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Sources of suspended sediment within a tropical catchment recovering from selective logging

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Abstract:

Quantification of the source of suspended sediments generated by selective forestry activities is central to the development of sustainable forestry guidelines. This assessment is hampered by a dearth of available studies, particularly from the tropics. This study involved the monitoring (at 10 s intervals) of surface discharge and turbidity from 15 contributory areas of a 44 ha catchment. The catchment is located within lowland dipterocarp rain forest on Borneo Island, in a region recovering from the first episode of selective timber removal that took place some 5 years previously. Both the within-storm dynamics of the sediment flux and the time-integrated sediment yields were analysed to link the source landforms to the catchment behaviour.

A 10 year rainfall event of 167 mm occurred during the monitoring period and triggered a debris slide and several log-culvert collapses along the area's main timber haulage road. The sampling design captured this event's dynamics and allowed lumped catchment response to be traced to the new landforms. During the 1 day period of the 10 year event, some 33 t of suspended sediment were transported from one debris slide, comprising a significant proportion of the 105 t discharging from the whole catchment, which itself constituted 40% of the annual yield of 592 t km^{-2}. The contributory areas with only ephemeral waterflows, including former haulage roads and tracks, generated relatively little sediment during this 10 year event or in other storms. This work suggests that though some sediment sources recover from the impacts of forest road construction and harvesting, collapse of roadfill materials or more local log-culvert failure persists for several years after harvesting. Sustainable forestry guidelines that do not focus on ameliorating these persistent instabilities may not significantly mitigate the geomorphic impacts of conventional, selective harvesting. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS erosion; forest roads; Malaysia; sediment budget; sediment delivery; turbidity

INTRODUCTION

One of the most significant environmental impacts of forestry within the humid tropics is accelerated soil erosion (Bruijnzeel, 1992). The resultant input of sediments into streams, leads to damage to fish populations (Martin-Smith, 1998), reduced quality of water supplies, reductions in channel capacity affecting flood risk and boat traffic (Sheffield *et al*., 1995), and the inundation of offshore corals (MacDonald *et al*., 2001). The mitigation of these deleterious impacts is, therefore, central to the goal of sustainable management of natural forests within the tropics (Bruijnzeel, 1992; ITTO, 1992).

Previous research has indicated that the terrain and canopy disturbance associated with forest road construction and harvesting operations can lead to the development of new 'erosional landforms', such as: road gullies (Croke and Mockler, 2001); zones of rain-splash and surficial wash on haulage roads and skidder-vehicle trails (Madej, 1982; MacDonald *et al*., 2001; Megahan *et al*., 2001; Ziegler *et al*., 2000a,b); collapses along streams, particularly at road crossings (Madej, 2001); landslides in cleared areas (Collison

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and Anderson, 1996; Sidle and Wu, 1999); landslides in road-cut materials (Swanson and Dyrness, 1975; Wemple *et al.*, 2001); and soil piping under roads. Whilst many of these landforms can be identified within any disturbed tropical forest catchment, understanding the relative role of each is often very difficult (Reid and Dunne, 1996). Quantifying the contribution of sediment by each landform type is difficult, because of: (1) the great number of different types of landform present, each requiring different measurement procedures; (2) the small size of an individual landform of a particular class (e.g. a single culvert collapse of 10 m^2), relative to the size of even a small experimental catchment of 0·1 to 1 km^2 (100 000 to 1 000 000 m^2); and (3) the different times of activity of different erosional features (e.g. debris slides may pulse most of their sediment into the channel only during very large events, whereas gullies may be active even during small storms).

Although it is difficult to understand which landform class is most dominant for a given region or forestry practice, such knowledge is critical to the improvement of guidelines of so called 'reduced-impact logging' (RIL) within 'sustainable forestry management' (SFM) systems. This is because different erosional landforms are sensitive to different forestry practices. For example, many RIL methods concentrate on the maintenance of canopy cover over skidder-vehicle trails and minimization of the length of such trails (Pinard *et al.*, 1995). This practice may reduce exposure of parts of the terrain to rain-splash and surficial erosion, but it does not affect the length and extent of slope cutting along timber haulage roads. Thus, where the RIL focuses on improvements to skidder trails rather than to haulage roads (which require much more costly engineering to stabilize), areas prone to landslide incidence may see no significant improvement over conventional selective harvesting. It is clear that an understanding of the source of stream sediments is important to the proper assessment of forestry guidelines. It is equally apparent that there are few sediment delivery studies available in tropical or even temperate forests in order to make the necessary generalizations (Bruijnzeel, 1990, 1993; Reid and Dunne, 1996; Yusop and Suki, 1994; Chappell *et al.*, 2004).

As a result of the dearth of studies quantifying sediment sources within forest catchments (so called 'sediment budgets'), this work aims to make a contribution for a region of tropical rain forest developed on the FAO Major Soil Group of Alisol that is recovering from conventional selective harvesting. The Alisol soil group is known to have unstable soil aggregates (Driessen and Dudal, 1991; Chappell *et al.*, 1999b), thereby making areas with such soils more sensitive to forestry disturbance. The study utilized specific discharge and turbidity data monitored every 10 s for 15 nested contributory areas. This spatial structure aimed to allow behaviour at individual landforms to be related to that at the landscape scale by a series of relatively small steps in scale. The high temporal resolution of the sampling allowed investigation of differences in the storm dynamics of the different sources, and hence helped to identify which sources regulate the landscape (i.e. catchment) scale behaviour. The combination of the nested spatial structure and high temporal resolution of monitoring should significantly reduce uncertainty in the identification of the dominant sediment sources (Kronvag *et al.*, 1997).

SITE CHARACTERISTICS

The experimental catchment under investigation is located within the Malaysian State of Sabah, on the northeastern tip of Borneo Island, Southeast Asia (Figure 1). The catchment lies 2 km northeast of the Danum Valley Field Centre (DVFC), and is known as the 'Baru catchment' (5°01′N and 117°48·75′E; Figure 1).

Climate, physiography and vegetation

The local climate is equatorial with observable annual seasonality and El Niño–southern oscillation cycles (Chappell *et al.*, 2001), and has a 15 year (1986–2000) mean rainfall of 2764 mm (466 mm standard deviation). The monitoring period for this suspended sediment study was the 1 July 1995 to 30 June 1996. This 12 month period had a higher than average 2956 mm of rainfall, due to the prevailing La Niña conditions (Bidin, 2001; Chappell *et al.*, 2001). A 10 year event of 167 mm of rainfall (over the Baru catchment; see Douglas *et al.* (1999)) in the middle of the monitoring period (19 January 1996; Figure 2a) generated

