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The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama rain forest, Sabah, Malaysia

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SUMMARY

Three stages of selective commercial logging in a 0.54 km^2 catchment in the Ulu Segama caused great changes in the output of sediment and water over a 27-month period from June 1988. The ratio of monthly suspended sediment yield from the logged catchment to that from a nearby undisturbed catchment changed from the order of 1:1 before disturbance; to 4:1 after a logging road had been built across the head of the catchment; to 5:1 after logging within 37 m of the road; and to 18:1 in the five months after logging of the remainder of the catchment. A year after logging had ceased the largest monthly sediment yields of the whole period were only 3.6 times those of the undisturbed catchment, indicating a degree of recovery. Sediment accumulated in the channel bed and on the narrow flood plain remained to be evacuated, and gullies on abandoned logging trails continued to supply sediment to the drainage system.

1. INTRODUCTION

Research on tropical rain forest disturbance and geomorphic processes at the Danum Valley Field Centre, Ulu Segama, Sabah, Malaysia began in October 1987 with the objective of establishing the roles of natural disturbance, such as gap formation, and people-made disturbance, particularly logging, on runoff, erosion and the export of chemical elements. The experimental design involved continuous monitoring of water level, specific conductance and temperature and automated water sampling during storm runoff events in three catchments of 0.5–10 km^2 (figure 1). This paper assesses the role of natural and people-made forest disturbance and vegetation dynamics on channel processes, sediment sources and suspended sediment loads in the two smaller catchments, A and C.

(*a*) *Field site and situation*

The Danum Valley Field Centre lies in the undulating country of the geologically heterogeneous melange unit of the Kuamut Formation, whose siltstones, sandstones, cherts, spillites and tuffs contain many easily eroded lithologies (see Marsh & Greer, this symposium). At 4° N of the equator, the area experiences only the edge effects of the seasonal monsoons, with a main wet season during the northeast monsoon from November to March and a lesser, and somewhat wetter period in the southwest monsoon during June and July. Two of the three study catchments, the 10 km^2 Sungai Palam Tambun (catchment B, figure 1) and the 1 km^2 W8S5 catchments are in areas of water supply catchment and conservation area respectively; they are not expected to be logged. The third catchment, the 0.56 km^2 Sungai Steyshen Baru (Baru), is in a logging concession where road construction began in June 1988 and logging in January 1989 (table 1).

The catchments of particular interest to this paper, W8S5 and Baru, differ in aspect, W8S5 flowing in a west–east direction and Baru from north to south. W8S5 has slopes around its rim of 18–25°, declining generally to 5° or less near the main stream, but with short slopes of up to 45° where outcrops of sandstone occur. Similar slopes prevail in the Baru catchment, but the overall gradient of the shorter main stream is steeper.

(*b*) *Field and laboratory methods*

Precipitation totals and time-distribution are measured by three recording raingauges, one with a weekly chart and two with a daily chart. Annual rainfall totals at the Field Centre in the last five complete years are: 1986, 2428 mm; 1987, 2576 mm; 1988, 2923 mm; 1989, 3205 mm; and 1990, 2842 mm.

Maximum recorded 24 h rainfalls are up to 170 mm, with maximum 30 min intensities of up to 100 mm h^{-1}. These three recording raingauges are too far apart to catch the full variability of localized cells of intense rainfall in individual storm events, and with

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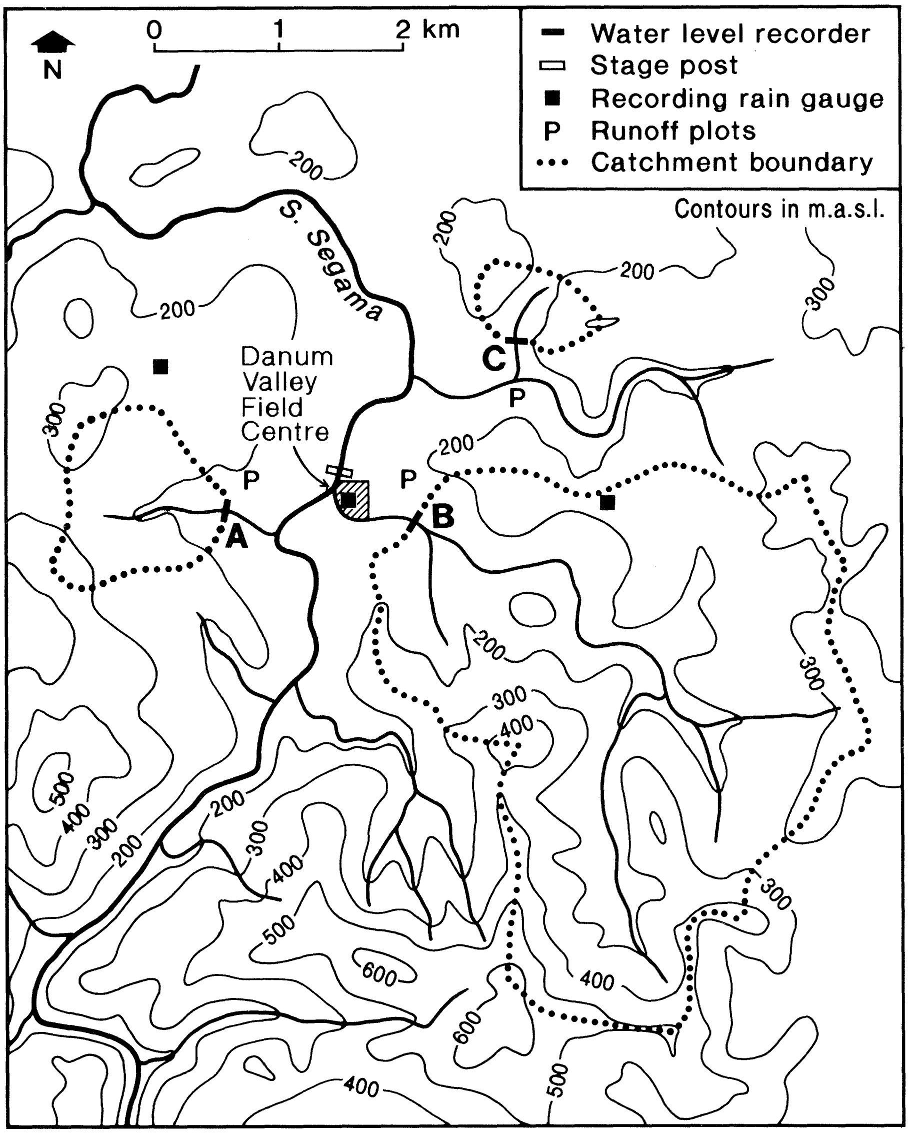

