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Contribution of intercepted subsurface flow to road runoff and sediment transport in a logging-disturbed tropical catchment

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Abstract

Hydrological and sediment fluxes were monitored for a 1 yr period in a tropical headwater catchment where a 3 yr old logging road caused substantial Hortonian overland flow (HOF) and intercepted subsurface flow (ISSF). On a 51·5 m road section, ISSF became an increasingly important component of total road runoff, up to more than 90% for large storms. The proportion of ISSF contributed by road cuts along more or less planar slopes compared with ISSF from a zero-order basin (convergent slopes) truncated by the road declined with increasing rainfall. During the monitored storms that generated ISSF along the road, on average, 28% of sediment export and 79% of runoff from the road section were directly attributable to ISSF. Estimates of total sediment export from the road surface (170 t ha^{-1} yr^{-1}) and suspended sediment export from the logging-disturbed catchment (4 t ha^{-1} yr^{-1}) were exceptionally high despite 3 yr of recovery. ISSF caused not only additional road-generated sediment export, but also exacerbated HOF-driven erosion by creating a poor foundation for vegetation recovery on the road surface. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: cutbank seepage; logging impacts; hydrogeomorphic controls; sediment yield; tropics

Introduction

Headwater areas have been increasingly recognized as important components of landscapes providing sources of water, sediments, solutes and organic matter downstream (Gomi *et al.*, 2002; Lowe and Likens, 2005). In Southeast Asia and other mountainous regions, these hydrologic source areas are being modified due to intensified land use, including logging, mining and agriculture (Bruijnzeel and Critchley, 1994; Myers, 1994; Fox *et al.*, 1995; Thapa, 2001; Sidle *et al.*, 2006). Land surface modification that involves removal of vegetation cover severely alters near-surface hydrologic processes and accelerates surface erosion (e.g., Lal, 1990), potentially resulting in a variety of on- and off-site consequences such as reduced site productivity, degradation of downstream water/habitat quality and channel morphology (Lyons and Beschta, 1983; Campbell and Doeg, 1989). A widely held view is that unpaved mountain roads are one of the landscape features that exert substantial influences on hydrological processes and sediment export in managed mountainous landscapes in tropics (Bruijnzeel and Critchley, 1994; Ziegler and Giambelluca, 1997; Ziegler *et al.*, 2000; Sidle *et al.*, 2004; Sidle and Ochiai, 2006; Sidle *et al.*, 2006).

Adverse effects of unpaved mountain roads have been an ongoing concern in temperate regions due to potential alteration of hydrological regimes (e.g. increased peak flows) as well as sediment export (e.g. increased sediment flux) in downstream areas (e.g., Hornbeck and Reinhart, 1964; Brown and Krygier, 1971; Beschta, 1978; King and Tennyson, 1984; Sidle *et al.*, 1985; Jones and Grant, 1996; Jones, 2000). Road surfaces are characterized by a limited infiltration capacity, thus are highly conducive to the generation of infiltration excess overland flow (i.e. Hortonian overland flow:

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HOF) early in storm events, even for small amounts of rainfall. Consequently, large volumes of sediment often enter streams as the result of (1) landslides caused by redistribution of overland flow (Swanson and Dyrness, 1975; Montgomery, 1994; Sidle *et al.*, 2006; Sidle and Ochiai, 2006) and (2) surface erosion caused by rain drop impact and disturbance due to road traffic (Reid and Dunne, 1984; Swift, 1984; Baharuddin *et al.*, 1995; Luce and Black, 1999; Ziegler *et al.*, 2000; Fransen *et al.*, 2001; MacDonald *et al.*, 2001; Megahan *et al.*, 2001; Ziegler *et al.*, 2001b; Sidle *et al.*, 2004; Negishi, 2005; Sidle *et al.*, 2006). These studies suggest that careful road management should consider construction and maintenance methods as well as various environmental factors such as soil and geological characteristics of the area, rainfall characteristics and connectivity via overland flow between sources and the receiving water body.

Roads also have potential to affect hydrological processes by intercepting subsurface flow along road cuts and transforming it into surface runoff if conditions are favorable (Burroughs *et al.*, 1972; Megahan, 1972; Megahan and Clayton, 1983). Intercepted subsurface flow (ISSF) has been frequently referred to as an explanation of hydrological regime changes (see, e.g., Harr *et al.*, 1975; King and Tennyson, 1984; Jones and Grant, 1996; Wemple *et al.*, 1996; Jones, 2000), at least suggesting its occurrence is unexceptional. Few studies have attempted to quantify the relative contribution of ISSF compared with HOF in road runoff (Megahan, 1972; Wemple and Jones, 2003), and virtually no research has been conducted on the relative roles of these two road runoff mechanisms associated with road sediment production and export. If road cuts produce ISSF, overall erosion unaccounted for by HOF may be substantial (see, e.g., Megahan, 1972). For instance, prolonged wetting of the road surface and erosion caused by ISSF may hinder establishment of vegetation on the road surface, which is an important factor in reducing road generated sediment (Beschta, 1978; Baharuddin *et al.*, 1995; Luce and Black, 1999; Negishi *et al.*, 2006), further exacerbating road impacts. Studies on ISSF related to hydrological and sediment fluxes are rare in the tropics (see Sidle *et al.*, 2006, for some descriptions), even though roadside ditches are commonly not used in the region to drain road runoff.

An experimental study site was established within a headwater catchment in Peninsular Malaysia that was disturbed by logging and associated roads to quantify the contribution of HOF and ISSF to road runoff and sediment production and relate these to catchment sediment export and in-stream sediment conditions. Here we elucidate processes related to the alteration of sediment and hydrological fluxes from road surfaces particularly due to ISSF in addition to conventionally studied HOF and HOF-driven erosion. Such empirical understanding will serve as a basis for developing models to predict and prevent adverse impacts of road construction in areas conducive to occurrence of ISSF. The following field information was collected in a small headwater catchment: (1) sediment export from the catchment outlet; (2) particle sizes and temporal dynamics of sediment stored within the channel; (3) variable responses of ISSF relative to HOF associated with rainfall amount and antecedent soil moisture; (4) variable responses of ISSF with and without influences of a geomorphic hollow (zero-order basin) and (5) relative roles of ISSF and HOF on sediment export from a 51·5 m road section. Also, data related to (1) and (2) were compared with similar data from an adjacent relatively undisturbed catchment.

Study Site

This study was conducted during the 1 yr period from 24 November 2002 to 23 November 2003 in catchments 1 (C1: 32·8 ha) and 3 (C3: 14·4 ha) of Bukit Tarek Experimental Watershed (3°31′N, 101°35′E), Peninsular Malaysia (Figure 1). Mean (±SE) annual precipitation for the period 1991–2000 was 2862 (±82) mm (Siti *et al.*, 2002); monthly rainfall patterns typically showed a bimodal distribution with two peaks around May and November (Noguchi *et al.*, 1996). During the study period, a total of 3516 mm precipitation fell; medians of total storm precipitation and 10 min maximum rainfall intensity (I_{max10}) were 19 mm and 48 mm h^{-1}, respectively, for 132 events with more than 5 mm of rainfall (see also Ziegler *et al.*, 2006). Daily air temperature measured at a nearby climate station ranged from 19 to 35 °C, with little inter-annual variation (Siti *et al.*, 2002). Surface geology consisted of metamorphic rocks and argillaceous sediments, including quartzite, quartz mica schist, schistose grit, phyllite, mica schist and indurated shale. Typically, a thin layer (0·3–0·7 m) of weathered quartzite dominates the lower portion of the regolith and is often exposed on disturbed surfaces such as roads (Saifuddin *et al.*, 1991). Along the main channel of the streams, riparian floodplains (total width of 2–5 m) existed on both sides. The average slope gradient in the catchment, which was measured from the foot of hillslope to the ridges, ranged from 40 to 45% with slope segments as steep as 65%. Representative forest species include *Koompassia malaccencis*, *Canarium* ssp., *Santiria* ssp., *Syzygium* spp., *Dipterocarpus crinitus*, *Dipterocarpus kunstleri*, *Shorea leprosula*; non-commercial rattan and bamboo (e.g. *Gigantuchloa scortechinii*) are frequent on lower slopes and valleys.

