Asia; cumulative effects

Received 8 June 2007; Accepted 28 February 2008

INTRODUCTION

The last few decades have seen rapid shifts from old-growth forest to fragmented secondary forest and agricultural fields in mountainous areas of SE Asia (Fox and Vogler, 2005). The improvement and expansion of roads and other transportation infrastructure linking market centres and rural areas has also been occurring (Castella *et al.*, 2005). This dramatic land-cover change influences water and energy fluxes at local to regional scales (Giambelluca, 2002). Such changes may have important consequences for water supply, water quality, soil conservation, agricultural productivity, and the well-being of the region's inhabitants (Wilk *et al.*, 2001; Bruijnzeel, 2004; Xu *et al.*, 2005; Sidle *et al.*, 2006; Thanapakpawin *et al.*, 2007).

Numerous field studies have found that deforestation increases total streamflow (Bosch and Hewlett, 1981; Hamilton and King, 1983; Calder, 1999), but reduction of dry season flow has also been reported (Hamilton and King, 1983). Compiling the results of numerous field and modelling studies, Bruijnzeel (2004) found deforestation in tropical areas resulted in streamflow increases roughly proportional to the amount of biomass removed, an effect attributed to decreased evapotranspiration (ET). Usually, reduced ET contributes mostly to baseflow, enhancing stream discharge in all seasons. However, where deforestation results in reduced soil infiltration rates over extensive areas, increases in wet season storm flow may become so large that groundwater recharge is limited, resulting in reduced baseflow and, hence, lower dry season flows.

Roads disrupt watershed hydrological and geomorphological systems and contribute to adverse cumulative watershed effects (Reid, 1993; Montgomery, 1994). In some instances, road impacts may be greater than those of other recognized disruptive activities. In northern Thailand, Ziegler and Giambelluca (1997a,b) found that surface runoff was relatively rare on agricultural lands, even under prolonged, high intensity rainfall, but infiltration-excess runoff, also called Horton overland flow (HOF), was generated on road surfaces during almost every storm (Ziegler *et al.*, 2001a,b). Despite evidence that

* Correspondence to: Thomas W. Giambelluca, University of Hawai'i at Mānoa, Department of Geography, 2424 Maile Way, Honolulu, Hawai'i 96822 USA. E-mail: thomas@hawaii.edu
† Current address: University of Washington, Department of Civil and Environmental Engineering, Seattle, Washington 98195 USA.

road-related impacts often outweigh those of other land-cover changes, conservation efforts in many parts of the world have historically focused on agriculture and timber harvesting, often ignoring road effects (Ziegler *et al*., 2004). While numerous studies have included road impacts (Bren and Leitch, 1985; Grayson *et al*., 1993; Jones and Grant, 1996; Megahan and Ketcheson, 1996; Foltz and Elliot, 1997; Thomas and Megahan, 1998; Wemple, 1998; Ketcheson *et al*., 1999; Luce and Black, 1999; Bowling *et al*., 2000; La Marche and Lettenmaier, 2001; MacDonald *et al*., 2001; Tague and Band, 2001; Wemple *et al*., 2001; Lane and Sheridan, 2002; Wemple and Jones, 2003; Croke *et al*., 2006), our ability to assess the hydrological impacts of road versus non-road land-cover changes is still developing.

Hydrological models can be important tools in understanding the complexities of land-cover change and road effects on basin hydrological functions. Distributed, physically based watershed models, such as the distributed hydrology soil vegetation model (DHSVM) (Wigmosta *et al*., 1994, 2002), allow the spatial patterns of vegetation and soils to be depicted in the context of topographic controls on surface and subsurface water flows, and provides detailed information on the spatial distributions of water and energy fluxes. DHSVM also incorporates modules to allow roads to be explicitly represented in the model. Most previous applications of DHSVM have been in the Pacific Northwest region of the USA and British Columbia, Canada (Leung *et al*., 1996; Schnur *et al*., 1997; Nijssen *et al*., 1997; Storck *et al*., 1998; Burges and Wigmosta, 1998; Bowling *et al*., 2000; Westrick and Mass, 2000; La Marche and Lettenmaier, 2001; Thyer *et al*., 2004).

In a related study, Cuo *et al*. (2006) used DHSVM to simulate the effects of roads on the hydrology of Pang Khum experimental watershed (PKEW), a 94 ha watershed in the mountains of northern Thailand. In this work, the interaction between roads and non-road surfaces in altering hydrological processes is investigated in a 107 km^2 mountainous watershed in northern Thailand. The paper analyses the effects of roads and agricultural land-use on average stream discharge, seasonal streamflow patterns, soil moisture, evapotranspiration, and peak flow. This work is based on DHSVM simulations for four land-cover scenarios, representing the original forest, historical, and extreme land covers, with and without roads.

METHODOLOGY

In this study, DHSVM was applied to Nam Mae Rim watershed (NMRW), using land-cover-specific soil and vegetation parameters calibrated within PKEW, a sub-watershed of NMRW. DHSVM performed well in simulating the time series of soil moisture measured at four sites and in three root-zone soil layers, during the 1 year calibration period and 2 year validation period. Simulation of stream discharge captured the major features of the stream hydrograph and reproduced the details of the observed flow reasonably well during two of the three years of simulation. A description of the calibration and testing of DHSVM within PKEW is given by Cuo *et al*. (2006). For this paper, the simulation was done for the whole of NMRW, rather than just PKEW, because the larger areal extent of NMRW provides a better sample of land-cover change and road density in the region. In this study, DHSVM was used to simulate hydrological fluxes in NMRW for a series of land cover scenarios, with and without roads. To test for statistical significance of simulated differences between pairs of scenarios, the Wilcox signed rank test was used.

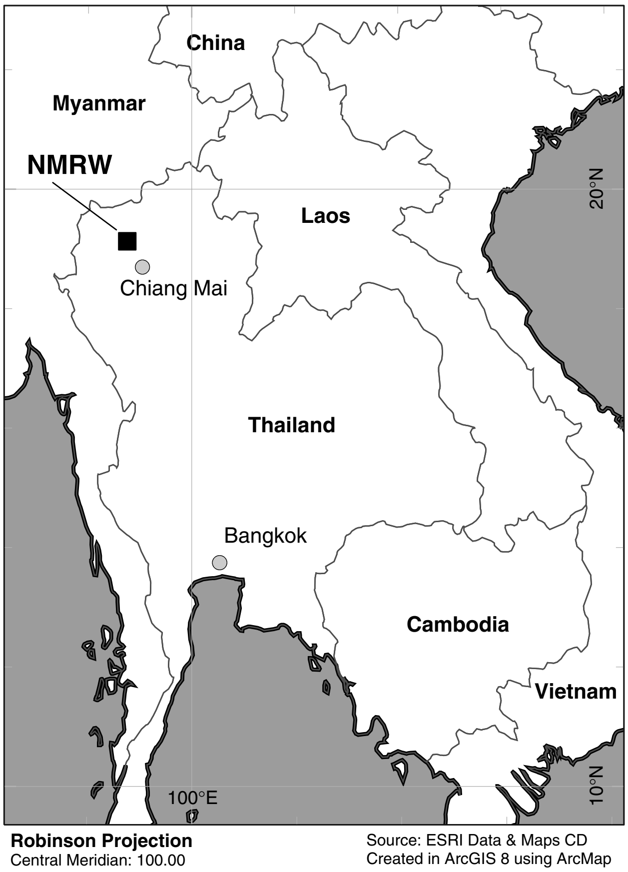

Figure 1. Geographical location of Nam Mae Rim Watershed (NMRW)

Study basin

NMRW (19°1′12″N to 19°10′12″N, and 98°37′12″E to 98°46′12″E) is located in Chiang Mai Province, northern Thailand (Figure 1). Elevation ranges from 680 to 1776 m, and slopes are between 0 and 47°, based on a 20 m digital elevation model (DEM). The area has a monsoon rainy season that extends from May to October. Based on data collected in PKEW, a headwater basin within NMRW, this 6 month period accounts for 80–90% of the annual rainfall total (1850 mm, mean from 1997–2006). One-third of the annual rainfall total occurs in August and September. The region experiences strong elevational rainfall gradients, which are related more to storm duration than rainfall intensity (Dairaku *et al*., 2004).

Annual stream discharge in PKEW is 20–40% of the precipitation total. The highest daily flows (0·03–0·08 $m^3 s^{-1}$) occur during the August–October period. By the end of the year, baseflow typically returns to that observed during the first few weeks of the rainy season (0·015 $m^3 s^{-1}$). Peak flows exceed 0·4 $m^3 s^{-1}$ only two or three times annually, but rarely for more than a few minutes. The maximum recorded peak was 1·3 $m^3 s^{-1}$. High flows typically occur in response to short-duration (<2 h) storms with peak 1-minute rainfall intensities exceeding 100 mm h^{-1}. Sustained periods of 50 mm h^{-1} rainfall typically last only 5–10 min. Infrequent floods in downstream rivers are generally associated with tropical depressions moving westward from the South China Sea.