Figure 1. Location map indicating the study catchments: A = W8S5; C = Sungai Steyshen Baru.

the two catchments 1.4 km apart, storm rainfalls do not always coincide nor produce the same volumes of water per unit area.

Water level recorders, with Ott horizontal float gauges, were established on W8S5 in October 1987 and on Baru in June 1988. Conductivity meters and temperature probes, linked to Rustrak recorders, provide continuous records which, together with the water level charts are digitized by using a Summagraphics digitizer attached to an IBM-compatible AT PC at the Field Centre.

Automatic liquid samplers with 1 l bottles were activated by float switches during storm events. As the rivers rise extremely rapidly, the sampling interval was set at 7.5 min. With such an interval 3 h of the hydrograph rise and fall were sampled, a period sometimes insufficient to cover the duration of storm runoff in the larger W8S5 catchment. The number of samples taken on the rising stage was always small as the rate of rise is rapid, but it also depended on the height above baseflow at which the float switch was set. After each storm suspended sediment concentrations were obtained by filtration through 0.22 μm cellulose nitrate membrane filters (Douglas 1971) after pH measurement and checking of the specific conductance level.

2. IMPACT OF LOGGING ON SUSPENDED SEDIMENT DISCHARGE

A general view of the impact of logging is provided by a comparison of the monthly sediment discharges of Baru and W8S5 (figure 2). Loads were lower in the Baru than in W8S5 in June, August and September 1988, but higher, when the catchments were still unaffected by forestry activities, in July 1988. Such a variation could arise from local differences in storm rainfalls. However, in October 1988, once logging road construction was almost completed (table 1), the suspended sediment load in Baru was almost 10 times that in W8S5. Thereafter, monthly totals from Baru remained consistently higher until the extremely dry month of April 1990, when the larger W8S5 catchment had slightly more runoff per unit area than the

Table 1. *Stages of forestry activity and storms analysed in the Sungei Steyshen Baru catchment 1988–89*

period	activity	dates of storms reflecting activity	
Aug–Sep. 1988	logging road construction	A B D	3 Oct. 1988 13 Oct. 1988 5 Dec. 1988
28 Dec. 1988	removal of trees two chains from road, including some high lead logging with some skid tracks	E F H	2 Jan. 1989 18 Jan. 1989 12 Mar. 1989
10 May 1989– 18 May 1989	cutting of logs on right bank between Sg. Steyshen Baru channel and divide		
21 May 1989	tractor activity with some skid tracks and placing of high lead machine		
25 May 1989	high lead machine in place		
30 May 1989– 2 Jun. 1989	high lead pulling of logs	I J K	15 June 1989 20 June 1989 27 June 1989
late Jun. 1989	removal of some logs by tractor	L M	2 July 1989 14 July 1989