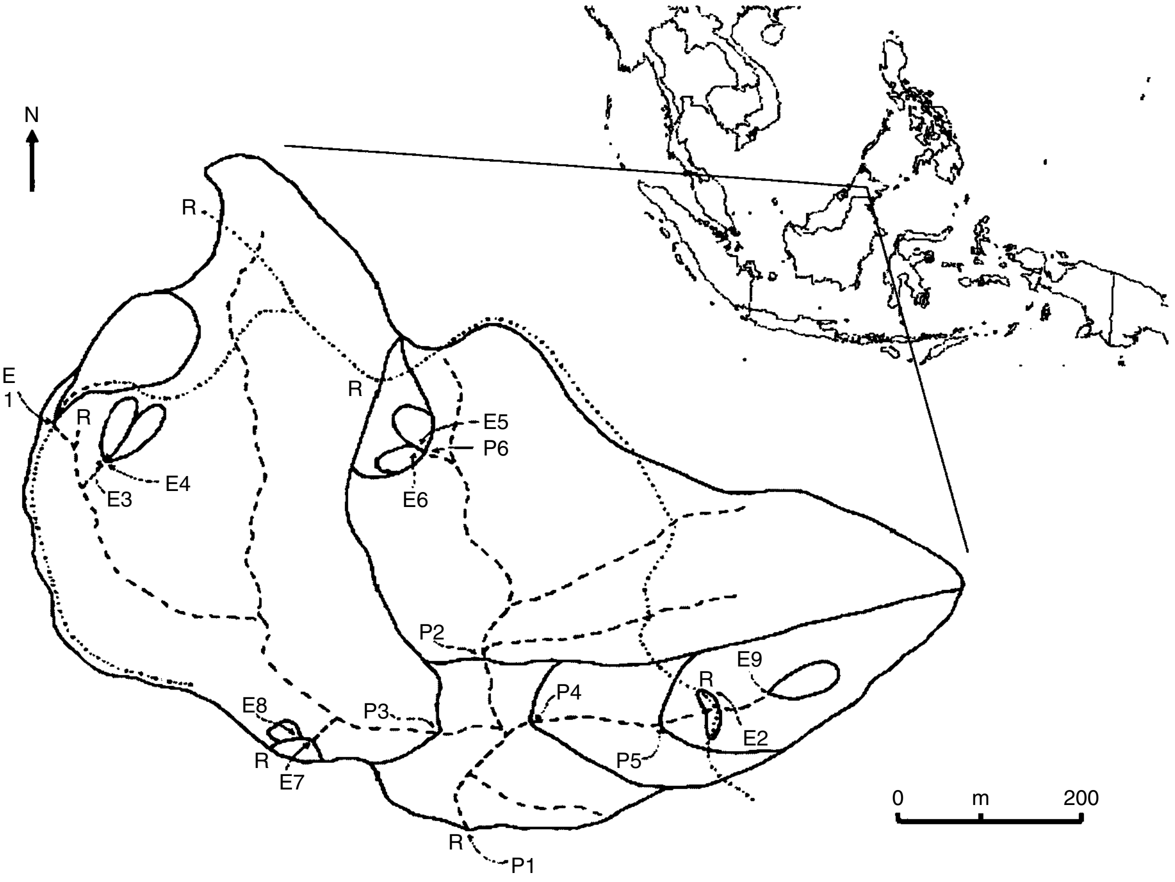

Figure 1. The nested contributory areas of the 44 ha Baru catchment (5°01′N and 117°48·75′E) located on the northeastern tip of Borneo Island, Southeast Asia. The boundaries of the contributory area divides (solid lines), the perennial streams (dashed lines) and lorry haulage roads (dotted lines) are shown. Contributory areas are labelled (see Table I) at their outlet and gauging location. Rain-gauge locations are shown with the symbol 'R'

significant geomorphic activity. Daily rainfall totals in excess of 100 mm occurred on only eight occasions throughout the 15 year record at the DVFC. Rainfall intensities, even during large storms, are, however, low within this non-cyclonic region. During the period 1 May 1995 to 30 April 1998, some 80·3% of all 5 min rainfall events had intensities less than 10 mm h^{-1} (Bidin, 2001). Further, Bidin (2001) noted that only two storms in a 3 year period (24 October 1995 to 16 January 1996) sustained rainfall intensities over 50 mm h^{-1} equivalent for more than 25 min.

The Baru catchment is underlain by the Kuamut geological formation, a melange comprising largely of mudstones and sandstones. Similar geological formations are found throughout eastern Sabah (Leong, 1974, 1999; Clennell, 1996). At Danum Valley, this geology has given rise to unstable soil of the FAO–UNESCO Haplic Alisol unit (Chappell *et al.*, 1999b). Locally, the solum (A and B soil horizons) of this soil is typically 1·5 m deep and overlies 1·5 m of weathered rock (C horizon) (Chappell *et al.*, 1999b). This FAO Major Soil Group, together with the Acrisol FAO Major Soil Group, dominates across lowland Southeast Asia (FAO–UNESCO, 1990). The catchment ranges in altitude from 171 m at gauging station P1 to 255 m on 'Baru Hill' at the extreme east of the catchment. Within the eastern portion of the catchment, average slope angles are about 10°, and about 5° in west, but locally can reach 50° close to the main channel in the centre of the catchment (Figure 1).

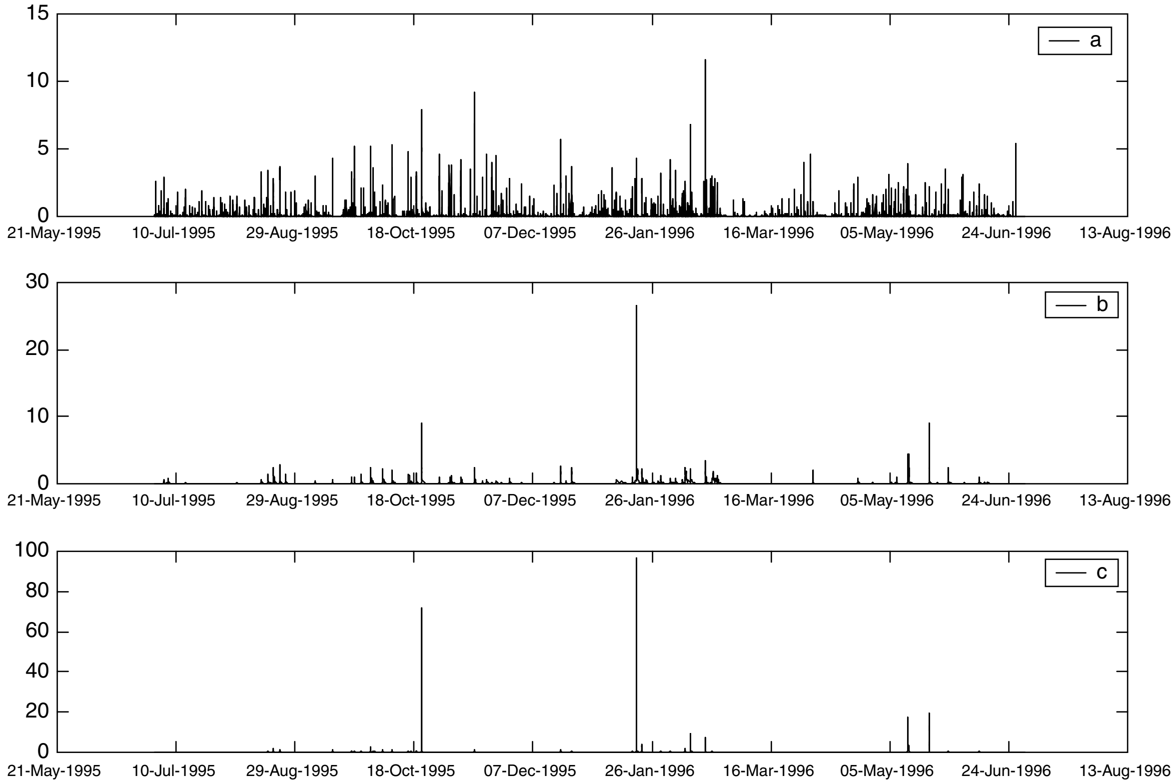

Figure 2. Rainfall, riverflow and suspended sediment yield for the whole Baru catchment (P1) during the 12 month period 1 July 1995 to 30 June 1996, showing (a) rainfall (mm per 5 min period), (b) riverflow (instantaneous flow (m^3 s^{-1} km^{-2}) per 5 min period) and (c) suspended sediment yield (instantaneous flux (kg s^{-1} km^{-2}) per 5 min period)

The Danum Valley region is covered by natural forest, which is classified as 'lowland dipterocarp rain forest' (Whitmore, 1998). This forest is managed by the Forestry Division of Yayasan Sabah as part of their 9728 km^2 timber concession (Marsh and Greer, 1992). The forest that covers the Baru catchment was disturbed for the first time in 1988 by road construction and roadside clearance, and was then more extensively harvested by the selective removal of large, commercial timber trees ('selective logging') in 1989. An average of 100 m^3 ha^{-1} of timber was removed from the encompassing 2262 ha 'Coupe 89' (Moura-Costa and Karolus, 1992). A combination of tracked vehicles (D8 skidders) and the highlead form of cable yarding (where timber is dragged to a central mast) was used to move the timber from the felling location to the haulage lorries (Conway, 1982). These lorries then transported the timber along gravelled haulage roads to the sawmill some 66 km to the east. Even after 6 years of terrain and vegetation recovery, some erosional landforms associated with forestry activities were still active. These included gullies along the haulage road, road-culvert collapses, collapse of soil pipes under haulage roads, landslides, and surficial erosion on some sections of unsurfaced haulage roads and skidder vehicle trails.