Bedrock is predominantly muscovite granite, with gneiss present. Large granite core stones are found throughout the basin. Valley floors often contain sorted material indicating prior mass wasting. Soils are predominantly Ultisols of the Udic moisture regime. Sparse zones of Inceptisols also occur on steep slopes on the western side of the basin. On moderate hillslopes, soils may reach depths in excess of 5–7 m. Thin A horizon soil (<0·25 m) is characterized by residual accumulations of quartz (>60%) and aluminium (Al_2O_3, 14%). Clay content increases from 10–20% near the surface to more than 40% at depths of 2–3 m. Bulk density increases over this range from <1 g cm^{-3} at the surface under forests to >1·4 g cm^{-3} in the weathered sub-horizons. The corresponding decrease in saturated hydraulic conductivity over this range is from >500 mm h^{-1} to <10 mm h^{-1} (Ziegler, 2000).

The major forest types include the deciduous forest associations of the lowlands (deciduous dipterocarp, bamboo, deciduous forest and mixed evergreen deciduous forest) and the evergreen forest of the uplands. Agriculture in the basin resembles a long-term cultivation system with short fallow periods, as opposed to traditional long-fallow practices that were common until a few decades ago (Schmidt-Vogt, 1999). Major crops include upland rice, maize, cabbage, beans, onions, tea, and fruit. Agricultural land is more prone to overland flow generation than forested land in the basin (Ziegler *et al.*, 2000; 2004).

Roads in NMRW evolved from walking paths connecting villages. Some road sections were created with hand tools, but the majority were constructed with backhoes or bulldozers in the 1970s for military/policing activities, logging, and to encourage settlement (Delang, 2002). Roads were built without side ditches or culverts to control the drainage of road surface water. Runoff water may flow down the road surface for distances exceeding 500 m until exiting onto a sideslope or entering the stream directly (Ziegler *et al.*, 2006). Road maintenance is typically done annually during the dry season with a backhoe, or intermittently by hand if needed in the rainy season. Because the road was not excavated deeply into the hillslope, the road surface typically does not intersect bedrock or saprolite. In PKEW, interception of subsurface flow (ISSF) by the cutbank has not been observed in more than 10 years of field work (Ziegler *et al.*, 2001b). In the greater NMRW, ISSF occurs in a few isolated locations—usually on concave hillslopes near the stream channel. As in PKEW, Hortonian overland flow is the dominant road runoff generation process in NMRW. Based on a digitized road map provided by Chiang Mai University, the total length of roads in the watershed is about 96 km, with higher density in the valleys. Road classes range from paved with two or more lanes to foot paths and trails. Roads one- or two-lanes wide total about 40 km in length, and frequently cross streams. Road area, including road surface area and bank area, is estimated to account for 0·6% of the total surface area, assuming the average combined width of road and road cutbank is 6·5 m. In the simulations, paved and non-paved roads were assumed to share the same morphological characteristics (road width and cutbank dimensions). Infiltration on unpaved roads was set at 1·08 mm h^{-1}, based on the measurements reported by Ziegler (2000). Figure 2a illustrates the topographic characteristics, roads, and streams of NMRW.

Model

DHSVM incorporates physical processes of canopy interception, ET, energy and radiation balance, runoff generation through saturation excess and infiltration excess mechanisms, ground water recharge and discharge, snow accumulation and melt, unsaturated soil moisture movement and saturated subsurface flow. The model can be run independently with observed climate data or can be coupled to a mesoscale meteorological model (Wigmosta *et al.*, 2002).

Using grids to represent spatial distribution of elevation, soil properties, vegetation properties, stream and road networks, DHSVM explicitly accounts for watershed spatial characteristics. A DEM is used to model downslope water movement and for climate data extrapolation. Each cell in the grid has user-specified root zone layers, root zone depths, and vegetation layers. DHSVM parameters can be classified into soil, vegetation (or land-cover), elevation, stream, road, and radiation categories. A detailed description of DHSVM can be found in Wigmosta *et al.* (1994), Storck *et al.* (1998), Nijssen and Lettenmaier (1999) and Wigmosta *et al.* (2002).

Data

NMRW has two fully-equipped climate stations, over advanced secondary forest (401) and agriculture (402), two stations in secondary vegetation measuring only soil moisture (403 and 404), and a stream gauge station (405). All stations are located in PKEW. Stream discharge at the NMRW outlet was not measured during the study period. Data collected at 401 are used as model forcing data, with measurements at 402 used to fill short gaps in the record. Measured net radiation (at 401 and 402), soil moisture (401, 402, 403, and 404) and streamflow were used to calibrate DHSVM (see Table I of Cuo *et al.*, 2006).

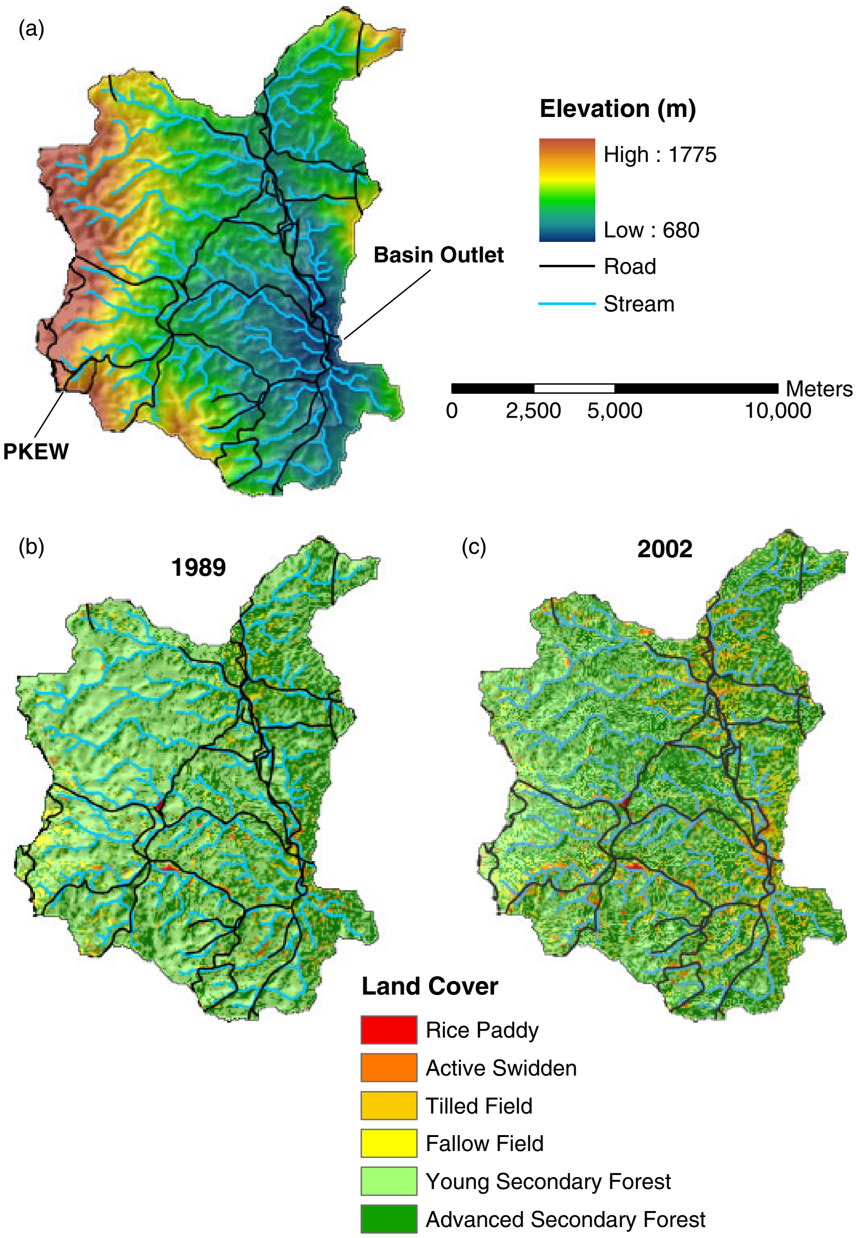

Figure 2. Nam Mae Rim Watershed, showing (a) elevation, stream network, and road network; (b) 1989 land-cover; and (c) 2002 land-cover

Table I. Land-cover distribution for PKEW (Cuo, 2005, Table 2.3) and each of the four scenarios used in this analysis

Land-cover class	Land-cover for PKEW and each NMRW scenario (%)				
	PKEW	1989	2002	Extreme deforestation	Forest
Rice paddy	1·0	0·2	0·1	0	0
Active swidden field	5·5	2·6	5·7	100	0
Tilled field	2·1	0·0	0·9	0	0
Fallow field	9·6	10·4	15·7	0	0
Young secondary forest	22·7	56·1	34·9	0	0
Advanced secondary forest	59·1	30·7	42·7	0	100

Simulations driven by hourly forcing data for the period from 1 February 1998 to 31 December 2000 are used to study road and land-cover effects. Two large gaps in the forcing data, 28 June to 3 August 1999 and 7 January to 27 February 2000, were filled with mean values of the periods 1 month before and after each gap. Model output for these gaps was excluded from subsequent analysis. Based on annual rainfall totals from station 401 in PKEW, the years 1998, 1999, and 2000 can be characterized as dry (1328 mm), wet (2264 mm), and slightly wet (1912 mm), in comparison with the measured 1997–2006 mean annual rainfall of 1850 mm.