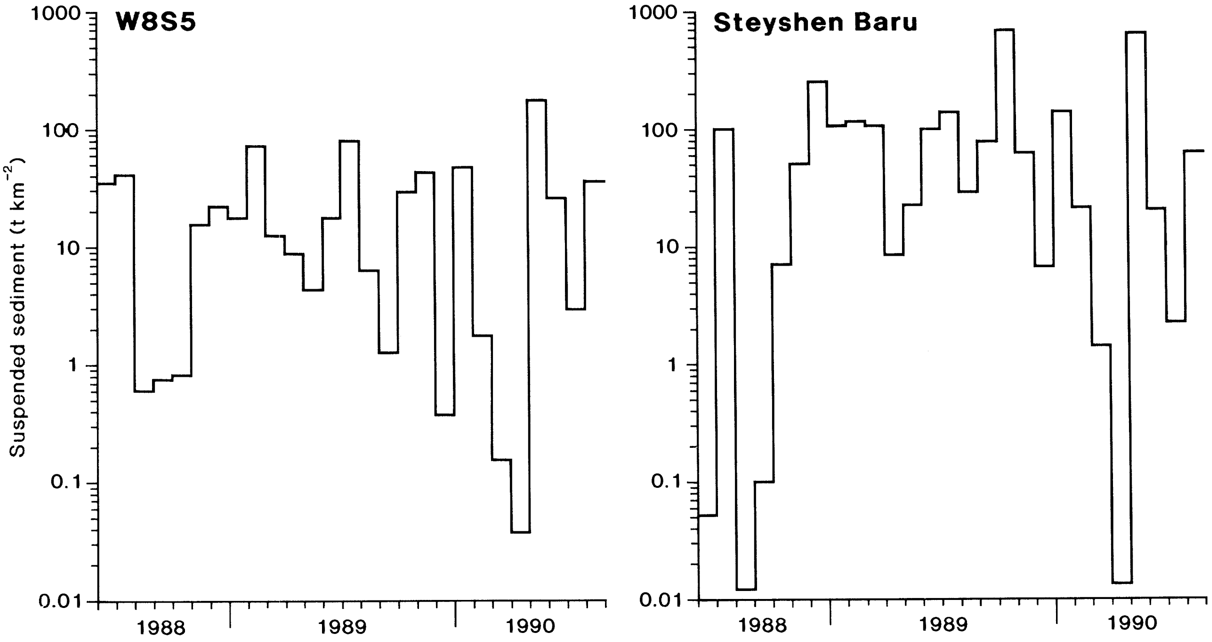

Figure 2. Monthly suspended sediment yields for W8S5 and Steyshen Baru June 1988–August 1990.

Baru and thus evacuated more sediment, albeit a minute quantity compared with earlier months. A large storm at the end of May 1990 produced the highest monthly sediment load so far measured in W8S5, but flushed an even larger amount of accumulated sediment out of the logged Baru. Since May 1990, the sediment yields from the two catchments have been less different, but peak loads in Baru remain higher.

The cumulative curves of sediment evacuated from the two catchments (figure 3) show how the loads of Baru increased after late 1988. The role of major storm events which flush large quantities of sediment out of the systems is well illustrated by the steps in the curves, especially in October 1989 for Baru and in May 1990 for both catchments. The significance of these large events is indicated by the calculation that over three years 51% of the load carried by W8S5 was evacuated by 11 storms and 51% of that for Baru by eight events. These proportions are particularly influenced by the storm of 30 May 1990 which carried 58% of the annual suspended sediment load for Baru and 46% of that for W8S5 for 1990.

(*a*) *Logging road construction*

Three storms (A, B and D in table 1) reflect the impact of logging road construction on the Baru catchment. In each of these storms the Baru stream rises steeply, although in storm B the rise is less

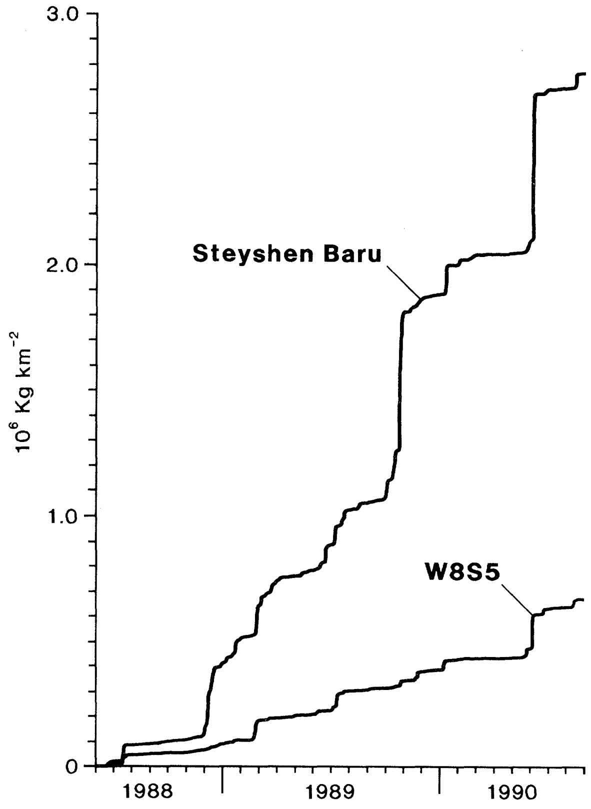

Figure 3. Cumulative curves of sediment yield for W8S5 and Steyshen Baru June 1988 – August 1990.

dramatic than that in W8S5 probably due to differences in rainfall volume and intensity. In all three storms the peak sediment concentration in the Baru is three to eight times that in W8S5 (figure 4), with maxima in the Baru of around 2000 mg l^{-1} at a discharge of 0.75–1.25 m^3 s^{-1} km^{-2}. Storm A was the first sizeable rainfall (34 mm) after road construction and the peak sediment concentration of around 2000 mg l^{-1} was more than double the previously highest recorded levels of 800–900 mg l^{-1}.

The hysteresis loops for suspended sediment concentration in the Baru in these three storms (figure 4) show a characteristic clockwise pattern with peak sediment concentration occurring on the rising stage before the discharge peak (Einstein 1964; Douglas 1977). Peak sediment concentrations of W8S5, much lower than those on the Baru, occur slightly earlier than those on the Baru in relation to peak discharge, indicating the lower volume of sediment available to be entrained by the streamflow and the likelihood that the main sources of sediment are the banks and immediate channel margin. While the overall pattern of the W8S5 loops is clockwise, the falling stages show many fluctuations in concentration, perhaps influenced by variations in runoff, but possibly due to the flushing of mixtures of sediment and organic matter out of ephemeral headwater channels which are usually dry, but are favoured zones of activity for mammals, worms, cicadas and termites. The smaller Baru catch-

