The role of pipe erosion and slopewash in sediment redistribution in small rainforest catchments, Sabah, Malaysia

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Abstract The role of pipe erosion and slopewash in the redistribution of sediment in small rainforest catchments was investigated at sites in the Danum Valley Conservation Area in Sabah, Malaysian Borneo. Data loggers coupled to turbidity and flow depth sensors were installed in pipeflow and streamflow sites and the erosion bridge technique and overland flow traps were used to examine slopewash. The discharge and sediment responses from pipeflow and streamflow to nine storm events are presented. A single monitored pipe was found to contribute between 8 and 33% of stream stormflow and 3 to 61% of the stream sediment load in individual storm events. Overland flow, though comprising only a small proportion of rainfall, was found to be widespread and frequent, which may help to explain the comparatively high slopewash rates indicated by the erosion bridge results.

Key words data loggers; erosion bridge; pipeflow; rainforest; Sabah; sediment load; slopewash

INTRODUCTION

Quantitative piping research has concentrated on temperate areas (e.g. Gilman & Newson, 1980; Jones, 1981; Uchida *et al.*, 1999; Holden & Burt, 2002). In contrast, until recently piping in the humid tropics had received little attention, with the exception of a few qualitative (e.g. Baillie, 1975) or semi-quantitative (Walsh & Howells, 1988) studies. Most early studies suggested overland flow to be of little importance in tropical rainforest environments (Walsh, 1980). Recent work in Amazonia (e.g. Elsenbeer & Lack, 1996), southeast Asia (Douglas *et al.*, 1999; Sinun *et al.*, 1992) and northeast Australia (Elsenbeer *et al.*, 1994) has suggested the importance of both soil pipe systems and overland flow in forested humid tropical catchments and highlighted a need for systematic assessments of their roles in stream sediment and water budgets. This paper addresses this need by presenting results of an investigation into pipe erosion, slopewash and stream sediment transport in small rainforest catchments in the Danum Valley Conservation Area (DVCA) in Sabah, Malaysia.

STUDY AREA

The Danum Valley Conservation Area (DVCA) covers approximately 438 km^2 of primary lowland dipterocarp and montane rainforest in eastern Sabah (Fig. 1). Mean annual rainfall (1985–2003) at the Danum Valley Field Centre (<1 km from the study sites) was 2783 mm. Rainfall falls throughout the year, but with two wetter periods from October to January and

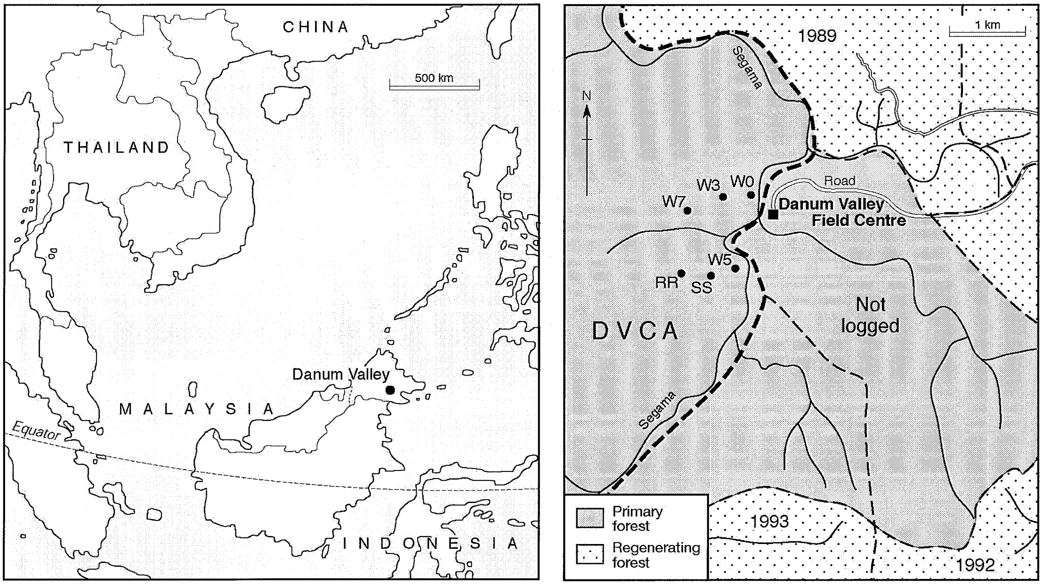

Fig. 1 Location map of study area and study sites.

