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The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah

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Ten years' hydrological investigations at Danum have provided strong evidence of the effects of extremes of drought, as in the April 1992 El Niño southern oscillation event, and flood, as in January 1996. The 1.5 km^2 undisturbed forest control catchment experienced a complete drying out of the stream for the whole 1.5 km of defined channel above the gauging station in 1992, but concentrated surface flow along every declivity from within a few metres of the catchment divide after the exceptional rains of 19 January 1996. Under these natural conditions, erosion is episodic. Sediment is discharged in pulses caused by storm events, collapse of debris dams and occasional landslips. Disturbance by logging accentuates this irregular regime. In the first few months following disturbance, a wave of sediment is moved by each storm, but over subsequent years, rare events scour sediment from bare areas, gullies and channel deposits. The spatial distribution of sediment sources changes with time after logging, as bare areas on slopes are revegetated and small gullies are filled with debris. Extreme storm events, as in January 1996, cause logging roads to collapse, with landslides leading to surges of sediment into channels, reactivating the pulsed sediment delivery by every storm that happened immediately after logging. These effects are not dampened out with increasing catchment scale. Even the 721 km^2 Sungai Segama has a sediment yield regime dominated by extreme events, the sediment yield in that single day on 19 January 1996 exceeding the annual sediment load in several previous years. In a large disturbed catchment, such road failures and logging-activity-induced mass movements increase the mud and silt in floodwaters affecting settlements downstream. Management systems require long-term sediment reduction strategies. This implies careful road design and good water movement regulation and erosion control throughout the logging process.

Keywords: tropical hydrology; erosion; sediment transport; logging impacts; extreme events; landslides

1. INTRODUCTION

In tropical rainforest areas there is a lack of information on the hydrological changes that take place after logging and on the time-span required for regrowth to return to pre-logging levels of evapotranspiration and streamflow (Bruijnzeel 1993). Although it is well established that logging leads to a sharp increase in erosion, the pattern of soil erosion and sediment yield in the recovery period is particularly poorly documented (Bruijnzeel 1993). Studies of hydrology and earth surface processes in undisturbed forests have seldom been maintained for long enough to understand the effects of extremes of exceptional rainfall or drought. Catchment studies in Puerto Rico, operated by the US Geological Survey as part of the long-term ecological research in the United States (Larsen & Torres-Sánchez 1998), have provided many insights into the role of extreme events, especially hurricanes, in causing landslides and high sediment yields. Over ten years of hydrological investigations at Danum Valley can similarly be viewed as a contribution to long-term ecological research.

Long-term ecological studies focus on the relatively straightforward notion that processes such as succession, the natural frequency distributions of climate regimes, or disturbances caused by treefalls and fires, are long-term processes and must be studied as such (Risser 1991). Although the need for long-term studies is well known, few comprehensive long-term investigations have been undertaken. Among the outstanding examples are the agricultural plots at Rothamsted, UK (Risser 1991), and the hydrological investigations at Plynlimon, UK (Kirby *et al.* 1997; Hudson *et al.* 1997), forest productivity research in Sweden (Risser 1991), and the Coweeta (Swift & Crossley 1988), Fernow and Hubbard Brook experimental catchment studies in the USA (Bormann & Likens 1981; Hornbeck *et al.* 1995). In the Asia-Pacific region, forest research studies in Taiwan (Cheng *et al.* 1987) and Thailand (Chunkao *et al.* 1981) have produced some high-quality hydrological information. In Malaysia, one of the most successful hydrological projects was the Sungai Tekam study in Pahang, which ran for nine years (DID 1989).

Many fundamental processes in ecological systems occur over relatively long periods of time while others are of short duration. For example, the generation times of some insects can be a matter of days, but some species of trees live for hundreds of years. Similarly soil erosion may occur rapidly with one, possibly unpredictable, storm, while soil-building processes may require centuries. Thus ecological processes, consisting of both organisms and their environment, are driven by dynamics of major events the periodicities and durations of which span many temporal and spatial scales.

In a tropical rainforest, hydrological processes are affected by both physical phenomena and the activities of forest organisms, and are therefore subject to both hydrometeorological and temporal and spatial biotic controls. Treefall and debris-dam formation and collapse, the fluvial transport of coarse woody debris, the actions of termites and burrowing organisms in creating subsurface pathways for water, and of deer and other quadrupeds in creating surface routes for soil erosion and water flow, are all part of the intimate links between ecological and hydrological processes. This paper examines the long-term role of extreme events in the erosion of primary and selectively logged catchments, and the pattern of hydrological recovery over eight years of catchments of differing size following selective logging.

2. THE DANUM VALLEY HYDROLOGICAL RESEARCH SITES

The Danum Valley Field Centre lies in the undulating country of the geologically heterogeneous melange unit of the Kuamut Formation of Miocene age, including siltstones, sandstones, cherts, spillites and tuffs, many of which are easily eroded. This formation, developed partly from debris coming from uplift and denudation of the centre of the island and coeval volcanism (Wilson & Moss 1999), covers a crystalline basement which includes some ultramafic and mafic intrusive rocks. The latter are exposed to the north-north-east of the Field Centre in the Bukit Rafflesia area. At 4° N of the equator, the area experiences only the edge effects of the seasonal monsoons, with a main wet season during the north-east monsoon from November to March and a lesser, and somewhat wetter period in the south-west monsoon during June and July. Over the period 1985–1998, annual rainfall at the Field Centre has averaged 2669 mm, but with annual totals ranging from 3294 mm in 1995 to 1918 mm in 1997 (Walsh & Newbery, this issue).

The top 5–10 cm of the soils of the FAO haplic alisol (Alh) unit (Chappell *et al.* 1998) on the Kuamut formation typically have 38–57% sand, 20–35% silt and 13–27% clay. The topsoil immediately beneath the litter layer has 1.5–6% organic matter. Organic matter, plant nutrient content and hydraulic conductivity all decrease rapidly with depth in undisturbed areas. Aggregate stability may vary considerably between horizons of the same profile. Such variations greatly influence soil erodibility and slope stability. A and B horizons together average *ca.* 1.5 m in depth, with a further 1.5 m of weathered rock below them, providing an average regolith depth of 3 m. The soils on the serpentinites of the Bukit Rafflesia area have a higher proportion of clay, but the regolith is shallower and many of the steep slopes have outcrops of bare rock.

Major changes in surface soil bulk density and hydraulic conductivity occur in areas compacted during logging at extraction rates of 73–166 $m^3\ ha^{-1}$ (Marsh & Greer 1992). Decreased infiltration of water on affected areas increases the potential for downslope sediment transport and gully development where the flow becomes concentrated.

Hydrological investigations concentrated on catchments in undisturbed forest and in the 1989 and 1992 logging coupes. In the area that was logged in 1989, a 0.44 km^2 catchment area on the Kuamut Formation, known as Sungai Steyshen Baru (Baru), was equipped with a water-level recorder and an automatic water sampler in early 1988. Similar instruments were set up in the 1.7 km^2 control catchment in the Conservation Area in late 1987 (figure 1). The water samplers collected samples at 7.5-min intervals once the river water level had risen sufficiently to activate a float switch set at a level to respond to all but the smallest run-off events. Automatic rain gauges were established at the Field Centre and in the two catchments. The original paper chart water-level recorders were later replaced by Technolog (Wirksworth, Derbyshire, UK) data-logging equipment, facilitating more accurate calculation of the lag times between rainfall and run-off peaks. At the water-level recorder established by the Sabah Drainage and Irrigation Department suspension bridge close to the Field Centre, water samples are collected from the Sungai Segama (catchment area: 721 km^2) daily during low flows and hourly in daylight in major storm run-off events. Continuous records since early 1988 are available for these three sites. Reference will also be made to the 1.4 km^2 Jauh and 0.8 km^2 Rafflesia catchments (figure 1) on the serpentinites of the ultramafic rocks in the Bukit Rafflesia area, affected by the 1992 coupe, which were studied from 1991 to 1994. The Jauh was logged during the 1992 coupe, with a 20 m wide buffer strip left along the stream for 500 m above the gauging station and water bars being placed across logging tracks to impede run-off and sediment transport. More detailed descriptions of these sites are available in Douglas *et al.* (1992), Suhaimi (1998), Balamurugan (1997) and Chappell *et al.* (this issue).