In the 1960s, the entire C1 and C3 catchments were selectively harvested for commercial timber. Thereafter C1 was left undisturbed, but C3 was again selectively harvested in November 1999–January 2000 with construction of a

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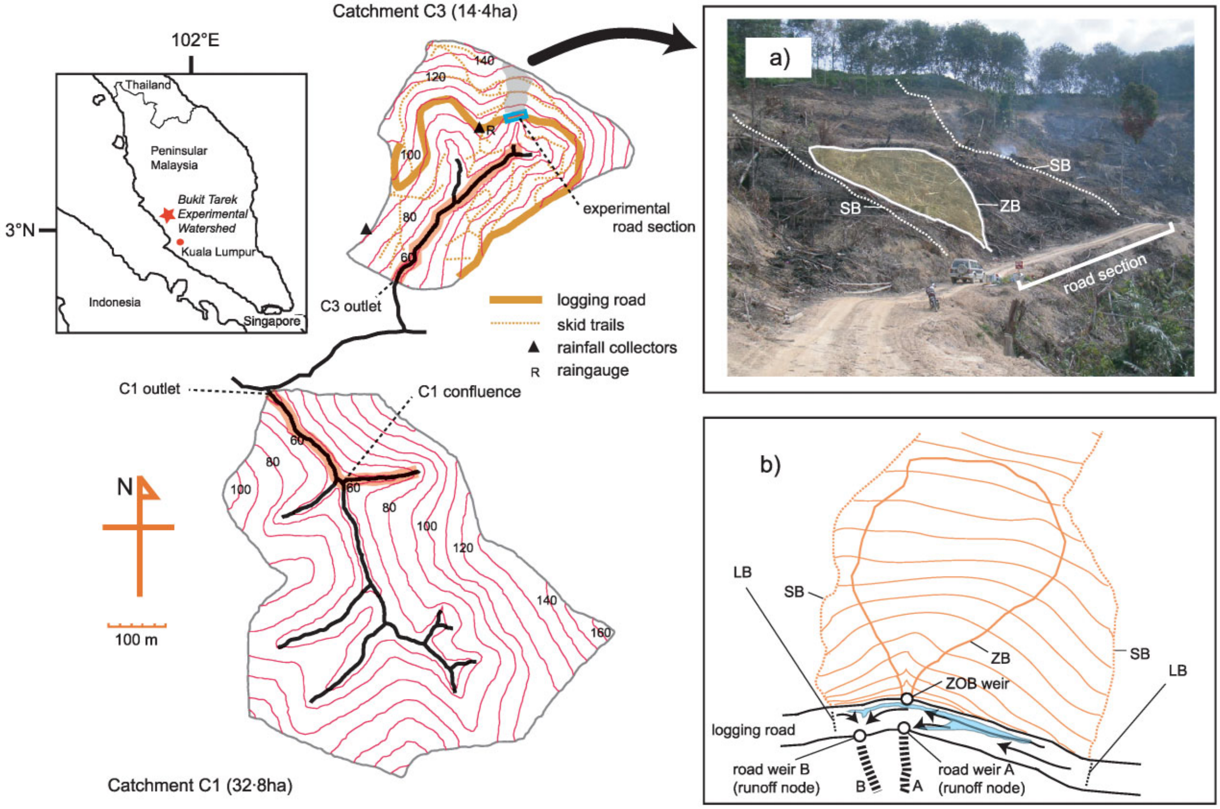

Figure 1. The location of Bukit Tarek Experimental Watershed (BTEW) and experimental road section, zero-order basin (ZOB), catchment outlets; shaded areas along the stream channel denote the section where the channel and substrate survey was conducted. (a) A view of ZOBC3: SB, slope boundary across which the road cuts down to the saprolite layer; ZB, zero-order basin boundary. (b) A schematic diagram of the runoff monitoring system showing the locations of road weirs and the ZOB weir and the directions of Hortonian road runoff; the shaded area on the road denotes noticeable rills where flow tended to concentrate. LB, logging road drainage boundary; A, B, gullies where road runoff drained to the downstream system. Note that the picture in (a) was taken in January 2004 immediately after the catchment was clear-felled and burnt, with little alteration of pre-disturbance surface topography. This figure is available in colour online at www.interscience.wiley.com/journal/espl

logging road and skid trails. The logging road, skid trails and landing areas constituted 3·2, 6·5 and 1·5% of the C3 catchment, respectively; roads are predominantly constructed by displacing surface soil down to at least the B_t/B_w horizon, often exposing weathered bedrock along the cutslope (Sidle *et al.*, 2004). Because the dominant stormflow generation process was via subsurface pathways along the saprolite–bedrock interface flow (Negishi, 2005; Negishi *et al.*, 2007), it was expected that road placements would strongly influence catchment processes. During 1999–2000, high value trees were extracted in C3 prior to a sequence of clear-felling, burning and tree plantation, which eventually was implemented from late November 2003 to January 2004. Hillslopes in C3 were well vegetated at the onset of the present study, with noticeable patches of organic debris (logging slash) and a few large trees (i.e. DBH >0·5 m), whereas logging road surfaces were largely bare without vegetation.

Monitoring locations included the following: (1) an experimental road section (length 51·5 m; average width 3·6 m; running surface area 183 m^2; average gradient 11·4%) that constituted a portion of logging road network (total length 690 m; average width 4·3 m; average gradient 8·6%), (2) the C3 outlet and (3) the C1 outlet (Figure 1). The saturated hydraulic conductivity (K_s) of the surface soil on roads (logging roads and skid trails) was extremely low (<2 mm h^{-1}) (Ziegler *et al.*, 2007). The road surface consisted of three different types of exposed material – i.e., subsoil, saprolite and bedrock. The preliminary measurement of the bulk density of exposed subsoil on the road (>1·58 Mg m^{-3}) was greater than that of undisturbed subsoil (<1·35 Mg m^{-3}) (see also Noguchi *et al.*, 2003), implying surface compaction. Exposed saprolite or bedrock was observed on 60% of the 5 m interval road survey transects along the main road

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(Figure 1, also see Negishi *et al.*, 2006), accounting for 15 and 8% of the running surface area of the entire logging road (21 and 9% in the experimental road section), respectively. Bedrock or saprolite was typically exposed within the remnant tire tracks of backhoes and vehicles; these ruts were further incised by road runoff. Consequently, HOF occurs on the road surface early in storm events, even for small events (Negishi *et al.*, 2006). The entire experimental road section was constructed by excavating into saprolite or bedrock, thus the road section intercepted most flow from upslope – i.e. shallow subsurface flow from the hillslope (0·42 ha) within which a zero-order basin (ZOBC3: 0·14 ha) was nested (Figure 1). ISSF generally occurred during the latter portion of storm events following HOF, in particular during large events (Negishi, 2005; Sidle *et al.*, 2006). Runoff generated on the road surface or from road cuts drained through either of the two road weirs, whereas runoff emerging from ZOBC3 traveled along the inside portion of the road and finally drained at the discharge node leading to gully B (Figure 1). Road runoff traveling downslope via the two discharge nodes formed extensive gullies that connected directly to the stream (Figure 1). Hillslope surface soil is generally highly permeable and rarely produces HOF (Negishi *et al.*, 2006; Ziegler *et al.*, 2006). In ZOBC3, however, based on field observations, areas along the lower part of the ZOBC3 valley generate Hortonian and/or saturation overland flow due to exposure of subsoil and relatively shallow soil (<0·7 m).

Methods

Characterization of In-Stream Condition

Selected reaches of stream channels in C1 and C3 were measured for wetted channel width, channel gradient, particle size of streambed material and fluctuation of the streambed surface elevation (Figure 1). A laser-based surveying system (Impulse 200, Laser Technology, USA) was used to obtain longitudinal channel profiles. Two substrate samples were collected from the streambed at 20–50 m intervals on 10–11 April 2003 using a 11·6 cm (diameter) × 10 cm (depth) stainless steel core. Only one sample was collected where the wetted stream width was less than 1 m. These sediment samples were immediately air-dried, followed by later over-drying at 105 °C for 24 h and sieved through mesh sizes of 0·5, 1, 2, 4, 8, 11 and 16 mm to obtain 50% weight percentile particle size (D_{50}). Streambed fluctuation was determined by burying one 50 cm scour chain (see Nawa and Frissel, 1993; Matthaei *et al.*, 1999) at mid-channel locations, 1 m downstream of each core-sampling location on 20–21 February 2003. The length of each scour-chain that was either buried or exposed was measured on 11 April, 16 May, 31 May and 15 June 2003 following the procedures of Matthaei *et al.* (1999).

Hydrological Monitoring

Two 60° v-notch weirs (road weirs: 0·6 m × 0·6 m × 0·9 m) were used to measure total outflow from the road section; another 60° v-notch weir (ZOB weir: 0·45 m × 0·5 m × 0·9 m) was installed to monitor discharge onto the road from ZOBC3 (Figure 1). Galvanized zinc flashing was cemented to exposed bedrock at the ZOBC3 outlet and road runoff nodes to facilitate the channeling of runoff to the respective weirs. Weir flow rates were continuously monitored at 2 or 3 min intervals using WT-HR water level sensors for more than 95% of the study period (TruTrack, NZ). The catchment outflow of C1 and C3 was continuously monitored by 120° v-notch weirs equipped with float-type water level instruments (W-021, Yokogawa, Japan). Incident precipitation was continuously monitored by a tipping bucket rain gauge in an open area approximately 80 m from the road section (Figure 1). Rainfall events were defined as a ‘storm’ if at least 5 mm of total rain fell with no periods of unmeasured rainfall for more than 60 min; 7 day antecedent rainfall index (ARI_7) was used as an index of soil moisture conditions because it was influential in characterizing stormflow responses (Negishi *et al.*, 2007). A total of 132 storms were monitored in the 1 yr study period, on average more than one every 3 days.