May to June. The area is also susceptible to occasional ENSO-related droughts (Walsh & Newbery, 1999). The geology, which comprises Miocene mudstones, slumped breccias and tuffs, promotes local heterogeneity of soils, but Ultisols (equivalent to Alisols in the FAO-UNESCO system) are the most common soil group. These relatively deep soils (at least 1.5 m and often much deeper) are typically silt-loams, with a coarser topsoil (30–48% sand; 48–62% silt; 3–11% clay) and finer textured subsoil (10–19% sand; 66–73% silt; 15–22% clay) at depths of approximately 1 m.

METHODS

Pipeflow, slopewash and overland flow studies focussed at sites located in the extreme east of the DVCA close to the Danum Valley Field Centre (Fig. 1). Two small catchments known as W3 and W7 (13 203 and 5267 m^2 in size, respectively) were instrumented in November 2002 with weirs and CR10X Campbell Scientific data loggers programmed to continuously record the 15-min average output from 195-Analite turbidity probes and PDCR1830 Campbell Scientific pressure transducers. W3 has ephemeral surface streams in its upper part but is extensively piped in the lower part of the catchment whereas W7 is an entirely piped catchment. In W3 (the main focus of this paper) a streamflow site and a pipe (approx. 20 cm in diameter) that feeds into the stream were monitored.

Slopewash and erosional activity along slope profiles, around channel heads, and around collapsed pipe features were measured using the erosion bridge (or microprofiler) technique which involves the repeat measurement of the ground surface profile relative to a bar (bridge) which is mounted upon stakes at either end of a transect providing a stable datum. Two versions of the bridge were used: a 1.1 m wide bridge (Shakesby, 1993) at the pre-1997 sites and a 3 m wide bridge (Clarke *et al.*, 2002) at the sites established since 1997. In 1990, 29 erosion bridge transects were established between W3 and W0 on slopes around first-order channel heads; in 1997–1998 a further 40 slopewash sites were established down slope profiles at sites SS and RR; finally in 2001–2002 another 88 sites were installed at W0, W3, W5 and W7 around pipe collapse features and slope sites (see Fig. 1 for site locations). Erosion bridge transects were re-measured generally at 6-monthly or yearly intervals.

Overland flow was assessed using networks of simple overland flow traps. These comprised a 50 × 15 cm sheet of aluminium bent at the mid-point to form a v-shape. An outflow pipe was connected to a hole drilled at the bend and the "v" was inserted 3 cm vertically into the soil. Overland flow reaching the device was collected by a 500 ml vessel connected to the outflow pipe. Networks of traps were installed in 1999 along slope profiles adjacent to erosion bridge transects at RR, SS and between W3 and W0 (6, 4 and 4 traps, respectively). In 2002, networks were installed at W3 and W7 (6 and 5 traps, respectively). In each case overland flow was assessed for short monitoring periods.

RESULTS

Pipeflow hydrology, sediment dynamics and erosion

Tables 1 and 2 give summary details of pipeflow and streamflow discharge and sediment responses in W3 to nine rainfall events. Visual examination of the form of typical streamflow hydrographs (Fig. 2) defined the stormflow period to extend from the point when discharge first started to rise until the data-point three hours after peak discharge.

Overall 17.3% of streamflow during the nine events can be attributed to the single monitored pipe. The percentage of streamflow delivered by the monitored pipe tends to decline at higher rainfall intensities, but there are anomalies. Thus the smallest contribution of 7.7% arose when both maximum 15-minute and mean rainfall intensities were high (52 and 36.8 mm h^{-1}, respectively) during a small (18.4 mm) rainstorm, whereas the largest

Table 1 Discharge responses made by streamflow and pipeflow to eight rainfall events.

Date	Storm rainfall (mm)	Max 15-min rainfall intensity (mm h^{-1})	Mean rainfall intensity (mm h^{-1})	Antecedent rainfall (3 days)	Total stream Q (mm)	Total stream Q_s (mm)	Total pipe Q (mm)	Peak specific stream Q (mm h^{-1})	Peak specific pipe Q (mm h^{-1})	% stream Q supplied by monitored pipe
22 Dec. 2002	16.6	12.0	5.5	4.8	2.1	1.6	0.7	1.5	0.7	32.8
27 Dec. 2002	18.4	52.0	36.8	5.8	3.7	3.4	0.3	1.9	0.4	7.7
10 Jan. 2003	23.8	32.0	13.6	3.5	5.2	3.9	1.2	2.6	1.1	22.3
11 Jan. 2003	29.5	34.0	7.9	30.2	18.9	12.8	4.9	7.1	1.3	25.8
7 Feb. 2003	9.8	3.0	4.4	43.8	1.8	1.6	0.4	0.5	0.1	21.0
2 Mar. 2003	35.0	82.0	28.0	0.0	7.4	5.8	1.1	4.4	1.1	14.5
3 Mar. 2003	42.0	52.0	21.0	42.5	19.3	16.1	3.1	14.7	1.2	15.9
8 Jul. 2003	24.5	60.0	16.3	14.9	17.6	13.0	3.0	12.3	1.2	16.8
11 Jul. 2003	96.8	96.0	55.3	26.5	51.2	44.4	7.5	39.0	2.6	14.6
Total	296.4	†	†	†	127.2	102.6	21.9	†	†	†
Mean	†	47.0	21.0	†	†	†	†	9.3	1.1	17.3

