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Throughfall, stemflow, overland flow and throughflow in the Ulu Segama rain forest, Sabah, Malaysia

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SUMMARY

On an annual basis 80.7% of the 3627 mm precipitation at a site of the East Ridge at Danum Valley, September 1989 to September 1990, reached the forest floor as throughfall and 1.9% as stemflow, giving an interception loss of 17.4%. The proportion of total rainfall intercepted decreases with storm magnitude. Stemflow amounts vary greatly from tree to tree.

Under forest, removal of the ground cover and understorey vegetation led to changes in runoff and soil loss; soil faunal activity under natural forest produced higher soil loss from undisturbed natural plots, than from adjacent, partly cleared plots. Between 2.0 and 2.5% of the rain reaching the ground forms overland flow, the remainder infiltrates and much may be evacuated by pipeflow. Storms of 35 mm or more, which accounted for less than 35% of all rain events, produced 70% of the runoff and soil loss.

1. INTRODUCTION

One of the most important hydrological processes to identify and quantify in analysing the effects of disturbance on tropical rain forests is the flow of water and the materials it carries through the forest vegetation and soils downslope towards the streams (Bruijnzeel 1990). The variability of the forest structure, its pattern of gap formation and regrowth, the diversity of tree species, the varied locations and activity intensities of animals produce wide local variation in patterns of water flows. These variations in turn lead to local differences in the concentrations, pools and fluxes of nutrients in the forest ecosystem (see, for example, Tanner (1985); Vitousek & Denslow (1986)). In the Danum Valley area in Sabah, Malaysian Borneo, an experiment was established with the goal of analysing the natural processes in forest unaffected by human activity. Water and material pathways are partitioned at three levels in lowland tropical rain forest: (i) the canopy; (ii) the soil surface; and (iii) within the soil rooting zone (Veen & Dolman 1989). To quantify what might be altered under disturbance this experiment had a threefold approach: (i) to quantify interception loss, throughfall and stemflow; (ii) to quantify overland flow and the material transfer on hillslopes of differing angle; and (iii) to establish the transfer of water laterally in the upper 2 m of the weathering profile.

The experiment involved work at Danum both in the Conservation Area of undisturbed forest and in areas which have been logged. In this paper, particular attention is paid to an experimental area on the east ridge in the Palum Tambun catchment area.

The terrain of the east ridge is rugged with short, steep slopes of up to 25° and varying depths of weathering profiles, supporting oxisols, on the siliceous members of the Kuamut formation (Leong 1974). The transects running used to study interception, and the runoff plots on slopes of angles of 20°, 14° and 7°, reflect the diversity of this terrain.

2. EXPERIMENTAL DESIGN

The interception study involved four transects each with 101 sample points, 1 m apart running across the main ridge, thus giving a primary division between northeast and southwest facing slopes, set 50 m from each other, providing a total of 404 possible interception collector location points (figure 1). Within this grid, 40 collectors were re-located randomly each week following the same procedure as that shown by Lloyd & Marques (1988) in the Amazon rain forest to be effective in minimizing the standard error of the mean of measured throughfall. The collectors consisted of a plastic jerry can surmounted by an inverted round plastic container whose base had been removed (figure 1). This provided high vertical sides for the collector funnel, thereby minimizing the effects of splash out of the funnel during times of high rainfall. A filter was placed in each collector funnel to prevent plant debris and insect frass remaining in the water container. The value of throughfall collected at the different points along the four transect lines varied considerably. The frequency at which a collector was located at any one point averaged 6.5 with a maximum of 15 and a minimum of zero.