CONTRIBUTORY AREAS AND MONITORING

The lumped effect of the initial road construction and timber harvesting upon the yield of water and suspended sediment was monitored during the initial logging phase. Water-level recording at stable rock sections and the extraction of water samples for suspended sediment determination by filtration were undertaken (Douglas *et al.*, 1992).

Beginning in 1995, the suspended sediment measurement was supplemented by data-logged turbidity monitors. These sensors, infrared IR15C probes (Partech Instruments, St Austell, UK), were also installed at 14 tributary areas of the main gauging station (P1), together with weir or tipping-bucket devices for measuring the specific discharge. Thin-plate, 120° V-notch weirs were installed where channel flows were continuous. Pressure transmitters and shaft encoders were used to measure water level in the weirs (for derivation of stream discharge), whereas datalogged contact-closures were used to measure tipping-bucket action at the sites with ephemeral channel and overland flows. At each tipping-bucket station, zinc plates inserted into the ground directed water into a zinc flume in which a turbidity probe was secured, before then directing the water into a 3 l tipping-bucket device.

Gauged ephemeral discharge

Of the 15 contributory areas selected and then gauged (Figure 1; Table I), nine were regions that had surface flow only during rain storms (i.e. ephemeral flows; Dingman, 1994). One of the regions monitored was on an almost planar slope. This contributory area was located in a small remnant of undisturbed climax forest, and was called E8. Further sites monitored water discharge from a lightly compacted, skidder-vehicle track (E4) and from an unsurfaced, haulage road (E1). A visual survey of contributory area E1 indicated that the monitored gully draining this area received water from a small stream channel that was inadequately drained by a culvert under the road. Further contributions from rainfall descending on the indurated road surfaces and failing to infiltrate were expected, given that, nearby, such vehicle-compacted tracks have been observed to have infiltration capacities as low as 0·005 cm h^{-1} (Chappell and Ternan, 1997; see also van der Plas and Bruijnzeel (1993)). Four channel-head gullies (E3, E5, E6, E9) were gauged some 50 to 90 m below their headwalls, plus one gully at only 5 m below its headwall (E7). The latter gully was observed to generate most of its channel flow from a 10 cm diameter natural soil pipe at the top of the gully headwall (see Bidin (1995), Sherlock (1997) and Chappell *et al.* (1998a) for details of piping in the Danum Valley area). Where the timber haulage road crosses the first-order stream gauged at P4, the road drain overtops and spills water across the road and down the fillslope below the road. This 'drain overflow' was gauged at the E9 tipping bucket.

Gauged perennial discharge

Other than the main gauging station on the third-order stream (P1), there were five other monitored sites with permanent channel flows (i.e. P2, P3, P4, P5 and P6) (Figure 1; Table I). Two second-order streams (P2 and P3) receive water from 76% of the Baru catchment. The western tributary (P3) receives specific discharge from an area that includes E1, E3 and E4 and has a high degree of canopy damage in its northwestern sector. The downstream reach has a relatively flat and wide channel that has flow discoloured by organic matter.

In contrast, the central tributary (P2) has two first-order channels in its eastern sector that have collapsing log culverts. Poorly sorted sediments, associated with small debris slumps at these culverts, are clearly observable and are deposited along the first-order channels. Contributory area P2 also includes P6 in its northwestern headwater.

Contributory area P6 was installed at the most upstream point along the channel that still maintained permanent flow (due to returning subsurface flow). This specific discharge, however, is very small due to the small size of the contributory area (0·75 ha). Only some 10 m upstream of the P6 gauge are the gauges for two channels (E5 and E6) with only ephemeral flows.

Outside of the two second-order channels, the first-order P4 channel adds a further 10% discharge through the main gauging station, P1 (Figure 1). The P4 contributory area contains two landslides in the centre of the area, just below the haulage road. A 0·3 ha debris avalanche on the line of the P4 stream was triggered on the 14 December 1994, and a further 0·2 ha debris slide some 15 m to the north was triggered on the 19 January 1996 (Chappell *et al.*, 1999a,b). Field observation indicated that both of these sites had experienced previous

Table I. Physical characteristics of the contributory areas within the Baru catchment, Sabah, Malaysian Borneo

Site	Name[a]	Area (km^2)	Basin order	Key geomorphological site characteristics
Permanent waterflow				
P1	1	0·441	3	Study catchment, containing all tributaries
P2	2-Middle	0·143	2	One of two large tributary areas. Contains two collapsing road culverts, and P6 in its headwater
P3	2-West	0·190	2	One of two large tributary areas. Contains E1 (road gully) and E4 (skid trail) and E3 (channel-head gully) and high degree of canopy damage in northwestern sector. Downstream channel slope is shallow and pounded; contains much organic matter accumulation
P4	2-East	0·046	1	Steep first-order channel, containing two adjacent large landslides. Contains P5 (destroyed by landslide on 14 December 1994), E2 (road drain overflow) and E9 (channel-head gully, above P5 and E2)
P5	6	0·029	1	Gauge with limited records due to destruction by a landslide on 14 December 1994. Site received sediment contributions from eroding road culvert, road drainage (E9), older landslide, and headwater gully above road (E6)
P6	5	0·0075	1	Most upstream point on the headwater channel that has permanent emergence of subsurface flow. Flows typically very small, due to small contributory area. Contains channel-head gullies E5 and E6 only approximately 10 m upstream
Storm-only (ephemeral) waterflow				
E1	4	0·013	0	Gully incised into unsurfaced, timber haulage road. Water sourced a combination of a stream diversion and infiltration-excess from the indurated road surface
E2	6TA	0·0024	0	Road drain overtops, feeds water over the road and down the slope to gauge E2
E3	4TB	0·0016	0	Channel-head gully (sourced from upstream, rather than local return-flow, as local water-table remains low)
E4	4TA	0·00155	0	Skidder vehicle trail. Soil not heavily compacted, with some vegetation regrowth
E5	5TA	0·00145	0	Channel-head gully (not known if return-flow, pipeflow or infiltration-excess flow generate the waterflow)
E6	5TB	0·0014	0	Channel-head gully (not known if return-flow, pipeflow or infiltration-excess flow generate the waterflow)
E7	3	0·0013	0	Gauged only 5 m below channel head. Waterflow sourced most 10 cm diameter natural soil pipe in root mat of channel head. Channel head only 10 m below knife-edge ridge (catchment divide). Limited records due to sensor problems
E8	3TB	0·0006	0	Planar slope section within an undisturbed forest block
E9	6TB	0·0003	0	Channel-head gully, above the road, and fed by water from the highest point of the catchment

[a] In Chappell *et al.* (1999a).

slope failures. The first landslide sent debris down the channel and buried the P5 gauging structure (Figure 1; Table I). The P5 gauging structure, installed to monitor (i) the erosion of the road culvert, (ii) erosion from the drain overflow (E9), and (iii) gullying within the old landslide materials, gave only limited data, but it did show the dry antecedent conditions at the time of this slope failure (Chappell *et al.*, 1999b). All of the contributory areas (as defined by surface topography) were delimited by a combination of compass-and-chain surveys and the use of an electronic theodolite.

Rainfall monitoring

A study using 50 rain gauges within a 400 ha region encompassing the Baru catchment indicated that the rainfall distribution was relatively localized (Bidin, 2001). This variability was, however, captured with six datalogged rain gauges installed in canopy gaps within the 44 ha Baru catchment (Figure 1, *cf.* Bidin (2001)). Gauges R1, R3, R4 and R6 were placed on Bornean ironwood (*Eusioderoxylon zwageri*) towers up to 6 m in height, to prevent disturbance from wild boar or cover by regenerating vegetation. The more exposed R5 gauge was located 60 cm above ground within a 2 m high and 5 m diameter chert/concrete wall to prevent elephant damage.

