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Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand

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Abstract

Unpaved road surfaces have extremely low infiltration rates compared with other watershed land surfaces and, therefore, are significant source areas for erosion-producing Horton overland flow. The hydrologic role of roads is an important issue in mountainous areas of the tropics where erosion control efforts are predominately focused on deforestation and agricultural practices. We report on an investigation of soil physical properties that control excess rainfall (rainfall intensity in excess of infiltration capacity) on rural roads and surrounding lands in a mountainous watershed in northern Thailand. The results of our disk permeameter measurements indicate that saturated hydraulic conductivity on unpaved roads is about one order of magnitude lower than on any other land-surface type. Median saturated hydraulic conductivities were not exceeded by measured rainfall intensity on any land use except road surfaces and roadside margins. By simulating excess rainfall, we found that in contrast with other areas of the watershed, the road surface tends to generate excess rainfall early in a rain event, and on nearly all of its area. Despite the relatively small areal extent of road-related surfaces ($< 0.5\%$ of basin area), they contribute a large portion of basin-wide total excess rainfall during frequently occurring, small rainfall events. However, during larger events, agricultural, secondary vegetation, and forested areas assume greater importance because of their larger areal extent. © 1997 Elsevier Science B.V.

1. Introduction

It is now widely recognized that roads play a significant role in altering near-surface hydrologic response and subsequently accelerating soil erosion in previously undeveloped areas (cf. Bruijnzeel and Critchley, 1994). Accelerated erosion is a critical component of global land degradation, particularly in developing areas of the tropics where land-cover

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change is taking place at alarming rates (Lal, 1990; El-Swaify, 1993). In developing countries, erosion contributes to nutrient loss from cleared lands, forcing farmers to clear more forested areas to maintain production, thus fueling increasing rates of tropical deforestation (Bruijnzeel, 1990; Myers, 1994; Pimentel et al., 1995). Increased sediment loading adversely affects water quality, threatens aquatic species, transports ecologically disruptive nutrients and sorbed chemicals, and generally degrades the landscape (Novotny and Chesters, 1989; Bilby et al., 1989; McCool and Renard, 1990). Understanding the relationship between land-cover change and erosion, and subsequent improvement of soil conservation strategies is of great importance for preserving the global environment.

Forest removal (e.g. for agriculture) exposes the soil surface to the direct impacts of raindrops and wind, reduces surface roughness with respect to overland flow, and reduces soil cohesion provided by tree roots (Meyer, 1986). These factors are most often identified as the underlying causes of hydrologic change and accelerated erosion resulting from land-cover change (Bruijnzeel, 1990; Craswell, 1993). National and international efforts to reduce soil loss and sedimentation in developing areas of the tropics have focused on agricultural practices, often advocating adoption of permanent cropping systems and conservation tillage methods in place of traditional swidden practices (cf. Hamilton and King, 1983; Magrath, 1992; Poffenberger and McGean, 1993). However, in many areas of Southeast Asia, roads, despite their relatively small areal extent, could be of equal importance to agricultural lands as sediment sources because they frequently generate erosion-producing Horton overland flow (e.g. Rijsdijk and Bruijnzeel, 1991; Giambelluca, 1996). This view is consistent with an earlier study showing forest destruction to be less significant than road construction in increasing annual runoff yields in one northern Thailand watershed (Pransutjarit, 1983). Such evidence calls into question the tendency of many conservation programs to focus only on agricultural practices.

Expansion of road networks is an inevitable consequence of rural development in Southeast Asia. If roads, as they are currently built and used, are the major contributors to surface erosion and sedimentation, soil conservation efforts should include improving the routing, design, and maintenance of existing and future rural roads. The primary objective of this study is to show how an expanding road network changes the overland flow response of a mountainous tropical watershed in northern Thailand. In this paper, we will show the importance of unpaved roads relative to other land-cover types as source areas for erosion-producing Horton overland flow by: (1) comparing soil hydrological properties on roads and other land-use types; (2) using soil properties in comparison with rainfall intensity measurements to identify excess rainfall thresholds; (3) evaluating contribution of roads to the total watershed excess rainfall volume; and (4) determining characteristics (i.e. intensity, duration) of rainfall events that typically produce excess rainfall on each land-cover type.

2. Background

2.1. Impacts of rural roads

At least four distinct features of unpaved roads can alter storm flow response in mountainous watersheds: (1) highly compacted road surfaces and disturbed roadside margins reduce infiltration of rain water, thereby producing overland flow and allowing all surface water to run off rapidly; (2) cutbanks can intercept subsurface flow, then re-route it via the faster overland flow mechanism toward the stream channel (Harr et al., 1975; King and Tennyson, 1984; Wright, 1990); (3) ditches and culverts capture both subsurface flow and surface runoff, and channel it more directly to streams (cf. Burroughs et al., 1972; Reid and Dunne, 1984; Wemple, 1994 cited in Jones and Grant, 1996); and (4) erosion gullies, 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 sooner flow peaks and slightly higher total discharges (Harr et al., 1975; Ziemer, 1981; Jones and Grant, 1996), and influence the distribution of erosional processes (Montgomery, 1994). Interception of subsurface flow is believed by some (e.g. Megahan, 1972 cited in Megahan, 1983) to be a far more important source of overland flow than that generated from precipitation falling on road surfaces. This point of view was developed in areas of the northwestern US where snowmelt and shallow soils underlain by impermeable bedrock are important contributing processes. However, in several studies done in the tropics, rural roads, tracks, and paths were found to be active runoff-generating components owing predominantly to their low infiltration capacities (e.g. Dunne and Dietrich, 1982; Malmer and Grip, 1990; Harden, 1992, 1993; Van der Plas and Bruijnzeel, 1993).

The geomorphological importance of roads in tropical watersheds has been described by Dunne and Dietrich (1982). In an agricultural area of Kenya they estimated that rural roads and paths, comprising about 2% of a basin area, contributed disproportionately to basin sediment yield. Rijsdijk and Bruijnzeel (1991) reported similar findings in East Java, Indonesia. In other monsoonal regions, such as mountainous South Asia, the introduction of roads has resulted in severe environmental degradation and slope instability (e.g. many examples reviewed in Bruijnzeel and Bremmer, 1989). Several studies within temperate regions have identified the importance of road location, geometry, and usage on sediment transport (e.g. Wald, 1975; Reid et al., 1981; Reid and Dunne, 1984; Burroughs et al., 1984; Bilby, 1985; Coker et al., 1993). Other studies have shown sediment source areas associated with unpaved roads, such as side cast material from construction/maintenance or mass wasting on adjacent hillslopes, provide unstable material that is easily transported into streams during overland flow events (e.g. Megahan and Kidd, 1972; Beschta, 1978; Swift, 1984; Anderson and Potts, 1987; Fahey and Coker, 1989; Grayson et al., 1993). Finally, road surfaces themselves constitute a continually renewable source of fine material that is detached by vehicle usage, gullying, and to some degree rainfall impact, livestock usage, and other biological activity (e.g. Burroughs et al., 1984).

3. Theory

In the classic runoff theory of Horton (1933), overland flow occurs as a result of prolonged rainfall at an intensity greater than the infiltration capacity of the soil. Rainfall in excess of infiltration accumulates in small surface depressions, eventually overflowing them if rainfall continues. The Horton overland flow (HOF) mechanism is generally thought to be rare in fully vegetated, undisturbed areas because of high infiltration rates (however, see Elsenbeer and Lack, 1996). However, in areas where infiltration has been reduced by human activity, such as vegetation removal, or compaction, the Horton mechanism can generate a significant amount of overland flow. In this respect, highly compacted, largely bare soil surfaces and disturbed margins of unpaved roads in mountainous tropical watersheds are certain sources of HOF. While roads may also enhance runoff by intercepting subsurface flow, HOF alone may explain most of the increased runoff and subsequent soil erosion associated with roads in many tropical watersheds.