For the collection of stemflow, 20 random locations

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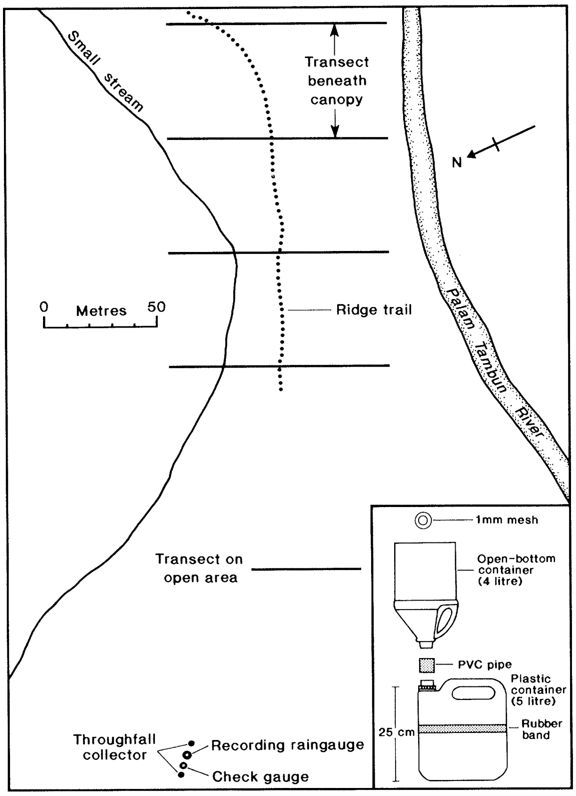

Figure 1. Location of interception transects on the East Ridge at Danum Valley and details of the throughfall samplers.

on the grid were selected and the tree nearest the chosen location was fitted with a collar to trap water flowing down the trunk. These collars were made of epoxy resin and usually fitted tightly round the tree. In some instances, ants tunnelled through the epoxy resin and caused some leakage. The water from the stemflow was taken by a pipe into a plastic jerry can collector. Because in certain trees the quantities of stemflow collected were very high it was soon found that large 4 l containers were necessary instead of the 1 l vessels originally used in the pilot study. Care was taken in all collectors to minimize water loss by evaporation between the end of storms and collection times.

On two slopes, one of 7° and one of 20° overlooking the Palum Tambun River, two pairs of plots measuring 2 m × 10 m were established to measure overland flow. One plot in each pair had the understorey vegetation removed up to a height of 5 m in order that the rain falling on the plot had approximately reached its terminal velocity. This would simulate some of the effects of canopy loss or removal during forest disturbance, although it was recognized that, as in a similar experiment at Maraca Island, Amazonia (Ross *et al.* 1990), the small size of these plots did lead to strong edge effects from uncleared vegetation. The plots were bounded by walls made of waterproof canvas and had wide plastic collecting troughs at their lower ends, from which runoff was fed by plastic hoses into plastic dustbin containers. The flow of water in the weathering profile was sampled by a throughflow pit in a gully head draining into the Segama River. This pit had a surface trough identical to the overland flow plot and troughs inserted at 50, 100 and 160 cm depth below the surface. Great care was taken to insert the upslope edges of the trough in a way that minimized disturbance of the soil, however it was felt necessary to replace some clay to have a good seal between the trough and the soil. A period was therefore allowed after the installation of the troughs before observations were recorded, such that the soil profile should recover from this disturbance. Although the runoff and throughflow from most storms could be trapped and held in the series of containers that overflowed one into the other, some runoff from the largest storms exceeded the storage capacity of the containers and was thus unmeasured. Therefore, the total quantity of overland flow may be under-recorded. Around each plot nine throughfall collectors at fixed locations similar to those used in the throughfall transect study provided an accurate measurement of the water falling on the plot surface. Rainfall in the open was measured 500 m from the field site at the Danum Valley Field Centre meteorological station.

3. HYDROLOGICAL RESULTS

Together, throughfall and stemflow account for an interception loss of 568.66 mm or 17.4% of annual incident rainfall, a quantity comparable to a 16% interception loss measured at Riam Tanan in Borneo (Bruijnzeel 1988).