Event-Based Monitoring of Sediment

Sediment export was directly measured from the road weirs, the ZOB weir and the outlet of C3 during 11 events, and the outlet of C1 for a subset of these events (Table I). As road runoff contained material of a wide range of sizes, samples were divided into fine (<250 μm) and coarse (≥250 μm) fractions by taking duplicate grab samples at each measurement time: one each for quantifying total (TS) and coarse (CS) sediment loads. TS and CS samples were collected using 150–1050 mL polyethylene bottles; bottle size depended on sediment concentration during the sampling periods. Because coarse material transported from the ZOB weir was negligible throughout the study period (see also Negishi *et al.*, 2006), only TS grab samples (150–1050 mL) were collected at each measurement time at the ZOB

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Table 1. General characteristics of event-based storms monitored during the study period

Date	Total precipitation (mm)	I_{max10} (mm/hour)	ARI_7 (mm)	Duration (min.)
Dec. 2, 2002†	7	20	13	54
Dec. 3, 2002†	24	84	18	47
Dec. 4, 2002†	10	26	34	68
Dec. 5, 2002†	55	110	45	159
Feb. 9, 2003	17	84	0.7	18
Feb. 12, 2003	48	112	23	125
Feb. 17, 2003	36	44	130	140
Feb. 24, 2003†	38	118	46	134
May 9 2003	15	40	194	123
Sept. 27, 2003	14	54	93	208
Oct. 7, 2003†	86	110	32	355

† Suspended sediment yield for C1 was quantified only for these events.

weir. The outlets of catchments C1 and C3 were instrumented with ISCO 3700 and 2700 automated water samplers (ISCO, USA), respectively, to collect suspended sediment samples. Sampling intervals were variable among all the locations (automated and grab) to ensure reasonably distributed samples over rising and falling limbs of storm hydrographs. Road and ZOB samples were typically collected at 1–360 min intervals, whereas catchment outlet samples were collected at 15–480 min intervals.

The TS samples were filtered through pre-ashed GF/F filters (pore size = 0·7 μm; Whatman, UK). The road CS samples were wet-sieved (250 μm) to exclude sediments of less than 250 μm. The difference between TS and CS was considered to be fine sediment (FS). TS samples from ZOBC3 were considered to contain only FS. Sediment samples were immediately frozen, and then later oven-dried at 105 °C to obtain concentrations.

A YSI 6000 probe (Yellow Springs Incorporated, USA) was installed 5 m upstream of the outlet of C3 to measure turbidity at 10 min intervals. Turbidity values (NTU units) were calibrated against the less frequently measured suspended sediment concentrations in samples collected by the ISCO 2700 sampler (for storms on 17 February, 24 February and 7 October 2003). Because sediment concentrations (C) were relatively well predicted by turbidity values ($C = 0{\cdot}0244e^{0{\cdot}003NTU}$, $r^2 = 0{\cdot}80$, $p < 0{\cdot}05$, $n = 35$), we used turbidity as a surrogate to produce a more detailed record of suspended sediment concentration at the outlet of C3.

Analytical Approaches

Event-Based Separation of Road-Related HOF and ISSF

Event-based, road-generated HOF and road-intercepted ISSF were segregated based upon the hydrograph separation procedures explained in detail by Negishi (2005). In brief, HOF was estimated as rain falling on the 183 m^2 road surface, allowing for a lag time (i.e. 1–20 min depending on distance from the weirs) for runoff to reach the road weir, whereas ISSF was the residual of total road runoff after subtracting estimated HOF. In the present study, we further separated ISSF into $ISSF_{hillslope}$ and $ISSF_{ZOB}$; $ISSF_{hillslope}$ was the residual of ISSF after subtracting ISSF measured at the ZOB weir ($ISSF_{ZOB}$). Thus, $ISSF_{hillslope}$ and $ISSF_{ZOB}$ were considered as components of ISSF that appeared respectively from the road cutslope with and without the influence of the converging hillslope that characterized ZOBC3. Event-based flow flux at the catchment outlet was determined by the separation procedure of Hewlett and Hibbert (1967, p. 280) using a constant slope. This commonly used hydrograph separation method was chosen because there was no logical basis to use more sophisticated procedures such as the ones with variable separation slopes.

Estimation of Sediment Export

Sediment fluxes for sampling intervals during storms were calculated by summing the product of average sediment concentration and average flow rate during the interval. Event-based total sediment export at given sampling locations was then calculated by summing sediment flux for these intervals over the duration of individual storms. For the experimental road section, total fine and coarse sediment export (FS_{total} and CS_{total}) from the road, which includes suspended sediment from the upslope ZOBC3, was estimated by summing the sediment export at road weirs A and B. Road-generated fine

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and coarse sediment export (FS_{road} and CS_{road}) was obtained by subtracting sediment export of ZOBC3 (only FS) from FS_{total}, whereas CS_{road} was always equivalent to CS_{total}. For the events with no observations of subsurface flow (and thus no upslope contributions) the entire FS_{road} was assumed to be HOF-derived sediment. In contrast, when upslope contributions occurred, FS_{road} and CS_{road} were calculated as the sum of HOF- and ISSF-derived sediment.

Linear regressions between flow rates and corresponding sediment concentrations during events in which ISSF was negligible (i.e. <1% of HOF; events on 2 December 2002, 3 December 2002, 4 December 2002 and 27 September 2003) were never significant because of variable sediment fluxes due to the influence of both rainfall intensity and hysteresis effects. Thus, separation of HOF-derived and ISSF-derived sediment was conducted using the following approach. First, volume-weighted average sediment concentrations were calculated for those events in which ISSF was negligible (i.e. four events listed previously where ISSF contributed <1% of HOF). Then, volume-weighted average sediment concentration was multiplied by estimated HOF volume for those events with significant ISSF. The ISSF-derived sediment component was calculated as the difference between total road-generated sediment and estimated HOF-derived sediment.

Statistical Analyses

To test for statistical assumptions of ANCOVAs, the data were first fitted to a complete general linear model and residuals were compared for deviations from normal distributions using the Shapiro–Wilks test. The dependent variables were $\log_{10}(x + 1)$-transformed to improve normality of residual distributions wherever appropriate. All the statistical analyses were conducted using SPSS (version 11, SPSS, USA) with a statistical significance (α) of 0·05.

Results

Catchment-Scale Suspended Sediment Export

Event-based suspended sediment export from C3 (standardized by area) was obtained by turbidity measurements and gravimetric analyses in water samples for 27 and 11 events, respectively. The relationship obtained by regressing event-based turbidity-derived sediment export against event precipitation was statistically indistinguishable from that determined using the direct measurements of suspended sediment for the 11 monitored events (Figure 2; ANCOVA with measurement type as the main effect and total event precipitation as the covariate, $F_{1,36} = 0{\cdot}1$, $p = 0{\cdot}76$). Therefore, suspended sediment export obtained by the two different methods was pooled to form one composite C3 dataset to compare with sediment export from the outlet of C1. Event-based unit area suspended sediment yield from C3 was

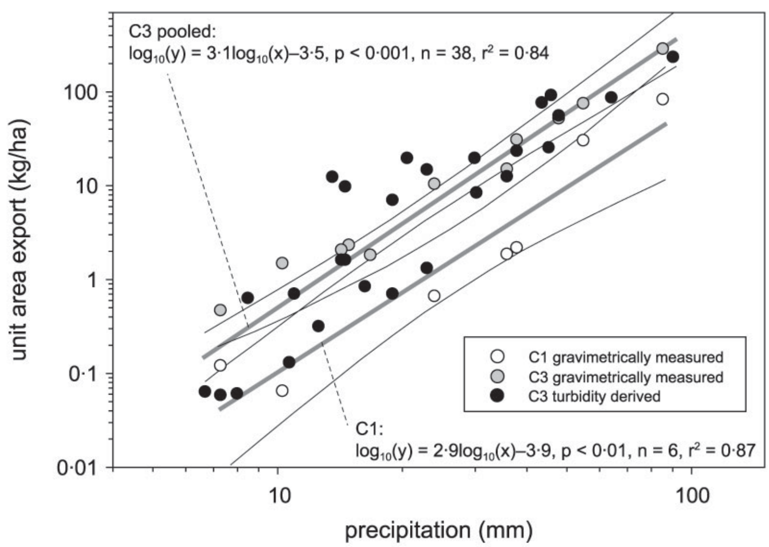

Figure 2. Event-based relationships between unit-area suspended sediment yield and precipitation for C1 and C3. Note that both axes are on a logarithmic scale. For C3, the export data include both turbidity-derived and gravimetrically determined (automated sampler) measurements. Linear regression lines and 95% confidence intervals are shown for C1 and C3.