Q, discharge; Q_s, stormflow discharge; †, not appropriate.

Table 2 Sediment responses made by streamflow and pipeflow to eight rainfall events.

Date	Total stream sediment load (kg)	Total pipe sediment load (kg)	% of stream sediment supplied by monitored pipe	Weighted mean streamflow SSC (mg l^{-1})	Weighted mean pipeflow SSC (mg l^{-1})	Peak streamflow SSC (mg l^{-1})	Peak pipeflow SSC (mg l^{-1})
22 Dec. 2002	1.3	0.8	61.0	103.9	193.6	284.0	495.4
27 Dec. 2002	2.1	0.4	16.5	93.7	200.0	287.4	387.8
10 Jan. 2003	5.1	1.5	28.9	159.2	207.6	599.2	443.2
11 Jan. 2003	12.5	4.0	31.8	108.8	134.2	245.8	477.9
7 Feb. 2003	0.5	0.1	16.6	48.5	38.4	65.8	55.4
2 Mar. 2003	13.7	1.7	12.4	305.8	261.7	2839.6	2655.6
3 Mar. 2003	27.5	3.6	13.0	234.3	192.3	609.3	1017.7
8 Jul. 2003	18.3	1.8	10.0	170.5	101.4	1226.0	557.4
11 Jul. 2003	440.8	11.5	2.6	1417.1	253.7	3320.1	858.0
Total	521.8	25.4	†	†	†	†	†
Mean	†	†	4.9	674.9	189.7	1053.0	772.0

SSC, suspended sediment concentration; †, not appropriate.

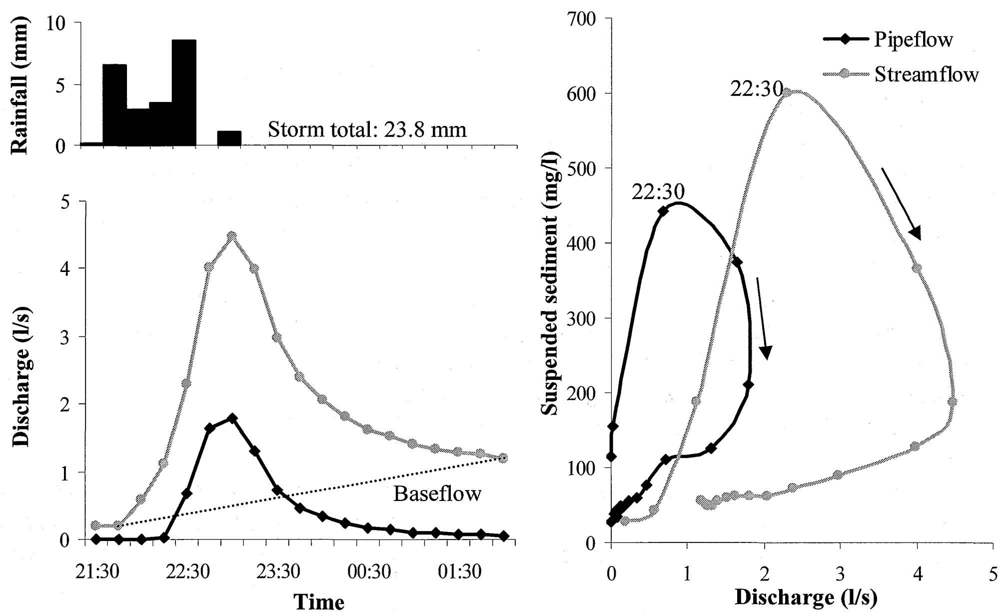

Fig. 2 Streamflow and pipeflow storm hydrographs and suspended sediment hysteresis responses to rainfall on 10 January 2003.

contribution of 32.8% arose from a similarly small storm (16.6 mm) but where maximum 15-min and mean rainfall intensities were much lower (12.0 and 5.5 mm h^{-1}, respectively). Total streamflow and pipeflow both increase with storm rainfall, but again anomalies indicate the influence of other variables. Figure 3 illustrates that responses are much lower after drier antecedent weather.