Land-cover analysis

A 50 m DEM was generated from a 20 m interval contour map provided by the Multiple Cropping Centre, Chiang Mai University. Soil and land cover class maps were generated, aligned in origin and resolution with the DEM. Four land cover scenarios are used in the study: 1989, 2002, extreme deforestation, and forest. Land cover distributions for 1989 and 2002 are derived from a Landsat TM image collected on 3 February 1989, and a Landsat ETM+ image collected on 7 February 2002. Both images have a resolution of 30 m. Before developing the land cover classification, the shading effect due to topography in the mountainous terrain was reduced in both images while preserving their original spectral properties. Details of the procedure used to reduce the topographic effect and the land-cover classification are described in Cuo (2005).

After reducing the topographic effect, supervised classification was applied to the 2002 image using Global Position System (GPS) data (ground truth data) collected during a field survey in July 2002. The overall accuracy of the classification for the 2002 image is 91%. Unsupervised classification was used for the topographic-effect-reduced 1989 image since there are no historical ground truth data available. Spectral properties of each land-cover class produced by the unsupervised classification were compared with those from the 2002 image. Classes with similar spectral properties were assigned the same land-cover classes. Table I shows the land-cover classes and their percentages for PKEW (for comparison) and the four NMRW scenarios used in this analysis. Figure 2b and 2c show the land-cover distributions for 1989 and 2002. In addition to the two historical land-cover scenarios, the forest scenario is added to represent pre-disturbance conditions against which the other scenarios can be compared. To examine the sensitivity of hydrological response to land-cover change, an extreme deforestation scenario is also included, in which all cells are assigned the active swidden class. 'Active swidden' here refers to agricultural land currently undergoing annual planting without tillage. The landscape of uniform active swidden used in this scenario is not meant to represent a realistic future pattern, and would not be possible in a true swidden system, which requires that a large proportion of the land be unused at any given time. Agriculture in the region is trending towards more permanent, as opposed to shifting, cultivation systems (Fox and Vogler, 2005). But even with this change, it is unlikely that the whole basin will ever be actively farmed at the same time.

Parameter settings

Soil class maps are generated for each scenario by assuming that soil properties in the basin are determined by the land-cover and elevation. Table II shows the soil classes and their areal extent in each scenario. Parameter values for each land-cover class and soil class were initially set based on field measurements from previous studies in PKEW (Giambelluca, 1996; Giambelluca *et al.*, 1996; Ziegler and Giambelluca, 1997a), literature values, and model defaults (Cuo, 2005). Calibration was accomplished by subsequently adjusting values of some parameters, chiefly lateral and vertical saturated hydraulic conductivity (K_s), field capacity, porosity, wilting point, albedo, and maximum and minimum stomatal resistance. Calibrated parameter values for the land covers and soils found in PKEW are given by Cuo *et al.* (2006, Tables III and IV). In NMRW, three additional soil classes are found, ridge rice paddy, ridge active swidden, and ridge tilled, each accounting for very small areas. Parameters for those classes are assigned the same values as the corresponding 'valley' soil class.

The distribution of total soil depth in NMRW was generated based on the DEM with reference to the calibrated soil depth in PKEW using an ArcInfo macro language (AML) script provided by the DHSVM modelling group.

The watershed boundary is defined based on the DEM. The stream network for the watershed is also defined from the DEM using ArcInfo commands. The DHSVM modelling team provided an AML script to generate the stream and road morphology and network files as model input. A constant drainage area threshold of 0·1 km^2 (roughly corresponding to slope lengths of 300–400 m) was used to define the stream channel network. Stream classes are assigned based on the slope and contributing area. In the initial model implementation in PKEW, the stream channel was generated based on the fieldwork done in the same basin by McNamara *et al.* (2006), who found that slope lengths on the order of 60–70 m were sufficient to generate channels. However, model streamflow was overestimated and unresponsive to parameter adjustment with that channel configuration.

Table II. Soil class distribution for PKEW (Cuo, 2005, Table 2.3) and each of the four scenarios used in this analysis

Soil class	Soil in PKEW and each NMRW scenario (%)				
	PKEW	1989	2002	Extreme deforestation	Forest
Valley rice paddy	0·8	0·1	0·1	0·0	0·0
Valley active swidden	6·5	1·3	3·0	45·1	0·0
Valley tilled	4·2	0·0	0·6	0·0	0·0
Valley fallow	9·9	6·1	7·3	0·0	0·0
Valley young secondary forest	12·8	23·1	14·2	0·0	0·0
Valley adv. secondary forest	20·3	14·5	19·9	0·0	45·1
Ridge rice paddy	0·0	0·0	0·0	0·0	0·0
Ridge active swidden	0·0	1·4	2·6	54·9	0·0
Ridge tilled	0·0	0·0	0·4	0·0	0·0
Ridge fallow	0·3	4·3	8·4	0·0	0·0
Ridge young secondary forest	13·0	33·0	20·7	0·0	0·0
Ridge advanced secondary forest	32·2	16·2	22·7	0·0	54·9

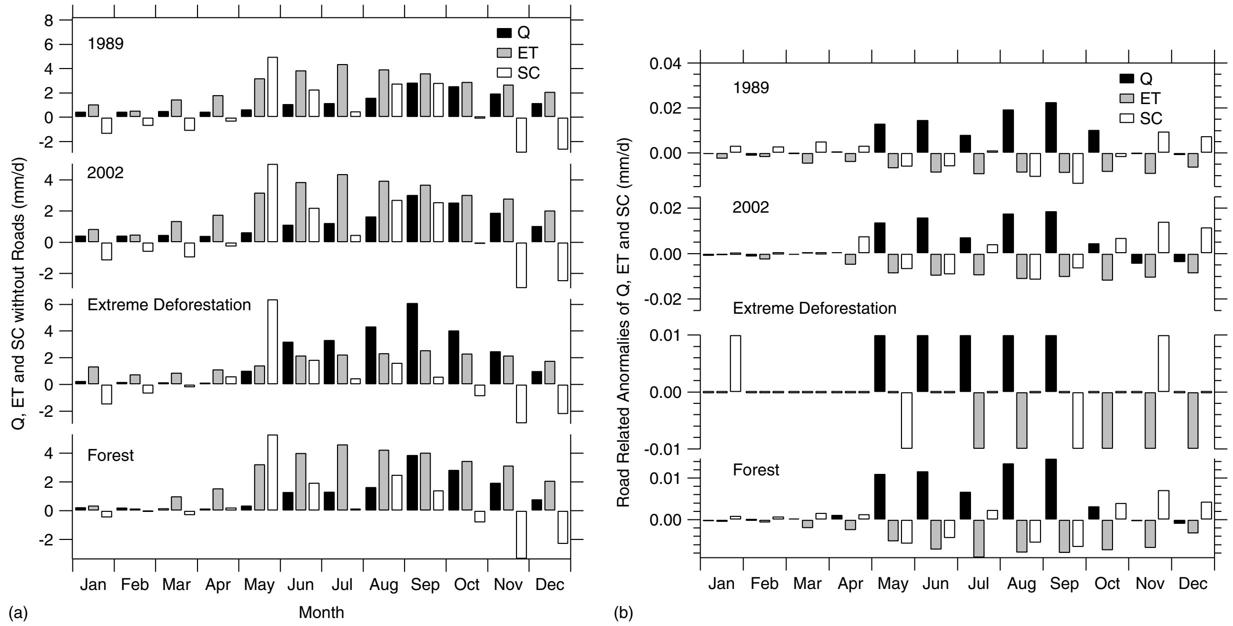

Figure 3. (a) Mean monthly streamflow (Q), evapotranspiration (ET) and storage change (SC) for the 1989, 2002, extreme deforestation, and forest landcover scenarios; and (b) road-related mean monthly anomalies (road minus non-road) in Q, ET, and SC for the four scenarios

Subsequently, it was necessary to reduce channel length to obtain a reasonable discharge simulation. The inability to represent the basin using the field observed channel network probably stems from the relatively coarse (50 m) resolution of the DEM used. Channel flow was routed via the linear storage mechanism. Flow routing on the road surface, generated by the AML and based solely on the DEM, was manually checked to remove errors in the flow routing network. Roads are divided into 1367 segments to reflect changing routing characteristics. Road and stream class parameters such as hydraulic width and depth are based on corresponding parameters in PKEW. Estimation of parameter values for stream classes found in NMRW but not in PKEW was guided by assuming that effective hydraulic width and depth increase, and Manning's number decreases, in the downstream direction.