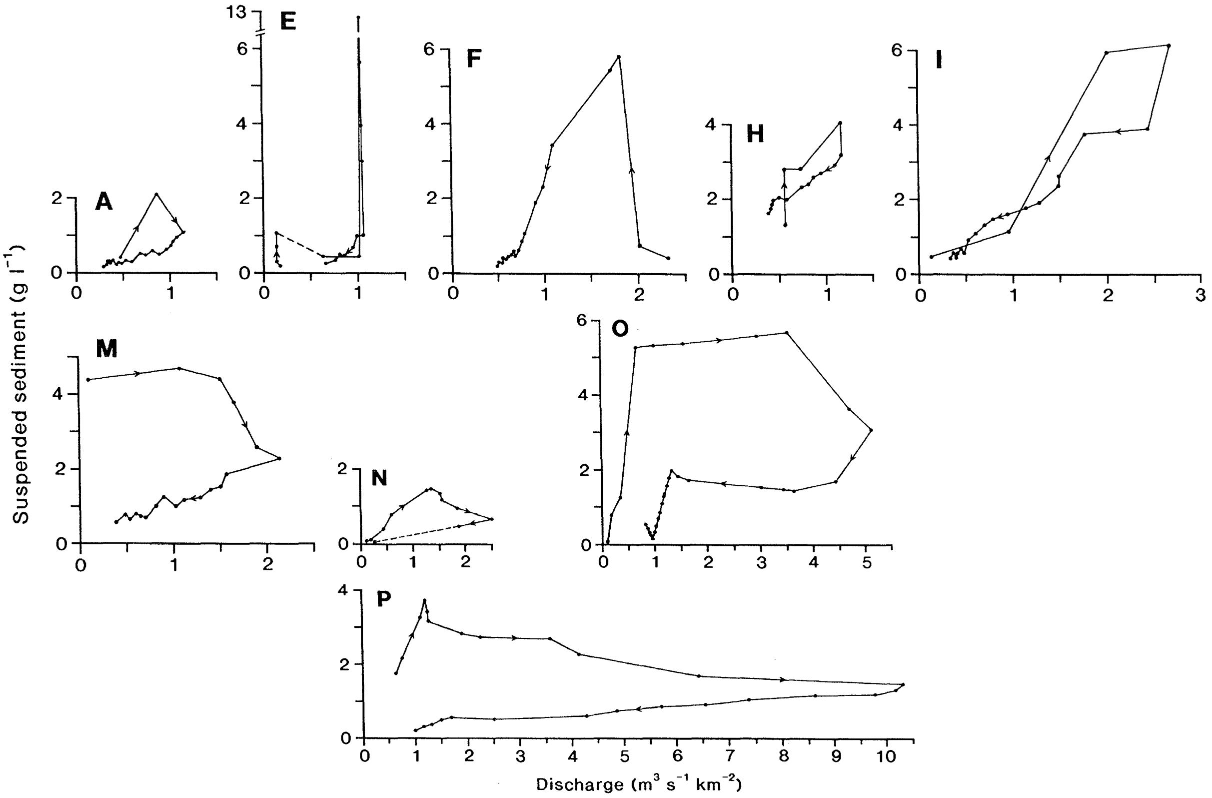

Figure 4. Representative hysteresis loops of change sediment concentration with discharge for selected storms in Steyshen Baru. Letters refer to storms listed in table 1.