Erosion and deposition around channel heads and along channels, in both the primary forest close to the W8S5 catchment and in the selectively harvested Baru catchment, have been monitored since 1990 using a variety of

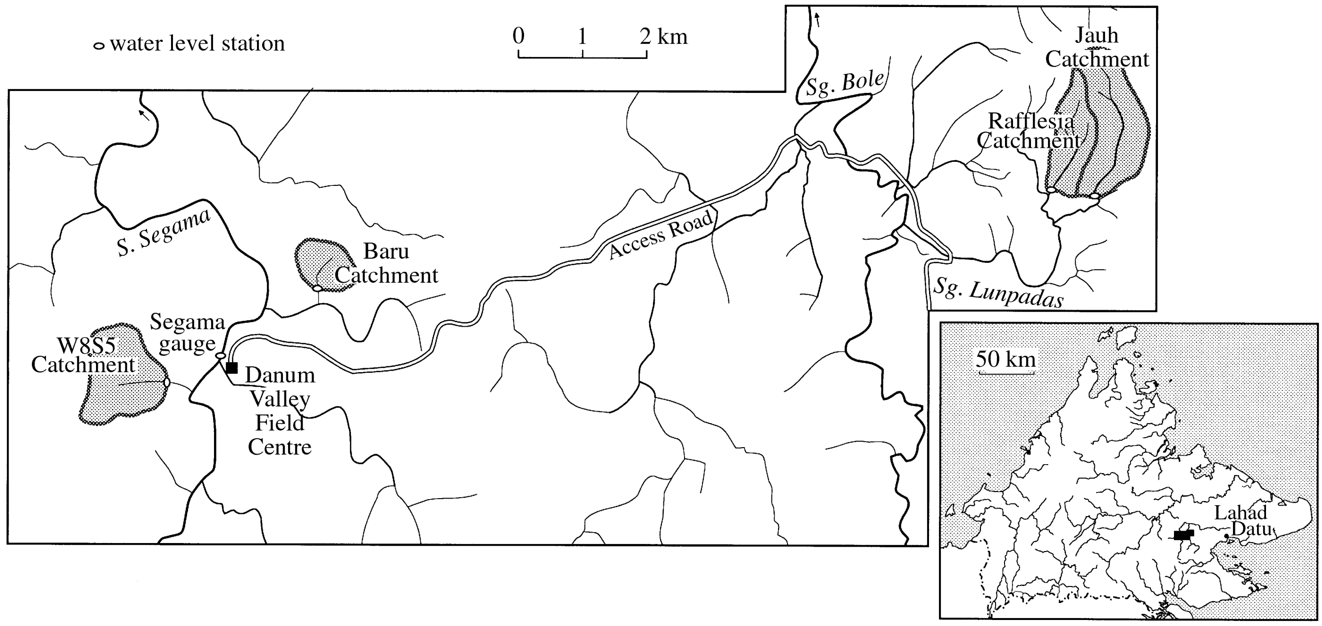

Figure 1. Map of the study area showing locations of the four catchments and the Segama gauging station.

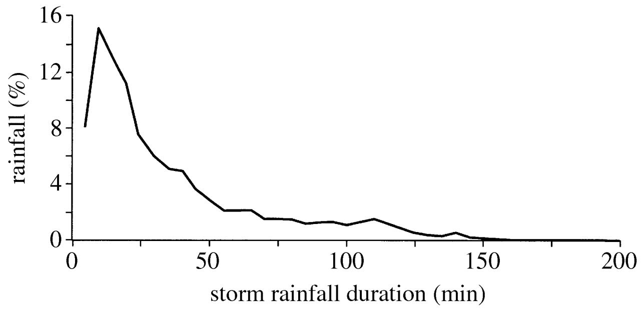

Figure 2. Size of rain events at the km 63 rain gauge near Danum Valley Field Centre.

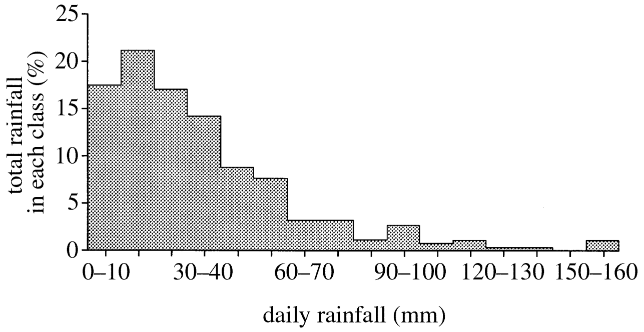

Figure 3. Daily rainfall magnitudes and frequencies at the Danum Valley Field Centre meteorological station rain gauge.

repeat-measurement methods to assess the dynamics of the critical channel head zone and to link the processes at the slope and catchment scales. Erosion has been assessed by periodic remeasurement of slope transects and channel cross-sections using either an erosion bridge (1.1–2.7 m wide, precision 1 mm) (Shakesby *et al.* 1991), an erosion bar (2 m wide, precision 5 mm) or a stretched tape (widths exceeding 2 m, precision 1–2 cm). The choice of method depended on the erosion expected and the width and depth of the transect or section. Each method involved measurements at a series of points between fixed metal or PVC stakes firmly driven into the ground. As the measuring devices were positioned on the stakes only when measurements were being made, the problems of interference with natural soil movement associated with permanent erosion pins (Haigh 1977) were avoided.

Rainfall events at Danum include many short bursts of low-intensity rain, but also ones of high intensity, short-duration storms (which produce rain with large drop sizes and thus high erosivity), and occasional multi-cell, complex, persistent heavy rain over hundreds of square kilometres for many hours. Localized, convective events of 30 min or less duration, usually occurring in the late afternoon, between 16.00 and 18.00, are the most frequent rain events (figure 2) and account for a large percentage of the total annual rainfall. Daily totals exceeding 75 mm occur in most years (table 2, figure 3), but rarely on more than four days in any year. The recurrence intervals for major storms show that a daily

Table 1. *Daily annual maximum series return period (Tp) (years) for the Danum Valley Field Centre Meteorological Station calculated by the Weibull and Gringorten methods*

daily total (mm)	Tp (Weibull)	Tp (Gringorten)
67	1.1	1.0
77	1.2	1.1
80	1.3	1.3
92	1.4	1.4
93	1.6	1.6
99	1.9	1.8
105	2.2	2.2
114	2.6	2.7
123	3.3	3.4
135	4.3	4.7
163	6.5	7.8
177	13.0	21.6

Table 2. *Erosion (mm) at the primary forest sites June 1990–June 1997*

(Negative figures indicate erosion; positive figures indicate deposition. Number of slope sites, 13; six to eight channel head sites depending on year; eight channel cross-sectional sites. Time of remeasurement was in July or August in each year. Figures in brackets are the number of sites recording average erosion and average deposition respectively. Each site represents the average of 37 points for erosion bridge sites and 10–15 points for erosion bar sites.)