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greater than from C1 for a given precipitation (ANCOVA with catchment type as main effect and precipitation as covariate, $F_{1,43} = 15 \cdot 9$, $p < 0 \cdot 001$) (Figure 2). Over the range of observed total event precipitation values (6·7–90·5 mm), event-based sediment export was on average 4·9 times greater in C3 relative to C1. Based on the 95% confidence intervals, for the storm precipitation in the range from 11 to 75 mm, sediment export was significantly higher in C3 than C1. We applied the relationships (i.e. linear regressions and 95% confidence intervals) of sediment export versus storm precipitation (Figure 2) to other events in which sediment export was not monitored but rainfall records were available. As a result, annual suspended sediment exports (mean, upper and lower confidence interval bounds) were estimated as 4·0, 7·1 and 2·3 t ha^{-1} yr^{-1} in C3 and 0·7, 2·6 and 0·2 t ha^{-1} yr^{-1} in C1.

In-Stream Characteristics

Average (±SE) wetted widths of C1 and C3 channels were 2·0 (±0·2) m and 1·8 (±0·5) m, respectively. Bedrock was exposed at two sections along the C1 stream channel (approximately 38 m^2 in total): only one location was within the main channel, the other was in the upstream tributary (Figure 3(a)). There was no bedrock exposure in the C3 channel. To obtain the average channel gradient, bedrock sections were excluded from this study because the total length of such areas accounted for only 8% of the entire channel length examined. Excluding the areas of bedrock outcrops, average gradients for the C1 and C3 channels were similar: 2·9 and 2·7%, respectively. Mean D_{50} was much larger in the C1 channel (11·4 mm) compared with the C3 channel (2·5 mm) (Figure 3(c), (d)). Furthermore, the average fluctuation of the streambed elevation, as determined by scour chains, was greater for the C3 channel than for the C1 channel (6·1 cm versus 1·9 cm) (Figure 3(e), (f)).

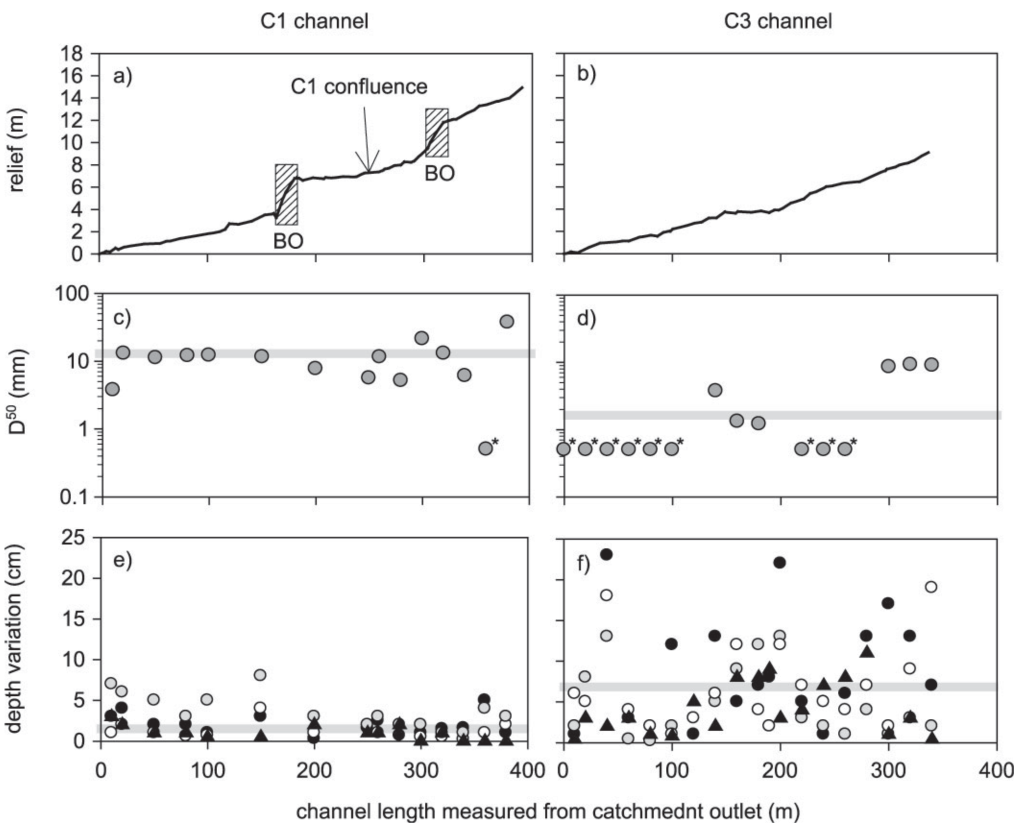

Figure 3. The following parameters were measured along both the C1 and the C3 channels: (a), (b) relief; (c), (d) 50th percentile for particle size (D_{50}); (e), (f) bed surface substrate fluctuation (based on scour chain data). Bedrock outcrops (BO) shown in (a). Different symbols in (e) and (f) denote different measurement days: closed circles – 11 April 2003; gray circles – 16 May 2003; open circles – 31 May 2003; closed triangles – 15 June 2003. Gray lines show mean values across sampling locations in (c)–(f). Data points in (c) and (d) accompanied by asterisks denote that D_{50} was less than 0·5 mm, which was the finest sieve mesh used. Note that the *y*-axes in (c) and (d) are on a logarithmic scale.

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Hydrologic Responses Attributed to the Road

HOF and ISSF were successfully separated in 56 of the 132 observed storms; these components could not be adequately segregated for 76 events due to malfunctioning of the WHR probes or the occurrence of multiple events during short periods. A strong linear relationship was found between the estimated HOF from the road section and total event rainfall; this relationship was not affected by antecedent moisture conditions (using ANCOVA with ARI_7 as the main effect and precipitation as the covariate, $F_{1,52} = 0{\cdot}1$, $p = 0{\cdot}74$; see also Figure 4(a)). In contrast, ISSF

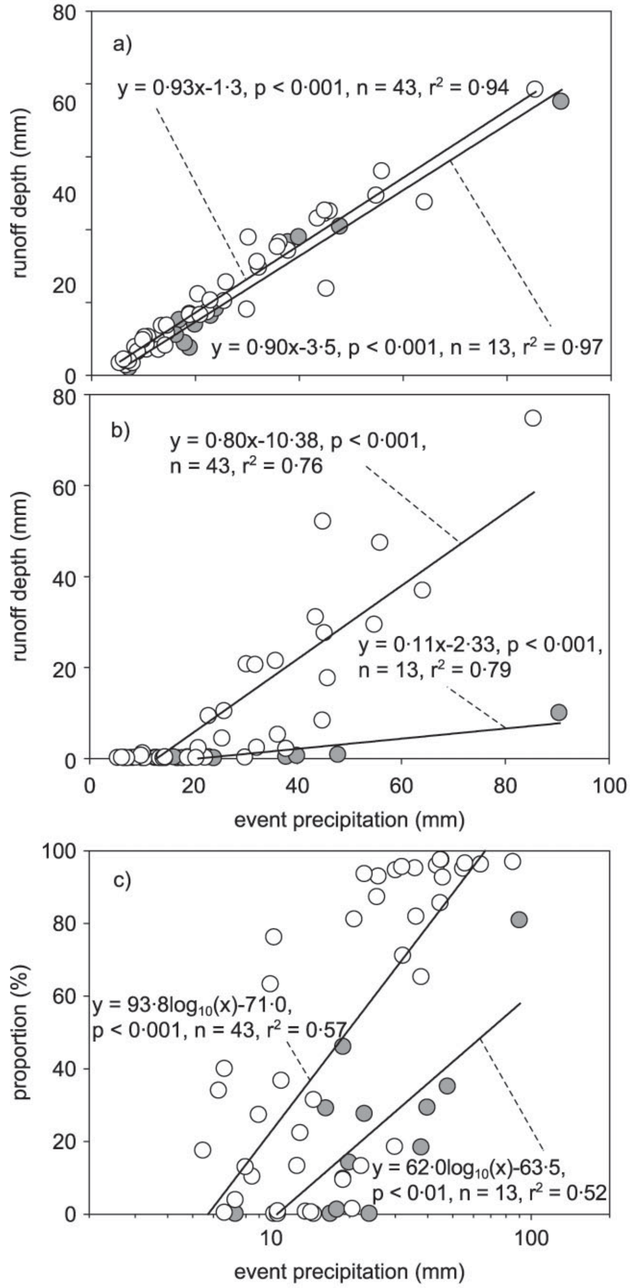

Figure 4. (a) Estimated HOF response on the road surface; (b) estimated ISSF response on the road surface; (c) ratio of ISSF to the sum of ISSF and HOF on the road section. Note that the *x* axis is on a logarithmic scale for (c). Open and closed circles denote the events with API_7 of 30 mm or more and less than 30 mm, respectively. Contribution areas of 183 m^2 and 41 200 m^2 were used to calculate runoff depth for (a) and (b), respectively.