Data sampling, quality assurance and analysis

Regular calibration of the tipping-buckets was undertaken by volumetric gauging, and the weirs were calibrated with dilution gauging and current metering. The turbidity probes were calibrated using water samples collected from a roving automatic sampler (North Hants ALS) following Clifford *et al.*, (1995). The dataloggers for the rain gauges, water level and turbidity sensors were downloaded at least weekly to ensure correct functioning of the structures, sensors and data. Both instantaneous streamflow ($m^3\ s^{-1}\ km^{-2}$) and instantaneous suspended sediment flux (SSflux: after Webb and Walling (1982); $kg\ s^{-1}\ km^{-2}$) were sampled on a 10 s cycle, with significant changes from the previous value being stored. For this analysis, the irregularly sampled data were converted to a regular 5 min sampled data-series. The Thiessen polygon method (Dingman, 1994) was then used to derive an average rainfall for the catchment. All pre-processing and subsequent analyses were undertaken within the Matlab programming environment (The Math Works Inc., Natick, MA, USA).

RESULTS AND DISCUSSION

Storms were separated as periods when the instantaneous streamflow at the main gauging station, P1, exceeded 0·05 $m^3\ s^{-1}\ km^{-2}$ with the 5 min data series (Figure 2a–c). These storms generated instantaneous peakflows of between 0·5 and 26 $m^3\ s^{-1}\ km^{-2}$ (Figures 2b and 3a–c). During the monitoring period, 1 July 1995 to 30 June 1996, 62% of the storms generated instantaneous peakflows at the main stream gauging station (P1) of between 1 and 3 $m^3\ s^{-1}\ km^{-2}$ (i.e. 37 out of 60 storms, e.g. Figure 3a and b). There were also 16 storms generating smaller peakflows of between 0·5 and 1 $m^3\ s^{-1}\ km^{-2}$, and six large flood events generating peakflows between 3 and 10 $m^3\ s^{-1}\ km^{-2}$. A 10 year event with an instantaneous peakflow of 26 $m^3\ s^{-1}\ km^{-2}$ was observed on 19 January 1996 (Figures 2b and 3c). Given this distribution, we evaluate the timing and yield of suspended sediment for a modal storm in the 1–3 $m^3\ s^{-1}\ km^{-2}$ peakflow class (18 December 1995), as well as the geomorphically significant 19 January 1996 event (peakflow 26 $m^3\ s^{-1}\ km^{-2}$).

Timing of suspended sediment flux

First-, second-, and third-order basin dynamics during a typical storm. Figure 4a–d shows the suspended sediment flux during the storm on the 18 December 1995. The instantaneous peakflow at this gauging station (P1) was 2·6 $m^3\ s^{-1}\ km^{-2}$ (Figure 3a and b). The broad broken line in Figure 4a shows the SSflux from the whole 44·1 ha Baru catchment (P1) in response to the catchment average rainfall (mm/5 min) shown with a fine black line. It can be seen that the sedigraph for the whole catchment has (i) a 30 min delay before response and (ii) a longer recession. The initial delay suggests that time is required either to mobilize sediments or transport sediments to the catchment outlet. The longer recession indicates that there is either temporary storage of the water that mobilizes and transports the sediment (*cf.* Figures 3a and 4a; also see Chappell *et al.* (1999a)) or possibly that the different sources within the Baru catchment contribute their sediment at different times (Chappell *et al.*, 1998b). The suspended sediment flux from the three largest tributaries that contribute sediment from 86% of the Baru catchment (i.e. P2, P3 and P4) are shown as bold black lines in Figure 4a–c. These different sources do indeed deliver sediment to the Baru main station at different times. The channel of P4 has a very flashy sediment response, with the peak occurring before that of the main Baru (Figure 4a), in part because of the quicker hydrograph response (Figures 3a and 4a). In contrast, P3 has a sedigraph peak after that of the main Baru, plus a slower recession (Figure 4c). The P2 channel has an intermediate response time (Figure 4b). Two key physiographical factors are different between these contributory areas. First, the

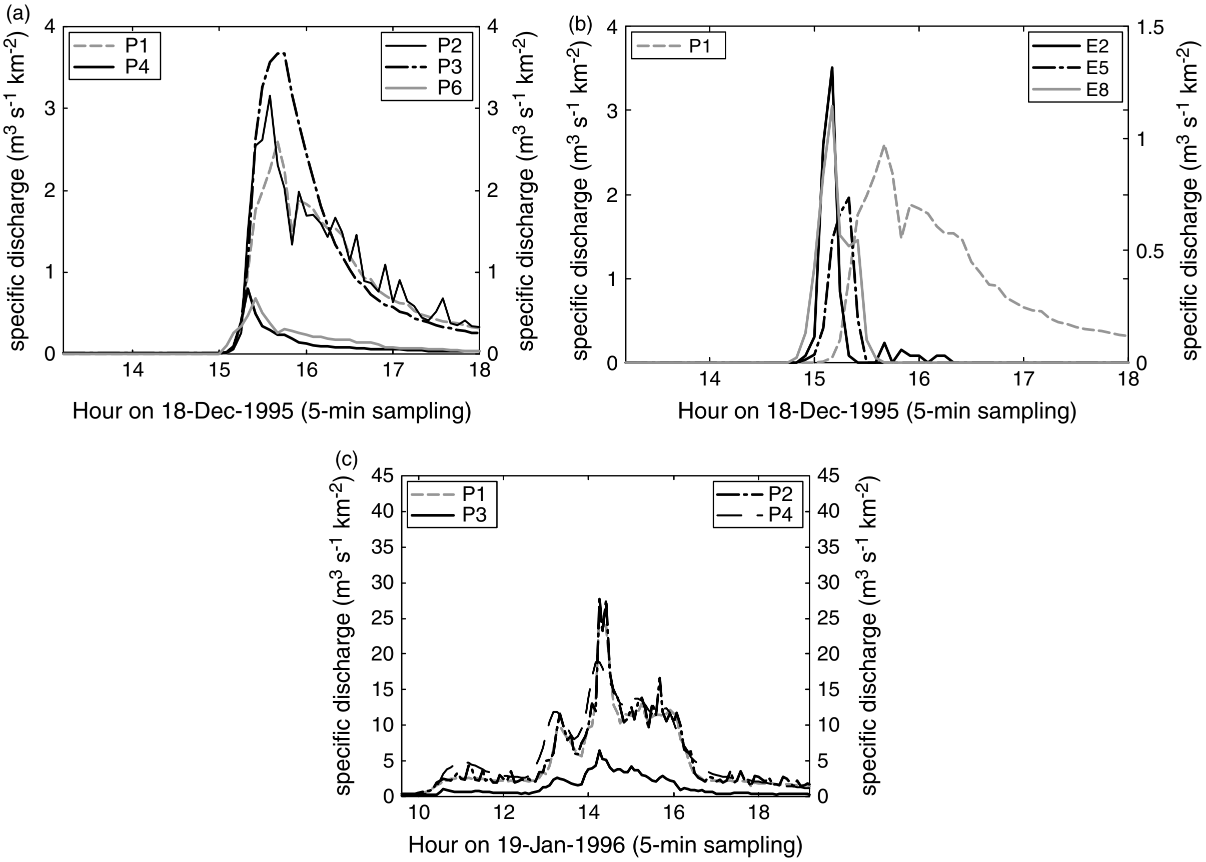

Figure 3. The instantaneous specific discharge (m^3 s^{-1} km^{-2}) averaged over 5 min from the whole catchment (P1) and from selected tributary catchments. (a) P1 with perennial flows P2, P2, P4 and P6 during a storm on the 18 December 1995 (day 352). (b) P1 with ephemeral flows E2, E5 and E8 during a storm on the 18 December 1995 (day 352). (c) P1 with perennial flows P2, P2, and P4 during a storm on the 19 January 1996 (day 384)

average channel length is only 300 m in P4, but it is 750 m in P3 and an intermediate 360 m in P2, largely related to the differences in catchment area (Figure 1). Second, the channel slope within P4 is 0·175 m m^{-1} (16°), but it is only 0·025 m m^{-1} (2·3°) within the downstream reaches of P3. Both factors could explain differences in sediment travel times between the P3 and P4 streams (Kasai *et al.*, 2001).