Infiltration capacity, the maximum rate at which water can be absorbed by the soil, decreases during a rainfall event, eventually approaching a more or less constant value. Infiltration will occur at a rate equal to the rainfall intensity at times when rainfall intensity is less than the infiltration capacity. If rainfall intensity is greater than the infiltration capacity, surface ponding will occur and the rate of infiltration will equal the infiltration capacity. Many attempts have been made to mathematically describe this process (for review, see Rawls et al., 1993). Philip (1957) approximated the time-dependent variation in infiltration capacity with a power series solution to Richard's equation. He proposed the first two terms of the series as a model of infiltration:

$$F = St^{\frac{1}{2}} + At \tag{1}$$

where F is the accumulated infiltration (L) and t is time since the beginning of surface ponding. The first term represents the filling of soil pores from the surface downward due to suction. S is sorptivity, the measure of the soil's ability to absorb water by matric forces. Sorptivity is determined in part by soil texture and structure, but also varies spatially and temporally depending on soil moisture content. The second term represents conductivity flow under gravity. Differentiating with respect to time gives:

$$f = \frac{1}{2}St^{-\frac{1}{2}} + A \tag{2}$$

where f is the infiltration capacity. As $t \rightarrow \infty$, the first term becomes less important and f tends to A, which approximates the saturated hydraulic conductivity of the soil. Although this model assumes surface ponding has occurred, the relationship between rainfall intensity and f gives an approximation of excess rainfall, the source of HOF.

4. Study area

4.1. Sam Mun

Most of the field work was conducted within the mountainous region NNW of Chiang Mai (city), Thailand, near Ban (village) Pang Khum (19°3′N, 98°39′E), within Samoeng District of Chiang Mai Province (Fig. 1). Field data was also collected within two small watersheds near Ban Kae Noi (19°41′N, 98°47′E), approximately 70 km NNE of Sam Mun. These two sites are representative of many mountainous areas throughout montane mainland Southeast Asia in that they are undergoing active rural development with

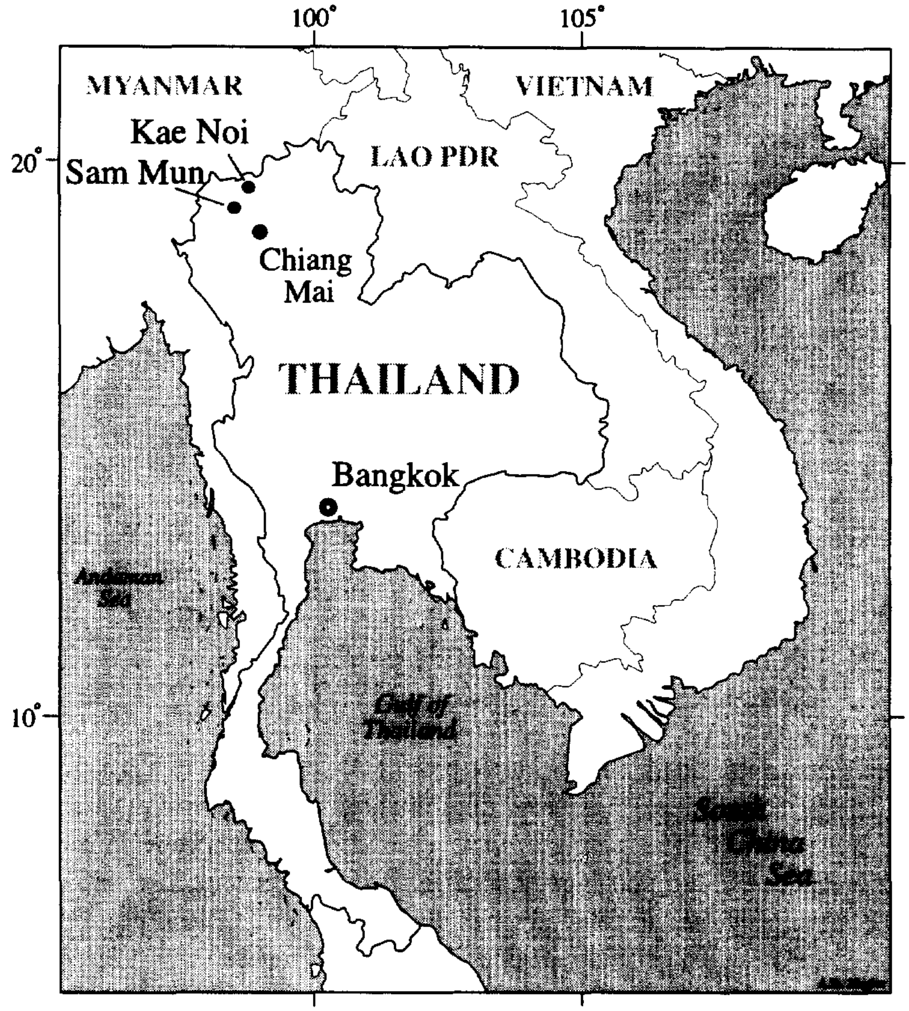

Fig. 1. The study area, Sam Mun, within the mountainous region NNW of Chiang Mai (city), Chiang Mai Province, Thailand. Field measurements were also taken near the village of Kae Noi.

expansion of unpaved road networks. The field data was used to make predictions regarding HOF generation in the larger 9600 ha Sam Mun watershed that encompasses Pang Khum.

Sam Mun ranges in elevation from 750 to 1850 m a.s.l. The area has a monsoon rainfall regime with a rainy season extending from mid-May through October or early November, during which approximately 90% of the annual rainfall occurs. Mean annual rainfall in the region is 1000–1200 mm (Alford, 1992), although data from Doi Mon Ang Get (1300 m a.s.l.), near Pang Khum, averaged 2929 mm during 1977 to 1982—suggesting that at least some areas receive greater amounts of rainfall due to orographic effects. Mid-November through late February is the cool season with mean air temperatures of around 17°C. Snowfall is rare, but does occur (Paluk Lamu, Karen villager, personal communication, 1996). During the hot season, March to mid-May, air temperature averages about 25°C, reaching daytime highs above 30°C. Soils in this region are mostly formed on residuum or colluvium from various parent materials such as granite, shale, sandstone, and limestone

(Pintong et al., 1994). Natural vegetation includes lower montane forest dominated by oaks (*Quercus* sp.), false chestnuts (*Lithocarpus* sp., *Castanopsis* sp.), laurels (*Cinnamomum* sp., *Neolisea* sp.), and birch (*Betula alnoides*). The region is managed by the Royal Forestry Department and occupied by northern Thai farmers and members of Hmong, Karen, and Lisu ethnic groups living in several small villages. Agricultural land use is dominated by paddy rice, swidden (slash and burn) fields of upland rice and corn, and cash crops such as tea, fruits, vegetables, and cut flowers. The population of the area increased five fold between 1954 and 1992 (Fox et al., 1995). With population growth, increased land pressure has reduced fallow periods from approximately 7–10 to 1–4 years (estimates are for northern Thailand in general, cf. Pintarak and Juntorn, 1995). Between 1954 and 1983, Fox et al. (1995) found that cultivation within the 9600-ha Sam Mun area increased from 539 to 2172 ha, mostly at the expense of dense forest. By 1989, only 55% of the area was estimated to have been covered by dense forest, having declined from 76% in 1954 (Fox et al., 1995).

4.2. Unpaved roads in Sam Mun

Table 1 lists area estimates for six land-use types in Sam Mun. We determined these values by regrouping the categories, determined by Fox et al. (1995) from Landsat imagery, to match our ground interpretation of the landscape: i.e. swidden, fallow, and tea were grouped as agriculture; grassland as initial secondary vegetation; forest, sparse forest, and plantation categories as forest; and rice paddies are not considered in this study. Areas for road surfaces and roadside margins were calculated by multiplying the total road length (53.9 km) by widths for each category. We determined the mean road width (3.9 m) from cross-sectional measurements (Table 2); roadside margins were considered to be the area 2 m on each side of the road. Because roads and the roadside margins were not included in the Fox et al. (1995) classification, we reduced the areas of other categories proportionally to preserve total area. With reclassification, land-use types associated with roads comprise a very small proportion of the study area.