	1990–1991 mm	1991–1992 mm	1992–1994 mm	1994–1995 mm	1995–1996 mm	1996–1997 mm	1990–1997 total mm	1990–1997 average mm
slopes	−2.62 (11–2)	−1.46 (10–3)	+3.81 (3–10)	−1.78 (8–5)	−3.84 (12–1)	−0.02 (7–6)	−5.92 (11–2)	−0.85
heads	−2.23 (6–2)	−3.14 (6–1)	+6.78 (0–6)	+1.40 (3–4)	−4.64 (6–1)	−0.61 (5–2)	−3.59 (4–3)	−0.51
channels	−3.49 (5–3)	−0.83 (4–4)	+0.91 (3–5)	−2.55 (5–3)	−6.90 (6–2)	+0.23 (6–2)	−12.59 (7–1)	−1.80
rain (mm)	2158	2525	5616	2658	3751	2265	18 973	2710
days > 50 mm	6	12	14	6	11	4	3	7.6
days > 75 mm	2	4	3	2	5	1	17	2.4
daily max mm	94.9	114.0	122.5	116.0	162.5	93.0	162.5	—

rainfall of 170 mm can be expected once in every 10 to 20 years (table 1).

3. EXTREME EVENT PROCESSES: GEOMORPHOLOGICAL AND HYDROLOGICAL SENSITIVITY UNDER PRIMARY (UNDISTURBED) FOREST

Physical phenomena and the activities of forest organisms lead to two kinds of response to extreme events in the undisturbed forest: (i) much more erosion and larger changes to the land surface than would be expected by the magnitudes of the water flows involved and (ii) the occurrence of changes due to biological and pedogenetic processes not linearly related to the magnitudes of the events concerned.

(a) *Disproportional development of existing landforms*

Hydrometeorological variations and geomorphic processes in the forest are controlled by rainfall and subsurface water, but rare events produce a disproportionately large amount of geomorphic change, erosion and deposition, in relation to the rainfall volumes involved, as erosion bridge measurements illustrate (table 2). Detailed erosion and deposition measurements at six channel head locations in the undisturbed primary forest in the W8S5 catchment from July 1990 to July 1997 show a complex year-to-year pattern, with erosion dominating in 1990–1992, deposition in the relatively drier years 1992–1994 and a combination of the two (erosion on the slopes and in the channel cross-sections, but deposition at the channel heads) in 1994–1995. The year 1995–1996, which included the extreme rainstorm of 19 January 1996, was characterized by the highest erosion in the entire record at all three categories of site. Erosion was recorded at 12 of the 13 slope sites, averaging 3.84 mm; at six of the seven channel head sites, where it averaged 4.64 mm; and at six of the eight cross-sections, where it averaged 6.90 mm. The next year, 1996–1997, saw relatively little change, with cases of both erosion and deposition. The high erosion rates in 1995–1996 clearly reflect the rarity and magnitude of the 19 January 1996 storm event that produced a flushing effect, scouring available sediment from all elements of the channel head area. Erosion rates on undisturbed forest slope sites averaged 0.85 mm yr^{-1} between 1990 and 1997, a rate exceeding the 0.28–0.32 mm yr^{-1} measured in the Rupununi, Guyana, but lower than vales of 1.5–3.5 mm yr^{-1} for the Ivory Coast (Rougerie 1960), 4.0–4.7 mm yr^{-1} for the Bukit Timah Reserve, Singapore (Chatterjea 1989), 2.61 mm yr^{-1} for the Pasoh Reserve, Peninsular Malaysia (Leigh 1978) and 7.6 mm yr^{-1} in the wet interior (annual rainfall: 5432 mm) of Dominica (Walsh 1993).

The critical areas regulating water outflow to streams at Danum are the streamhead hollows, beneath which water tables respond rapidly to rain events. Early work in the undisturbed W8S5 control catchment (Bidin *et al.* 1993) confirmed that the water table was extremely sensitive even to rainfall of only 2–3 mm, in the fashion described in the USA by Hewlett & Nutter (1970). Response to rainfall was almost nine times faster than the hydraulic conductivity values suggested, depending on rainfall intensities and antecedent conditions. The rapid response probably arose from lateral subsurface flow, possibly partially through macropores, converging in the stream head hollow where the observation wells were located. Major rain events cause the water table to rise to the channel floor and create channel flow capable of evacuating accumulated sediment. Eventually large, prolonged storms cause the zone of saturation around the channel heads to extend up all slope hollows. The 19 January 1996 storm produced lines of concentrated flow along every slope convergence line from within a few metres of the catchment divide to the topographically defined stream head hollow. In the W8S5 catchment this drainage network extension produced a total main stream length of 1.9 km above the gauge. In the other weather extreme during the exceptionally dry month of April 1992, the whole length of the stream down to the gauging station dried up completely, illustrating the pulsed nature of sediment outputs and the high variation of water table, soil moisture and streamflow in these forests.

Hydrological variability at Danum Valley is not only confined to extreme events, but also occurs between storms of the same magnitude. Peak discharges, peak suspended sediment concentration and storm suspended sediment loads all vary depending on antecedent hydrological

Table 3. *Contrasts in the W8S5 catchment response to storms of similar magnitude in the Danum Valley Conservation Area*

	storms		
variable	8 June 1993	14 February 1994	22 March 1994
storm rainfall (mm)	27.6	27.0	26.8
storm duration (mins)	40	45	45
average intensity ($\mathrm{mm\,h^{-1}}$)	41.4	36.0	35.7
max 30-min intensity ($\mathrm{mm\,h^{-1}}$)	45.6	51.2	50.4
rain in previous 48 h (mm)	2.6	5.6	8.6
rain in previous ten days (mm)	32	105	168
peak discharge ($\mathrm{m^3\,s^{-1}}$)	0.393	1.273	1.273
peak suspended sediment concentration ($\mathrm{mg\,l^{-1}}$)	285	1130	1675
storm suspended sediment load (tonnes)	0.350	4.440	5.656

conditions and the availability of sediment in the stream channel. Three storms of *ca*. 27 mm rainfall over the W8S5 catchment illustrate this varied response (table 3). The three storms had similar durations, rainfall totals and intensity patterns. However, the peak suspended sediment concentration on 24 March 1994 was over five times that on 8 June 1993 and the total suspended sediment load was 15 times greater. Antecedent conditions may explain the differences between the storms, with over five times more rain falling in the ten days prior to 22 March 1994 than before 8 June 1993. The higher outputs of suspended sediment on 14 February and 22 March may arise from any of three causes: (i) saturation of much of the soil before the day of the storm, thus converting more rainfall to concentrated overland flow which locally eroded more soil and transported it to the stream; (ii) mobilization of sediment already in the stream channel by the higher discharge; and (iii) detachment and displacement of sediment by storms in the days before the storm allowing more available sediment to be entrained by the higher stream discharges (Balamurugan 1997). The storms in wet periods are clearly transporting more sediment than similar magnitude storms in dry periods. This questions whether the 'flushing-out effect' of high sediment yield from the first storm after a dry period (Walling 1974; Bird 1987) applies to these undisturbed tropical rainforest catchments. Perhaps the frequency of rain events is such that the soils in the forest do not dry out sufficiently for the 'preparation' of the erodible material required for the 'flushing-out effect' to occur. In the three undisturbed catchments studied at Danum Valley (W8S5, Rafflesia and Palam Tambun; figure 1) storm suspended sediment yield is positively correlated with antecedent rainfall. More sediment is moved by storms in wet periods than in dry periods (Balamurugan 1997).

This wet period high sediment output reflects the importance of sediment sources within and close to the channels: bank erosion, minor landslips, slumping around stream head hollows and outflows from pipe systems. Bank erosion probably accounts for at least 50% of the sediment supply to these undisturbed forest streams. Tree undercutting by the stream sometimes leads to treefall that releases a pulse of sediment into the channel and causes a lateral shift of the stream. Minor landslips occur along channels in extreme events, for example in March 1988 in Palam Tambun, an undisturbed forest stream south-east of the Field Centre, and in January 1996 in W8S5, causing large inputs of sediment directly into the stream. However, after the initial surge of sediment, the bare surface of the slip continues to be both eroded by raindrop splash and undercut by the stream until the surface is revegetated or the stream channel shifts.