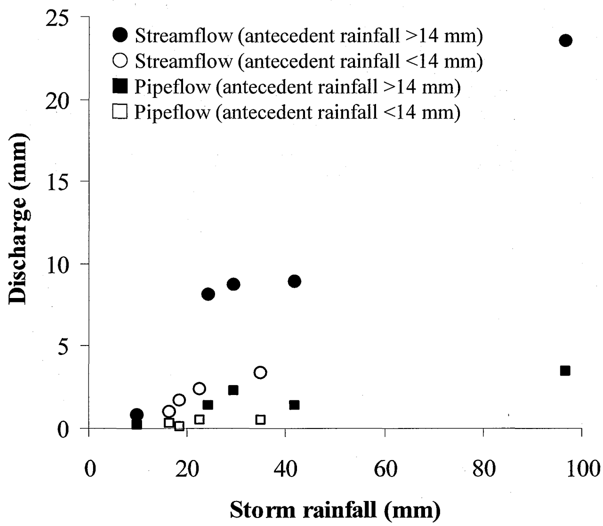

Fig. 3 Scatter plot showing the effect of antecedent rainfall (in the 3 days prior to the storm) on the relationship between storm rainfall and streamflow and pipeflow discharge.

Sediment transported by the monitored pipe accounted for 2.6–61% of the stream sediment budget in individual storm events (Table 2). Both streamflow and pipeflow sediment loads tend to increase with storm rainfall. The largest pipeflow sediment load of 11.5 kg (45% of the total pipe sediment discharge in the nine events) occurred in the 96 mm storm of 11 July 2003. Despite this response being three times larger than the next largest load, it accounted for only 2.6% of the stream sediment load of 440.8 kg, which in contrast, was 16 times greater than that of the next largest event.

The largest rainfall events do not necessarily result in the highest peak suspended sediment concentration (SSC). Although the 11 July 2003 storm resulted in the highest stream SSC (3320 mg l^{-1}), the peak pipeflow SSC response (858 mg l^{-1}) from this storm was exceeded in two smaller storms (35 and 42 mm; peak SSC 2656 and 1018 mg l^{-1}) when maximum 15-min rainfall intensity was exceptionally high (82 mm h^{-1} in the 35 mm storm) or there were very wet antecedent conditions.

Figure 2 illustrates the streamflow and pipeflow hydrographs and suspended sediment hysteresis responses in relation to the 23.8 mm storm of 10 January 2003. Response times of both the stream and pipe to rainfall are short (in this instance 90 min from the start of rainfall to peak discharge). Both the stream and the pipe exhibit clockwise hysteresis with SSC peaking before discharge. Discharge and sediment responses of the entirely piped W7 catchment, are very similar to those in W3.

Measurements of cross-sectional change between July 2002 and July 2003 at erosion bridge sites established in collapsed pipe sections and gullies downstream of pipe outlets at sites W0, W3, W5 and W7 all point to considerable erosional and depositional activity (Table 3). Many cross-sections show a combination of widening (erosion) and basal accretion (deposition) of a few centimetres over the period, but a few sites showed more dramatic change. Thus the headward erosion of one pipe window involved enlargement of a shallow surface depression into an incised 1.1 m deep and 30 cm wide gully over the monitoring period.

Overland flow and slopewash

Overland flow, although accounting for only a small percentage of rainfall, was widespread and frequent at all locations. During a monitoring period from late May to early July 1999, when 413 mm rain fell in 25 events, overland flow was most prolific at the high slope (mean 29°) RR site, where all six traps were found overflowing on three measurement occasions. At the intermediate slope (mean 23°) SS site, the results were more variable at the slope-top where one trap overflowed on two occasions and was 25–50% full on the other three but one trap did not record overland flow at all; the two mid-slope traps overflowed on every or all but one occasion. At the low slope (7°) W0 sites, traps on the mid-slope overflowed on each measurement occasion and traps at the slope-top sites varied from 25 to 100% full. During the monitoring period of 21–22 July 2002 when daily rainfalls were 19.8 and 17.5 mm, respectively, the relatively low-angle (5–18°) sites at W3 and W7 recorded overland flow in 10 of the 11 traps with catches of between 40 and 320 ml. Suspended sediment concentrations of overland flow recorded at W3 and W7 in July 2002 were very high (1953–8827 mg l^{-1}). Rates of erosion by slopewash at erosion bridge transects (Table 3) tend to increase sharply with slope angle. Thus mean surface lowering rates are much higher at the RR site (3.40 mm $year^{-1}$) than on the lower angle slopes at the two groups of W sites (0.36 and 0.55 mm $year^{-1}$). Much of the erosion at the long-term sites monitored since 1990 was recorded in the year (1995–1996) containing the largest rainstorm (Table 4).