The road density in Sam Mun is approximately 0.56 km km^{-2}. Many road sections were built from existing footpaths or animal trails within the last 10–15 years. Some sections are as steep as 18°. Daily usage includes motorcycle, both light and heavy truck, livestock (mostly cattle and water buffalo), and pedestrian traffic. Surface erosion on roads in Sam

Table 1
Land-use areas and percentage of total area for the 9600-ha Sam Mun study site. Values adapted from Fox et al. (1995)

Land-use type	Area (ha)	Percent of total
Unpaved roads[a]	21.0	0.22
Roadside margin	21.6	0.23
Agriculture	1954.3	20.44
Initial secondary vegetation	442.0	4.62
Forest	6912.2	72.31
Paddy	208.7	2.18

[a] Road length = 53 930 m (Jefferson Fox, personal communication, 1996).

Table 2

Mean road width for different slope classes in Sam Mun, based on six cross-section measurements for each class. The physical description states what percentage of the mean width is compacted, non-compacted, grass-covered, or an erosion feature (such as a rill, gully, or ditch)

Class	Slope (°)	Mean width (m)	Physical description			
			Compact (%)	Non-compact (%)	Grass (%)	Erosion feature (%)
Flat	< 2	3.7	68	16	14	2
Medium	2–10	3.4	53	23	9	15
Steep	> 10	4.5	58	9	2	31
Weighted class mean		3.9	59	15	8	18

Mun is acute, in part, because of the texture of the soils (Monat Suengjernying, Rural Area Development Program, Chiang Mai, personal communication, 1996). Our measurements indicate soil texture on road-related areas average 58% sand, 21% silt, and 21% clay (n = 11). Soils in the general area are paleudults, haplahumults, kandiustults, paleustalfs, and dystropepts (soils map, Department of Land Development, Bangkok).

Road surfaces are often ‘mud wallows’ during the rainy season and ‘dust bowls’ in the dry season. Chains, used for traction on steep, wet road sections, create deep ruts that further incise during overland flow events, eventually becoming gullies. On long, steep sections, gullies reach dimensions exceeding 1 m wide × 1 m deep. Irregular maintenance by villagers includes filling ruts and gullies with soil removed from cutslopes and non-incised areas of the road surface. This non-mechanized maintenance partially offsets lowering, but contributes to additional sediment availability: the unconsolidated fill is easily eroded during overland flow events; and soil removal from cutslopes make them more susceptible to slumping, which produces new easily erodible material. To preempt gullying on some long and/or steep road sections, channelized flow is diverted onto the hillslope. The diverted water, however, sometimes leads to erosion in downslope forested and cultivated lands. Road surface leveling using a tractor and blade occurs every 1–2 years. In general, steeper road sections are more eroded and wider than the lesser sloped sections (Table 2). The greater width may be attributed to more intense/frequent maintenance by both villagers and machinery. During the dry season, many road surfaces are covered with a deep layer of fine sediment, at depths sometimes in excess of 100 mm. This fine material is then easily transported downslope by overland flow events early during the next rainy season; and because many road slopes terminate at or near stream crossings (e.g. one 7.4-km section near Pang Khum crosses the stream seven times), the impact on stream sediment load is significant.

5. Methods and measurements

5.1. Overview of the field investigation

To examine the potential for Horton overland flow generation we determined saturated hydraulic conductivity (K_s) and sorptivity (S) on roads and adjacent lands, and measured rainfall during part of one rainy season. Surface bulk density (ρ_b) was determined at each measurement site to characterize differences in soil compaction between the different land-surface types. The soil measurements were taken on two distinct areas of the road surface: highly compacted areas (often tracks) and less-compacted non-track areas. Measurements were also taken on four other land covers including roadside margins, agricultural lands (active or fallow), initial secondary vegetation (including grasslands and areas with woody shrubs, but not trees), and forest (including exploited primary forest and areas of advanced or intermediate secondary vegetation with trees). In 1995, K_s, S, and ρ_b, were determined at 23 sites in Sam Mun and 20 sites at Kae Noi; 16 measurements were previously collected in Sam Mun in 1993. The sites were selected using a stratified sampling scheme based on land-cover type; and care was taken to include measurements throughout the watersheds surrounding Pang Khum and Kae Noi. Most measurements were conducted in pairs approximately 2 m apart, but were recorded as separate measurements in the data set. Additionally, the data from Kae Noi was determined to be indistinguishable from that from Pang Khum (Mann–Whitney non-parametric U test, $\alpha = 0.05$), allowing the two sets to be combined. Rainfall was measured at 10-min intervals with a TE525 tipping bucket rainguage (Campbell Scientific, Logan, UT) and recorded with a Licor (Lincoln, NE) LI 1000 datalogger at Ban Pang Khum in Sam Mun during the period 8 March to 3 September 1993.

5.2. Soil physical properties

Saturated hydraulic conductivity and sorptivity were estimated from infiltration measurements taken in situ with disk permeameters. The 1993 data set was collected using a Franklin Precision Eng. (Brookvale, Australia) CSIRO disk permeameter; the 1995 data set was measured with a Vadose Zone Equipment Corporation (Amarillo, TX) disk permeameter, fitted with a pressure transducer, and recorded with a Campbell (Logan, UT) 21x data logger. Changes in water volume in the latter permeameter reservoir correspond to changes in pressure, which are measured by the pressure transducer and stored in the data logger. The relationship between water volume and pressure was determined in a laboratory setting using linear regression ($r^2 > 0.999$). The permeameter is a modification of the design described by Perroux and White (1988). The technique for estimating K_s with this device is described by Cook et al. (1993). The soil at each measurement location was prepared by cutting the vegetation and leveling the surface to allow the permeameter to stand vertically. Care was taken to disturb the surface as little as possible. Sand was used as a contact medium between the surface and the permeameter base. Measurements continued until a steady state infiltration rate was detected or until all water had been drained from the permeameter reservoir, typically 1–3 h on roads, and less than 1 h on other land-surface types. K_s (L T^{-1}) was calculated with the equation defined by White (1988):

$$K_s = I - \frac{4bS^2}{\pi r(\Theta_0 - \Theta_n)} \quad (3)$$

where Θ_n is volumetric moisture content of the 'dry' in situ soil (0), determined from the bulk density core collected before measurement; Θ_0 is volumetric water content of the 'wet' in situ soil (0), collected immediately after measurement from the upper 1 cm of soil; r is the radius of the disk permeameter base (L); b is a constant set to 0.55, the estimate of the hydraulic conductivity corresponding to soil water pressure head applied by the disk; S is sorptivity (L $T^{-1/2}$), obtained by plotting cumulative infiltration vs the square root of time near the start of infiltration; and I is the infiltration rate (L T^{-1}) calculated as:

$$I = \frac{q}{\pi r^2} \tag{4}$$

where q ($L^3 T^{-1}$) is the slope of the plot of cumulative flow (from the permeameter into the soil) versus time, after the flow rate has become steady state; and r is the radius of the permeameter base. Occasionally we encountered difficulty in determining sorptivity values. If S is too high, the calculated K_s value can be negative (cf. Smetten et al., 1995). In such cases (three of 43 measurements) we had to use the lowest possible value of S present in the data set.

Bulk density (M L^{-3}) was calculated as the ratio of dry mass to the bulk volume of the soil. Soil volumes for measurements of θ_n and ρ_b were collected from the upper 3 cm with a 68.7-cm^3 corer. The samples were oven dried at 105°C to a constant dry mass.

5.3. Spatial distribution of K_s

Several studies provide direct and indirect evidence that the probability density function (p.d.f.) of hydraulic conductivity is log normal (see reviews by Freeze, 1975 and Dahiya et al., 1984). Therefore, using this assumption a new variable $Y = \ln(X)$ can be defined that is normally distributed, having a mean μ_y and variance σ_y^2 (estimated by $\bar{Y}$ and S_y^2, respectively). We determined a p.d.f. for each land-surface type based on field measurements of K_s. Each land-surface type was then disaggregated into 20 equal areas, each with a unique K_s corresponding to the midpoint of 20 probabilities classes defined by the cumulative density function (c.d.f.). These K_s values were then used in the simulation of excess rainfall on each land-surface type.