Stream head hollows are not only highly sensitive to the water table fluctuations, but are also a major source of sediment. When the water table rises above the channel bed, initiating flow in the ephemeral hollow, water begins to seep out of the back wall and sides of the hollow, producing small-scale slumping of fragments of rock and clay no more than 3 cm in diameter down the sides of the hollow into the channel. Macropores, the large subsurface voids, which include pipes (or tunnels), provide pathways for rapid subsurface flows, which during major storms are powerful enough to entrain sediment and act as sources of suspended sediment which is delievered to the stream channel system. Thus a combination of mechanisms exists which favour higher sediment supply and transport in wet periods.

(b) *Increased incidence of stochastic, time-discrete processes*

Large localized sediment inputs to these streams are, however, not confined to the major storms. In the natural forest, debris dams commonly act as a regulator in small streams up to 5 m in width, and sometimes in larger channels. Treefalls across streams create blockages behind which organic and mineral debris builds up, but high flows can lift this woody blockage and wash it away. Such irregular debris-dam formation and removal is a major contributor to surges of sediment and to the inconsistent relationship between the highest sediment concentrations and discharge. Repeated surveys on W8S5 (Spencer *et al.* 1990) reveal a much shorter life for debris dams than that described for temperate-zone forests (Robinson & Beschta 1990; Gurnell & Sweet 1998). Dams build up and are removed within months, although the biggest can persist for years. The 19 January 1996 storm event lifted or washed all loose material out of all debris dams in W8S5. Out of the five effective debris dams recorded in a survey on 3 August 1994, all had ceased to be an obstacle on 21 January 1996, two days after the major storm. In most cases, the original log that blocked the stream had been washed aside and all the stored debris had been carried downstream.

Large tree trunks firmly wedged across streams may only be removed, however, when they become sufficiently decayed. The highest peak sediment concentration in W8S5 occurred late in the falling stage of a major storm on 14 November 1991, when a rotted log debris dam finally gave way. Thus the timing of debris-dam removal is regulated by biological decay processes as much as by hydrometeorological events.

Just as biological decay can cause release of sediment (Spencer *et al.* 1990), so subsurface changes in the regolith and colluvial slope mantles can produce mass movements. Slopes do not fail systematically. Change may occur because soil surface and infiltration characteristics have been altered by pig wallows or treefalls. Therefore although there is a tendency for geomorphic work to be concentrated in the large events, recurring less frequently than once a year, failures are not linearly related to rainfall or streamflow volumes, but also result from biotic and pedogenetic processes.

4. HARVESTING IMPACTS AND RECOVERY

Forestry operations, including both access road construction and tree-felling and removal, can be interpreted as disruptions or extreme disturbances which temporarily dramatically alter rainfall–run-off regimes and increase sediment supply. Their effect will be greatest if rare storms occur during or immediately after the forestry operations, when the areas of bare soil are greatest. The immediate effects of logging in increasing storm discharge, reducing the lag time between peak rainfall and peak discharge and in creating sediment loads up to 20 times those in undisturbed areas at Danum have been reported previously (Douglas *et al.* 1992, 1993). The longer records now available enable the changes during the recovery stage and their relationship to extreme rainfalls and drought periods to be examined more closely. As in the undisturbed forest, they can be interpreted in terms of temporal and spatial variability and the impact of irregular stochastic events.

(a) *Changing spatial patterns of sediment sources and rapid development of modified landforms*

Detailed slope studies show how erosion decreased over time after forestry operations ceased, until exceptional events caused major landslides. In the logged Steyshen Baru stream, 19 erosion bridge sites were set up in June 1990 and a further 31 in 1994–1995. The 1990 sites revealed a gradual decrease in post-logging erosion over time (Walsh & Bidin 1995) until disturbances caused by road-related landslides in 1994 and 1996 along the abandoned logging access road through the Baru catchment. The November 1994 landslide in the headwaters of the eastern Baru tributary filled the stream head depression, with only a small degree of reincision evident at site 6.11 by June 1995 (figure 4*a*). The 19 January 1996 storm triggered seven further landslides along the same access road including at site 6.9 (figure 4*b*) and resulted in major erosion of the fill at the 1994 landslide site (figure 4*a*), but with little further erosion occurring subsequently. The January 1996 landslides and the erosion in January 1996 of the 1994 landslide material resulted in downstream aggradation of the eastern tributary (figure 5*a*), with continued siltation between February and August 1996 as material was washed down from above. Since August 1996, erosion has occurred as the stream re-excavated its channel (figure 5*a*). Such changes did not occur along the middle and western tributaries (figure 5*b*,*c*), as their catchment areas were unaffected by landslides; their channels show minor amounts of aggradation and erosion in different parts of the measured sections over the same time-periods.

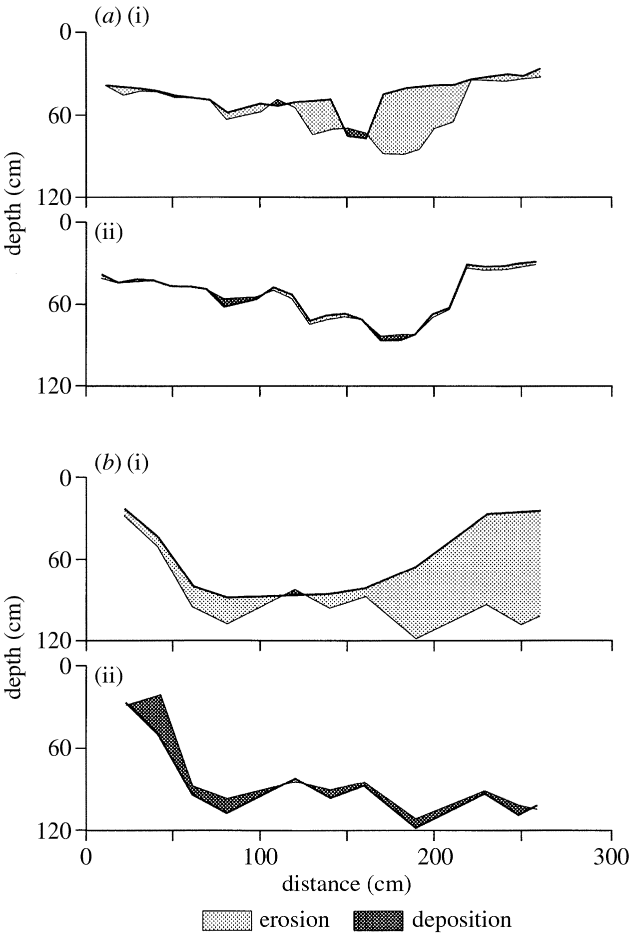

Figure 4. Erosion bridge measurements over the period June 1995 to April 1998 at (*a*) site 6.11 on the scar of a landslide of November 1994 and (*b*) site 6.9, which was eroded by a landslide of 19 January 1996. Periods of measurement are (*a*) (i) June 1995–February 1996, (ii) February 1996–April 1998; (*b*) (i) June 1995–August 1996, (ii) August 1996–April 1998. At site 6.11 the incipient gully that had formed by June 1995 enlarged greatly during the January 1996 storm (i). Both sites stabilized after the January 1996 storm (ii).

The relationships between suspended sediment concentration and storm suspended sediment load and storm variables at the Baru gauge changed greatly from the 1989–1991 (logging and immediately post-logging) period to the 1992–1994 (post-logging recovery) period (figure 6). The regression lines for individual years all differ statistically from each other, save those for 1992 and 1993 (table 4). Sediment supply conditions changed after 1991, but it must be remembered that 1992 was a drought year with long periods of low flows, which influenced the long-term trend.