The very small perennial stream draining P6 (Figure 4d) has an initial response that is faster than the other perennial streams (Figure 4a–c; see Figure 1 for the locations). This may be because of the relatively significant role of two contributory areas with only ephemeral flows gauged only 10 m upstream (i.e. E5 and E6). The very fast response of E5 to the same rainfall event (Figure 5a) may indicate a significant initial contribution from a fast flow-path such as infiltration-excess overland flow (Figure 3b). The P6 sedigraph peaks at the same time as P2 (Figure 4b and d), yet the recession is even slower than P3 (Figure 4c). The slower recession is mostly likely associated with the emergence of delayed subsurface flows. The streamflow generated per unit area is very small at this site relative to the other sites (Table I; Figure 3a). Most of the water leaving this contributory area (defined by surface topography) is likely to be via subsurface exchanges (Chappell *et al.*, 1999a).

Dynamics during a typical storm of areas with ephemeral specific discharge. During the storm on the 18 December 1995, the short section of planar slope with an undisturbed forest remnant (E8, see Figure 1)

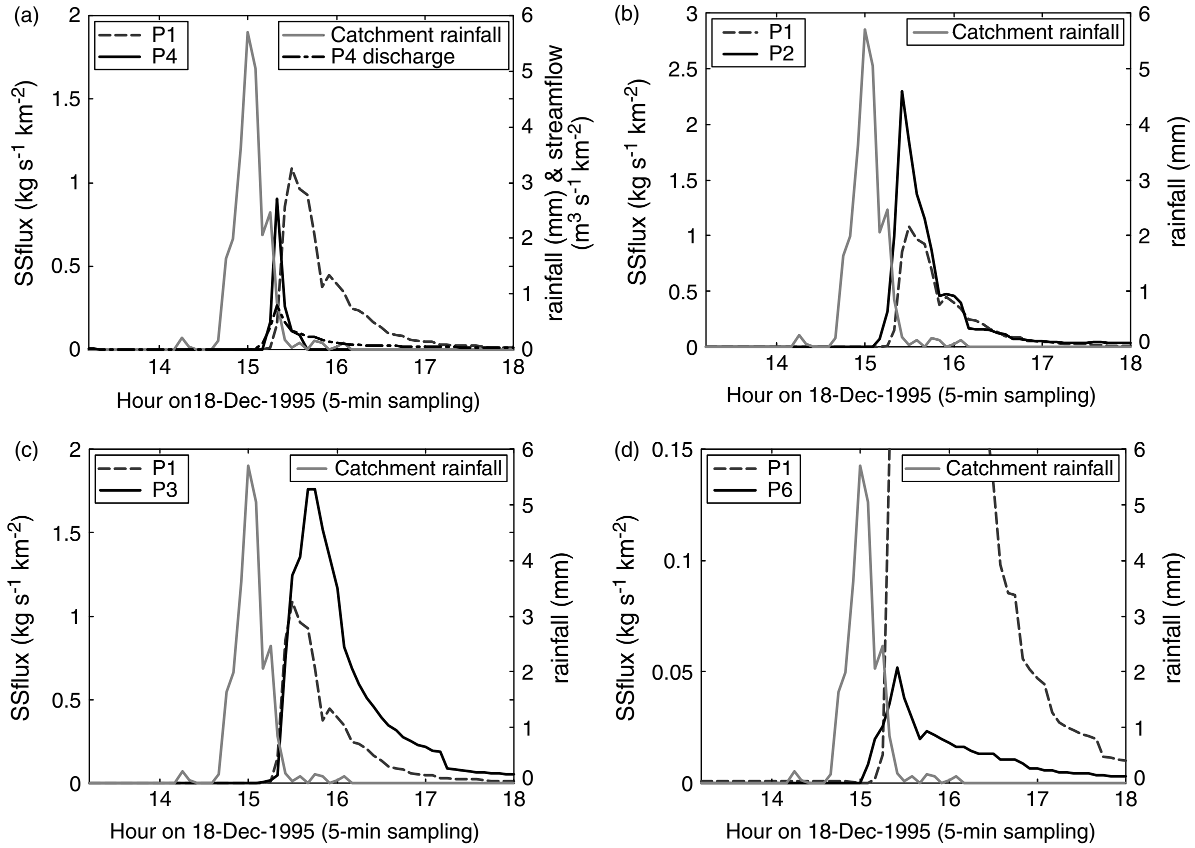

Figure 4. The instantaneous suspended sediment yield (kg s^{-1} km^{-2}) averaged over 5 min from the whole catchment (P1) and from selected tributary catchments with perennial flows, together with rainfall (mm per 5 min) during a storm on the 18 December 1995 (day 352). (a) P1 and P4 suspended sediment yield plus rainfall. (b) P1 and P2 suspended sediment yield plus rainfall. (c) P1 and P3 suspended sediment yield plus rainfall. (d) P1 and P6 suspended sediment yield plus rainfall

generated only a small suspended sediment yield per unit area (Figure 5b). The sediment was mobilized around the peak of the rainstorm, when the rainfall intensity was greatest. The small volume of sediment mobilized probably relates to the limited quantity of overland flow (Chappell *et al.*, 1999a; Figure 3b), which was partly due to the low rainfall intensities. The maximum rainfall intensity only reached 1·9 mm per 5 min (22·8 mm h^{-1} equivalent) during this storm. Such low storm rainfall intensities are, however, not atypical for the Danum Valley region. (Bidin, 2001). Thus, the overland flow may have been generated either by *very local* saturation at the soil surface (Sherlock, 1997) or by flow over the surfaces of large fallen leaves on locally steep slopes, the effect described by Zaslavsky and Sinai (1981).

If we examine the sedigraph for the same December storm for two storm-only contributory areas that have a defined channel, then it is clear that the sediment delivery is greater (Figure 5a and c). Suspended sediment yield from these two gullies (E2 and E5) is greater, as there is more specific discharge (Table II; Figure 3b) and hence erosivity, plus the gully walls are steeper and more exposed to the action of water than the planar slope of E8. The very flashy nature of the sediment delivery (Figure 5a and c) matches that of the specific discharge (Figure 3b), and indicates that there is little sustained, returning subsurface flow from these sites. In the case of E5, however, it is not known whether the flashy response is generated by (i) infiltration-excess overland flow, (ii) emergence of shallow subsurface flow, or (iii) pipeflow (Chappell *et al.*, 1998a). Visual observations during storm events do, however, show that specific discharges monitored at E2 (Figure 3b)