5.4. Excess rainfall

Excess rainfall (R_t) is the water that is neither infiltrated nor retained on the surface of a storm event. It is therefore the water that can become Horton overland flow once ponding is overcome. Excess rainfall (L T^{-1}) is calculated as the difference between rainfall and infiltration when rainfall is greater than infiltration:

$$R_t = \begin{cases} P_t - I_t & P_t > I \\ 0 & P_t \le I_t \end{cases} \tag{5}$$

where P_t is rainfall intensity (L T^{-1}), and I_t is infiltration rate (L T^{-1}). We simulated excess rainfall on each land-surface type during the 25 largest storm events of the rainfall collection period. Because we used measured 10-min rainfall data, rainfall intensity remained constant for 600-s intervals during each simulation. To calculate infiltration, we used a variation of Eq. (2):

$$f = \frac{1}{2}St^{-\frac{1}{2}} + \frac{1}{2}K_s \tag{6}$$

with the latter term as suggested by Loague and Freeze (1985). With this equation, infiltration rate is initially high, then declines, approaching one-half K_s as $t \rightarrow \infty$. Median values of S for each land-surface type were used in each simulation; K_s values were generated from the functional expression of the c.d.f. (Section 5.3). Limitations of this model are that it does not account for water stored on the surface, water infiltrated at periods during the storm with low rainfall intensities, or infiltration after rainfall cessation.

6. Results and discussion

6.1. Saturated hydraulic conductivity

The Mann–Whitney non-parametric U test (M–W U) revealed that the K_s values for compacted and non-compacted road surfaces were not from different populations (α = 0.05; n = 10 and 8). Saturated hydraulic conductivity for agriculture and secondary vegetation sites were also determined to be statistically indistinguishable ($\alpha = 0.05$; n = 10 and 12). Therefore, we combined these 'similar' land-surface types into two groups, reducing the total categories considered in this study to four: (1) road surfaces, (2) roadside margins, (3) agriculture/secondary vegetation, and (4) forest. Summary statistics of K_s, S, and ρ_b are presented in Table 3; the p.d.f. of K_s for the four land-surface types is shown in Fig. 2.

Saturated hydraulic conductivity on road surfaces was significantly lower than on non-road surfaces (M–W U, $\alpha = 0.05$; n = 18 and 41). The maximum value was 5.1 mm h^{-1}; the minimum, 0.2 mm h^{-1}; the median, 2.3 mm h^{-1}. Our values compare well to the range of values (1×10^{-5}–8.82 mm h^{-1}) reported for forest road surfaces by Luce and Cundy (1994), and are slightly lower than the range (0.5–45 mm h^{-1}) reported by Van der Plas and Bruijnzeel (1993) for former tractor tracks in Malaysia. Median K_s on the roadside margins was substantially higher than on road surfaces. Occasionally, K_s values on roadside margins were within the range of values found on road surfaces (minimum = 4.4 mm h^{-1}), but in other instances they were much higher (maximum $>$ 45 mm h^{-1}). The remaining two land-surface types had large maximum K_s values and ranges compared with road-related surfaces. Note the maximum forest value ($>$ 1666 mm h^{-1}) was recorded in undisturbed primary forest; the low value (52.3 mm h^{-1}) was recorded in forest disturbed by frequent grazing and wood gathering. In general, road K_s tended to vary little (coefficient of variation = 0.52).

6.2. K_s vs bulk density

Bulk densities were much higher on road surfaces and margins than on the other land surfaces due to compaction (Table 3). Median ρ_b was, respectively, 1.41 and 1.36 Mg m^{-3}

Table 3

Descriptive statistics for saturated hydraulic conductivity (K_s), sorptivity (S), and bulk density (ρ_b) for four land-use types in Sam Mun

Land cover	Forests	Ag./sec. veg.	Roadside margin	Road surfaces
n	11	22	8	18
K_s (mm h^{-1})				
Median	146.1	82.8	8.0	2.3
Mean	523.9	104.8	14.3	2.3
Std dev.	601.6	87.4	14.6	1.2
COV (dimensionless)	1.15	0.83	1.02	0.52
Maximum	1666.8	396.0	45.3	5.1
Minimum	52.3	5.3	4.4	0.2
S (m s$^{-1/2}$)				
Median	8.30E–04	8.40E–04	2.80E–04	1.80E–04
Mean	1.00E–03	1.20E–03	3.80E–04	1.80E–04
Std dev.	6.90E–04	8.70E–04	3.20E–04	7.50E–05
COV (dimensionless)	0.69	0.74	0.83	0.42
Maximum	2.60E–03	3.00E–03	1.10E–03	3.10E–04
Minimum	1.10E–04	2.20E–05	8.30E–05	5.20E–05
ρ_b (Mg m^{-3})				
Median	0.89	1.02	1.36	1.41
Mean	0.92	1.04	1.36	1.39
Std dev.	0.10	0.14	0.13	0.14
COV (dimensionless)	0.11	0.14	0.09	0.10
Maximum	1.14	1.25	1.56	1.6
Minimum	0.81	0.78	1.17	1.19

on road surfaces and margins, compared with 0.89 and 1.02 Mg m^{-3} on forest and agriculture/secondary vegetation lands. In comparison, two studies in Malaysia reported that bulk densities on forest tractor tracks were often significantly greater than non-track or undisturbed areas down to depths of 15–20 cm (Malmer and Grip, 1990; Van der Plas and Bruijnzeel, 1993). Compaction destroys soil structure, thereby often reducing K_s. This inverse relationship between ρ_b and K_s is evident in Fig. 3. Road surfaces form a cluster represented by high ρ_b and low K_s, while forest, secondary successional vegetation, and agricultural areas tend to have lower ρ_b and higher K_s. Fig. 3 reveals that road surfaces are much different than the other surfaces with respect to these hydrologic soil properties, and that roadside margins often resemble roads in this respect—especially when compacted by road building, maintenance, vehicle usage, or livestock trampling.

6.3. K_s *vs measured rainfall intensities*

Rainfall was recorded during 710 of the total 21 456 10-min periods from 8 March to 3 August 1993. All values in this record are greater than or equal to 0.254 mm ($P_t \geq$ 1.5 mm h^{-1}). Fig. 4 shows the frequency distribution for 10-min rainfall intensities during the collection period. As a first approximation, median K_s values can be considered thresholds for initiation of Horton overland flow on each surface; therefore, periods