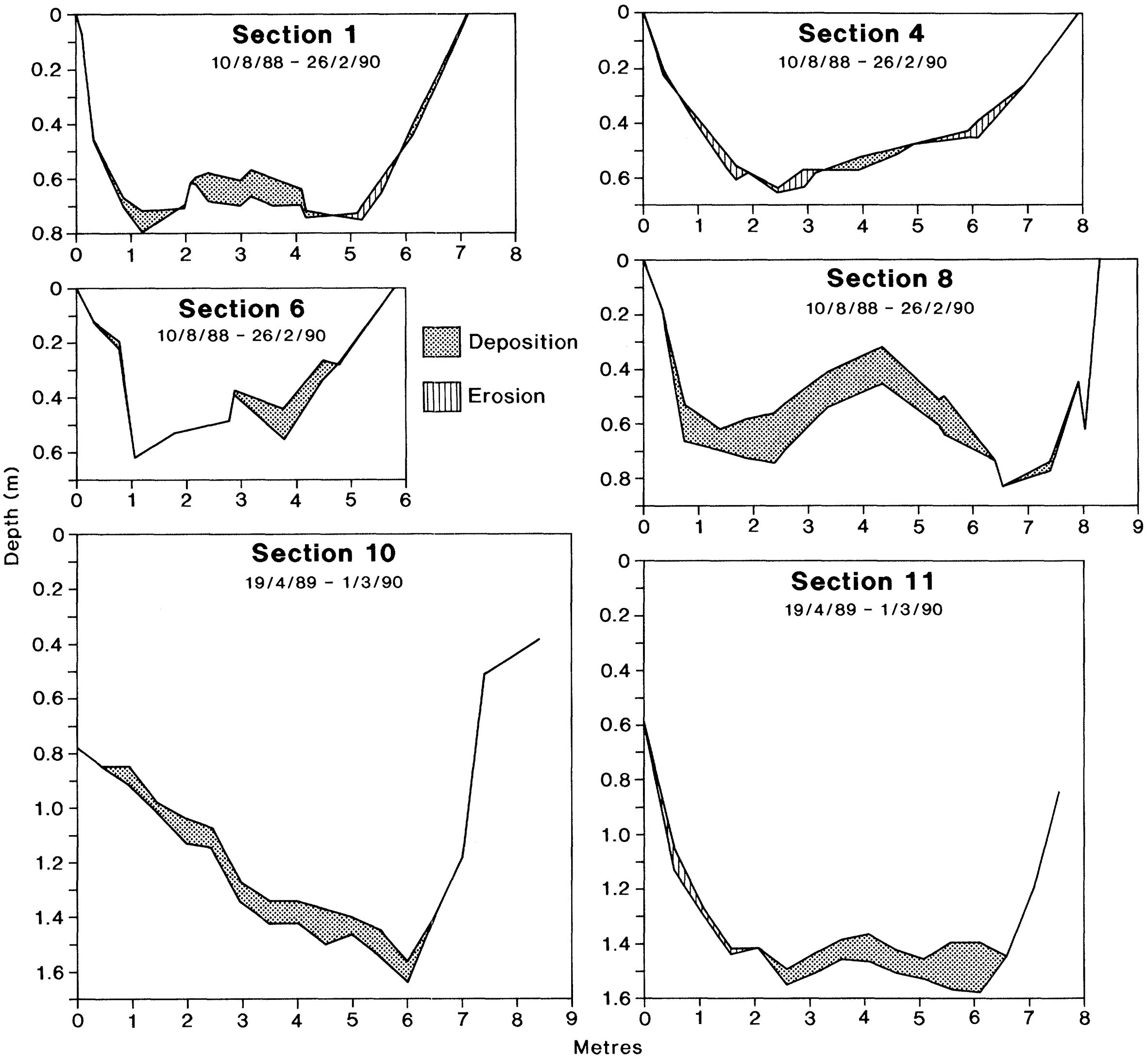

Figure 5. Representative cross-section surveys of the Steyshen Baru channel upstream of the gauging station to show accumulation of channel sediment after logging. The dates indicate the times when surveys were made and the shading the net change in the channel bed over that period.

ment would be expected to have a sharper and high peak of suspended sediment concentration due to its size and narrowness, but the difference would not be as great as that observed in these three storms.

(*b*) *Logging within two chains (36.7 m) of the logging road*

The first major storm (storm E, figure 4) after the high-lead road clearance logging in the headwaters of the Baru triggered a sediment concentration of 12947 mg l^{-1}, much more than any previously recorded event. Concentrations were high in all the succeeding storms, including storms F and H (figure 4). The availability and downstream transport of greater volumes of sediment is also demonstrated by the build-up of a veneer of fine clay over the bed material of the channel. After the logging road construction, peak sediment concentrations occurred 15 or more minutes before peak discharge, but after the logging they were either coincident with or only 7.5 min before the discharge peak, or the first peak of a multi-peaked runoff event. Storms A and E have similar peak discharges but in storm E the suspended sediment concentration remained above 1000 mg l^{-1} for 75 min, whereas such levels only prevailed for 15 min in storm A. The second phase of disturbance had supplied much more sediment to the streams, not all of which was being evacuated past the gauging station. The build up of fine material in the bed indicated that in some storms, more sediment was available for transport than stream energy to carry it.

Among the readily available sediment sources, lateral bars of fine sediment play an important role in natural forest streams in this part of Sabah. Fine material may be washed downslope by overland or sub-litter flow, or may be transferred by lateral mechanical eluviation to accumulate at the stream margin until a storm event flushes it a little further downstream. The runoff and throughflow plot studies reported elsewhere (Sinun *et al.*, this symposium) confirm the importance of both overland flow and piping in this environment. Sediment washed out from natural pipes may be a major contributor to these lateral bars. The new accumulations of fine silt as a veneer over the sands and gravels of the bed of the Baru may result, in part, from the sudden decrease in runoff energy and volume on the falling stage with a drop in the competence of the stream.

Although the hysteresis loops for the Baru (figure 4) are truncated as the automatic samplers were triggered only slightly before peak discharge, they show sediment concentrations on the falling stage similar to, or higher than, the rising stage. For example, at a discharge of 0.55 $m^3\,s^{-1}\,km^{-2}$ on the rising stage in storm H, the suspended sediment concentration was 1259 $mg\,l^{-1}$, whereas at that discharge on the falling stage it was over 2000 $mg\,l^{-1}$. Such a situation occurs when the sediment source is in the headwaters and when there is abundant material available in the stream channel.

(*c*) *High lead and tractor logging*

After the general logging of the catchment in May and June 1989, suspended sediment concentrations did not again reach the high level of almost 13 000 $mg\,l^{-1}$ experienced in storm E, but remained well over 1000 $mg\,l^{-1}$ for at least 75 min in most storms, whether or not the rainfall was of short duration (for example storms I and M in figure 4). By the end of June 1989, the Baru catchment was showing an immediate response to any rainfall input in excess of 5 mm, probably as a result of the considerable extent of compacted bare areas left by the logging operations. Observations on a runoff plot on an abandoned logging track indicate that surface runoff is likely to increase 10 times on such surfaces compared with that in undisturbed forest (Sinun *et al.*, this symposium). Elsewhere in Sabah, Malmer (1990) has reported a reduction in infiltration capacity from 154–0.22 $mm\,h^{-1}$ after tractor passes.