(*a*) *Throughfall*

In the year September 1989 to September 1990 used for the interception study a rainfall total of 3103.25 mm was recorded in the standard raingauge at the Danum Valley Field Centre. This is slightly more than the long-term average (22 September 1985–21 September 1990) of 2824 mm. The research period had a higher number of rain days (241) than the annual average of 216. In comparison with the previous four years, the study year had the highest number of rain events exceeding 50 mm and the highest rainfall in any one month, in May 1990. Otherwise the storm pattern differed little from that of other years. Logistic problems meant that the surface runoff and throughflow investigations both started and ended slightly earlier than the interception studies but the eleven months – September 1989 – August 1990 – were covered by both studies.

During the study period throughfall amounted to 2638.6 mm which is 80.7% of the incident rainfall. This is comparable to results obtained elsewhere in the tropics (Bruijnzeel 1989). Forty-four single rain events were sampled and for these the regression equation $T = 0.84P - 0.51$ ($r^2 = 0.97$, $P < 0.001$), where P = rainfall (mm) and T = throughfall (mm), was obtained.

At 25 throughfall location points 110% of the rainfall in the open was recorded while at 22 others less than 40% of the open total was collected. Generally there were no distinctive variations in canopy density or tree species that might account for funnelling or concentration of throughfall in large volumes at certain collection points. The collector that recorded the highest throughfall percentage was under the edge of a 7 m tree inclined towards the collector site, where rain might be routed from leaves to leaf tips and accumulate as water dripping down the outermost leaves of the tree.

Quite often, locations that caught a high amount of rainfall were by saplings with large leaves, often within 1 m of the ground surface. Again, leaf tip drips may be a contributing factor to high rates of collection in these instances. Some locations under trees with vines and creepers had high rates of collection. Interestingly, even in forest gaps, the amount of rain caught in a single storm varied from 88% to 102% of that collected in the open.

Some time elapsed between the start of rain in the open and the passage of throughfall at what appeared to be approximately the same intensity as the rainfall in the open. This time-lag was a function of rainfall intensity, being as much as 5 min for rain with a 15 min intensity of 4 mm h^{-1} but only 1.8 min with rain with an intensity of 32 mm h^{-1}.

The pattern of variation in throughfall beneath the canopy is not clear. No direct relation exists between measured throughfall and gaps in the canopy, as indicated by the amount of light reaching the forest floor, and none to particular types of tree, although those situations which allow water to be funnelled down leaves do seem to give high rates of collection. This all suggests that the random relocation of raingauges under the trees, on a weekly basis, is an important process to be undertaken if an accurate assessment of throughfall is to be made in the tropical rainforest environment. If ten collectors out of the 40 used in the experiment are selected at random, their measures would predict the annual throughfall within 4% of the total determined by using 40. Random relocation of gauges is more important than having over 20.

(*b*) *Stemflow*

Stemflow was calculated to amount to 60.5 mm or 1.85% of the incident rainfall, comparable to findings from other tropical moist forests (Bruijnzeel 1989). The production of stemflow requires a certain measure of antecedent rainfall which here was calculated as averaging 4.24 mm. However, small amounts of stemflow were produced from some small trees after as little as 0.9 mm of rain. All the 20 trees sampled produced stemflow after a 1.8 mm shower. The amount of stemflow varies in an irregular manner between trees. When one tree lost its leaves, it tended to produce more stemflow than when its foliage was complete. Another tree was surrounded by taller trees from whose leaves water may have dripped and added to the stemflow of the sample tree. After the collapse of these larger trees the sample tree tended to yield less stemflow than usual.

Although stemflow elsewhere has been shown to favour smaller tree trunks (Bruijnzeel 1989; Manokaran 1980), at Danum the amount of stemflow collected was not related to tree size. Only after large events such as a 32 mm rainfall did the large trees systematically produce more stemflow than smaller trees; in other rain events stemflow was not related to size. Two of the trees with the highest stemflow collection rates were of the same Euphorbiacae species *Mallotus wrayi* King ex Hook. f.; together they collected 29.9% of all the stemflow recorded.