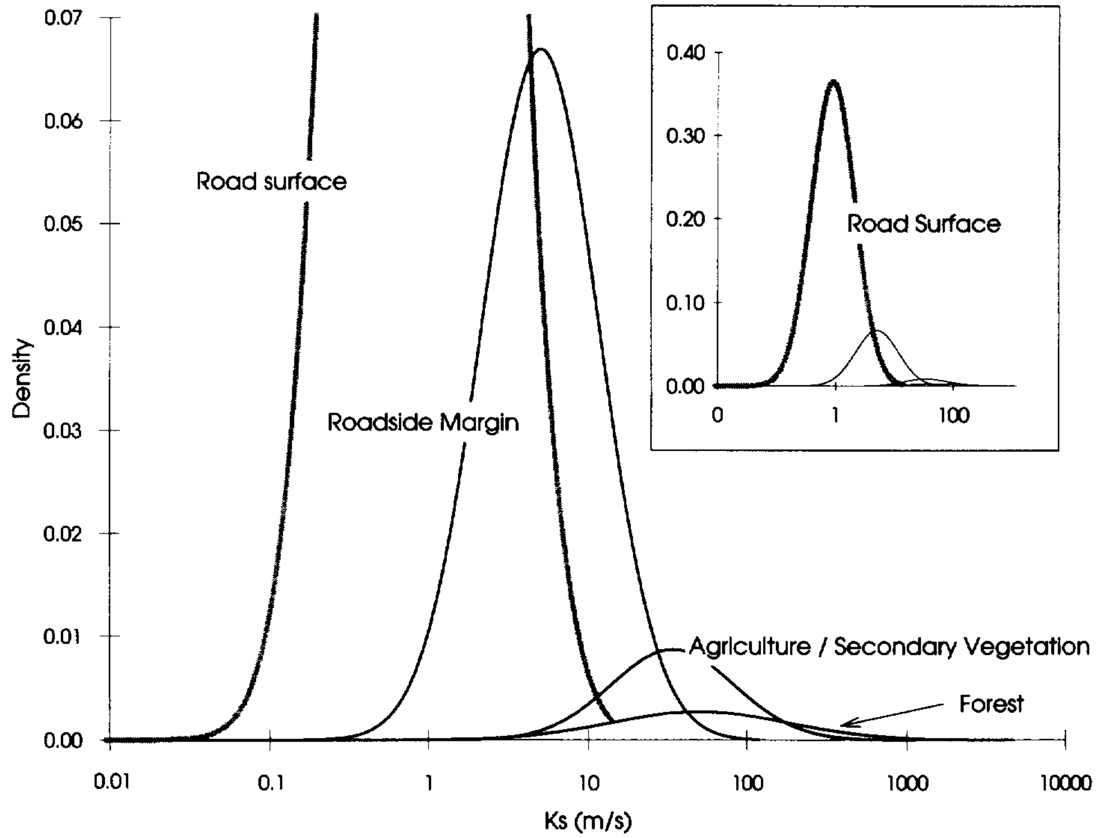

Fig. 2. Probability density function of K_s on four land-use types in Sam Mun. The p.d.f. is calculated using the field data set for each surface, and assuming K_s is distributed log normally. The inset is a smaller-scale depiction of the main figure. The p.d.f. for each surface appears normal because the X-axis is $\ln(K_s)$.

when $P_t > K_s$ represent times when overland flow could be initiated. Rainfall intensity exceeded K_s on road surfaces during $\approx 50\%$ of the 710 rainfall periods, but only during 12.7% of the rainy periods on roadside margins, and very rarely on the remaining land-surface types (Fig. 5; Table 4). These results indicate the relative importance of roads as source areas for Horton overland flow during typical wet season rainfalls.

In general, longer periods with rainfall intensity greater than K_s are more likely to generate Horton overland flow than shorter periods because the infiltration capacity decreases with time. We identified non-overlapping 20-, 30-, and 60-min periods during which P_t continuously (based on 10-min totals) exceeded median K_s for each land cover (Table 4). For the longer durations, P_t exceeded median K_s less frequently on each land surface. For example, K_s was never exceeded by P_t on agriculture/secondary vegetation or forest lands for durations of 20, 30, or 60 min. For roads on the other hand, several long-duration events had sustained P_t exceeding K_s.

6.4. Simulation of excess rainfall

We simulated excess rainfall during the 25 largest storm events in the data set to determine when road surfaces are significant source areas for Horton overland flow.

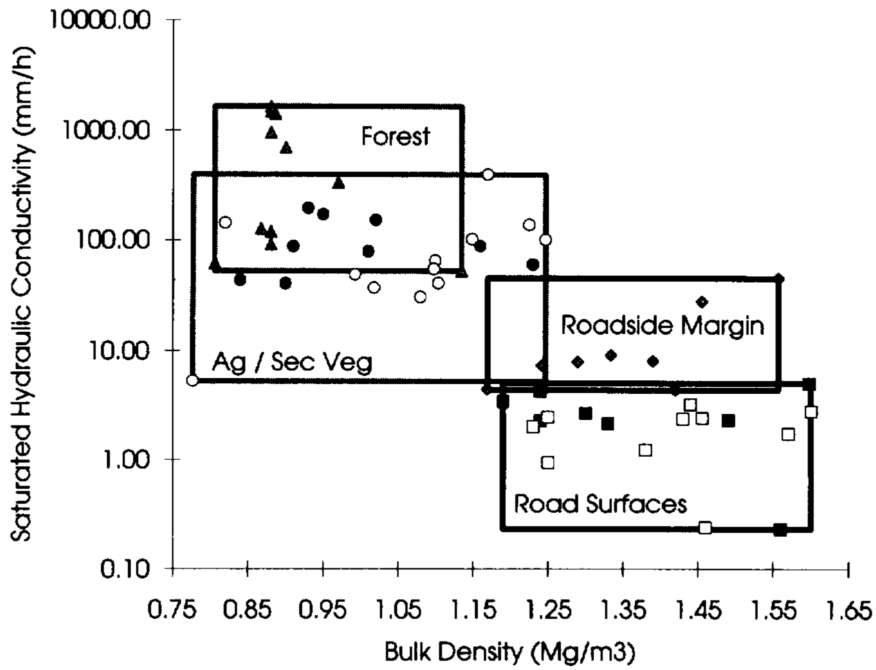

Fig. 3. The relationship between bulk density and saturated hydraulic conductivity on land-surface types. Road surfaces tend to have a much higher ρ_b and a correspondingly lower K_s compared with other surfaces. White squares correspond to compact road surfaces; black squares, less compacted road surfaces. White circles correspond to secondary vegetation lands; black circles, agricultural lands.

Fig. 6 is a conceptualization of rainfall and infiltration on four land-surface types during one of the largest storm events (Event 2; Table 5). Excess rainfall occurs when the rainfall curve is greater than the infiltration curve. In the simulation of each event, 20 separate infiltration curves are used for each land-surface type. During this particular event, P_t exceeds I_t on all road surfaces from 68 s until 40 min after the start of rainfall

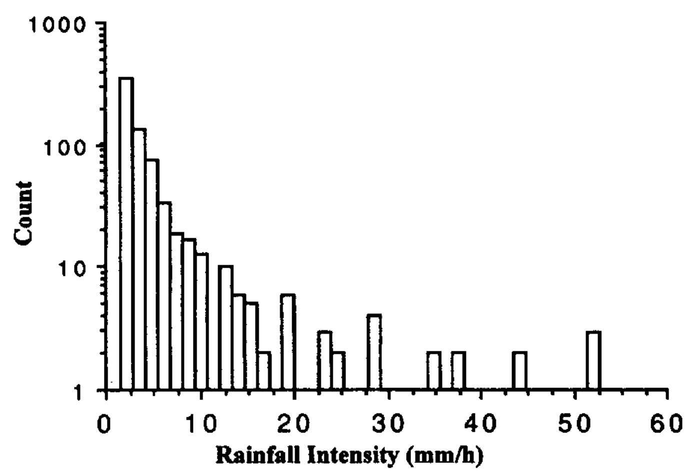

Fig. 4. Frequency distribution for 10-min rainfall, recorded from 8 March–3 September 1993 in the Sam Mun study area. This period includes most of one rainy season.

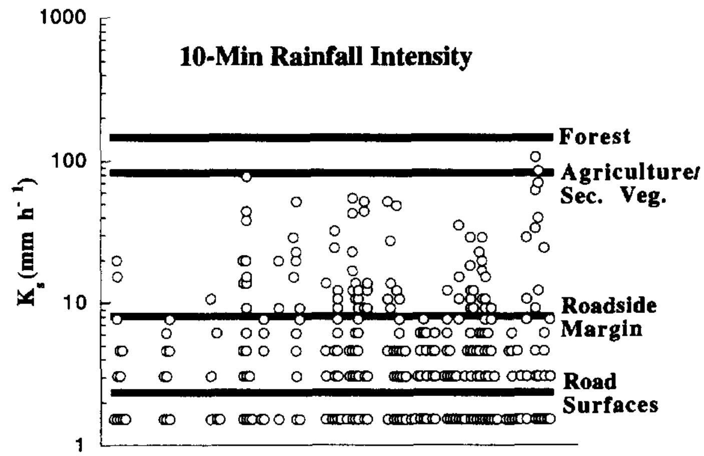

Fig. 5. Measured 10-min rainfall intensities (dots) superimposed on median values of saturated hydraulic conductivity (horizontal lines) for four land-use types in Sam Mun. Median road K_s values are at least one magnitude lower than all other land-use types. Numerical values for these figures appear in Table 3. Rainfall intensity never exceeded K_s on any non-road-related land surface during the collection period.