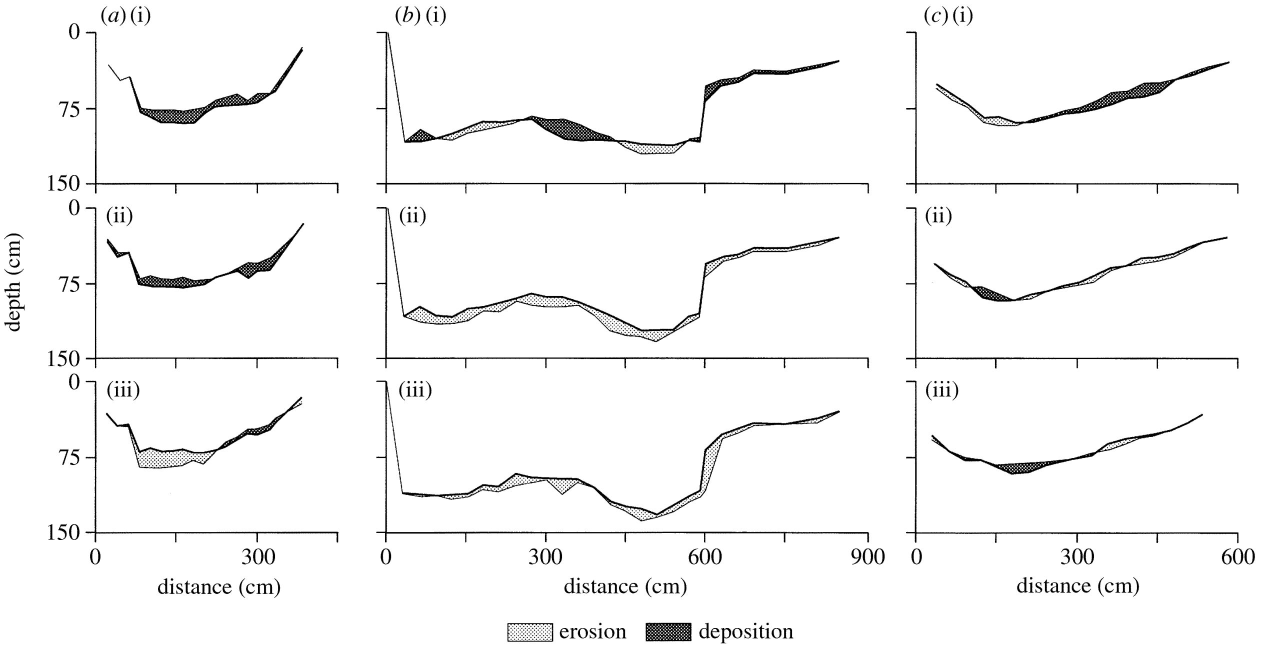

Figure 5. Erosion bridge measurements on the Baru (*a*) eastern, (*b*) middle and (*c*) western tributaries during the periods (i) July 1995–February 1996, (ii) February 1996–August 1996, (iii) August 1996–April 1998. The eastern tributary was affected by the 1994 and 1996 landslides and demonstrates periods of excavation during the following January 1996 storm (i, ii) followed by infill since August 1996, while the other tributaries exhibit less change.

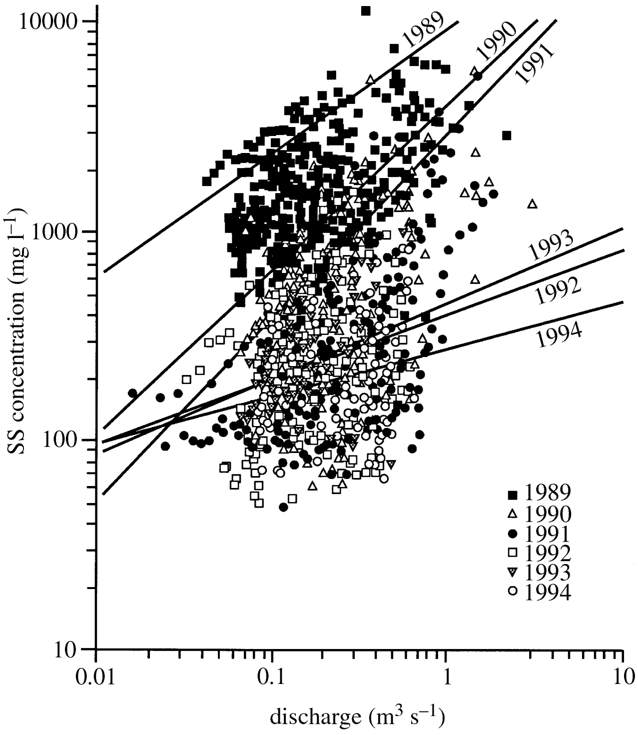

Figure 6. Regressions of sediment concentration against discharge for Baru 1989–1994 (after Balamurugan 1997) showing the decrease in concentrations during the post-logging period.

In the Jauh catchment, similar magnitudes of changes occurred during and after logging. The pre-logging sediment concentrations are similar to those of both control catchments, the immediately adjacent Rafflesia and the distant W8S5 (figure 1) on different, less steep, but more erodible terrain. During logging, the suspended sediment loads per unit area carried by the Jauh were lower than those of the Baru in 1989, because of the climatic differences between 1989 and 1992 and because of the buffer strip and water bars employed to reduce erosional impacts.

Logging creates large gaps in the forest canopy, which allow raindrops to detach particles on the bare areas along roads, tracks and log-landing areas. Surface run-off carries the loosened material along gullies developed down abandoned logging tracks and skid trails, sometimes directly into the streams. Many of these bare areas quickly become covered by some form of vegetation and the sediment supply decreases, but some major gullies remain active, beneath an overarching canopy, extending the storm-period concentrated flow network and continuing to erode their channels (Walsh & Bidin 1995). The re-establishment of the vegetation cover reduces the sediment supply and thus the peak sediment concentrations and loads. Nevertheless, the disturbed areas retain the potential for release of large quantities of sediment.

The concentration:discharge ratios for Jauh and Baru (figure 7) increase during logging and decrease subsequently. The ratios are much lower in the Jauh than the Baru, partly because the harvesting took place in a dry period, and because sediment control measures were implemented when the Jauh was logged. A 20 m wide buffer strip was left along the stream for 800 m upstream of the gauging station and timber extraction was carried out using only D6 skidders. After timber removal, earth barriers to trap sediment and run-off were pushed up across all the abandoned log haulage tracks. This prevented gully formation along tracks and speeded the revegetation of bare areas. However, before the lower

Table 4. *Regression equations for suspended sediment concentration* (C) *against discharge* (Q) *for four gauging stations at Danum Valley sediment*

(Compiled from data in Balamurugan 1997 (n.s., not significant).)

catchment	years	n	regression equation	r	significance level	F-value for difference from previous year	significance level
W8S5 (control)	1987–1994	983	$C=268Q^{0.63}$	0.51	0.01	—	—
Rafflesia (control)	1991–1994	713	$C=303Q^{0.87}$	0.41	0.01	—	—
Baru (logged 1989)	1989–1994	1589	$C=763Q^{0.32}$	0.21	0.01	—	—
	1989	488	$C=2022Q^{0.27}$	0.27	0.01	—	—
	1990	295	$C=863Q^{0.46}$	0.35	0.01	250.25	0.01
	1991	368	$C=674Q^{0.56}$	0.26	0.01	26.6	0.01
	1992	231	$C=398Q^{0.31}$	0.27	0.01	4.41	0.01
	1993	118	$C=461Q^{0.36}$	0.38	0.01	0.40	n.s.
	1994	89	$C=257Q^{0.22}$	0.22	0.01	9.90	0.01
Jauh (logged 1992)	1991–1994	482	$C=350Q^{0.25}$	0.09	n.s.	—	—
	before logging	139	$C=238Q^{1.05}$	0.50	0.01	—	—
	during logging	110	$C=1655Q^{0.70}$	0.29	0.01	154.9	0.01
	after logging	233	$C=425Q^{0.51}$	0.158	0.05	52.6	0.01