Table 3 Slopewash erosion rates measured with the erosion bridge. For location of sites see Fig. 1.

Site	Period of measurement	n	Slope angle °		Erosion rate (mm $year^{-1}$)	
			Mean	Range	Mean	Range
W0–W3	June 1990–December 2002	12	18	6–31	–0.36	+0.6 to –1.9
RR	May 1999–January 2002	13	29	18–37	–3.40	+0.1 to –6.4
SS	May 1999–January 2002	11	23	17–28	–1.40	+1.3 to –5.5
W0/3/5/7	October 2002–June 2003	23	7	5–18	–0.55	+7.6 to –3.4

Table 4 Rainfall during the monitoring period.

Year	Annual rainfall (mm)	>50 mm falls	> 100 mm falls	Highest daily fall (mm)
1990	2729	10	1	135
1991	2609	10	1	114
1992	2366	8	0	77
1993	2501	8	0	92
1994	2978	7	3	123
1995	3294	11	0	99
1996	2989	6	1	163
1997	1918	3	0	93
1998	2139	6	2	124
1999	3382	15	0	90
2000	3501	13	3	140*
2001	3075	11	1	141
2002	2728	12	0	95

* 183 mm over a 20-h period straddling two rainfall days.

DISCUSSION AND CONCLUSIONS

Pipeflow is clearly an important contributor to the stormflow component of streamflow in the study area. The fact that the contribution of the monitored pipe to streamflow decreases at higher rainfall intensities may have two possible explanations. First, it may be that overland flow, which the traps showed to be frequent but volumetrically of limited importance in small–moderate events, becomes relatively more important at higher rainfall intensities. The exact mechanism (saturation or infiltration excess) by which overland flow is generated in the study area is unclear from previous studies (e.g. Sinun *et al.*, 1992; Bidin *et al.*, 1993). Alternatively, other pipes may be activated at higher intensities (which have been observed to occur) and the monitored pipe may have reached its maximum output. A large pipe outlet (approx. 50 cm) was witnessed to flow with hydrostatic pressure and with high turbidity during the storm of 8 July 2003 when 15-min max rainfall intensity was 60 mm h^{-1}.

Pipes clearly play a major role in supplying sediment to the stream, with the monitored pipe generating 10–61% of the stream's load in eight of the nine events. The tendency for the proportion of streamflow provided by the pipe to decline in more intense and larger rainstorms, with only 2.6% supplied in the largest event of 11 July 2003, is linked (as with storm runoff generation) to enhanced contributions from other pipes and perhaps also overland flow. The relative importance of the two remains, however, unclear as SSC of collected overland flow are of a similar order to peak pipe and stream SSC. The erosion bridge evidence both at slopewash and collapsed pipe sites records evidence of deposition as well as erosion and so not all the sediment mobilized by pipes and slopewash in a storm event reaches the gauging stations. It is therefore clear that pipes in the study area play a significant role in sediment redistribution and sediment load generation. Pipeflow and streamflow discharge and sediment responses to rainfall cannot, however, be explained solely by one variable. Total rainfall, rainfall intensity, antecedent weather conditions and associated changes in sources from pipes and overland flow have been highlighted here as important factors; future work will seek to elucidate the perhaps changing roles of these variables using a longer data set.

Acknowledgements The research was funded by a NERC studentship (NER/S/A/2001/06422), EU grant ERBIC18CT960102, a Dudley Stamp Memorial Fund grant from the Royal Society and by grants from the Royal Society's Southeast Asia Rainforest Research Programme. Grateful acknowledgement is also given to the BGRG for financially supporting conference attendance to present this paper. The authors would like to thank the Economic Planning Unit of the Prime Minister's Department of Malaysia and the Danum Valley Management Committee for research permission. Thanks also for the field assistance from Muhamad Jamil Hanapi and Johnny Larenus at the Danum Valley Field Centre and Dr Will Blake, University of Plymouth. This paper is number A/401 of the Royal Society's SE Asia Rain Forest Research Programme.

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