The rapid increase in suspended sediment concentration at the start of every storm (e.g. Storm I on figure 4) reflects an initial uptake of sediment from the channel perimeter. Each rise in river flow mobilizes the fine sediment deposited on the falling stage of the previous storm. Deposition exceeded scour during this period of forest activity as resurvey of several cross-sections upstream of the sampling site indicates (figure 5). The aggrading channel is an active store, capable of being scoured out by runoff from the heaviest and most prolonged storms.

3. POST-DISTURBANCE RECOVERY OF THE HYDROLOGIC SYSTEM IN TERMS OF SUSPENDED SEDIMENT YIELD

As indicated by the cumulative curves (figure 3), the difference in sediment output between the two streams has decreased since 1989. Major storms in 1990 and 1991 still produced occasional suspended sediment concentrations in excess of 5000 $mg\,l^{-1}$ in Baru, but such levels quickly fell and seldom did concentrations of over 1000 $mg\,l^{-1}$ prevail for more than 30 min. The hysteresis loops for this period (Storms O and P in figure 4) show this in terms of much lower suspended sediment concentrations on the falling than on the rising stage. In both these storms, the peak sediment concentration occurred well before the peak water discharge indicating that the supply of sediment is less than the transporting power of the stream. The four storms listed in table 2 illustrate the continuing difference in peak suspended sediment concentrations between the two streams, Baru and W8S5.

Table 2. *Differences in peak suspended sediment concentrations (in milligrams per litre) between the streams Baru and W8S5 after four storms*

	Baru	W8S5
31 May 1990	5734	2613
8 August 1990	2454	484
9 February 1991	3338	1885
15 February 1991	5486	1524

The storm of 31 May 90 had a daily sediment discharge of 131 $t\,km^{-2}$ from Baru and 51 $t\,km^{-2}$ from W8S5 with mean daily discharges of 0.64 and 0.40 $m^3\,km^{-2}\,s^{-1}$ respectively. The discharge of Baru was only 60% greater, but it evacuated 160% more sediment, indicating the continuing roles persisting low infiltrability, and thus high runoff, on logging tracks (see Malmer 1990), of the increased drainage density caused by gullying of logging tracks and the lasting availability of sediment, from both continued erosion and from the channel and floodplain stores.

4. FACTORS ACCOUNTING FOR THE INCREASED SEDIMENT LOADS AFTER DISTURBANCE

The increase in sediment yields following logging in temperate and tropical forests is well documented (Gilmour 1977; Dunne 1979, 1984; Dietrich *et al.* 1982). Road construction is well known as a cause of great increases in sediment yield (Megahan *et al.* 1986; Bernard-Allee & Cosandey 1991), but in the Baru, the impact of road building was delayed as the first two months after construction were relatively dry, but a series of storms from late November to mid-December produced daily sediment discharges exceeding 10 $t\,km^{-2}$, the sediment supplied by the roadworks causing the load evacuated by the Baru in December 1988 to be over 11 times that carried by W8S5. Logging close to the road then created new sources of sediment for the storms of early January 1989.

The similarity of the patterns of suspended sediment concentration change with discharge on W8S5 and the Baru suggests that the basic sources of sediment remain the same, but that more sediment is being supplied. The main sources in W8S5 are the mobilization of detritus in ephemeral channels, rapid bank erosion and remobilization of metastable sediment in the main channel. Road construction increases the length of ephemeral channels by providing new routes for surface runoff. Roadside rills and gullies develop by bank erosion and operate as part of the channel sediment supply. Steep cut and fill slopes along the roads and on mounds of weathered material bulldozed during logging operations provide effective new sediment sources. Detailed plot studies are required to quantify the relative significance of these possible contributors of sediment.

The importance of the initial phase of disturbance is borne out by comparing storms E and F on the Baru (figure 4). Total hydrograph rise in storm F is much greater, as the rainfall of 24 mm in 30 min was heavier and more intense than in storm E. However, as storm E was the first rain (22.5 mm in 45 min) after the logging along the road had begun, this picked up all the loosened material and reached a far higher peak sediment concentration than storm F. There is no systematic relation between streamflow and suspended sediment concentration in such circumstances of episodic disturbance. As often noted elsewhere, for example on Behana Creek in North Queensland (Douglas 1973), the first storm after a dry period or after change in a catchment usually carries a higher sediment load than other events of a similar size.

Comparison of the two catchments however reinforces the role of the biggest rain events in the sediment dynamics of humid tropical streams. Major storms will always pick up and release large quantities of sediment. In some cases they lift debris dams (Spencer *et al.* 1990) and carry more sediment than would be predicted by extrapolation from smaller events. During the disturbance of the Baru catchment, the proportions of the total annual sediment load carried by individual storms differed from those in W8S5. Some ten weeks after logging road construction, the heavy rains of late 1988 had differing effects on the two catchments, events from 27 November to 10 December carrying 65% of the sediment yield of the Baru for the period June–December 1988, whereas in W8S5 the same events evacuated only 12% of the yield for the period. This change in the significance of major events persisted after logging activity ceased, the storm of 31 May 1990 carrying 58.3% of the sediment load in the Baru, but only 46% of that for W8S5 for the first eight months of 1990. The dominance of a few major storms for sediment budgets is as evident in these tropical rain forest catchments as elsewhere (Tropeano 1991).