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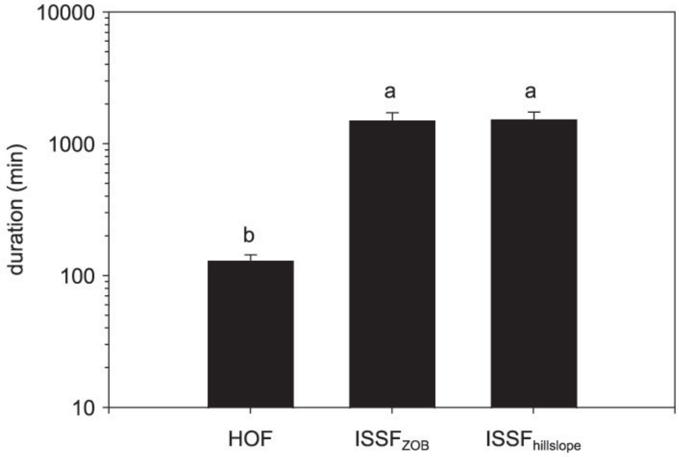

Figure 5. Means (±SE) of runoff duration of HOF, ISSF$_{ZOB}$ and ISSF$_{hillslope}$ for the events with ISSF inputs ($n = 32$). Letters above bars denote statistical results of one-way ANOVA followed by Tukey's multiple comparisons among HOF, ISSF$_{ZOB}$ and ISSF$_{hillslope}$ with events as the repeated measure. Different letters indicate statistical differences among the groups.

responses to precipitation were significantly dependent on ARI$_7$ (using ANCOVA; significant interaction effect between the main effect and covariate, $F_{1,52} = 34{\cdot}3$, $p < 0{\cdot}001$; see also Figure 4(b)). The threshold rainfall that induced ISSF response was about 20 mm when ARI$_7$ was 30 mm or more (open circles, Figure 4(b)). However, even storms with 40–50 mm of total rainfall did not generate a noticeable HOF response when ARI$_7$ < 30 mm (closed circles, Figure 4(b)). Consequently, the proportion of total runoff (sum of ISSF and HOF) attributed to ISSF increased progressively for events with higher amounts of rainfall. This proportion was especially large when ARI$_7$ was 30 mm or more (ANCOVA with flow type as the main effect and precipitation as the covariate, $F_{1,52} = 20{\cdot}1$, $p < 0{\cdot}001$) (Figure 4(c)).

For events when ISSF occurred (32 of the 56 events that were separated), runoff duration was significantly different among HOF, ISSF$_{ZOB}$ and ISSF$_{hillslope}$, (one-way ANOVA with event as a repeated factor, $F_{2,62} = 60{\cdot}3$, $p < 0{\cdot}001$; Figure 5). For example, durations of ISSF$_{ZOB}$ and ISSF$_{hillslope}$ were significantly longer than those of HOF; means of runoff duration were one order of magnitude longer for the ISSF components compared with the HOF (Figure 5). Peak rates of HOF recorded during individual events were higher relative to that of ISSF for all three event types when calculated on a unit-area basis; there was a trend that the mean peak rates of ISSF became higher for the events with high ISSF inputs (Figure 6(a); event types are defined in the figure caption). Without applying unit-area corrections, the observed peak flow rate of ISSF was as high as that of HOF for the events with exceedingly high ISSF inputs (>90% of road runoff) (paired *t*-test on log$_{10}$-tranformed peak flow; $p = 0{\cdot}32$) (Figure 6(c)).

Characteristics of ISSF$_{ZOB}$ and ISSF$_{hillslope}$

The responses of ISSF from the hillslope and ZOBC3 were variable depending on total storm rainfall and antecedent moisture conditions. While the ISSF$_{ZOB}$ contribution to total ISSF was generally smaller than the ISSF$_{hillslope}$ component for relatively small events, the ISSF$_{ZOB}$ contribution became progressively dominant for larger events (Figure 7). Furthermore, when antecedent conditions were relatively dry, no subsurface flow interception occurred from ZOBC3 (ISSF$_{ZOB}$) until rainfall depth exceeded approximately 20 mm. The contribution of ISSF$_{ZOB}$ then increased relative to ISSF$_{hillslope}$ for larger storms. Peak rates of ISSF$_{hillslope}$ during individual events were higher than those of ISSF$_{ZOB}$ for events with relatively lower ISSF event (storm type 1, paired *t*-test on log$_{10}$-transformed peak flow; $p < 0{\cdot}001$) with and without using unit-area corrected values (Figure 6(b) and (d)). In contrast, peak rates of ISSF$_{ZOB}$ became as high as those of ISSF$_{hillslope}$ for those events with relatively high ISSF event (storm types 2 and 3) (paired *t*-test on log$_{10}$-tranformed peak flow; $p > 0{\cdot}52$).

Sediment Responses Attributed to the Road

Of the 11 storms that were intensively sampled for sediment, four events experienced no ISSF input. Furthermore, sediment separation for HOF and ISSF was not conducted for the 27 September 2003 event because the total road flow rate was estimated to be in excess of HOF for only 3 min; thus, the sampling interval at that time (30 min) was

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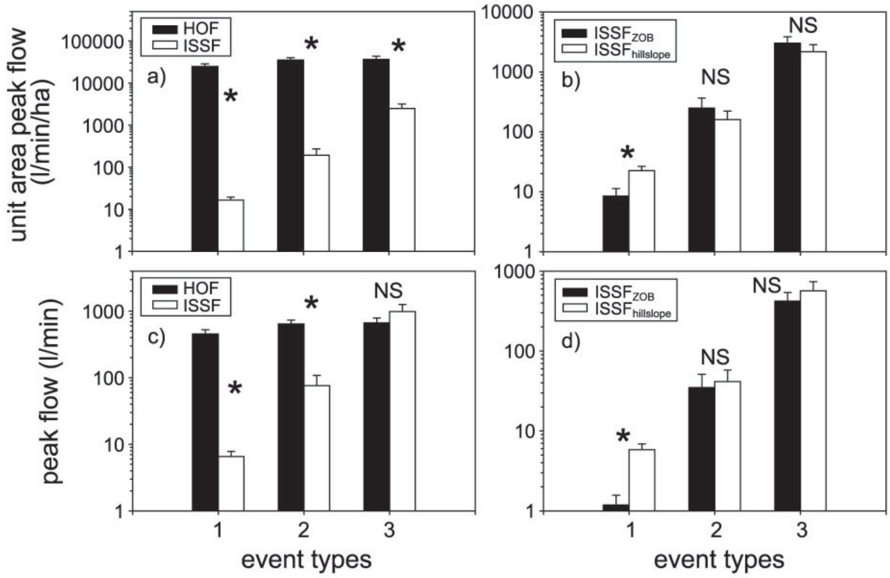

Figure 6. Means (±SE) of (a) peak flow rate of HOF and ISSF and (b) peak flow rate of $ISSF_{ZOB}$ and $ISSF_{hillslope}$ for three event types using unit-area corrections; Means (±SE) of (c) peak flow rate of HOF and ISSF and (d) peak flow rate of $ISSF_{ZOB}$ and $ISSF_{hillslope}$ for three event types without using unit-area corrections. Event types are based on ISSF inputs relative to the total road runoff measured at two weirs: type 1 ($n = 11$, ISSF inputs < 30% of total road runoff), type 2 ($n = 10$, ISSF inputs 30–90% of total road runoff) and type 3 ($n = 11$, ISSF inputs > 90% of total road runoff). Letters above bars denote statistical results of paired *t*-tests; NS indicates absence of statistical significance; astericks indicate presence of statistical significance ($p < 0{\cdot}01$).

considered inappropriate to represent the potential influence of ISSF on sediment export. Consequently, six out of the 11 storms for which sediment data were available were examined to determine the relative contributions of HOF and ISSF to sediment export (Table II). Event-based sediment export from the road section was dominated by fine sediment (>80%) (Table II). The proportion of ISSF-derived FS_{road} to total fine sediment export from the road (i.e. the sum of HOF-derived FS_{road} and ISSF-derived FS_{road}) ranged from 19 to 43% with a mean (±SE) of 27·7 (±3·5)%. Furthermore, the proportion of ISSF-derived CS_{road} to total coarse sediment export from the road (i.e. the sum of HOF-derived CS_{road} and ISSF- derived CS_{road}) ranged from 11 to 29% with a mean (±SE) of 15·7 (±3·9)%. The ISSF contribution to total sediment export was consistently less than its contribution to total road runoff, for which the mean (±SE) was 78·8 (±10·0)% (Table II). Log_{10}-transformed event-based total sediment export from the road section (y) was linearly predicted from log_{10}-transformed total rainfall (x) ($y = 1{\cdot}93x + 0{\cdot}22$, $p < 0{\cdot}001$, $n = 11$, $r^2 = 0{\cdot}79$) for the events shown in Table II.