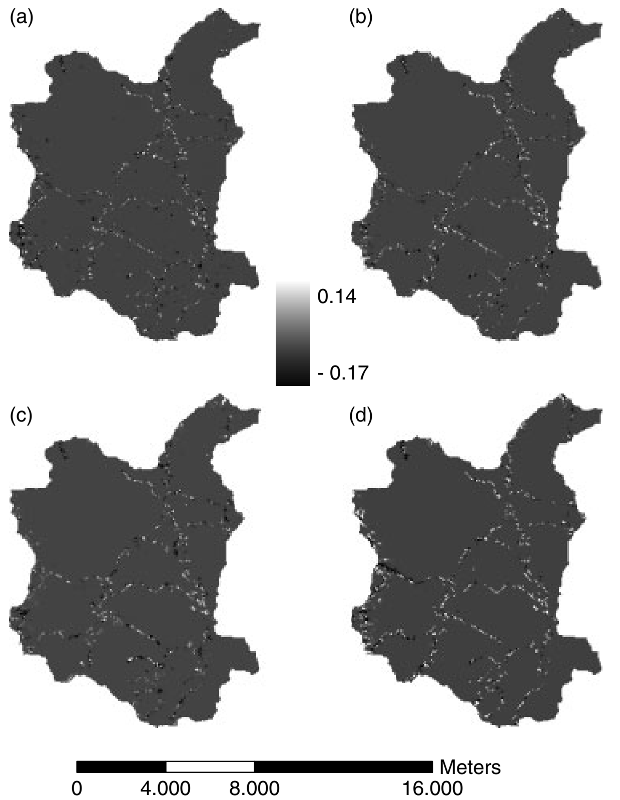

Figure 4. Spatial distribution of road-related anomalies (road minus non-road) in the first-layer soil moisture during the wet period of 1–8 September 1998 for the four land-cover scenarios: (a) 1989; (b) 2002; (c) extreme deforestation; and (d) forest. Broad areas of uniform medium gray are cells with no change. Units: $m^3\ m^{-3}$

RESULTS

Road effects

Mean monthly water balance. Road effects on basin-averaged water fluxes are shown in Figure 3. For all four land- cover scenarios, very small road versus non-road differences are seen in mean monthly streamflow (0·2 to 0·5%), evapotranspiration (around −0·2%), and basin water storage change (−0·6 to 0·4%).

Soil moisture. Roads have essentially no effects on the time series of daily averaged and basin aggregated soil moisture for all four scenarios. However, in cells where the road is located and in downslope cells, significant changes in soil moisture are seen in the model results. The spatial pattern of first-layer simulated soil moisture, averaged for an 8 day sample period in the wet season (1–8 September 1998, rainfall = 217 mm), is shown in Figure 4. In general, roads increase simulated soil moisture downslope of road sinks, points where water flow on road surfaces converges, but decrease soil moisture in road-traversed cells in all four land-cover scenarios. This model result probably exaggerates actual road effects on the soil moisture distribution in the basin. In the model, runoff from the road surface to the hillslope takes place as diffuse flow (spread evenly over the whole 50×50 m grid cell). Field observations in the basin indicate that runoff exiting the road at locations other than stream crossings often flows efficiently into the stream system via concentrated flow paths, thus affecting hillslope soil moisture only in the localized area around the flow path. Where gullies connect road-flow exit points with the stream, the channel network is effectively extended during storms. It would be possible to survey the road system and assess the nature of each connection between road and stream, information that could be used to simulate these connections using DHSVM. Lacking this detailed information, such connections are not specified in these model runs.

Streamflow. Hourly streamflow estimates are consistently higher with the road simulation for all four scenarios (Figure 5), but the average increase is very small, only about 0·4%. Differences in total, dry season, and wet season stream discharge due to roads are shown in Table III. Differences in streamflow are statistically significant for the whole period and for the wet season, but in all cases, the differences in mean values are negligible in magnitude (range: −0·2% to 0·7%).

Road effects on peak flows vary somewhat with the land cover (Table IV). The effect of roads on the maximum peak flow is greatest for the forest scenario and least for the extreme deforestation scenario. Mean and median peak flows increase the most for the 1989 and 2002 scenarios and least for the extreme deforestation scenario. Small peaks ($<10\,000$ m^3 h^{-1}) are increased by up to about 18% in all four scenarios (Figure 6). Mean peak flow increase due to roads declines from around 7% for small peaks to 2–4% for larger peaks for forest, and from around 7·5% to 1–2% for extreme deforestation. For the 1989 and 2002 scenarios, on the other hand, mean peak flow increase remains at around 4–6% for most of the peak flow range. The two historical land-cover scenarios are also found to experience the largest increase in the frequency of higher peak flows ($\geq 60\,000$ m^3 h^{-1}) as a result of roads (Figure 7).

Combined effects of land-cover and roads

To study the combined effects of land-cover and roads, water balance, available soil moisture, and streamflow of the experimental scenarios (the 1989, 2002 and extreme deforestation scenarios with roads) are compared with those of the control scenario (forest without roads).

Mean monthly water balance. In Figure 8, mean monthly values of streamflow, ET, and basin storage

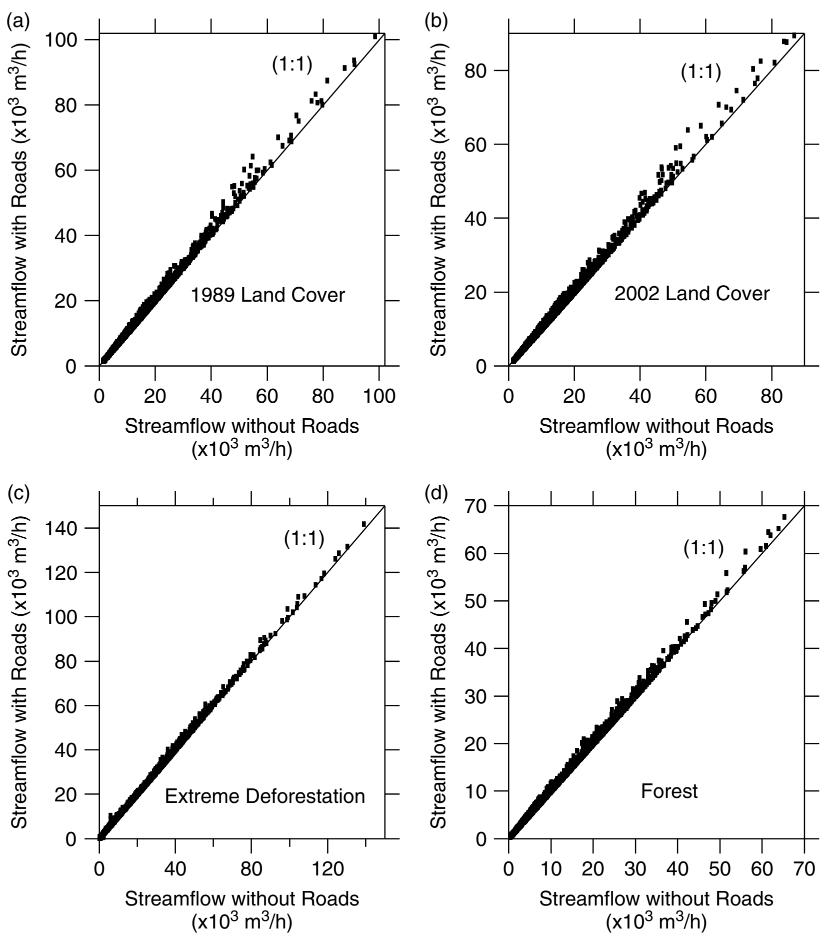

Figure 5. Scattergrams of road versus non-road hourly streamflow, simulated for (a) forest; (b) extreme deforestation; (c) 1989; and (d) 2002 land-cover scenarios

Table III. Road and combined land-cover and road effects on mean and median streamflow

Mean and median streamflow (mm day^{-1})									
		1989 non-roads	1989 roads	2002 non-roads	2002 roads	Extreme def. non-roads	Extreme def. roads	Forest non-roads	Forest Roads
All	Mean	1·29	1·30	1·29	1·29	2·30	2·31	1·30	1·30
	Median	0·73	0·73	0·69	0·71	1·69	1·70	0·51	0·52
Dry Season	Mean	0·57	0·57	0·51	0·51	0·32	0·32	0·28	0·28
	Median	0·48	0·48	0·44	0·44	0·17	0·18	0·19	0·19
Wet Season	Mean	1·73	1·74	1·75	1·76	3·49	3·50	1·91	1·91
	Median	1·44	1·45	1·52	1·52	3·82	3·83	1·65	1·65

0		Effects of roads: roads minus non-roads (%)				Combined effects of roads and land cover (%)			
		1989	2002	Extreme def.	Forest	1989 minus forest	2002 minus forest	Extreme def. minus forest	2002 minus 1989
All	Mean	0·6%	0·5%	0·2%	0·4%	0·3%	−0·4%	77·9%	−0·6%
	Median	0·1%	2·3%	0·5%	2·9%	45·0%	39·6%	235·2%	−3·7%
	Signif.	*	*	*	*			*	
Dry Season	Mean	0·0%	−0·2%	−0·1%	0·1%	101·5%	80·7%	13·6%	−10·3%
	Median	−0·3%	−0·4%	0·1%	0·5%	159·1%	136·2%	−5·5%	−8·8%
	Signif.					*	*		*
Wet Season	Mean	0·7%	0·6%	0·2%	0·5%	−8·7%	−7·6%	83·6%	1·2%
	Median	0·9%	−0·02%	0·2%	0·4%	−12·0%	−7·5%	132·5%	5·2%
	Signif.	*	*	*	*			*	

* Indicates pairs of samples are significantly different ($P < 0.05$, Wilcoxon signed rank test applied to monthly totals).