(Fig. 6(a)). In contrast, P_t exceeds I_t for less than 20 min on a very small portion of forest lands (Fig. 6(d)). Note that only the curves corresponding to the five lowest K_s values produce excess rainfall.

Reid and Dunne (1984) report a stabilization of infiltration rates on road surfaces in Washington State within the first 3–5 min of rainfall simulation. In contrast, our simulated infiltration rates are still approaching their one-half K_s limits after 50 min. However, our modeled steady state infiltration value of 1.15 mm h^{-1} (Eq. (6) using the median K_s value 2.3 mm h^{-1}) is only slightly higher than the average infiltration capacity found by Reid and Dunne (1984), approximately 0.5 mm h^{-1}. Our value is also between mean steady state infiltration rates reported for new and 6-year-old tractor tracks in Malaysia, 0.28 and 1.26 mm h^{-1}, respectively (Malmer and Grip, 1990).

A summary of all 25 simulations appears in Table 5, from which the following characterization can be made: (1) Simulated excess rainfall on road surfaces and margins occurs very frequently: e.g. all 25 simulated events produced R_t on road surfaces; all

Table 4

Frequency of 10-, 20-, 30-, and 60-min periods during which measured rainfall intensities continuously (based on 10-min totals) exceeded median values of saturated hydraulic conductivity (K_s) on each land-use type, during the 149-day period 8 March–3 September 1993

Surface type	Duration			
	10 min	20 min	30 min	60 min
Road surface	352	116	50	7
Roadside margin	90	34	10	0
Ag./sec. veg.	2	0	0	0
Forest	0	0	0	0

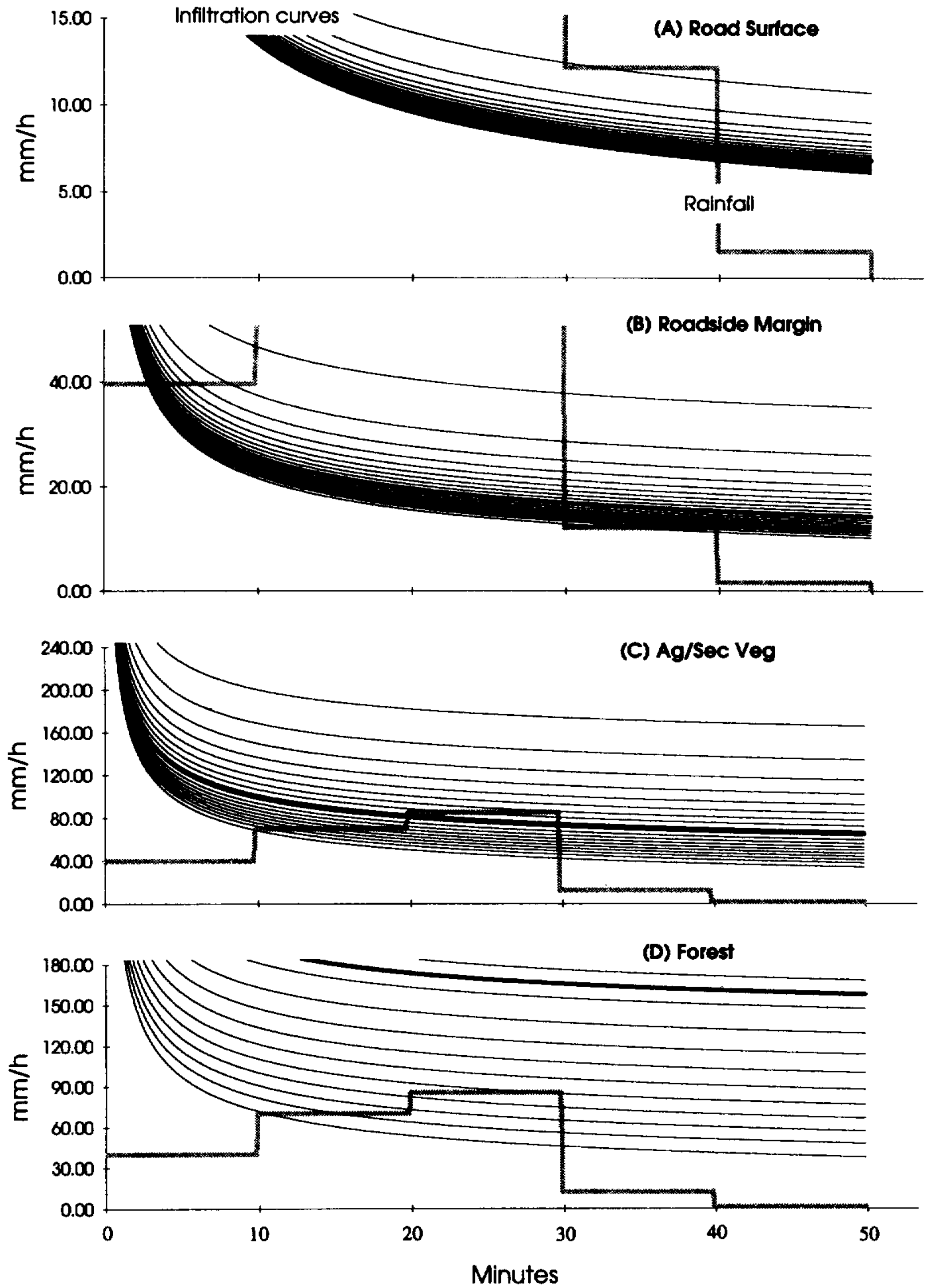

Fig. 6. Simulation of excess rainfall during a 35.3-mm, 50-min storm event on 29 July 1993 (Event 2, Table 5). Excess rainfall occurs when the rainfall curve (gray) is greater than any of the infiltration curves (black). Each surface is represented by 20 infiltration curves derived from probability classes of the K_s c.d.f. The bold curves correspond to infiltration calculated using the median K_s value.

Table 5
Summary statistics for simulation of excess rainfall during 25 in situ and eight design-type storms

No.	Storm description			Road surfaces			Roadside margin			Ag./sec. veg.			Forest		
	T	D	M	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
1	35.3	40	106.7	5589	75	95	4574	60	240	84829	10	600	85030	3	600
2	34.8	50	85.3	5391	74	68	4189	56	171	57541	7	600	55588	2	633
3	30.2	50	77.7	4436	70	73	3077	47	185	14927	2	600	13967	1	600
4	20.8	290	12.2	1212	28	3000	191	4	4200						
5	17.5	60	35.1	1946	53	600	1035	27	600						
6	16.8	120	38.1	1136	32	573	521	14	600						
7	16.8	40	51.8	2597	74	600	1870	51	600	1704	< 1	1200	1492	< 1	1317
8	16.0	280	18.2	393	12	600		4 < 1	848						
9	14.2	150	12.2	777	26	2400	51	2	3811						
10	14.2	70	54.8	1508	50	382	1110	36	600	166	< 1	989	30	< 1	1143
11	13.0	50	28.9	1042	38	382	424	15	717						
12	12.7	70	32.0	1343	50	1200	710	26	1200						
13	11.9	230	10.6	304	12	2996	50	2	9600						
14	11.4	50	27.6	384	16	142		12 < 1	364						
15	11.4	60	28.9	710	30	600	216	9	600						
16	11.2	60	49.0	1580	67	1800	1113	46	1800	3248	1	1800	3148	< 1	1800
17	10.9	20	42.7	1181	51	205	673	29	531						
18	10.9	180	12.2	254	11	1895		6 < 1	2400						
19	9.9	30	51.8	965	46	40	480	22	99						
20	9.7	50	29.0	669	33	600	216	10	600						
21	7.9	50	19.8	596	36	1200	100	6	1200						
22	7.4	280	4.6	26	2	12600									
23	6.6	50	13.7	93	7	600									
24	5.8	30	19.8	113	9	273									
25	5.8	50	22.9	462	38	1200	152	12	1200						