The sediment yields in the Ulu Segama streams, both in the natural forests and after commercial selective logging, appear to be much higher than those reported for other parts of Malaysia (table 3). Two reasons contribute to this. The mudstones of the Kuamut Formation are much more erodible than the weathered granites and partly metamorphosed sediments of the areas studied in peninsular Malaysia, and also probably more erodible than the orthic acrisols of the Sipitang area of Sabah. However, many other

Table 3. *Estimates of sediment yield from small forested and disturbed humid tropical catchments*

catchment name	catchment area km^2	sediment yield (t km^{-2} y^{-1})	source
A. Forested catchments in Malaysia			
Sg. Telom, Cameron Highlands	77	53	Shallow (1956)
Sg. Mupor, Johor	21.8	41	Leigh & Low (1973)
Sg. Gombak, Selangor	140	97	Douglas (1975)
W8S5, Ulu Segama	1.1	312	
B. Secondary forest catchments in Malaysia			
Sg. Tekam, Pahang	0.47	35	Malaysia (1986)
Sipitang, Sabah	0.15	60	Malmer (1990)
C. Cleared or logged catchments in Malaysia			
Sg. Tekam, Pahang	0.47	660	Malaysia (1986)
Bukit Berembun, Negeri Sembilan			
(supervised)	0.13	22	Zulkifli *et al.* (1990)
(normal)	0.30	189	Zulkifli *et al.* (1990)
Sipitang, Sabah	0.15	300	Malmer (1990)
Baru, Ulu Segama	0.56	1600	
D. Catchments affected by urbanization in Malaysia			
Sg. Jinjang	10.3	1056	Balamurugan (1991)
Sg. Kelang, Zoo Negara	14.2	1480	Balamurugan (1991)
E. Other tropical catchments with yields of over 1000 t km^{-2} y^{-1}			
Cigulung, East Java	43	1085	Walling (1982)
Cikeruh, Java	250	11 200	Walling (1982)
Ok Ningi, New Guinea	4.56	10 746	Pickup *et al.* (1981)
Ok Tedi, New Guinea	420	7857	Pickup *et al.* (1981)

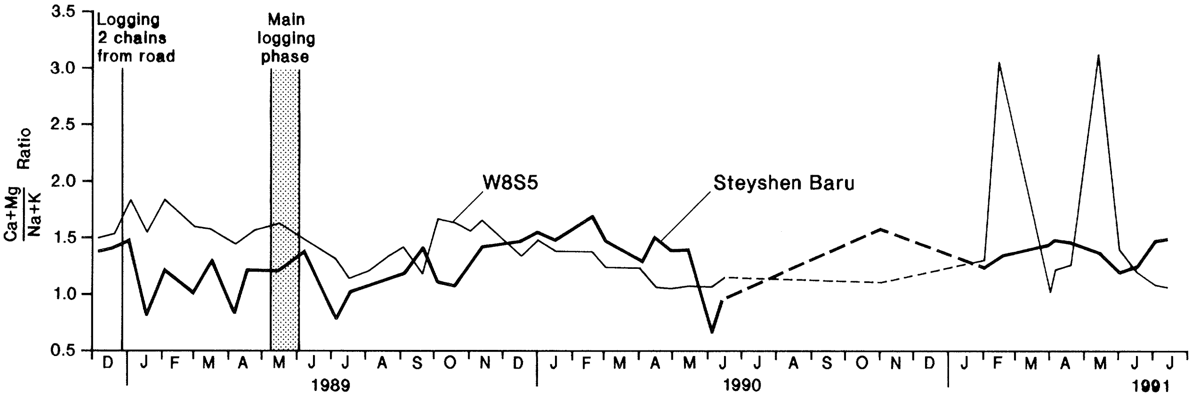

Figure 6. Changes in the $(\mathrm{Na}+\mathrm{K}):(\mathrm{Ca}+\mathrm{Mg})$ ratios in samples of baseflow discharge waters from W8S5 and Steyshen Baru 1989–1991.

Table 4. *Comparison of baseflow solute loads when stream discharges per unit area on given dates are nearly the same (loads in tonnes per square kilometre per year)*

	Ca load		K load		Si load	
date	W8S5	Baru	W8S5	Baru	W8S5	Baru
2 Nov. 1988	4.19	2.41	n.a.	n.a.	3.05	2.68
19 Dec. 1988	10.53	4.81	2.20	2.40	10.94	10.97
22 Apl 1989	1.17	0.88	0.15	n.a.	1.35	1.33
17 Jly 1989	1.59	0.68	0.26	0.06	2.16	1.63
18 Sep. 1989	0.94	0.86	0.13	0.13	0.96	0.20
4 Oct. 1989	1.90	0.58	0.28	0.24	1.59	1.59
16 Oct. 1989	3.04	1.53	0.43	0.62	3.90	4.83
1 Nov. 1989	1.24	0.64	0.20	0.26	1.68	1.65
15 Feb. 1990	0.28	0.44	0.04	0.11	0.28	0.69
2 Apl 1990	0.28	0.24	0.06	0.08	0.26	0.34

investigators acknowledge that their sampling procedures do not always measure suspended sediment concentrations in streams during all storm runoff events. Furthermore, extensive sampling strategies may miss storm peaks; we have shown in this study the rapidity of rise-to-peak flow in these catchments. Thus calculations may underestimate sediment loads during the all-important extreme events.