Table IV. Road and combined land-cover and road effects on peak flow

Peak flow statistics (mm h^{-1})								
	1989 non-roads	1989 roads	2002 non-roads	2002 roads	Extreme def. non-roads	Extreme def. roads	Forest non-roads	Forest roads
Maximum	0·921	0·945	0·812	0·836	1·301	1·325	0·610	0·633
Mean	0·132	0·139	0·129	0·136	0·215	0·219	0·105	0·109
Median	0·082	0·087	0·085	0·088	0·181	0·184	0·079	0·081

	Effects of roads: roads minus non-roads (%)				Combined effects of roads and land (%)			
	1989	2002	Extreme def.	Forest	1989 minus forest	2002 minus forest	Extreme def. minus forest	2002 minus 1989
Maximum	2·6	2·9	1·9	3·8	55·0	37·1	117·3	−11·5
Mean	5·3	5·4	1·9	4·0	32·8	29·5	109·0	−2·5
Median	5·6	3·6	1·7	2·7	9·3	11·1	131·6	1·6
Signif.	*	*	*	*	*	*	*	*

* Indicates pairs of samples are significantly different ($P < 0.05$, Wilcoxon signed rank test applied to monthly totals).

change are given for each of the four land-cover scenarios: 1989, 2002, and extreme deforestation, all with roads, and forest without roads. ET is 33% lower on average and streamflow 78% higher on average for the extreme deforestation scenario than for forest. Water balance changes associated with the 1989, 2002, and extreme deforestation scenarios in relation to the forest-without-roads scenario are shown in Figure 9. Compared with forest, the other three scenarios have higher dry season ET and lower wet season ET. Most of the streamflow increase for the extreme deforestation scenario is seen during wet season months, with little change in dry season flow. The 1989 and 2002 scenarios are very similar to each other, in terms of monthly means. In contrast with the extreme deforestation case, the two historical land cover patterns result in lower streamflow during September and October. From December to May, average stream discharge is 93% and 77% higher for the 1989 and 2002 scenarios, respectively, than for forest. The reduced September–October flow is accompanied by lower ET and greater increases in basin water storage. Higher dry season flow is coincident with higher ET (January to April ET is higher by an

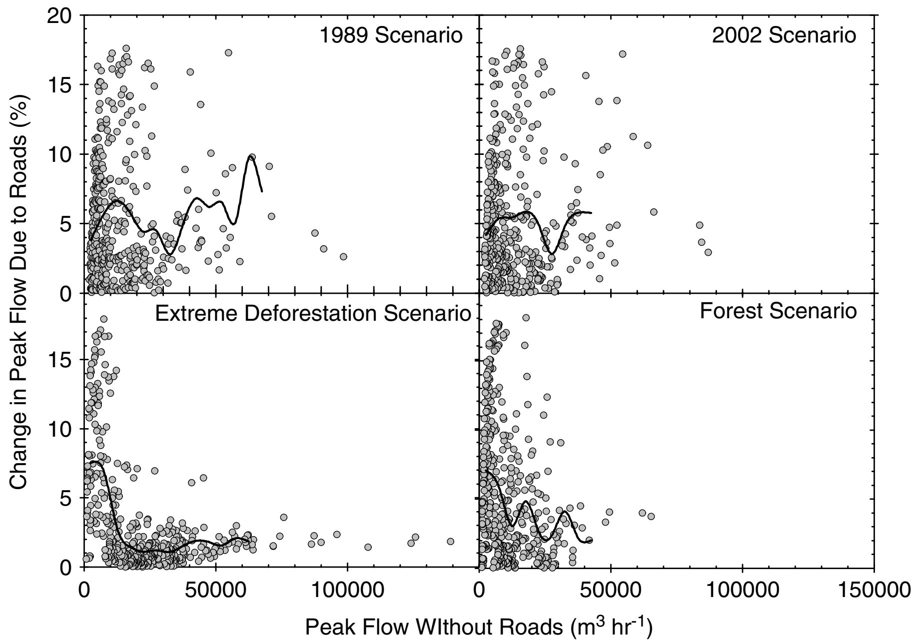

Figure 6. Percentage change in peak flow magnitude due to roads as a function of peak flow without roads for each land-cover scenario without roads. Lines show mean change within each 5000 m h^{-1} peak flow classes

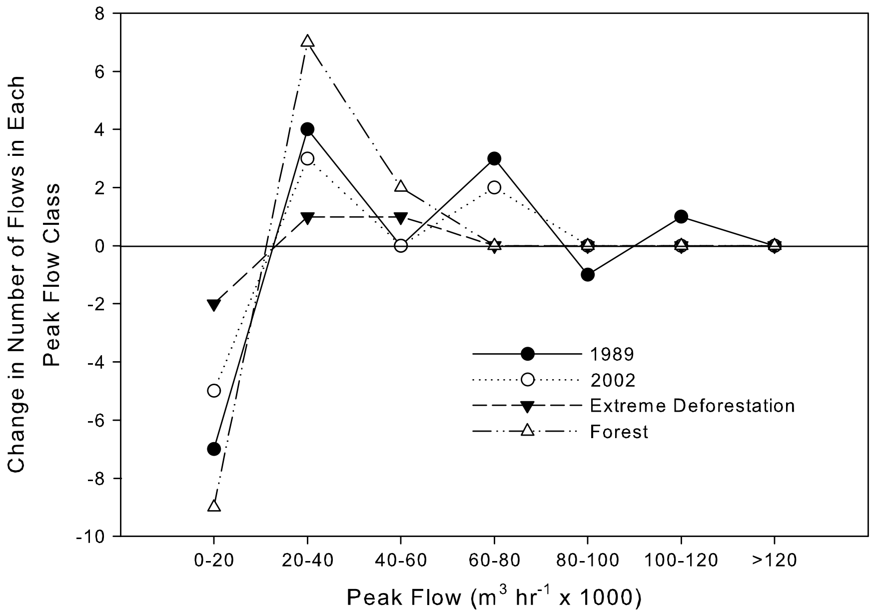

Figure 7. Change in peak flow frequency due to roads in each of four land-cover scenarios

average of 44% and 36% for the 1989 and 2002 scenarios, respectively, than for forest) and greater decreases in basin water storage.

Available soil moisture. Daily averaged, basin-aggregated available soil moisture anomaly (the difference between the forest scenario and the 1989, 2002 and extreme deforestation scenarios) in three root zones is shown in Figure 10. During most of the study period, scenarios 1989 and 2002 have higher available soil moisture than forest in all three root zones. For the extreme deforestation scenario, available soil moisture is higher than forest in all three layers, except in the lowest layer where available soil moisture is lower in the wet season.

Figure 11 shows the spatial distribution of first-layer available soil moisture anomalies averaged for the wet season sample period 1–8 September 1998. Available soil moisture is spatially redistributed as a result of recent historical land cover patterns, with 45% and 51% of cells in the 1989 and 2002 scenarios, respectively, having higher values than those of the forest scenario. For the extreme deforestation scenario, more than 99% of the cells have higher available soil moisture than in the forest scenario.