Table II. Event-based ISSF contribution relative to HOF, sediment export, size-specific sediment export and ISSF contribution to sediment export from the experimental road section. Asterisks mark the events in which detailed road hydrologic and sediment responses are given in Figure 8

Date	ISSF volume %: ISSF/(ISSF + HOF)	Unit area FS (kg/ha) transport	Unit area CS (kg/ha) transport	FS weight %: FS/(FS + CS)	FS_{ISSF} weight %: FS_{ISSF}/(FS_{ISSF} + FS_{HOF})	CS_{ISSF} weight %: CS_{ISSF}/(CS_{ISSF} + CS_{HOF})
Dec. 2, 2002*	0	23	0.9	96	0	0
Dec. 3, 2002	0	1402	140	91	0	0
Dec. 4, 2002	0	198	18	92	0	0
Dec. 5, 2002	95	6136	184	97	43	24
Feb. 9, 2003	0	656	46	94	0	0
Feb. 12, 2003*	35	3036	273	92	19	11
Feb. 17, 2003	95	2121	28	99	23	14
Feb. 24, 2003*	65	2253	293	89	26	20
May 9, 2003	75	568	28	95	23	12
Sept. 27, 2003	<1	110	7	94	N.A	N.A
Oct. 7, 2003*	97	1973	237	89	32	29

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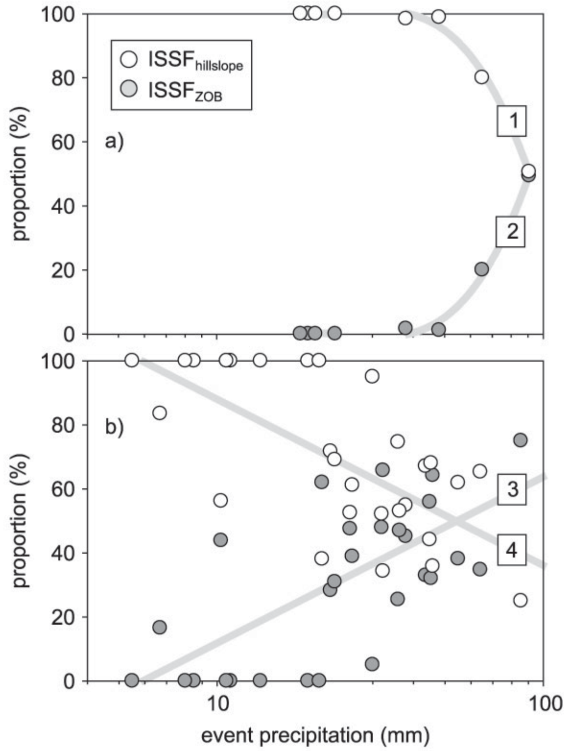

Figure 7. Relative contribution of $ISSF_{hillslope}$ and $ISSF_{ZOB}$ to total ISSF for $API_7 < 30$ mm (a) and ≥30 mm (b). Note that the *x* axis is on a logarithmic scale for both graphs. Open and closed circles denote the contribution of $ISSF_{hillslope}$ and $ISSF_{ZOB}$, respectively. Linear and cubic relationships are indicated by thick gray lines and numbers 1–4 were obtained by best-fit univariate regressions to demonstrate variable contributions of $ISSF_{hillslope}$ and $ISSF_{ZOB}$ to total ISSF depending on antecedent moisture condition. Regressions are the following: 1, $y = 1004 - 1946 \log_{10}(x) + 1390 \log_{10}(x)^2 - 329 \log_{10}(x)^3$, $r^2 = 0{\cdot}99$, $p < 0{\cdot}001$; 2, $y = -904 + 1946 \log_{10}(x) - 1390 \log_{10}(x)^2 + 329 \log_{10}(x)^3$, $r^2 = 0{\cdot}99$, $p < 0{\cdot}001$; 3, $y = -41 + 52 \log_{10}(x)$, $r^2 = 0{\cdot}45$, $p < 0{\cdot}001$; 4, $y = 141 - 52 \log_{10}(x)$, $r^2 = 0{\cdot}45$, $p < 0{\cdot}001$.

Examples of temporal dynamics of road sediment concentrations and fluxes are presented for a small event without ISSF and a large event with substantial ISSF, and also two intermediate events (Figure 8; Tables I and II). The responses observed for the two weirs were similar to each other except that peak flow rate of ISSF was lower for weir A due to the lack of $ISSF_{ZOB}$; only the data for the weir B was shown in Figure 8. During these storms, both fine and coarse sediment concentration peaked near the beginning of runoff except for the Feb. 12 event, in which peak of the coarse sediment concentration occurred during the second runoff peak, associated with the highest storm intensity (Figure 8(c), (d), (i), (j)). Coarse sediment (CS) concentrations were always lower than fine (FS) concentrations for all events. Consequently, the flux of fine sediment was always greater than that of coarse sediment (Figure 8(e), (f), (k), (l)) and these fluxes reached the highest rates approximately at the time of maximum HOF rate. Mean (±SE) volume-weighted average concentrations of HOF-derived FS_{road} and CS_{road} were 3·1 (±1·5) and 0·006 (±0·002) g l^{-1}, respectively. These means were the values used to estimate HOF-derived FS_{road} and CS_{road} for events with substantial ISSF inputs.

Discussion

Our findings provide several important implications for the management of unpaved roads in mountainous catchments where characteristics of soil horizons and prevailing stormflow generation processes are conducive to the occurrence of ISSF along the road, and drainage ditches don't exist. In addition to acting as a source of HOF and associated surface erosion, roads cut into hillslopes intercept subsurface flow, which in turn generates an additional export of sediment from road surfaces. Importantly, response of ISSF was highly dependent on both hydrologic (i.e. antecedent moisture conditions and total event rainfall) and geomorphic (i.e., ISSF responded differently with and without the influence of convergent topography) controls. Exceedingly high suspended sediment export from catchment C3, even

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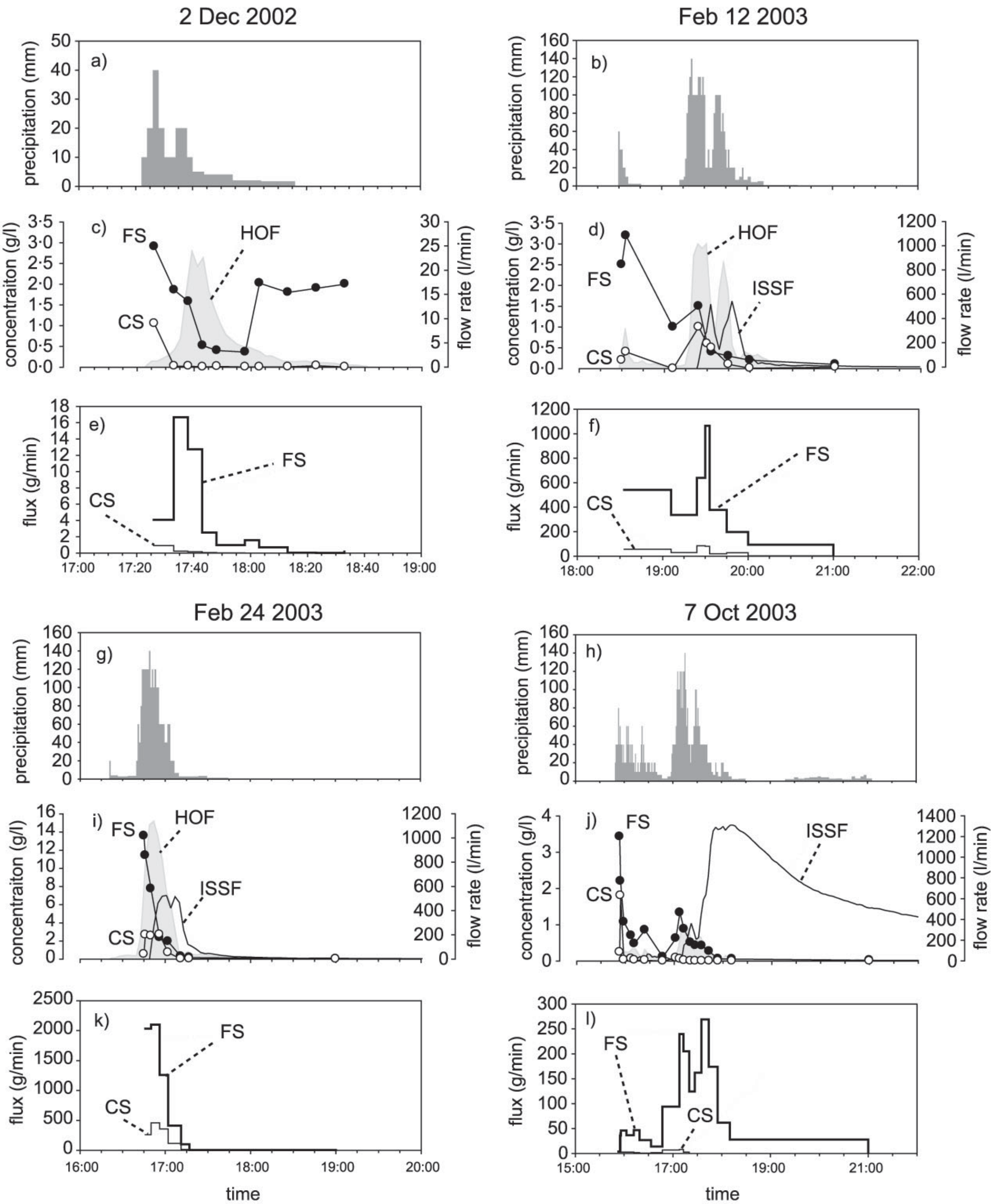

Figure 8. For storms on 2 December 2002, 12 February, 24 February and 7 October 2003 the following measurements are shown: (a), (b), (g), (h) precipitation; (c), (d), (i), (j) HOF- and ISSF-related flow rate and sediment concentration for road runoff; (e), (f), (k), (l) flux of coarse (≥250 μm, CS) and fine (<250 μm, FS) sediment. All discharge and sediment data are from road weir B.