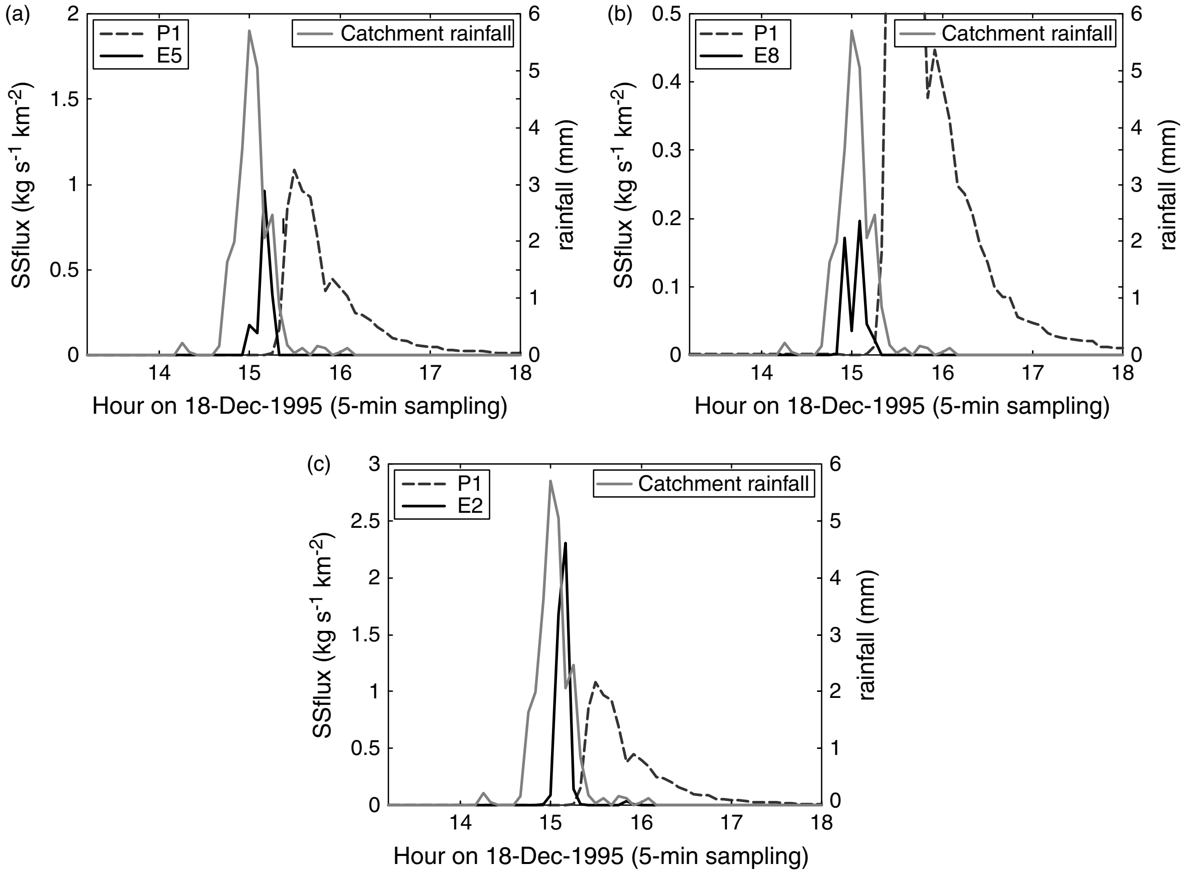

Figure 5. The instantaneous suspended sediment yield (kg s^{-1} km^{-2}) averaged over 5 min from the whole catchment (P1) and from selected tributary catchments with ephmeral flows, together with rainfall (mm per 5 min) during a storm on the 18 December 1995 (day 352). (a) P1 and E5 suspended sediment yield plus rainfall. (b) P1 and E8 suspended sediment yield plus rainfall. (c) P1 and E2 suspended sediment yield plus rainfall

derive from a roadside drain that overtops, spills across the road and then flows down the slope a further 5 m to the gauging structure. The importance of road drainage spilling over surrounding slopes has been recorded within forested terrain in southeastern Australia (Croke and Mockler, 2001). The very flashy nature of the contribution (Figure 3b) relates to the limited time that the drain is overtopping. Water discharge from a drain length of 60 m contributes to the point that overtops the road. Most of this flow is likely to be intercepted subsurface flow from the slope above the road (Wemple *et al.*, 2001), with a further contribution from the indurated road surface by infiltration-excess overland flow. Field observations indicate that the sediment is coming from erosion of (i) the drain itself, (ii) the upslope wall of the roadcut, and (iii) the unprotected slope immediately above the E2 gauging structure. Montgomery (1994), working in the Pacific Northwest of the USA, clearly demonstrated that road drains were important foci for erosion.

Timing of suspended sediment flux during a 10 year storm event. The storm on the 19 January 1996 deposited 167 mm of rainfall on the Baru catchment, largely within a 7 h period. This event had approximately a 10 year recurrence interval (Douglas *et al.*, 1999). The maximum rainfall intensity was 4·3 mm per 5 min (51·6 mm h^{-1} equivalent), against the maximum intensity recorded during the 12 month monitoring period of 11·6 mm per 5 min (or 139·2 mm h^{-1} equivalent) on 17 February 1996. At the main Baru gauging station

Table II. Masses of suspended sediment generated from selected contributory areas during the 12 month period between 1 July 1995 and 30 June 1996, and during the 24 h period of 19 January 1996

Site	Surface contributory area (ha)	Basin order	Surface waterflow (mm)	SSflux t km^{-2} year^{-1}	SSflux (t)	19 Jan 96 SSflux (t)
Sites with permanent surface waterflow						
P1	44·1	3	1867	592	261	105
P2	14·3	2	1684	685	98	40
P3	19·0	2	1611	361	69	11
P4	4·6	1	908	1467	67	33
P6	0·75	1	187	14	0·107	0·012
Sites with surface waterflow only during storms						
E1	1·3	0	1162	643	8·4	1·1
E2[a]	0·03	0	78	99	0·030	0·010
E4[b]	0·155	0	60	81	0·126	—
E5[b]	0·145	0	60	15	0·022	—
E6	0·14	0	57	41	0·058	0·020
E8[b]	0·06	0	31	24	0·015	—

[a] Annual values extrapolated from 8 months data.
[b] Some data lost during 19 January 1996 rainstorm.

(P1), the time series of suspended sediment flux for this storm was dominated by one peak, with two minor peaks (Figure 6a). The rainfall peak preceding the dominant peak in the sedigraph (by about 30 min) was only slightly larger than the five other principal peaks in the rainfall distribution. The changing relation between hyetograph magnitude and sedigraph magnitude may have been related to the non-linearity inherent within the relation between rainfall and sediment delivery (Chappell *et al*., 1999a), or may indicate that a new sediment source had been generated (Chappell *et al*., 1998b).

Examination of the sedigraph for the P4 tributary stream (Figure 6a) indicates that the sediment peak at the main station (P1: 97 kg s^{-1} km^{-2}) corresponds to an extremely large instantaneous sediment peak of 400 kg s^{-1} km^{-2} in the P4 stream. Visual observation of the P4 catchment directly after the storm confirmed that a 0·2 ha debris slide had been generated below the haulage road, and that the toe of the slide supplied sediment directly in the P4 stream, just below the P5 weir (Figure 1). Failures within roadcut materials are dominant sources of stream sediments in disturbed forests of Oregon (Wemple *et al*., 2001) and British Columbia (Jakob, 2000).

The peak sediment delivery in the P2 stream (Figure 6b) coincided with the sediment peak in the main stream (P1) and P4. The last three main rainfall peaks during the same storm, however, generated very significant pulses of sediment within P2. Visual observation of this contributory area directly after the storm indicated that road culverts carrying the two eastern tributaries of the P2 basin (Figure 1) underwent accelerated collapse by small-scale mass movements. These culverts were constructed from hollow logs, buried in re-formed soils. Some of the poorly sorted materials from these failures were clearly observable in sediment bars along the two eastern tributaries, whereas the northern tributaries (Figure 1) remained relatively clear of such deposits. The strong multi-peaked sedigraph of the P2 stream (Figure 6b) indicates that these small-scale collapses occurred either (a) in response to three of the five rain peaks in the storm, or (b) that sediment input to the two eastern tributaries during the main rain peak was being remobilized during the two subsequent rainfall peaks (Figure 6b). Other studies have reported accelerated erosion/failure of soils near road culverts during large storm events (e.g. Madej, 2001).