(*c*) *Overland flow*

Having determined the rate of arrival of rainfall at the forest floor the next step was to establish the infiltration excess overland flow, the amount of water that reached the forest floor but did not enter the soil. The two overland flow plots under natural undisturbed forest conditions experienced runoff of 102.0 mm on the 7° slope (plot 4b) and 80.9 mm on the 20° slope (plot 3b), whereas the surface runoff on the nearby throughflow pit (plot 2) on a 14° slope was 75.2 mm. The plots which had had the surface vegetation removed had a higher runoff rate, 137.8 mm and 86.4 mm on the 7° and 20° slopes respectively. These surface runoff volumes account for only 2.0–3.5% of annual throughfall reaching the ground, a proportion similar to that noted in Sarawak (Hatch 1983) and South America (Cales 1982; Nortcliff *et al.* 1979). In contrast it is interesting to note that a smaller plot on an abandoned forest track studied for the same period had a runoff of 1594.5 mm, or 52.51% of the annual rainfall. Here is a good illustration of the role of the forest vegetation and organic matter in protecting the soil and facilitating infiltration.

The lower overland flow on the steeper slope deserves some comment. Except for June 1990, in every month plot 4, with 7° slope, recorded more throughfall than plot 3, with 20° slope, the respective annual totals being 3078.0 and 2835.4 mm. Plot 2, the site of the throughflow pit, recorded even less, with a total of 2409.3 mm. The annual runoff:rainfall ratios were 2.2, 2.3 and 2.0 respectively, strongly suggesting that local variation in the amount of rain reaching the ground is the prime cause of these differences between plots. The slope control would explain why plot 3b has a slightly higher percentage of surface runoff than plot 4b.

Particular attention should be paid to large rain events in terms of runoff generation. In the period from 9 August 1989 to 25 July 1990, 25 rain events totalling 1539 mm at plot 2 accounted for 75.8% of the total runoff. At plot 3 from 30 April 1989 to 13 August 1990, 49 events totalling 2079 mm accounted for 74.7% of the total runoff, whereas at plot 4, from 18 June 1989 to 13 August 1990, 45 events totalling 1879 mm accounted for 86.9% of the total runoff. The higher percentage of runoff accounted for by large storms in plot 4 is probably related to the shallower weathering profile at this location. During wet periods, the rotted rock and soil profile becomes saturated and soil moisture storage capacity is reduced more quickly than in plot 3.

(*d*) *Throughflow*

The throughflow pit, plot 2, was located in a stream head hollow in order to evaluate surface and subsurface flows as controls of stormwater discharge. Elsewhere in the Ulu Segama area, piping, the creation of subsurface channel by washing out of clay particles in the soil and weathering profile, had been observed above the permanent heads of perennial streams and it was realized that such phenomena could exert a strong influence on subsurface runoff. Plot 2 yielded a total of 3644.2 l of runoff in the study year, with 41.2% as overland flow, 33.3% at the 50 cm trough, 17.1% at the 100 mm trough and 8.4% at the 160 mm trough (figure 2). The total water yield was only 48% of that in another throughflow pit in a different site to the west of the Segama River. The low volume of surface flow and throughflow raised the possibility that pipeflow occurs beneath this plot.

The monthly pattern of surface flow and throughflow at plot 2 showed a marked change after March 1990. Before that period, overland flow had always exceeded discharge into any of the subsurface troughs, but in the dry month of April 1990, when only 38 mm of rain fell in the entire month, no runoff at all occurred at plot 2. In the two following months, May and June, discharge at the lower levels exceeded that from the surface.

The April 1990 dry period would have allowed considerable desiccation of the soil. The subsequent intense storm on 30 May 1990 (63 mm in 2 h) would have provided a sufficient hydrostatic head and hydraulic gradient for piping to develop. The creation of an artificial free face by excavating the pit may have concentrated the high hydraulic gradient at the lower levels of the weathering profile exposed in the pit, whose location in a hollow where subsurface drainage would converge may have enhanced this effect. The tendency for pipes to form may well have been enhanced by the montmorillonite in the clays of this area.