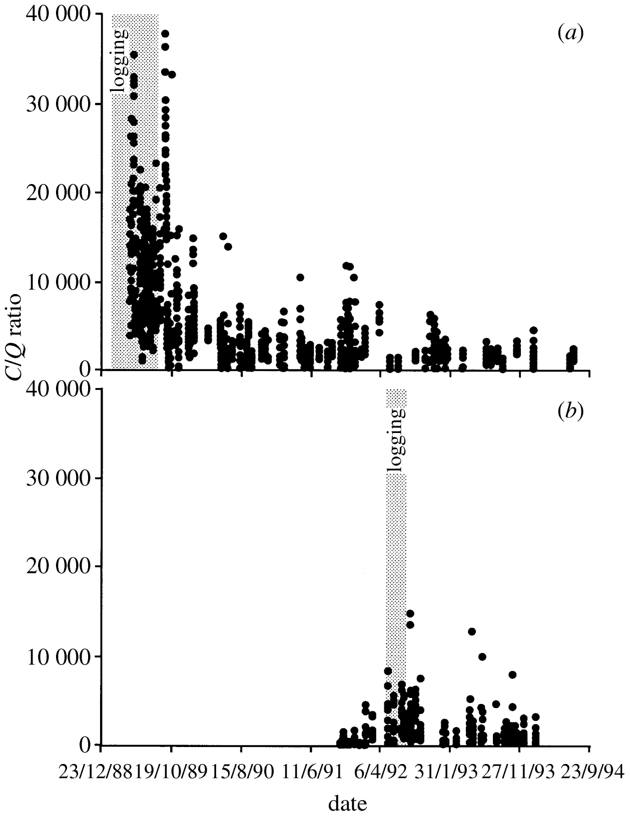

Figure 7. Ratios of suspended sediment concentration in mg l^{-1} to discharge in $\mathrm{m}^3\,\mathrm{s}^{-1}$ for the Baru and Jauh catchments (after Balamurugan 1997), showing the marked decrease in the ratio as sediment supply to the stream decreases during the recovery period in the Baru, but lower ratios during logging on the Jauh due to buffer strips and water bars, which reduced sediment supply, and the generally dry weather during logging in 1992.

sediment yields of the Jauh are credited entirely to the management practices adopted during harvesting, the influence of both lithological characteristics and the dry weather of April–May 1992 logging period must be taken into account. As the pre-logging sediment concentrations were similar to those of W8S5, which has similar lithology to the Baru, the bulk of the natural influence is probably climatic. Several natural high-energy events occurred on the Baru during or immediately after harvesting, up to the major event of 31 May 1990 when 91 mm fell on a catchment already wetted by a total of 104 mm over the previous two days. However, the Jauh experienced few such major storms in the whole of 1992, just one significant wet period with 180 mm in three days occurring in mid-June.

(b) *Increased incidence of stochastic, time-discrete processes*

The 0.2 ha landslip below the access road in the Baru catchment occurred on 14 November 1994, after a rainfall of only 14 mm in a period of relatively low catchment wetness and river flow, and illustrates the preparatory role of pedogenetic processes. The cut-and-fill construction of the road along the contour had impeded subsurface water movement from upslope and a series of large puddles were usually present on the upslope side of the road at the foot of the cut slope. The substrate of the road had become gleyed and potentially unstable over six years since the slope was disturbed. The small rainfall produced the final trigger to set off the movement.

However, in disturbed areas, major storms will create high soil water pressures, exert stresses on naturally accumulated debris jams and any artificial structures in channels, and thus lead to many failures. The 1996 landslides in the Baru catchment occurred because of failures associated with roads triggered by the 164 mm rainfall of 19 January 1996. Hollow log culverts finally gave way to water pressure on decayed wood. In the cut and fill of the road along the contour, excess pore water pressures caused by water from upslope being retarded in its movement by compacted road material caused failures between different substrate materials on the road. The net result of all these slips was a major new supply of sediment to stream channels. The January 1996 event triggered a series of high sediment concentrations in subsequent

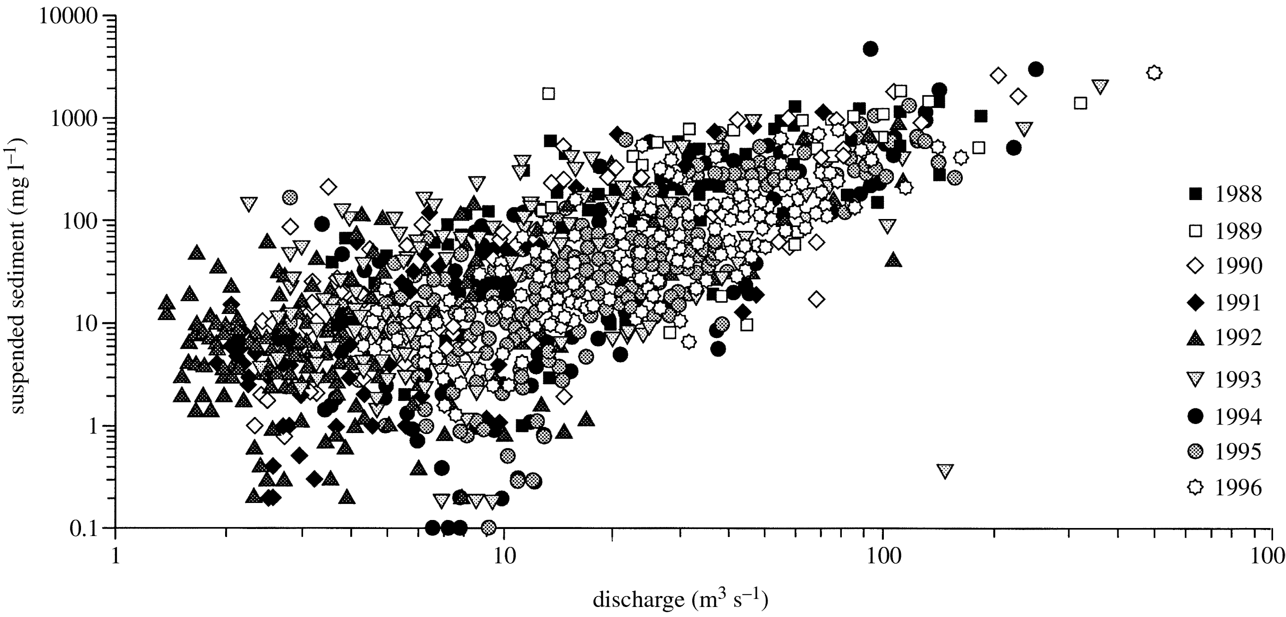

Figure 8. Combined plot of sediment concentration against discharge for all daily and storm period samples collected at the Segama Gauging Station at Danum Valley Field Centre, February 1988 to June 1996.

storms, to some extent reproducing the pattern of events that followed the logging of the Baru in 1989.