5. CHANGES IN SOLUTE BEHAVIOUR AFTER LOGGING

The detailed analysis of storm-by-storm variations in water chemistry is not possible due to logistic difficulties over chemical analysis. Specific conductance is measured on all storm period water samples, but individual elemental concentrations are available only for a few storms and for fortnightly baseflow samples. The latter show an interesting trend (figure 6) with the $(\mathrm{Ca}+\mathrm{Mg}):(\mathrm{Na}+\mathrm{K})$ ratio for Baru dropping below that of W8S5 throughout the period of disturbance and then rising after November 1989. No clear corresponding difference in the solute loads carried by the two streams emerges. If sampling dates when the baseflow discharges per unit area of the two streams are approximately the same are taken, the solute loads being evacuated are generally quite similar (table 4). This small difference in the solute loads carried at baseflow would reflect the dominant role of mineral interactions with waters moving through the soil and weathering mantle to stream channels. Even in the most compacted areas, such as logging tracks, only 55% of the water reaching the forest floor runs off as overland flow. In undisturbed forest the proportion is as low as 5%. At baseflow, streamflow is essentially from the shallow groundwater table which intersects finger-tip tributary channels several tens of metres below their stream head hollows.

Export of solutes during storm runoff events will control most of the loss of material by stream discharge. Storm-by-storm conductivity measurements show much greater dilution of chemical contents of Baru waters compared with those of W8S5 in the post-logging period. However, storm runoff peaks are usually higher and so the solute removal rates are likely to be at least as high as in W8S5. Conductivity levels during storms in Baru decreased as logging progressed, dropping to 11 μS cm^{-1} in storm E, compared with 37 μS cm^{-1} in storm A. In major storms as late as February 1991 conductivities at peak discharges of over 2 m^{3} km^{-2} s^{-1} were still as low as 14–16 μS cm^{-1}. The actual conductivity level may be more closely related to volume of rainfall than the actual discharge and may reflect how quickly the rain runs off over the remaining largely impermeable, compacted areas left behind after logging.

Concentrations of individual elements at peak storm discharges also fell with the onset of logging, calcium levels dropping to 0.68 mg l^{-1}, magnesium to 0.35 mg l^{-1}, sodium to 0.93 mg l^{-1} and silicon 2.79 mg l^{-1} in the storm of 23 April 1989. On 24 May 1990, at a peak discharge of 0.96 $m^3\ km^{-2}\ s^{-1}$, concentrations were: calcium 1.18 mg l^{-1}, magnesium 0.64 mg l^{-1}, sodium 1.39 mg l^{-1} and silicon 4.45 mg l^{-1}. When the loads carried at various discharges in this storm are compared with those of a storm 10 October 1988, the later storm evacuated less calcium and magnesium and more sodium and silica. The most obvious source of the silica is the particulate matter carried into the stream, but the source of the sodium is less clear, although more of the sodium brought in in rain may now be leaving the catchment.

Decreases in solute concentrations, but increases in macronutrient exports, following logging or clearfelling were noted in the Hubbard Brook experimental forest (Bormann & Likens 1979). Similar increases were noted after clearfelling at Leading Ridge, central Pennsylvania, but the increases were restricted almost entirely to the first post-harvest growing season (Lynch & Corbett 1991). Both these cases involved clearfelling in a seasonal temperate climate. In tropical rain forests, selective logging is followed by rapid regrowth of vegetation in many disturbed areas, much of the decaying plant matter being decomposed to yield nutrients to support new growth, as shown, for example, in increased foliar nutrient concentrations in disturbed areas of forest in Queensland (Lambert & Tanner 1986). Impacts on the nutrient budget may be less drastic in the Baru than in the U.S.A. Nevertheless, at this stage, conclusions about changes in water chemistry after logging have to be tentative. No difference in baseflow loads can be demonstrated. Too few detailed analyses have been made of storm runoff events for a detailed biogeochemical budget to be calculated.

In addition to the lack of detailed temporal sequences of solute determinations, logistic difficulties, mainly the deterioration of samples during storage, made the analysis of some important elements impossible. The type of change in nitrogen output after logging noted at Bukit Berembun in peninsular Malaysia, a 300% increase in concentrations (Abdul Rahim 1989; Zulkifli 1989), may have happened in the Baru catchment, but no nitrogen data are available.

6. CONCLUSIONS

Logging had a marked effect on the sediment yield of the Baru catchment, leading to an 18-fold increase in sediment yield immediately after the bulk of the catchment had been logged. Even though these figures are dramatic, it should be noted that part of the catchment close to the stream monitoring station was not logged to the extent a normal stream would have been, due to the researchers plea that no harm should befall their instruments! The key to the whole sequence of hydrological change in the catchment area is the reduction in opportunities for infiltration and the exposure of bare soil. Many of the artificially bare surfaces remained after logging activity had ceased. One particular snig track ran directly downslope to the stream channel and although foliage covered it, its surface was gullied and provided a direct path for concentrated overland flow to the stream. Parts of the logging road were gullied and remained active sediment sources. Some barriers bulldozed up on old log loading areas had begun to be breached and thus, despite the rapid growth of protective vegetation, many routes for wash of material towards the stream remained active.

A model of the sediment yield response to logging would thus see an initial increase in sediment yield following road construction, but the peak, when high loads are carried throughout most of the storm runoff hydrograph, comes when disturbance is at a maximum and logging activity is at its height. After work has ceased, peak sediment concentrations remain high, but do not persist past the discharge maximum. Gradually small and moderate storms evacuate less and less sediment. Major discharges, however, scour the accumulated sediment from the channel floor and floodplain stores which gradually are reduced. The supplies from upslope no longer replenish the store and gradually the sediment loads decline. However, by August 1991, two years after logging, the system appeared to be well short of recovery from logging. Many of the sediment sources created by disturbance remained, and much sediment carried downslope remained to be evacuated by the stream.

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