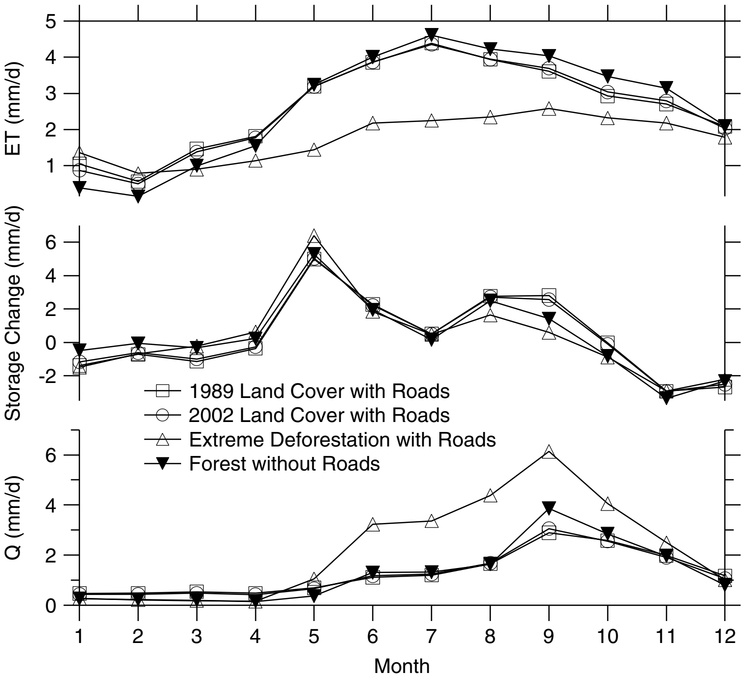

Figure 8. Simulated mean monthly stream discharge (Q), storage change, and evapotranspiration (ET) of the 1989, 2002, extreme deforestation, and forest land-cover scenarios

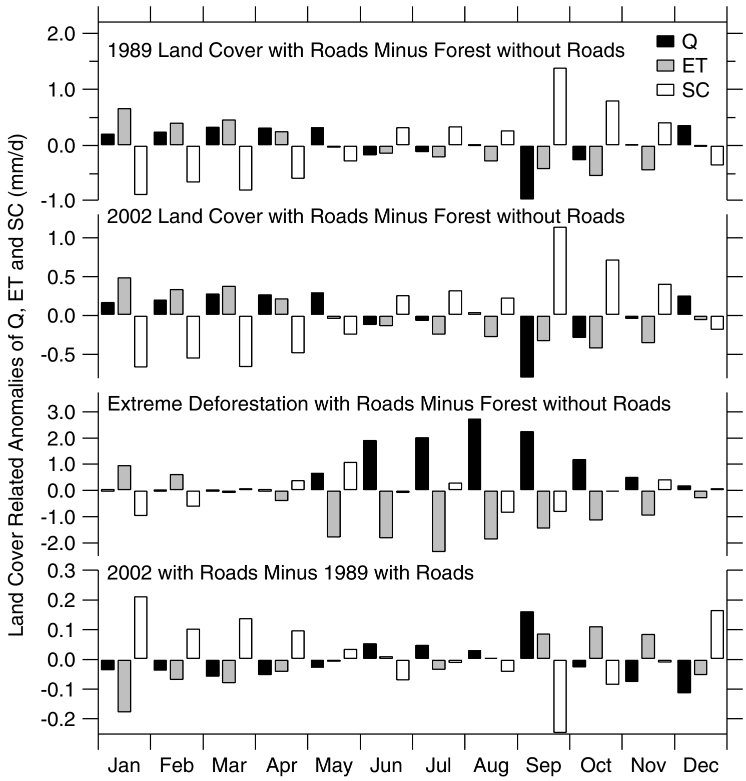

Figure 9. Land-cover-related anomalies in streamflow (Q), evapotranspiration (ET), and storage change (SC). The anomaly is the mean value from the 1989, 2002, or extreme deforestation scenarios with roads minus the mean for the forest without roads scenario. In the bottom panel, the 1989 and 2002 scenarios are compared

Streamflow. Compared with the forest scenario, average stream discharge is not significantly different for the 1989, 2002 scenarios, but is sharply higher for the extreme deforestation scenario (Table III). For the 1989 and 2002 simulations, dry season flow is markedly increased, while wet season flow is not changed statistically. A change from forest to extreme deforestation results in a large streamflow increase, of which all the significant change is seen in the wet season. Scattergrams of streamflow show that high flows increase for the

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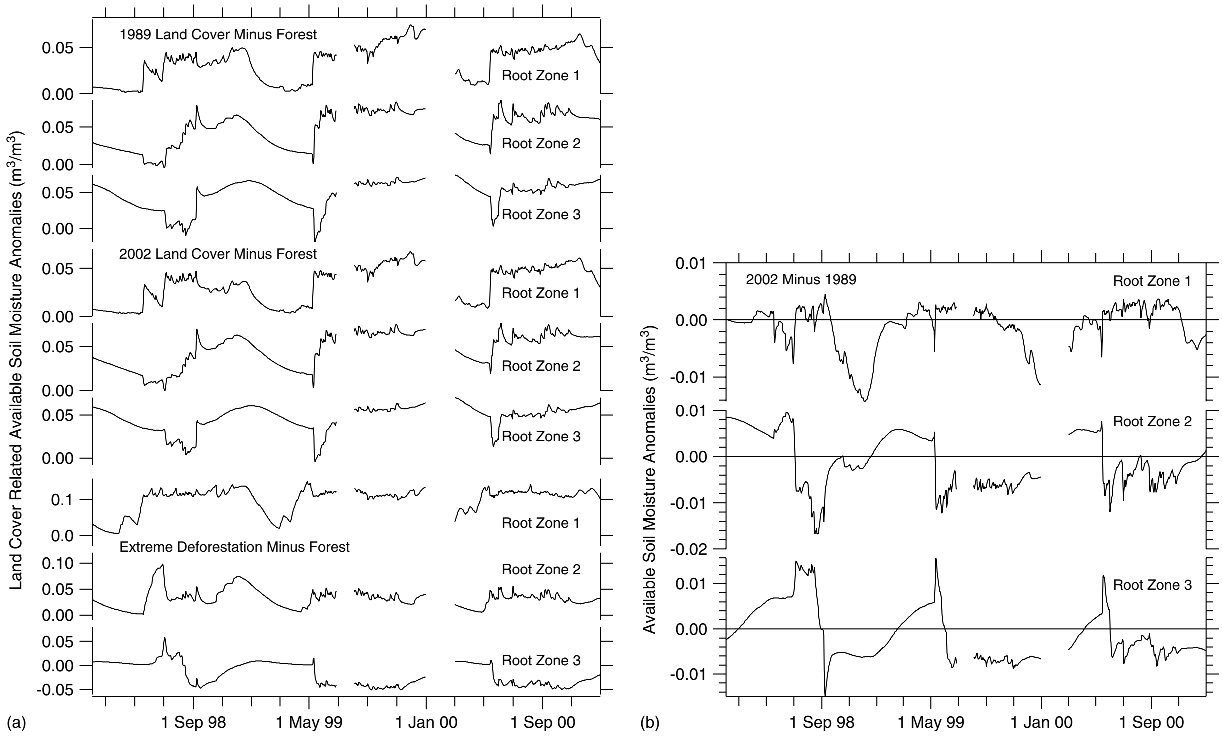

Figure 10. Time series of basin averaged land cover-related available soil moisture anomalies in each soil layer. The anomaly is (a) the soil moisture from the 1989, 2002, or extreme deforestation scenarios with roads minus the soil moisture for the forest scenario without roads, and (b) the soil moisture from the 2002 scenario minus the soil moisture from the 1989 scenario, both with roads. Root zone 1 is 0 to 0·3 m below the surface. Root zone 2 is 0·3 to 0·9 m below the surface. Root zone 3 is 0·9 to 1·5 m below the surface

1989 and 2002 scenarios compared to the forest scenario (Figure 12a, b). For the extreme deforestation scenario, most of the hourly flows are much higher than those of the forest scenario (Figure 12c).

As expected, the combined effects of land-cover and roads on peak flows are quite large for the extreme deforestation scenario (Table IV). The 1989 and 2002 scenarios also exhibit significant increases in peak flows. Frequency increases for all peak size categories except the smallest were generally greater for the extreme deforestation scenario than the two historical scenarios (Figure 13).

Effects of recent historical land-cover change. Land-use change between 1989 and 2002 resulted in mostly small changes in mean monthly ET and stream discharge (Figure 9). Daily averaged, basin aggregated available soil moisture is generally higher in the first layer but lower in the bottom two layers during the wet season for the 2002 scenarios than for the 1989 scenario (Figure 10b). Among affected cells, about two-thirds of the cells have higher available soil moisture in the 2002 scenario than in the 1989 scenario for the wet period of 1–8 September, 1998 (Figure 11d).

Compared with the 1989 scenario, the 2002 scenario has about the same total stream discharge, with significantly decreased dry season flow (Table III), and lower maximum peak flow (Table IV). Scattergrams of hourly streamflow for 1989 versus 2002 (Figures 12d) suggest that recent land cover change has caused a slight reduction in high flows, although the median peak flow is slightly higher (Table IV).

DISCUSSION

Road effects

Studies of the hydrological impacts of roads have produced a range of results. The model-based finding that roads have negligible effects on the annual water balance in NMRW is consistent with prior field studies (Rothacher, 1970; Harr *et al*., 1975; King and Tennyson, 1984; Wright *et al*., 1990). While total streamflow was not affected greatly by roads in this study, roads were found to produce higher peak flows. Measurements from paired catchments have tended to show that road effects on peak flows were more important for small events (Wright *et al*., 1990; Jones and Grant, 1996; Thomas and Megahan, 1998; Beschta *et al*., 2000). Previous studies using DHSVM (Bowling *et al*., 2000; Storck *et al*., 1998; La Marche and Lettenmaier, 2001), on the other hand, found significant increases in peak flows for the largest events.