5. SPATIALLY INTEGRATED EFFECTS IN LONG TIME-SERIES

With all the harvesting operations between 1988 and 1996 affecting discrete coupes within the Segama catchment upstream of Danum, some changes in the suspended sediment concentration discharge relationship for the Segama analogous to those observed on the Baru and Jauh might be expected. However, the annual plots of sediment concentration against discharge for the Segama are remarkably similar. More low suspended sediment concentrations occur in the dry period of 1992, and in relatively dry periods in 1993 and 1994, but the highest concentrations and discharges remain remarkably similar throughout the period. No clear differences emerge, apart from the low discharges of 1992 (figure 8).

The discharge and suspended sediment yield pattern of the Segama reflects how in extreme events, such as the 19 January 1996 storm, much of the forest becomes saturated. The foliage and much of the soil become so wet than any extra rain runs off as if it were running off a tiled roof or concrete runway. Thus, almost regardless of land cover, the biggest tropical rainfalls will always produce the biggest floods.

The influence on downstream sedimentation in the Segama system will, however, be different, for many of the disturbed tributaries affected by the storm will have had similar landslips and pulses of sediment into the channels. Instead of just having high sediment yields from the coupe being operated at the time of a major storm, every disturbed tributary catchment with unstable structures will be affected. Thus channel sedimentation in the larger rivers may be a lot worse and any impoundments or riparian structures could be seriously affected.

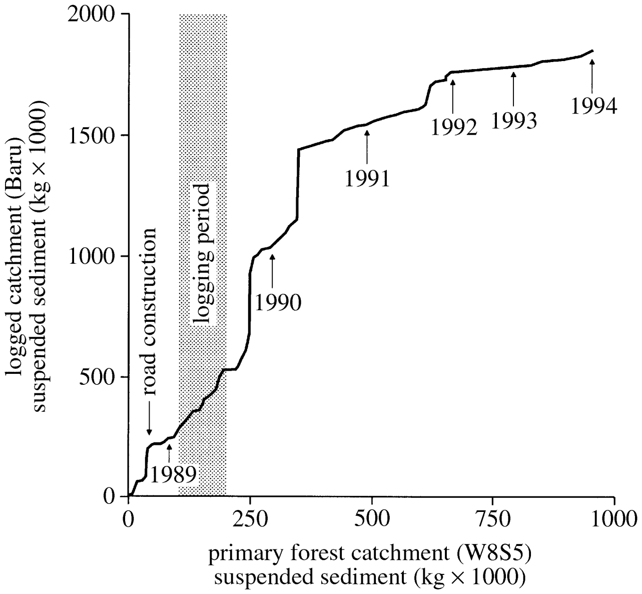

Figure 9. Double mass plot of sediment yields from Baru and W8S5 1998–1994 showing the large increments in sediment yield due to individual storm events, particularly soon after disturbance by road building and logging (after Greer *et al.* 1995).

When daily sediment load is plotted as a double-mass curve for W8S5 and Baru (figure 9), clear steps in the relationships show the importance of individual storm events. Both curves show the effect of a major storm at the end of May 1990 which accounted for the bulk of the sediment load discharged from those two catchments in that year. In 1989, individual storms played a much bigger role in the Baru, which was then undergoing logging and had large bare areas readily yielding sediment. However, whatever the state of the catchment

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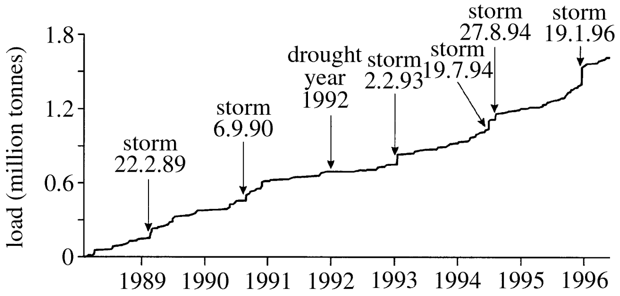

Figure 10. Cumulative plot of daily sediment loads on the Sungai Segama at the Segama Gauging Station at Danum Valley Field Centre, February 1988 to June 1996 showing the large increments due to rare storm events and the small total annual load in the 1992 drought year.

Table 5. *Largest daily suspended sediment loads carried by the Sungai Segama at the Danum Valley Field Centre gauging station between 1 February 1988 and 30 June 1996*

date of storm	load (tonnes)	% of total suspended sediment transported in the study period
19 January 1996	136 004	8.3
2 February 1993	74 575	4.6
19 July 1994	69 738	4.3
6 September 1990	48 338	3.0
27 August 1994	40 773	2.5
2 February 1989	40 701	2.9
proportion of load carried in eight years and five months removed by above six days		25.6%

surface, the large rain events are the key to sediment removal by the streams. The long-term monitoring, using automatic samplers triggered by rises in stream water level, provides the information on the role of the few major storms that account for a large part of the total sediment removal.

While the impact of individual storms on small catchments is readily apparent on the Baru and W8S5, these individual storms may not be significant in the sediment transport pattern on the major Segama River, as measured at the gauging station at the Danum Valley Field Centre where a US DH 48 sampler (Water Resources Division, US Geological Survey, Reston, VA, USA) is used daily to take a water sample for suspended sediment concentration determination, with hourly samples being taken during daylight in major storms. Daily data show that the Segama responds at a different rate to its small tributaries, depending on the depth–area–duration characteristics of individual major rain events. While high-intensity localized convectional storms lasting 1 or 2 h produce extremely rapid rises and high sediment loads in the small tributaries, more prolonged rains from complex, compound low-pressure cell systems lasting 6 h or more and extending over hundreds of square kilometres, produce the major flood flows and high sediment loads on individual days in the Sungai Segama.

The cumulative plot of daily suspended sediment load against discharge for the Segama from February 1988 to June 1996 (figure 10) shows the key role of six storms (table 5) which in six days carried more than a quarter of all the sediment carried in eight years and five months. These storms are not necessarily those that accounted for the bulk of sediment transport in the W8S5 and Baru catchments. Thus the May 1990 storm, so important in the two tributaries, was not a major event on the Segama. The record does demonstrate, however, that key storms will carry much more sediment than is moved in the whole of a dry year like 1992. On the Baru, the 19 January 1996 storm carried 261 tonnes (43% of all the sediment mass evacuated in the year 1 July 1995 to 20 June 1996) in a single day. Only long-term monitoring can give this perspective on rare, yet powerful events in humid tropical forest fluvial systems.

This event-based sediment production is similar to the behaviour of a system in 'punctuated equilibrium' found in other environmental situations (e.g. Boettcher & Paczuski 1996; Ito 1995) but also relates to event-based sedimentation concepts (Einseile 1982; Douglas & Spencer 1985) and to the ideas that landscapes have long periods of quasi-stability and short periods of rapid change (the biostasy–rhexistasy concept of Erhart 1956). These ideas of interruptions to stability may have been conceived for different time-scales, but their basic notion is the same. Natural environmental systems are disrupted at varying space and time-scales.

6. HYDROLOGICAL AND EROSIONAL RECOVERY OF SELECTIVELY HARVESTED TROPICAL RAINFORESTS

The preceding comments on punctuated equilibrium raise questions about the time-scale of forest recovery in terms of erosion and hydrology. Selective logging, as with any other in land cover, fundamentally alters the detail of forest geomorphology. Despite the declines in sediment yields revealed by the detailed study of the Baru and Jauh up to 1994, the storm of 19 January 1996, and an earlier, smaller one in late 1994 in the Baru, have set off a new phase of high sediment loads. The time-scale of impact and recovery is thus much longer than previous work has suggested.