The P3 stream generated much smaller flows of suspended sediment per unit area (Figure 6c), compared with P4, P2 and the whole Baru catchment (P1, Figure 6a and b). This finding is supported by the absence

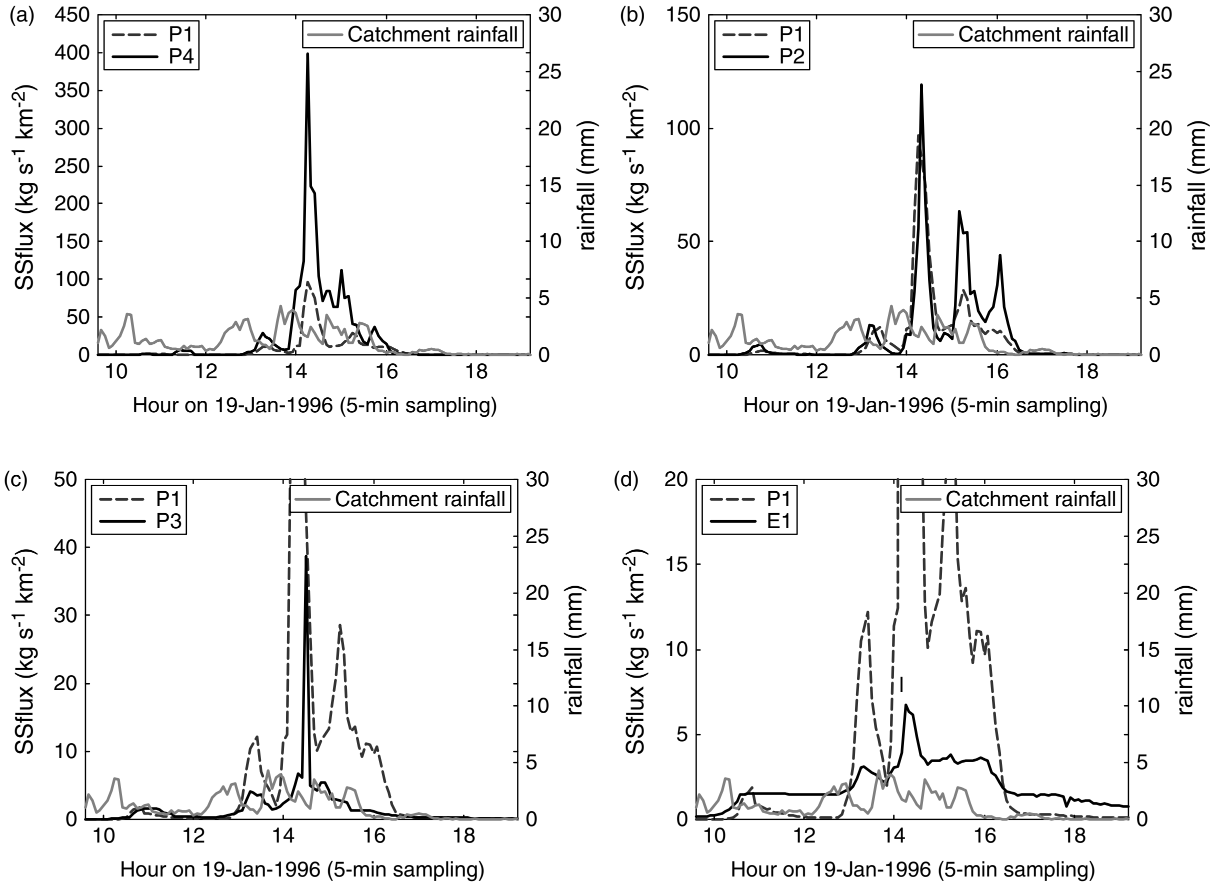

Figure 6. The instantaneous suspended sediment yield (kg s^{-1} km^{-2}) averaged over 5 min from the whole catchment (P1) and from selected tributary catchments, together with rainfall (mm per 5 min) during a storm on the 19 January 1996 (day 384). (a) P1 and P4 SSflux plus rainfall. (b) P1 and P2 suspended sediment yield plus rainfall. (c) P1 and P3 suspended sediment yield plus rainfall. (d) P1 and E1 suspended sediment yield plus rainfall

of new sediment bars within the central and lower reaches of the P3 stream, compared with the P2 and P4 streams. As suspended sediment flux through the main gauging structure receded, a short-lived pulse of sediment was, however, observed at the P3 structure (Figure 6c). A small bank collapse observable a few metres upstream of the structure may have been the cause. It may be useful to note that the northwestern sector of the P3 catchment has the greatest degree of forest canopy disturbance (from aerial and ground observations) compared with other parts of the forested Baru catchment. It would seem reasonable to conclude that canopy disruption is not the principal cause of sediment mobilization within the Alisols at Danum Valley at this stage of terrain recovery.

The P3 contributory area contains the most road gullying, compared with the other major tributories P2 and P4. A 100 m gully cut into the middle of the unsurfaced haulage road in the northwestern corner of the sub-catchment was the main channel for El (Figure 1). Other gullying is also present on a steep section of haulage road in the northern part of the P3 catchment. Contributory area E1 generated its greatest specific discharge peak (11·0 m^2 s^{-1} km^{-2}) during the 10 year storm of the 19 January 1996. This flow was, however, not very turbid, and as a consequence did not generate the highest instantaneous suspended sediment yield observed at this site (which was 14 kg s^{-1} km^{-2} on 20 August 1995). The indurated surface of the gully, therefore, appeared relatively stable against the action of the large storm event. Indeed, during the 19 January 1996 storm, peak sediment flux per unit area for E1 (6·8 kg s^{-1} km^{-2}; Figure 6d) was more than an order of magnitude less than that observed from areas with mass movements (i.e. P2 and P4).

Examination of the shape of the sedigraph for different tributary areas provides possible evidence of the variability and sources of suspended sediments discharging from a larger 44 ha 'landscape-scale' region. Comparison of the total mass (rather than timing) of sediment generated by each area throughout a 12 month period is, however, necessary to support the findings of the within-storm dynamics.

Suspended sediment yields

Table II shows the masses of suspended sediment generated by most of the contributory areas studied. Contributory areas with significant breaks in the sediment records are not detailed.

Changes since the logging period. The suspended sediment yield for the entire catchment was 592 t km^{-2} $year^{-1}$ for the period 1 July 1995 to 30 June 1996. This was considerably less than the 1600 t km^{-2} $year^{-1}$ generated during the logging and immediate post-logging period (mid-1988 to mid-1990), some 5 to 6 years previously. During the earlier monitoring period, the undisturbed, control catchment generated 312 t km^{-2} $year^{-1}$ (Douglas *et al.*, 1992). This catchment has similar Alisol soils and is only 2 km to the southwest of the Baru catchment (Chappell *et al.*, 1999b; Douglas *et al.*, 1999).

To illustrate the role of the 10 year event, if the mass of sediment delivered by the event on 19 January 1996 (see Figure 2c) is omitted from the annual suspended sediment yield during 1995–96, then the yield decreases from 592 t km^{-2} $year^{-1}$ to 240 t km^{-2} $year^{-1}$. This, therefore, underlines the geomorphic impact of an isolated large storm lasting a few hours on the longer term sediment budget (Evans, 1997), and thus illustrates the need to (a) adopt very intensive temporal monitoring of stream sediments, and/or (b) carefully consider landslide incidence with sediment budgets assessed by rapid spatial surveys (Reid and Dunne, 1996).

Photographs of the bed of downstream reaches of the main Baru channel during 1990 show that all of the coarse cobbles that comprised the bed were covered with a layer of fine sediment. Though sediment bars comprised of poorly sorted, mass movement material were observable within the Baru channels during 1995–96, the veneer of fine sediments was absent. This qualitative evidence indicates that some of those sources of fine sediments may have stabilized since the period of forestry operations. Perhaps, the logging operations exposed much bare soil, which was eroded by surficial processes, overloading the channels with fine sediments. With vegetation growth on the skidder vehicle trails (notably grasses and vines; see Bidin (2001) and Tangki (2001)), surficial erosion was reduced. Indeed, this mechanism has been observed on a single plot in an area close to the Baru catchment (Douglas *et al.*, 1995), and is well attested within other regions (e.g. Luce and Black, 1999). Thus, it could be that, after a few years, surficial erosion on bare surfaces, notably unsurfaced haulage roads, log landing areas, and skidder vehicle trails, does return to near natural rates (Douglas *et al.*, 1999).