In the 1 km^2 PKEW sub-watershed, it was previously found that roads caused peak flows to increase by 3, 12, and 34%, respectively, for small, medium, and large peaks (Cuo *et al*., 2006). In the larger NMRW, roads in a contemporary (2002) land-cover setting were found to cause smaller peak flow increases, averaging 5·4%, regardless of storm size (Table IV and Figure 6, 2002 land-cover). The small peak flow increases for

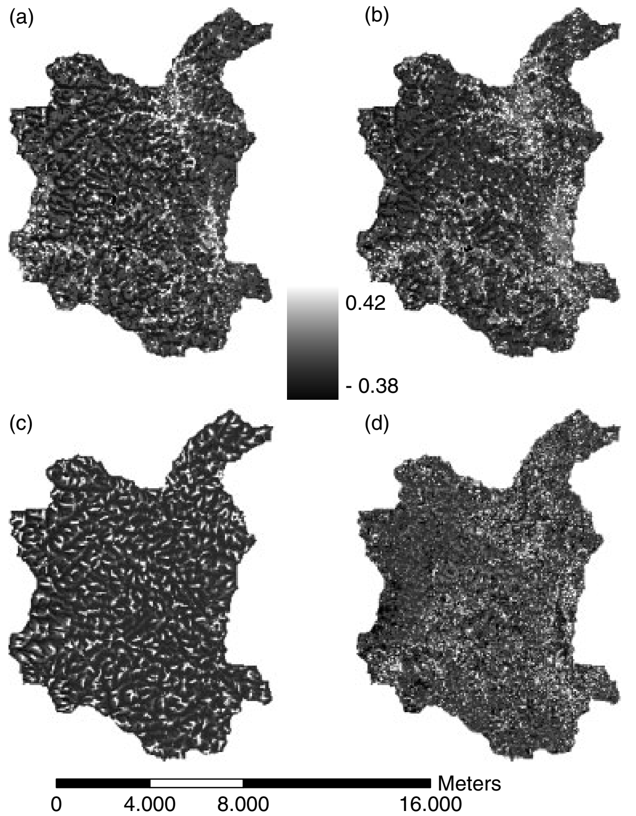

Figure 11. Spatial distribution of land cover-related anomalies in available soil moisture in the first root zone (0 to 0·3 m below surface) for the wet period of 1–8 September 1998: (a) 1989 with roads minus forest without roads; (b) 2002 with roads minus forest without roads, (c) extreme deforestation with roads minus forest without roads, and (d) 2002 minus 1989, both with roads. Units: m^3 m^{-3}

NMRW may be explained, in part, by the lower road density in NMRW (0·90 km km^{-2}; 0·6% of drainage area) compared with PKEW (3·40 km km^{-2}; 1·2%). Previous research suggests that a threshold road density is necessary to cause changes in peak discharge, and both NMRW and PKEW have relatively low road density. For example, Harr *et al.* (1975) concluded that a minimum road density of 12% was needed to produce significant peak flow increases; and Wright *et al.* (1990) found little or no effects on peak flows in basins with roads covering 5% of the drainage area. The contrast between PKEW and NMRW may also be related to differences in land-cover distribution (Table I) and basin size. Jones and Grant (1996), Thomas and Megahan (1998), and Beschta *et al.* (2000) found that the combined effects of clear-cutting and road construction on peak flows diminished with increasing drainage area.

In NMRW, the effects of roads on peaks depend on the land cover context in which the roads are placed. Overall, roads have the least effect on mean peak flow when added to the extreme deforestation scenario. This may be because this extreme land-cover scenario already maximizes overland flow generation and allows relatively unimpeded overland flow paths to the stream channel. For the forest scenario, peaks less than 10 000 m^3 h^{-1} increase on average by more than 6%, while larger peaks increase by only around 3%. Placed within the high infiltration soils of an all-forest landscape, the additional overland flow production is limited to that generated on the road surface itself. Any surface flow from the road to adjacent hillslopes is likely, within the model, to be fully or mostly infiltrated into the forest soils before reaching the stream channel.

Roads have a greater effect on most moderate and high peak flows within the two historical scenarios compared with the forest and extreme deforestation scenarios. This suggests that, within a heterogeneous land cover setting, roads are especially important in converting greater amounts of overland flow into high peaks by conveying surface flow quickly to the stream. For the two historical scenarios, overland-flow-generating land-cover patches are scattered around the watershed. The fragmented nature of the landscape ensures that many such runoff source areas are separated from the stream channel network by land-cover patches associated with high-infiltration soils. Without roads, this arrangement may serve to buffer the effects of the overland flow source areas (Ziegler *et al.*, 2007) and limit increases in peak flows. Roads reduce the effectiveness of buffering land covers by short-circuiting overland flow patterns, collecting overland flow from tributary source areas, redirecting and, in many cases, more efficiently delivering flow to the stream. Jones and Grant (1996) also found evidence that interaction between patches of cleared land and roads magnified peak flow increases.

Roads effects on soil moisture and streamflow were found to be relatively small within the forest scenario, compared to the other scenarios. This result can be attributed to two types of interactions between the road and the surrounding landscape. First, roads capture overland flow (especially HOF) generated on slopes above, concentrating and redirecting this flow, and efficiently delivering this water to the stream channel. Because the forest land cover rarely produces HOF, this impact of roads is minimized within a forest context. Second, a larger proportion of flow exiting the road at points other than stream crossings would infiltrate if it flows onto a forested hillslope rather than onto a non-forested slope.

Higher peak flows caused by roads are associated with a greater proportion of water reaching the channel by overland flow paths, which causes higher rates of soil erosion. Because the additional overland flow is produced on road surfaces, which form conduits for efficient transport of sediment to the stream channel, roads tend to have significant negative impacts on water quality (Ziegler *et al.*, 2000). Prior studies in PKEW have shown that overland flow generated on the roads during storms results in severe gullying of the road surface (Ziegler *et al.*, 2004). In the wet season, when the probability of flooding is already high, roads further increase the flood risk. From some sections of the road, concentrated overland flow is directed to hillslopes, damaging crops and eroding soil from farm fields.

Comparing these results with those of previous work on roads, done primarily in the Pacific Northwest region,

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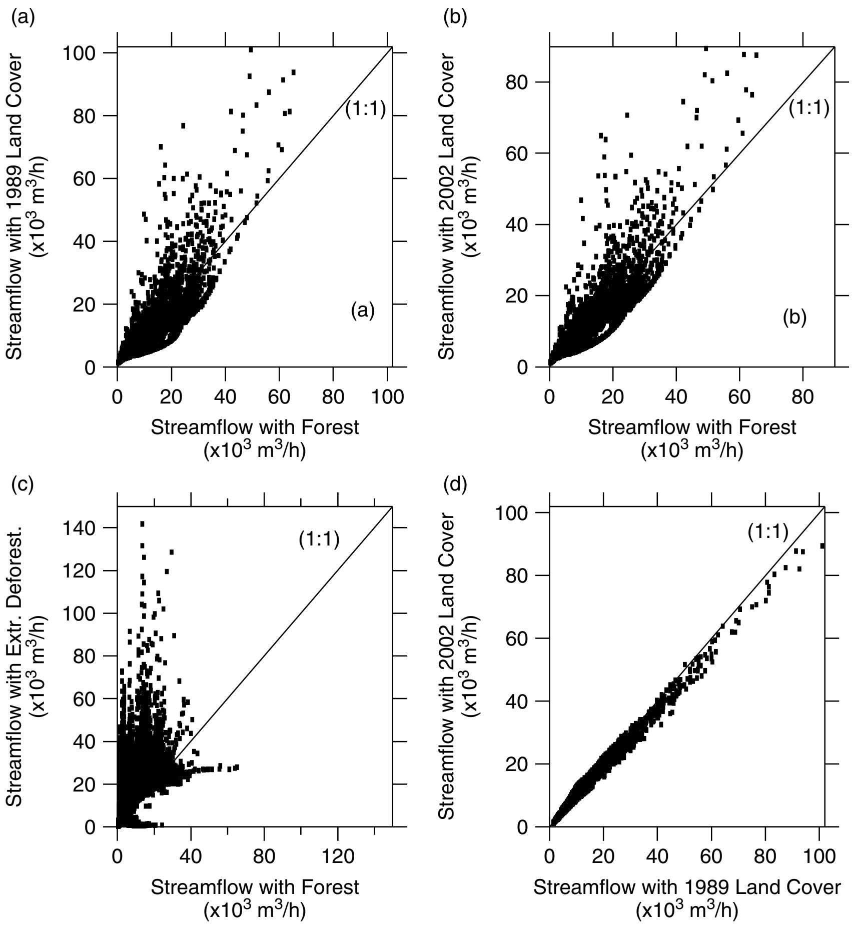

Figure 12. Scattergrams of hourly streamflow for: (a) 1989 land-cover with roads versus forest without roads; (b) 2002 land-cover with roads versus forest without roads; (c) extreme deforestation with roads versus forest without roads; and (d) 2002 land-cover with roads versus 1989 land-cover with roads