Using space–time substitution by studying four catchments logged at different times, Lai (1992, 1993) has suggested that in the steeplands of the Main Range south-east of Kuala Lumpur, recovery of erosion conditions from logging may take eight to 20 years. He found rapid recovery in the first two years after logging followed by a more gradual recovery thereafter. This pattern has not emerged at Danum Valley. Timber harvesting leaves a legacy of disturbance that may be reactivated by rare large storms at any time. The landslide events of late 1994 and particularly January 1996 disrupted the progressive recovery of the Baru catchment by activating new sediment sources and setting off a renewed phase of debris dams, channel storage and sediment movement downstream in the catchment. Of course, the landsliding could have occurred earlier, with recovery being disrupted sooner. However, as the severity of the landsliding was influenced by changes in soil conditions, due to the ponding of water on the upslope side of the road, and by the advanced decay of hollow log culverts, any mass movements from events of similar magnitude earlier in the recovery stage may not have been so severe. Time of preparation during recovery is necessary for major disruptive events to produce sediment volumes of the magnitude recorded in the 19 January 1998 storm event. Thus it is possible to envisage, perhaps, a three-phase logging disturbance regime, in which an initial disturbance (rhexistasy) stage is succeeded by a punctuated recovery (biostasy) stage, leading ultimately to a third phase where the impacts of natural disruptions are no greater than in the natural forest.

(a) *Phase 1: forestry-activated increase in sediment supply*

In phase 1, greatly enhanced slopewash occurs with some gullying of areas severely affected by logging operations, especially logged slope areas, skid and tractor trails, log landing and loading areas. Sediment yields rise to at least 18 times those of undisturbed areas with periods of sediment supply exceeding the transporting capacity of the streams, in contrast to the shortage of sediment available for transport in undisturbed areas. Excess sediment is stored in stream channels, on gravel bars, behind debris dams and as deposits on and at the base of slopes and in channel heads. Later storms gradually evacuate this stored material.

(b) *Phase 2: trend towards equilibrium, punctuated by further releases of sediment during rare, large storms*

In this phase, rapid vegetation regrowth stabilizes many disturbed areas. Incipient gullies on slopes and the rutted heads of log haulage tracks are infilled. However, large storms still cause headward erosion and incision of gullies that are connected to the natural stream network (Walsh & Bidin 1995); streams continue to evacuate accumulated sediment; and pulses of sediment are released as debris dams decay or are washed out by high flows. The net pattern, however, is a reduction in the rate of sediment supply from both the Baru and Jauh, as the sediment supply becomes restricted, as opposed to a transport-limited sediment removal in the first months after road construction and harvesting fed huge volumes of material into channel heads.

In time, especially as pedogenetic and biological decomposition processes take effect, road failure-related landslides occur in major storms, with gullying and slopewash on the exposed landslide scars. The spatial location of the key sediment sources thus shifts towards the lower slopes and the tributary channels. A few well-incised gullies on steep log haulage tracks close to streams remain active. New landslips below roads continue to supply sediment in every storm until they too become revegetated. New pulses of sediment aggrade stream channels, with disturbed trees forming new debris dams. High sediment yields recur with additional scour of channel sediment in every major storm flow.

Phase 2 is thus built of two opposing trends: the biostasy conditions of revegetation, gully infilling and sediment supply reduction; and the rhexistasy condition of punctuating events creating new sediment sources and renewed high sediment loads. The punctuation may occur at any time, but its effects will differ according to when it occurs in relation to time since harvesting and time since the last similar major erosional event.

(c) *Phase 3: an unknown number of years after logging*

In the final phase, the area reverts to conditions that produce sediment yields and slope erosion rates at the level under natural conditions before disturbance and logging commenced. A major management consideration is the likelihood of the one in ten-year frequency storms continuing to disrupt the trend towards equilibrium right up to the time when a second phase of harvesting, involving new road works and ground disturbance, recreates the conditions of phase 1.

The spatial context of recovery must be emphasized. The spatial distribution of sediment sources both changes during recovery and can be influenced (and therefore be beneficially manipulated) by logging management practices and policy. During the early stages of recovery, erosion of the bare areas on slopes and log haulage tracks supplied most of the sediment. Later, a few gullies on log haulage tracks, the abandoned access roads and road-related landslides become the key sources of sediment. The landslides activated in January 1996 represent a small fraction of the total catchment area, quite unlike the widespread landsliding affecting steepland areas such as parts of Puerto Rico (Larsen & Torres-Sánchez 1998) or the North Island of New Zealand. Management should concentrate on those vulnerable areas, essentially the road and track network and the stream head hollows. The Jauh study, brief as it was, indicated the benefits to be gained from measures such as buffer strips and water bars. Now stream crossings and drainage of cut-and-fill areas of main access roads have emerged as key issues. Such matters are mentioned in guidelines on good practice, but perhaps they deserve more practical attention than they have had.

For the sciences of geomorphology and hydrology, both the magnitude and frequency and the biostasy: rhexistasy concepts of earth surface change have emerged as through these long-term studies at Danum Valley. Fluvial processes here are as event-driven as elsewhere. Sediment removal, and consequently downstream and, eventually offshore sedimentation, occur in pulses of varying magnitude and irregular frequency. Event-based geomorphic change thus links to event-based sedimentation.

7. CONCLUSIONS: THE LESSONS FROM LONG-TERM HYDROLOGICAL MONITORING AT DANUM VALLEY

The theme of punctuated equilibrium provides a new way of interpreting the geomorphological concepts of disturbance and recovery, and of evaluating relaxation times. Biological, biogeochemical and pedogenetic processes regulate lags between disturbance and system response (Brunsden & Thornes 1979) in this tropical rainforest environment. Far from being a steady, regulated, water-conserving environment, the tropical forest is an event-driven hydrological system, subject to long periods of relative inactivity and sudden dramatic changes during rare large storms. The bulk of the sediment transport by major rivers occurs in less than five days in any year. A one in ten-year storm event may remove more sediment in 24 hours than the river carries in a dry year.

The geomorphological and hydrological impacts of forestry operations, particularly in terms of the influence of roads and tracks on erosion and sediment yield, are similar in character to those observed elsewhere (Megahan 1972; Megahan & Kidd 1972) and not unlike the impact of drainage operations before afforestation in the UK (Robinson & Blyth 1982; Burt *et al.* 1983). However, they differ in magnitude, scale and frequency, because of the frequency of high intensity rain events and the year round, continuous biotic and biogeochemical activity. Debris dams develop and are removed rapidly. Landslide scars and disturbed, bare areas are usually revegetated quickly, unless subject to rill or gully erosion. The rapid appearance of a pioneer vegetation cover is an asset for erosion reduction. However, even that cannot regulate the deep-seated decay and pedological changes that give rise to the delayed road failures and culvert collapses.

The scientific implications of these findings are that we need long-term monitoring to obtain a data set which adequately reflects the distribution of extreme events from drought to extreme rainstorms if the natural rates of erosion from tropical basins are to be understood and compared with rates of sedimentation reconstructed from offshore sediment cores (Douglas 1967; Curtis & Douglas 1993). A more realistic view of the geomorphic process regimes in tropical forests would be obtained if models of the punctuated equilibrium type situations (e.g. Boettcher & Paczuski 1996; Ito 1995) were applied to the rainfall–sediment system to estimate long-term sediment yields from tropical forest basins of different size. Any estimates of the impacts of forestry operations on sediment yield that ignore the lagged, storm event-triggered impacts on sediment availability are likely to underestimate the true long-term consequences.

For forest management, major storms during or soon after the harvesting are a threat to the stability of key access roads and tracks as road cuts and embankments may fail. Large mass movements and severe erosion of bare ground and disturbed areas may lead to the severe siltation of rivers, affecting people downstream. However, the reliance on systems subject to decay, such as hollow log culverts, also leads to delayed risks when those structures have become so weak that they fail under the stress of exceptional storm run-off. Attention to adequate drainage of roads, and minimization of the area and length of time of exposure of bare ground are important, but above all road and log haulage track design, drainage, maintenance and treatment on cessation of harvesting warrant extreme care and further research.

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