Design storms (based on the data of Apichart et al., 1980)														
26	52.0	60	52.0	8517	78	40	6441	57	98	30030	2	1118	27383	1	1306
27	62.0	60	62.0	10600	81	28	8533	64	69	81761	6	751	75661	2	848
28	70.0	60	70.0	12270	83	22	10221	68	54	143264	9	574	135170	3	635
29	82.0	60	82.0	14781	86	16	12771	72	39	265968	14	406	260914	5	440
30	40.0	30	80.0	6749	80	17	5526	64	41	57884	6	428	54955	2	466
31	45.5	30	91.0	7895	82	13	6684	68	32	105982	10	324	103858	3	347
32	59.0	30	118.0	10719	86	8	9551	75	19	275573	19	186	295353	7	195
33	69.5	30	139.0	12919	88	6	11793	79	14	444740	27	132	509298	11	137

T, total rainfall (mm); D, event duration (min); M, maximum intensity (mm h^{-1}); (a) total excess rainfall generated on land-use type (m^3) (excess runoff × total area of land-use type); (b) excess rainfall coefficient (%) (excess rainfall/precipitation × 100); (c) time to excess rainfall initiation (s).

but three events produced R_t on roadside margins. In contrast, R_t on agricultural, secondary vegetation, and forested lands is rare. (2) Events with high rainfall intensities are required to produce R_t on non-road surfaces. For example, the lowest maximum rainfall intensity for an event producing R_t on agriculture/secondary vegetation and forest was 49 mm h^{-1}, while R_t was generated on road surfaces by events with maximum intensities as low as 4.6 mm h^{-1}. Rainfall intensity alone, however, is not the sole determinant of excess rainfall. A substantially high intensity must occur at a time during the storm when infiltration capacity has decreased from its initially high starting value. This is demonstrated by comparing Storms 7 and 19, in which R_t was generated on both agriculture/secondary vegetation and forest only during Event 7. Although both events have a maximum P_t of 51.8 mm h^{-1}, the maximum occurred during the first 10 min for Event 19, compared with the third 10-min period (when infiltration was much lower) during Event 7. (3) Simulated excess rainfall on road surfaces is often a large portion of total rainfall. For example, nine events had excess rainfall coefficients ≥50%—in agreement with the mean runoff coefficient (≈ 65%) reported for unpaved roads in poor condition in East Java (Rijsdijk and Bruijnzeel, 1990). Non-road surfaces on the other hand, typically have low excess rainfall coefficients. Compared with non-road surfaces, roads generate R_t sooner in a rain event, and on nearly all of the areal extent. However, if R_t is generated on agriculture/secondary vegetation and forested lands, total simulated excess rainfall often overwhelms that from road-related surfaces because the areal extent is larger for these surfaces (i.e. area for forest and ag./sec. veg. is 6912 and 2396 ha, respectfully, compared with 21 ha each for road surfaces and roadside margins).

To further explore excess rainfall generation on roads, we simulated eight design storms, based on I_{30} and I_{60} values reported for Thailand (Table 6; from Apichart et al., 1980). Fig. 7(a) and (b) show the relative contribution of four land-use types to the predicted excess rainfall hydrograph during 60-min storms of probability 0.083 and 0.05, respectively. These simulations demonstrate that for smaller events, excess rainfall on roads comprises a greater percentage of the total excess rainfall. In Fig. 7(b), excess rainfall on road-related surfaces makes up 21% of total R_t volume, and solely comprises the hydrograph until nearly 20 min; however, for the larger event (Fig. 7(a)), the road contribution to total excess rainfall volume is only 5%, and R_t from non-road-related areas dominates in less than 10 min. In general, the smaller the storm size, the greater the road contribution to the predicted basin excess rainfall hydrograph; the near-linear relationship of this phenomenon, calculated for four I_{60} events of different magnitudes, is shown in Fig. 8.

Table 6
Probability of n-min maximum rainfall intensities for Thailand (adapted from Apichart et al., 1980)

Probability	Return period	Rainfall intensities (mm h^{-1})			
		10-min	30-min	60-min	360-min
0.50	2	131	80	52	14
0.25	4	152	91	62	15
0.167	8	181	118	70	18
0.083	12	212	139	82	20

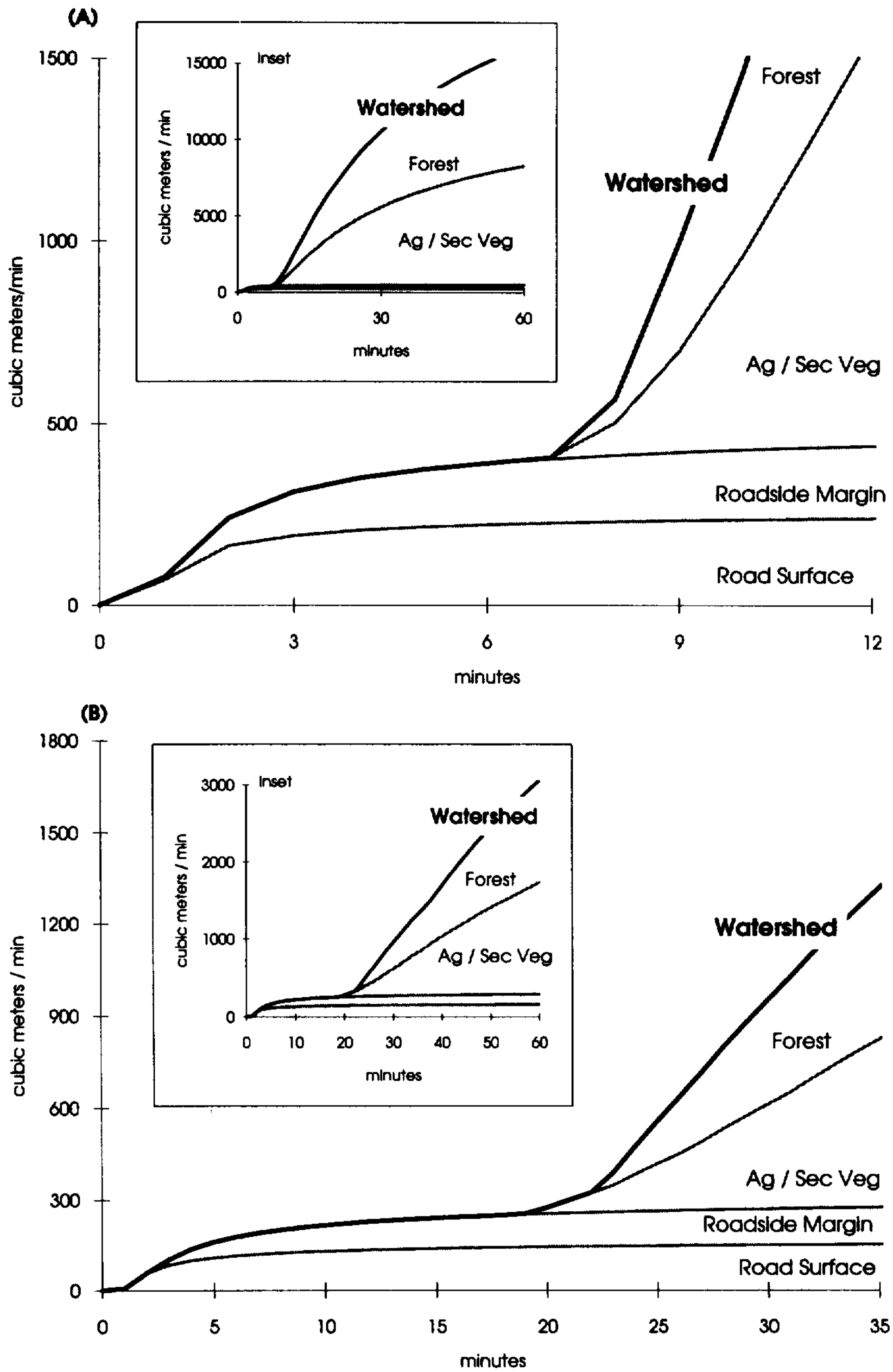

Fig. 7. Contribution of each land-use type to total predicted basin excess rainfall volume during 60-min design storms of probability 0.083 and 0.50 (for (a) and (b), respectively). Insets are smaller-scale versions of the main figure. During the smaller event (b), road surfaces and margins comprise a greater proportion (21%) of the total watershed excess rainfall volume than for the larger event (5%).