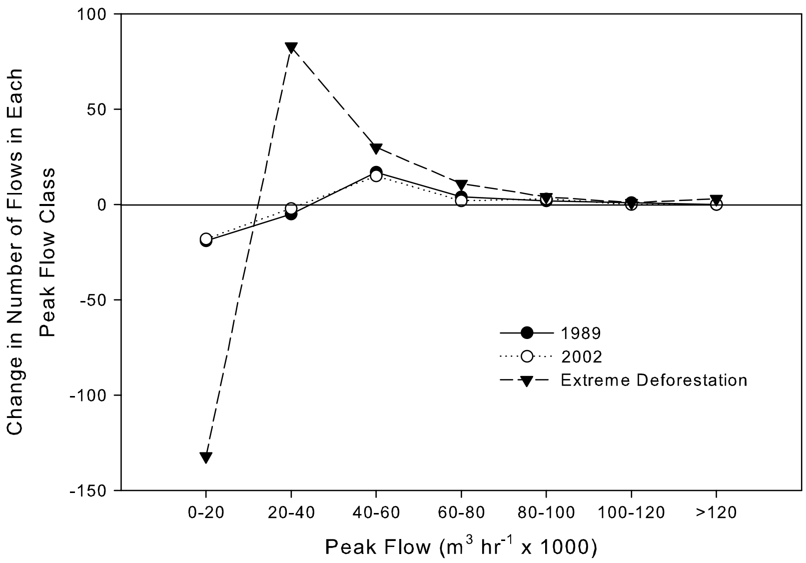

Figure 13. Change in peak flow frequency due to the combined effects of roads and land- cover in each of three land-cover scenarios in comparison with forest

general agreement is found with those studies showing that roads result in higher peak flows (Jones and Grant 1996; Stork *et al.* 1998). Differences were found in the impacts of roads and in the relationship between peak flow increase and storm size among the different land-cover settings, which may help to explain some of the apparently conflicting findings in this regard. This finding, however, may result from the predominance of HOF production on the roads in the study area, in contrast to the PNW region. As previously explained, interception

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of subsurface flow by the road cut is not an important process in this study area, based on observations within PKEW (Ziegler *et al*., 2001b), and the model parameter settings reflect this. In the Pacific Northwest region with its relatively shallow soils, road cuts often go all the way to bedrock allowing subsurface flow to be intercepted by the road, a process identified as the dominant road-related mechanism affecting peaks flows in that region (Jones and Grant, 1996; Megahan, 1972). In that case, streamflow response within forested landscapes, where water tends to be directed to streams via subsurface pathways, would be more strongly affected by the presence of roads.

Model simulations used in this study may not fully characterize the effects of roads on peak flows because, as previously mentioned, concentrated flow paths from the road to the stream channel are not represented in the model. Of the 96 km of roads in NMRW, 31 km (32%) are directly connected to the stream network in the model. As a result, an average of 34% of simulated surface flow on roads flows directly into the model channel network. If a higher percentage of road flow actually reaches the stream directly, as is believed from observations in PKEW, then the impacts on peak flows are probably higher than simulated. The issue of road–stream connectivity has been identified as a critical determinant of road impacts on streamflow by Jones and Grant (1996). Bowling and Lettenmaier (2001) showed that failing to connect roads in DHSVM with the stream channel significantly reduces modelled road effects on streamflow.

Land-cover effects

The two historical land-cover scenarios (1989 and 2002) produced water balance results which were much more similar to those of the forest scenario than the extreme deforestation scenario. As expected, ET was lower throughout the wet season for the historical land-cover scenarios. Surprisingly, ET was higher during the dry season. Streamflow was lower in September and October and slightly higher during the dry season. Note that the two historical scenarios change the timing of ET and streamflow by changing the storage and release of basin water; i.e. by increasing wet-season storage gain, especially during September–October, and increasing dry season storage loss.

For the extreme deforestation scenario, ET was greatly reduced during the wet season, as expected, but increased during January and February, compared with forest. Again, this dry season increase in ET was accomplished by greater stored water loss. Streamflow was much higher during the wet season, but nearly unchanged during the dry season.

Forests are traditionally seen as the optimal land cover for water and soil conservation. Many believe that deforestation contributes to a wide range of negative hydrological impacts including higher flood frequency and reduced dry season flow (see Calder, 1999 for a discussion of beliefs on the hydrological benefits of forests). Using the extreme deforestation scenario, it is clearly seen that removing all the forest would significantly lower ET and increase wet season streamflow. For the more realistic historical scenarios, it is found that changes in the mean partitioning of water in the basin, especially changes in mean streamflow, are very small.

Bruijnzeel (2004) points out that the net effect of forest conversion on dry season flow depends on whether reduced ET or reduced soil infiltration dominates. Effects on ET, streamflow and soil properties depend on numerous factors related to the original forest and soil type, and the land use history. It was found that shifting from forest to alternative land covers changes the annual ET and streamflow regimes mainly by changing the timing of storage and release of water in the basin. In the extreme deforestation scenario, reduced ET leads to significant increases in streamflow, but only during the wet season. For the historical scenarios, dry season streamflow increases despite higher dry season ET.

In agreement with most prior research, forests were found to produce the smallest peak flows, which would probably result in less surface erosion and better water quality than for the other scenarios. The extreme deforestation scenario, in contrast, produces the highest peak flows, which would probably result in much greater erosion and other flood damage, and a decrease in water quality.

Table I shows that despite an expansion of active swidden and fallow land between 1989 and 2002, advanced secondary forest increased in area from 31% to 43% of the cover. The simulations predict that the 2002 land-cover generates lower maximum peak flow than does the 1989 cover, a possible benefit of the observed land-cover shift. On the other hand, the 2002 simulation also had significantly lower dry season flow than the 1989 scenario, an apparent negative consequence of the recent increase in forest cover.

CONCLUSION

Using DHSVM, it was found that roads in NMRW: (1) do not significantly affect the mean annual partitioning of rainfall into ET, streamflow, and basin water storage; (2) produce large changes in simulated soil moisture for cells crossed by roads or cells immediately downslope of road sinks, however, these simulated effects probably exaggerate actual road effects on soil moisture in downslope cells; (3) produce higher peak flows for all storms, but the effects on peaks depend on the land-cover context; (4) have the least effect on peak flows within an extreme deforestation context; (5) affect small peaks more than large peaks within the two homogeneous landscapes tested (forest and extreme deforestation); and (6) have the most effect on peak flows within the two historical scenarios, indicating that roads are especially important in converting greater amounts of overland flow into high peak flows within the fragmented landscape of realistic land-cover scenarios.

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Based on model results, the combined effects of land-cover and roads include the following: (1) recent historical land-cover patterns result in water balance results much more similar to those of forest than of extreme deforestation; (2) compared with forest, the 1989, 2002, and extreme deforestation scenarios have higher dry season ET and lower wet season ET; (3) streamflow is lower in the late wet season and higher in the dry season for the historical scenarios in comparison with the forest scenario; (4) changes in the timing of ET and streamflow are associated with changes in the accumulation and release of water stored within the basin; (5) the extreme deforestation scenario results in greatly reduced ET and greatly increased streamflow; and (6) no significant change in dry season stream flow is seen with extreme deforestation.

The effects of land-cover change and roads on streamflow amount and timing and the local and downstream effects of land-cover induced change will continue to be a topic of concern to policy-makers in areas such as northern Thailand, and a challenging area of hydrological research. Results presented here, while specific to the study area and based on model simulations, suggest that many, but not all, of the negative hydrological impacts for which upland agriculture is commonly impugned, may be less severe than believed, while the effects of roads are significant, especially within heterogeneous land-cover.

Results presented here should be interpreted in light of uncertainties arising from the use of a model calibrated in a small sub-basin, and from the imperfect representation of initial conditions, boundary conditions, and processes inherent in any model-based study. As described previously, the model was implemented with a lower density channel network than suggested by the fieldwork of McNamara *et al*. (2006). Field observations also suggest the connectivity between the road and channel network may be higher in reality than it was in the model. As a result, the model may have underrepresented the effects of roads on peak flows, for example. Improvements to this study could be made by using a higher resolution DEM, assessing road–channel connectivity in the basin and making appropriate adjustments in model routing, and obtaining flow discharge measurements at the basin outlet to allow for better model calibration and testing.

ACKNOWLEDGEMENTS

This paper is based upon work supported by the National Science Foundation under grant no. EAR-0000546. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation. DHSVM authors Dennis Lettenmaier (Department of Civil and Environmental Engineering, University of Washington, WA, USA), Pascal Storck and Bart Nijssen (3TIER Environmental Forecast Group, Seattle, WA, USA), and Laura Bowling (Department of Agronomy, Purdue University, IN, USA) generously supported our efforts to implement DHSVM, by answering our numerous inquiries. John Vogler (East-West Center, Honolulu, HI, USA) contributed substantially to field data collection for the 1989 and 2002 scenarios. The authors are also grateful to the three anonymous reviewers, who provided insightful comments and suggestions for improving the paper.

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