Tangki (2001) showed that landslides are present within large areas of undisturbed forest within the Danum Valley region. It is likely, however, that the cutting of roads into slopes has accelerated both the spatial and temporal incidence of the landslide hazard (Swanson and Dyrness, 1975; Jakob, 2000). Given the significance of mass movements (landsliding and culvert collapse) to the sediment delivery within the rain forest landscape at Danum, the possible persistence of these geomorphic features several years after logging must be a significant concern.

Component sediment sources during the recovery period. The three tributary areas that constitute most of the Baru catchment (P2, P3 and P4) generate very different suspended sediment yields, ranging from 361 to 1467 t km^{-2} $year^{-1}$ (Table II). These differences seem to relate to the presence or absence of mass movements, with large landslides having the greatest impact per unit area. In our example, if we had monitored a single contributory area of 20 ha or less, then we may not have identified the role of these mass movements. Visual observation along 10 km of the haulage road that crosses the Baru catchment (Figure 1) indicates the presence of other landslides in close proximity to the road. Such features have an approximate spatial occurrence of one every kilometre of road, so the presence of at least one landslide within a 44 ha catchment area (with its effect on the sediment budget) may not be atypical. Some assurance of the reliability of the suspended sediment data for each contributory area (see Kondolf and Matthews (1991)) is gained from the observation that the second-order regions of P2, P3 and P4 (comprising 86% of the third-order Baru catchment and probably most of the primary sediment sources) yield only 10% less annual suspended sediment yield (234 t in total) compared with that recorded from P1 (261 t).

Role of contributory areas with ephemeral flows. As expected, the planar slope still maintaining a cover of virgin rain forest (E8, Figure 1) generated very little suspended sediment, i.e. only 24 t km^{-2} year^{-1} (Table II). Perhaps surprisingly, the contributory areas with ephemeral flows in defined channels generated only slightly greater local sediment totals. Given that the heads of these gullies can have relatively high rates of headwater retreat (Walsh and Bidin, 1995; Chappell *et al.*, 1999b), perhaps the rest of the channel walls of many of these gullies (at least those studied) are relatively stable, due to the lack of continuous water discharge.

The highest rates of sediment delivery from the contributory areas with only ephemeral flows were from those sourced from an unsurfaced, timber haulage road (E1) and a skidder vehicle track (E4). Some 8 t of sediment was generated from the gully incised into the haulage road (Table II). This higher rate of erosion was probably caused by the road receiving streamflow from a point where a road culvert was blocked. The unit area suspended sediment yield from this site (643 t km^{-2} year^{-1}) should, however, be considered an estimate, given the difficulties associated with defining the contributing area, even where only surface topography is considered. Uncertainties associated with defining the contributing areas for surface flow in the Baru catchment seem to become significant with basins smaller than 1 ha. Further, large exchanges of subsurface water between catchments defined by their surface topography occur in catchments less than 5 ha (and possibly larger) within this terrain (Chappell *et al.*, 1999a). Though this may be less of a significant issue for estimating sediment losses, it is important for water and nutrient budgets (Bruijnzeel, 1991). Comparison of the suspended sediment yields for E1 versus those from the other contributory areas with ephemeral flows (E2, E4, E5, E6 and E8) does, however, suggest that there may be an association between the specific discharge and the quantity of suspended sediment generated (Table II). Most of the areas in the Baru catchment with ephemeral water discharge generate very little surface flow (most water being lost from their basins by subsurface exchanges), and hence generate little erosion. In contrast, E1, has much more surface flow during storms (because a stream over-spills along the road), and hence has relatively large suspended sediment yields compared with other basins with ephemeral flows.

Channel bank erosion and collapse. Comparison of the sediment yield from P3(361 t km^{-2} year^{-1}) with rates from the side slopes (represented by E8: 24 t km^{-2} year^{-1}) and other contributory areas with ephemeral flows (represented by E1 and E4: 643 t km^{-2} year^{-1} and 81 t km^{-2} year^{-1} respectively) is possibly worthy of note. The 69 t of sediment generated by P3 cannot be generated by the 8 t from E1 (plus a similar quantity from the other gully system in the north) or the rates from the areally extensive sides slopes, if E8 is representative. Perhaps a significant proportion of suspended sediment yield of the P3 basin comes from unmeasured channel bank collapse and erosion as a result of the continuous abrasion of the perennial stream. Balamurgan (1997) postulated that channel banks were a significant source of stream sediments within the undisturbed 'W8S5' catchment, 2 km to the southwest of the Baru catchment. If this is the case, then unmeasured, channel bank collapse and erosion is also likely to be a significant source of suspended sediment yield within the P2 and P4 sub-catchments.

Whereas issues such as the need to quantify channel bank erosion confound accurate assessment of all of the key sediment sources within the Baru catchment, the nested catchment structure has given some confidence in the quantification of significant elements of 'landscape-scale suspended sediment yield'. This has been because a significant proportion of the large pulse of sediment passing the main gauging station (P1) during the 10 year event on the 19 January 1996 (105 t) can be directly associated with the failure of an individual landslide in P4 (33 t), and to a lesser extent by the two culvert collapses in P2.

CONCLUSIONS AND RECOMMENDATIONS

The great variability in suspended sediment yield and the small scale of individual landforms (Table II) underlines the importance of measuring many contributory areas arranged in a nested structure. If we had not experienced a 10 year storm event during the monitoring period then we may not have observed the role of forestry-related sediment sources that persist for several years after harvesting. These persistent sources play a significant role in the non-stationarity of the relation between rainstorm size and geomorphic activity (Chappell *et al.*, 1998b) and in the overall sediment budget.

The high temporal resolution of sampling (5 min averages of 10 s data) was necessary to describe the shape of the sedigraph for the 10 year storm event and for other large events. Given that a high proportion of the annual sediment yield comes from such events, it is clearly important to utilize intensive monitoring. The flashy nature of these large events, combined with the rapid regrowth of pioneer vegetation within lowland dipterocarp rain forest (Tangki, 2001), means that the role of these events and their associated mass movements may be easily overlooked in rapid visual surveys of sediment sources.

This study measured and discussed only sediment movement via transport in the water column. Work on bedload migration of sediments has not been undertaken in the Danum Valley area. Given the development of new sediment bars in channels below mass movements, it is likely that debris torrents and bedload transport may play a measurable role during large storms (Swanston and Swanson, 1976). There are very few bedload studies anywhere in the forested humid tropics (Douglas *et al.*, 1999; Chappell *et al.*, 2002). The work of Lai (1992) in very steep mountain catchments in Peninsular Malaysia indicates that the role of bedload transport relative to losses of suspended sediment can be very different between catchments with very similar geology, climate and forestry practice. Therefore, it is unrealistic to attempt to estimate the possible role of bedload migration within the Baru catchment without a detailed sampling campaign. Work on the volumes (Chappell, unpublished results) and characteristics (Fletcher and Muda, 1999) of sediments stored temporarily within the Baru channels has begun. New sediment work within the Baru catchment, and indeed elsewhere within the forested humid tropics, should, however, involve the quantification of bedload transport during larger storms.

In a year containing a 10 year storm event some 5 years after harvesting, forest slopes, zero-order basins, natural ephemeral channels, skidder vehicle trails, and even well defined road gullies generate relatively little sediment in comparison with areas containing mass movements and perennial streams. This may be attributed to (a) smaller erosivity due to smaller surface discharge and (b) stabilization of the surfaces due to vegetation regrowth.

It may be that the long-term sediment budget in a post-logging period is most sensitive to mass movements, rather than to surface-wash and/or gullying. If this is the case, then sustainable forestry guidelines that do not focus on ameliorating the persistent instabilities of road-related landsliding and culvert failure may, therefore, not significantly mitigate the geomorphic impacts of conventional, selective harvesting.

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