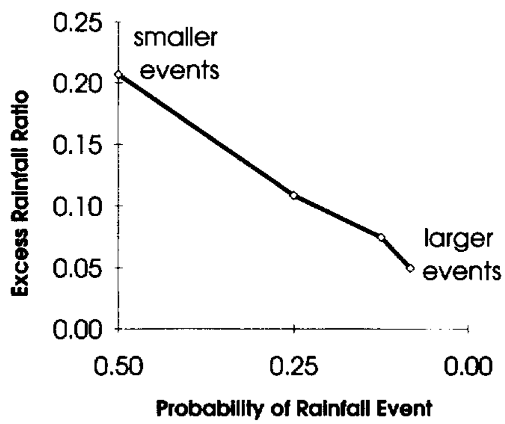

Fig. 8. Proportion of predicted watershed total excess rainfall volume contributed by roads and roadside margins as a function of rainfall event size. As the size of an event increases (i.e. probability decreases), the contribution from these two road-related surfaces increases in a near-linear fashion. The 60-min design storm simulations in Table 5 were used to show this relation.

The above two suites of simulations give quantitative support for field observations of others (e.g. Dunne and Dietrich, 1982; Reid and Dunne, 1984; Rijsdijk and Bruijnzeel, 1991; Harden, 1993; Van der Plas and Bruijnzeel, 1993) regarding the ease with which HOF is produced on roads in comparison with other surfaces of much larger spatial extent. Our results show that for small, commonly occurring storms, road-related surfaces often contribute more to total simulated excess rainfall volume than all other surfaces combined. During many simulated rainfall events, in fact, excess rainfall is generated only on roads and roadside margins. The implications of these simulations are that during smaller 'everyday' storms, the Horton flow component from roads might be quite large compared with all other streamflow generation components operating in the watershed (HOF or otherwise).

It is interesting that our simulated excess rainfall on agriculture lands is rare, but surface erosion rates on fields in northern Thailand are often reported to be high (e.g. Hurni, 1982; Forsyth, 1994). One might, therefore, question the representativeness of these simulations. It is obvious that many agricultural areas in northern Thailand are indeed substantial sediment sources, e.g. those around the three highland villages of Mae Haeng, Pakha, and Mae Sa Mai (Turkelboom et al., 1995). Our simulations suggest that HOF-induced erosion may not be as active in Sam Mun as in other areas, which may differ in population density, conservation practices, slope steepness, soil type, or rainfall. In addition, our simulations are based on an infiltration model that may not accurately describe all physical influences on the hillslope (e.g. it does not account for surface sealing during storms). Another likely explanation for the discrepancy is that high erosion rates on steep agriculture fields are often associated with HOF originating on adjacent paths, which we were unable to include (Section 6.6). A final explanation is that the short rainfall record may not have captured large rainfall events with periods of rainfall intensities high enough to produce significant excess rainfall, and hence, erosion-producing HOF.

6.5. Implications of spatial variability of K_s

On land surfaces other than roads and road margins, 'partial areas' exist where infiltration capacity is low and HOF is possible. For example, on one abandoned agriculture site, we found $K_s = 5.3$ mm h^{-1}, a value exceeded by 20% of non-zero 10-min rainfall measurements. However, these areas are rare. On a hillslope, low K_s areas are likely surrounded by areas of higher K_s that allow infiltration of excess rainfall from upslope. Overland flow is therefore unlikely to travel significant distances downslope, or to reach velocities capable of initiating erosion or transporting sediment as far as the stream channel. In contrast, a road is a linear feature of the landscape that tends to conduct concentrated overland flow along its surface. Because the entire surface is relatively impervious, runoff has little chance to infiltrate until it is released onto the hillside or into the stream. Prior to road construction, erosion resulting from Horton overland flow probably occurred only during relatively rare, large events. With roads, HOF is generated during virtually every rainfall event. Where road surfaces are composed of easily erodible material, as in Sam Mun (Section 4.2), significant sediment transport takes place throughout each rainy season.

Runoff response in watershed models is known to be more sensitive to spatial variability in K_s for small events (cf. Woolhiser et al., 1996). Our results show that this is especially true where roads are a principal component of K_s variability. The sensitivity to spatial variability in small events is insignificant where areas of low K_s are spatially random and disconnected. But, because roads form connected pathways of exceptionally low K_s, the cumulative effects of road-related runoff during numerous small events cannot be ignored. It is clear that the runoff response on roads operates on different time and space scales than other parts of the watershed. This fact has important implications for incorporating roads into watershed models (cf. de Roo, 1993).

6.6. Paths, tracks, and trails

Footpaths and trails are also important linear features that behave similarly to roads with respect to runoff generation and erosion. In mountainous northern Thailand, footpaths on steep agricultural lands are known to create HOF and erosion (Francis Turkelboom, personal communication). The impacts of paths have been noted in other tropical areas. For example, Harden (1992) reported visible erosion features (e.g. rilling) were generally traceable to runoff from upslope footpaths in the Andes. Dunne and Dietrich (1982) estimated sediment yield from paths to be on the same order of magnitude as that from rural roads in central Kenya. Rijsdijk and Bruijnzeel (1990) reported a measured surface erosion rate of approximately 70 t ha^{-1} $year^{-1}$ for a trail in East Java—a rate that is in close agreement with the values determined for nearby roads. In Sam Mun, an extensive path network exists on nearly all lands. We determined a median K_s value of 8.1 mm h^{-1} on ten footpaths; minimum and maximum values were 0.2 and 16.3 mm h^{-1}, respectively. When converted to steady-state infiltration rates (i.e. approximately $0.5 \times K_s$ via Eq. (6)), our values are slightly lower than the values reported for 12-year-old logging tracks in Malaysia, 0.5–45 mm h^{-1} (Van der Plas and Bruijnzeel, 1993). Despite the hydrological significance of paths, we were not able to include them in this analysis because of lack of spatial information on the path network in Sam Mun.

6.7. Influence of roads via non-Horton mechanisms

As discussed earlier (Section 2.1), roads can increase storm flow volume by two processes: the Horton mechanism, and interception of shallow subsurface flow by cutbanks, ditches, or culverts. We do not address the latter process in this paper; however, the results presented here and our observations in the field support the idea that the Horton mechanism is the dominant process by which roads increase storm runoff in Sam Mun. In mountainous northern Thailand, where soils are generally deep and underlain by regolith (Hansen, 1991) and where snowmelt is not a factor, shallow subsurface flow does not appear to be as important as in the northwestern US. Based on visual examination, the portions of roads and cutbanks that experience exfiltration during storms in Sam Mun are confined to intersections of the road with intermittent stream channels. These sites generally occur along the lower part of hillslopes near the main stream channel. While we do not yet have the necessary field measurements to make a conclusive statement, we believe non-Horton influences of roads on streamflow in Sam Mun are likely to be small in comparison with the large amount of excess rainfall produced throughout the road network.

7. Conclusion

As previous researchers have observed in other regions, we found unpaved roads to be critical source areas for erosion-producing overland flow in the Sam Mun area of mountainous northern Thailand. Our research provides a quantitative evaluation of the hydrologic significance of roads in relation to other land surfaces in a tropical watershed. Specifically, our measurements and simulations suggest the following regarding the importance of unpaved roads in generating excess rainfall, the source of Horton overland flow: (1) saturated hydraulic conductivities are 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 rarely exceeded the median saturated hydraulic conductivity of any land use except road surfaces and highly disturbed roadside margins; (3) during most storms, a significant portion of rain falling on roads does not infiltrate into the soil; (4) compared with non-road surfaces, an unpaved road generates excess rainfall sooner in a rain event, 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); however, for high intensity or long duration storm events, when excess rainfall is generated in non-road areas, the contributions of agriculture/secondary vegetation and forested lands often overwhelm those from road-related surfaces because of their larger areal extent. The significance of this latter point depends on the likelihood of HOF generated on non-road land-use types of reaching the stream system, which we believe to be much smaller than that generated on road surfaces.

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