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after nearly 3 years since the last land disturbance, was largely attributable to ongoing surface erosion on the road exacerbated by continuous wetting and surface wash by ISSF, which suppresses natural vegetation recovery.

Observations at the Catchment Scale

Because sediment and flow data were not available in catchment C3 prior to the 1999–2000 selective harvesting, we acknowledge the difficulties in attributing any differences found between C1 and C3 to the 1999–2000 road construction and harvesting operations. However, as C1 and C3 are less than 1 km apart and share similar geology, soils, topography, management history and original vegetation (and basically identical climate), it is reasonable to expect that sediment sources, transport and yields would be similar in these catchments if recent land disturbance had not occurred in C3. During the study period, the stream channel of C3 had much finer substrate material, compared with the C1 channel. Furthermore, streambed levels fluctuated more in C3, indicating that scour and fill were more active in this channel relative to the C1 channel. As the hillslope in C3 was well vegetated during the study period (Negishi *et al.*, 2006; Ziegler *et al.*, 2006), the elevated catchment sediment yield was most likely caused by a combination of ongoing sediment export from open, disturbed areas (i.e. main roads, skid trails and landings) and the release of sediment stored within the stream channel and gullies leading to the channel after the 1999–2000 harvesting and related intense road use. Alteration of streambed substrate characteristics by increases in fine sediment fluxes attributed to land disturbance has been widely reported (see, e.g., Murphy *et al.*, 1981; Moring, 1982; Davies and Nelson, 1993). Studies citing increased rates of catchment sediment export resulting from land disturbance are also ubiquitous (see, e.g., Hornbeck and Reinhart, 1964; Brown and Krygier, 1971; Harr *et al.*, 1975; Beschta, 1978; King and Tennyson, 1984; Douglas *et al.*, 1992; Zulkifli and Suki, 1994; Chappell *et al.*, 2004). Furthermore, relatively infrequent large storms may trigger landslides even years after lingering effects of catchment disturbances (Douglas *et al.*, 1999; Chappell *et al.*, 2004; Gomi *et al.*, 2004). Our results agree with such generally observed increases in erosion due to catchment disturbance.

Based on the regression models of sediment export versus storm precipitation (Figure 2), annual suspended sediment export was estimated as 4·0 t^{-1} ha^{-1} yr^{-1} in C3 and 0·7 t^{-1} ha^{-1} yr^{-1} in C1; export was 5·7 times greater from C3 than from C1. Uncertainty exists in estimates of total sediment yields as shown by the confidence intervals for the regressions in Figure 2. Nevertheless, total sediment yields of C1 calculated using the upper confidence interval bound (2·6 t ha^{-1} yr^{-1}) only slightly overlapped the C3 yield calculated based on the lower bound (2·3 t ha^{-1} yr^{-1}), suggesting the differences in sediment export between the two catchments were rather substantial. It is important to note that these estimates do not include bedload, which was obviously an important component of the sediment budget, particularly given the deposition observed in the C3 channel. In comparison with other catchment studies of logging impacts, the estimated range of suspended sediment export in C3 was higher than other values for clear-cut catchments (typically <1·5 t ha^{-1} yr^{-1}; see Gomi *et al.*, 2005), and as high as the export from catchments that experienced debris flows in the US Pacific Northwest (see, e.g., Grant and Wolff, 1991).

In the Southeast Asian context, our estimated value (4·0 t ha^{-1} yr^{-1}) is among the highest reported for managed forest catchments (see, e.g., Douglas *et al.*, 1992; Baharuddin and Abdul Rahim, 1994), but not for forest catchments converted to agriculture (Sidle *et al.*, 2006). One of the highest sediment yields from managed tropical forests (16 t ha^{-1} yr^{-1}) occurred immediately after timber harvesting in Danum Valley, Sabah, Malaysia (Douglas *et al.*, 1992). However, this very high sediment export was partly related to high natural levels of sediment export as well as additional inputs from periodic mass wasting; export in a neighboring undisturbed catchment was approximately 2·7 t ha^{-1} yr^{-1}; thus, export from the disturbed catchment was six times higher, about the same relative difference as in our study. Because mass wasting was not significant in C3 during the timeframe of our investigation (see, e.g., Sidle *et al.*, 2004), sediment export was most likely much higher immediately after the harvesting and particularly road construction, when small-scale sloughing along road cuts occurred (Sidle *et al.*, 2006) in addition to road surface erosion.

Hydrogeomorphic Controls on ISSF

Both the flux and spatial extent of lateral subsurface flow through soil horizons, including preferential flow, are strongly controlled by antecedent moisture conditions and rainfall depth (Whipkey, 1965; Mosley, 1979; Tsukamoto and Ohta, 1988; Sidle *et al.*, 2000; Noguchi *et al.*, 2001; Negishi *et al.*, 2007). Besides such antecedent moisture controls, the spatio-temporal variability of subsurface flow that is intercepted by roads also depends on the depth of the road cuts relative to the zone of soil saturation and subsurface flow (typically the soil–bedrock contact). For example, in mountain regions of Idaho, USA, development of soil saturation sufficient to generate lateral subsurface flow that intersected road prisms primarily occurred during snow melt (Burroughs *et al.*, 1972; Megahan, 1972). Wemple and Jones (2003) parameterized the likelihood of ISSF occurrence based upon the height of cutslopes and

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related it to observed fluxes of intercepted subsurface flow in Oregon, USA. In contrast, studies in northern Thailand concluded that HOF is the major source of road runoff; ISSF rarely occurred owing to shallow road cuts relative to depths of active lateral subsurface flow (Ziegler and Giambelluca, 1997; Ziegler *et al.*, 2001a). In our site, a hydrologically impeding saprolite/bedrock layer occurs at depths of ~1 m (Saifuddin *et al.*, 1991; Ziegler *et al.*, 2006), above which shallow groundwater generally accretes, providing a major stormflow component (Negishi *et al.*, 2006, 2007; Sidle *et al.*, 2006). Because approximately 60% of the main road system in catchment C3, including our entire experimental section, is cut into the saprolite/bedrock layer, shallow subsurface flow is readily intercepted when a rainfall threshold is reached. In addition to rainfall amount, antecedent moisture also plays a role in mediating the threshold rainfall that induces ISSF response, and thus the contribution of ISSF to total road runoff. In particular, when antecedent moisture and event rainfall are sufficiently high, ISSF becomes a dominant component of road runoff, and peak flow rates of ISSF increase to levels comparable to HOF (Figure 6(a), (c)).

In addition to hydrologic controls, geomorphic factors also influence the spatial and temporal dynamics of subsurface flow. Previous studies have demonstrated that hillslope areas with converging topography tend to be more hydrologically active than planar hillslopes (see, e.g., Anderson and Burt, 1978). Thus, the disproportionate stormflow contributions (in both time and space) from various geomorphic components depend on the scale of observation (Sidle *et al.*, 2000; Tsuboyama *et al.*, 2000; McGlynn *et al.*, 2004). In fact, substantial variability in stormflow responses among geomorphic components (i.e. zero-order basins relative to planar hillslopes) has been shown in C1 (Negishi, 2005). The current findings are consistent with the notion that the likelihood of occurrence, response and flux of ISSF also depends on how roads are placed in relation to geomorphically distinct landforms (e.g. convergent, divergent and planar), each of which should differ with respect to subsurface hydrological processes (Tsukamoto and Ohta, 1988; Luce, 2002; Wemple and Jones, 2003; Mirus *et al.*, 2007).

In C3, the experimental road section dissects a landform that includes both concave and planar features. As a result, ISSF was characterized by a disproportionate response from the convergent portion of the hillslope relative to the more planar portion. For example, increases in flow volume with increasing rainfall were more punctuated for the zero-order basin compared with the more planar slope (see Sidle *et al.*, 2000). Furthermore, such geomorphic differences accentuated when antecedent moisture was high, highlighting the differential threshold rainfall required to produce runoff (Figure 7). These observations support the view that conditions that exceed certain rainfall and antecedent moisture thresholds trigger nonlinear increases in the contribution of converging headwater hillslopes to stormflow generation (see, e.g., Sidle *et al.*, 2000; Tsuboyama *et al.*, 2000). Although roads inevitably have to be constructed across different topographic features to provide efficient accesses throughout managed catchments, the proportion of the road length that crosses hydrologically active concave hillslopes is important in determining the total volume of ISSF runoff intercepted by the road (see also Wemple and Jones, 2003).

ISSF-Driven Sediment Export

Despite much research and inferences related to effects of land disturbance on changes in ISSF (Burroughs *et al.*, 1972; Megahan, 1972; Megahan and Clayton, 1983; Jones and Grant, 1996; Wemple *et al.*, 1996; Jones, 2000; Wemple and Jones, 2003), the influence of ISSF on road-generated sediment export has not been examined rigorously for more than three decades since the topic was initially discussed by Megahan (1972). For the storms that we observed, excluding the event on 27 September 2003 (Table II), ISSF accounted for 28% of the total sediment export from the experimental road section, indicating that its direct contribution to road sediment export was less than HOF, but not negligible. Because ISSF contributed an average of 79% of the road runoff volume during six intensively monitored events, sediment export was apparently influenced by factors other than flow volume. Such potential factors include the differences between HOF and ISSF in terms of erosion causes and sediment availability for fluvial export. First, ISSF-transported sediment was generally not exposed to the influence of raindrop impact (i.e. splash erosion) because ISSF typically initiated after the peak rainfall intensity and usually after rainfall ceased. Thus, splash erosion was almost strictly associated with HOF (Figure 8). Because splash erosion was a major source of sediment on the logging road (Negishi *et al.*, 2006), the sources of transportable sediment via ISSF were less. Second, the spatial extents of the road surface on which respective runoff mechanisms can exert tractive forces were different between HOF and ISSF. Specifically, HOF potentially washed the entire road area, whereas ISSF concentrated on a portion of road near the cutslope (in particular along the rills in remnant tire tracks on the inside of the road running surface); this was a substantially smaller area. Third, sediment sources generated during inter-storm periods on the road might be disproportionately depleted at a greater rate early in the road runoff hydrograph (shown by the initial flush of sediment by HOF; see Figure 8). On the other hand, bank sloughing may occur late in storm events, or even after rainfall ceases; thus, additional pulses of sediment may be available for ISSS transport that were not available during the portion of the storm when HOF dominated. However, such a phenomenon was not prevalent during the study

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period. Last, peak HOF was generally greater than peak ISSF for the observed events (Figure 6(a), (c)), lending further support to this hypothesis of disproportional depletion of sediment.

Differences in source areas (and spatial extent) of sediment transported by HOF and ISSF are strongly linked with different sediment production processes. HOF-generated sediment primarily originates from the running surface of the road where rain splash erosion occurs and generates surface runoff. In contrast, the major source of sediment exported by ISSF is from erosion of disturbed soil, part of which might have been supplied by small-scale sloughing of the road cutslope. Areas on or near the cutslope are probably less affected by HOF than the areas on the running surface of the road, where a large volume of HOF runoff travels with its greatest tractive force. In particular, locations near the outlet of ZOBC3 were potentially exposed to the greatest hydraulic forces of ISSF relative to the rest of the road cutslope, initiating significant erosion unique to this ISSF pathway. This is also partly because peak flow from the ZOB weir is concentrated in a small area compared with the more diffuse peak runoff for $ISSF_{hillslope}$ (i.e. distributed across the entire road section cutslope). Consequently, sediment exported by ISSF was most likely the combination of sediment originating from cutslope areas and also mobilization of materials that were deposited near the road weirs during declining HOF (and corresponding transport capacity) of the same event. This latter process may be particularly important when ISSF peak flows become as high as HOF peaks during large storms. For instance, during relatively large storms on 5 December 2002 and 7 October 2003, contributions of ISSF to road sediment export were higher than their contributions during smaller storms (Table II).

Occurrence of ISSF and Road Impacts on Sediment Export

Using empirical relationships derived from event-based sediment yield versus event precipitation for all storms in the study period (see results section), annual sediment export (total sediment) from the experimental road section was roughly estimated as 170 t ha^{-1} yr^{-1}. This figure is 30% less than the sediment yield of 244 t ha^{-1} yr^{-1} that was indirectly estimated from the main logging road in C3 for the first 16 months after the road construction primarily by measuring residual soil pedestals and rill/gully dimensions (Sidle *et al.*, 2004). Comparison of these two figures suggests that a moderate level of recovery has occurred during the 20 months between the two studies, although the extent of these differences attributable to methodologies is uncertain. Nevertheless, given that the erosion rate estimated in this study (170 t ha^{-1} yr^{-1}) was based upon the measurements made three years after road construction with infrequent road traffic during the intervening period, this rate is still about two orders of magnitude greater than rates of other studies, which show substantial decreases in runoff volume and sediment production 2–3 years after road construction (see, e.g., Megahan, 1974; Baharuddin *et al.*, 1995). Thus, the current high catchment sediment yield can be attributed to ongoing high levels of erosion from the road surface, a part of which is efficiently exported through discharge nodes that connect roads to the stream. Thereafter, the sediment is either directly transported to the catchment outlet or deposited within the stream channel for subsequent remobilization during large events (Sidle *et al.*, 2004).

In general, reduction of sediment export at the catchment scale coincides with the timing of vegetation recovery on the road surface – i.e. within several years after the cessation of major disturbances (Beschta, 1978; Baharuddin *et al.*, 1994; Zulkifli and Suki 1994; Black and Luce, 1999; Chappell *et al.*, 2004). Recovery of vegetation on the road surface generally suppresses road surface runoff and surface erosion (Baharuddin *et al.*, 1995; Luce and Black, 1999). A major difference of the road condition in C3 compared with other relevant studies is the absence of vegetation recovery on the road surface of C3 (Negishi *et al.*, 2006). We argue that the adverse effects of cutting forest roads into water impeding substrate are not just limited to the direct alteration of hydrologic processes and associated sediment export by transforming subsurface runoff into surface runoff. Additionally, unpaved mountain roads that are conducive to the generation of ISSF *indirectly* prolong the occurrence of HOF and related sediment generation processes by delaying vegetation recovery and therefore, road recovery. The water impeding layer is characterized by a low hydraulic conductivity relative to shallower soil horizons; the impeding layer has relatively high bulk density and low porosity (e.g. saprolite and bedrock in the study site) (Ziegler *et al.*, 2006). Such surfaces provide very poor foundations for plant establishment and growth (Kozlowski, 1999). Furthermore, extended periods of surface wetting and wash caused by ISSF (Figure 5) preclude successful colonization by vegetation (Pinard *et al.*, 1996). Although the direct influence of ISSF on sediment export was only approximately 28% during the 1 yr study period, and HOF was the major direct cause of road sediment export, the effective contribution of ISSF to sediment export might have been much greater if indirect influences were also considered.

Conclusion

Headwater catchment C3 was characterized by high suspended sediment export (4.0 t ha^{-1} yr^{-1}) relative to other forest catchments and an unstable streambed consisting of fine sediments nearly three years after the selective timber

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harvesting with road construction. Based upon hydrological monitoring of the experimental road section, the road cutslope intercepted a substantial volume of ISSF, with its contribution increasing to more than 90% of total road runoff when rainfall amounts and antecedent moisture were high. In particular, the zero-order basin with converging slopes tended to increase its contribution to total ISSF disproportionately relative to that of the more planar adjacent hillslopes. Consequently, for the 11 intensively monitored storms, ISSF-derived sediment accounted for 28% of the total sediment exported from the road section. Erosion rate from the road surface was exceptionally high (170 t ha^{-1} yr^{-1}) during the study period, largely explaining the very high sediment yield at the catchment outlet. Our findings suggest that road cuts conducive to ISSF not only provide additional sediment sources for fluvial transport downstream, but also prolong road impacts by delaying vegetation recovery on the road surface. Such adverse effects may occur particularly when roads are constructed across hydrologically active areas such as zero-order basins. Therefore, we emphasize that managers and engineers should carefully examine locations of road placement in the context of subsurface flow processes and topographic characteristics of the areas. Although our study design did not allow such testing due to the absence of multiple road monitoring stations crossing various landforms, both total contributing area and hillslope gradient may well also affect ISSF response (see, e.g., Wemple and Jones, 2003). From the findings presented herein, we suggest that sediment loss from the road surface can be greatly reduced by installing proper ditch lines along the cutslope that would at least shorten periods of road wetting and surface wash extending after the cessation of HOF. Furthermore, road abandonment and restoration practices should prioritize rerouting of major overland pathways to allow flows to follow their original pathways as much as practical so that hydraulic forces can be dissipated.

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