During the storm of 31 May, it was noticed that the section of the weathering profile above the 50 cm depth collector wetted up first. However, as the storm progressed, much water was observed to emerge from a pipe which had opened up just below the lowest trough. No major overland surface flow was observed at this time. The next day, the pipe appeared to have enlarged slightly and fine silt and organic matter appeared to have been deposited by the emerging water. This dynamic process of changing pathways of water flow beneath the forest indicates the sensitivity of streamhead hollows to disturbance and the significant role that piping plays in both hydrologic and geomorphic processes in the Ulu Segama area. Further investigations of streamhead hollows, particularly in terms of the effects of disturbance during logging operations are a major component of the hydrology programme at the Danum Valley.

The low proportion of the water reaching the forest floor that runs off as overland flow or as throughflow in the top 2 m of the weathering profile suggests that in this environment there is a major soil–weathering profile water store, and that both soil matrix flow and macropore flow regulate the response of streams to rainfall, as indicated by Nortcliff & Thornes (1989). The manner in which the permanent flow in channels commences several tens of metres downvalley of the topographic streamhead hollows indicates that infiltration and soil water storage replenishment have to occur before stream discharge operates. Studies of the relationship between baseflow and stormwater discharge in channels, currently in progress, may help to clarify this point.

4. MOVEMENT OF CHEMICAL ELEMENTS THROUGH VEGETATION AND SOILS

(*a*) *Solute concentrations*

Analysis of water samples was limited by the need to transfer samples from the field station to Manchester. Far fewer determinations were made than we would have wished. Throughfall and stemflow were sampled for some individual storms, but not always on the same dates as overland flow and throughflow. Rainfall was found to be extremely dilute, with no element exceeding a concentration of 1 mg l^{-1}, calcium and potassium dominating the elements determined (nitrogen could not be measured). In throughfall, the concentration of sodium decreases, but all other measured and measurable elements increase, especially silica and potassium which are leached and washed off the foliage (table 1). Overland flow

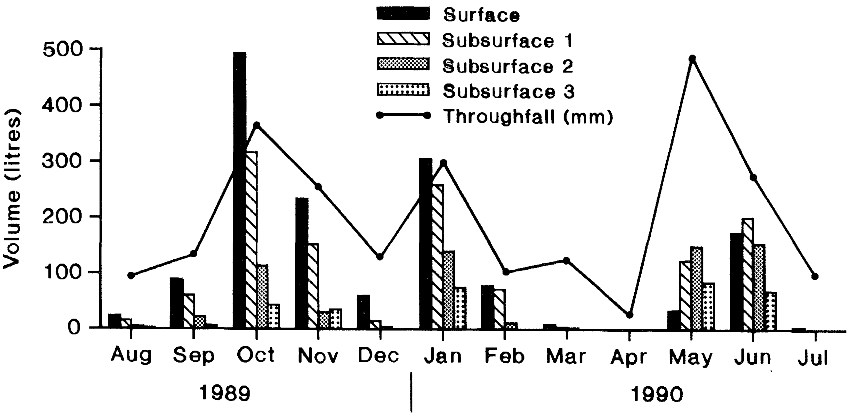

Figure 2. Throughflow measurements at plot 2 showing the change after April 1990.

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Table 1. *Mean chemical composition (in milligrams per litre) of water in various pathways of the hydrologic system at East Ridge, Danum Valley*

	Ca	Mg	Na	Si	P	K
rainfall	0.22	0.07	0.02	n.d.[a]	0.08	0.18
throughflow	0.81	0.34	0.01	0.59	0.30	6.04
overland flow	3.34	1.14	1.03	2.26	0.09	5.22
trough 50 cm	1.40	0.81	0.99	1.81	0.16	2.52
trough 100 cm	0.55	0.53	0.66	4.76	n.d.	0.89
trough 160 cm	1.36	0.45	0.9	3.92	0.16	1.7

[a] n.d. = no data.

exhibits the influence of contact with mineral matter, with considerable increases in the concentrations of mineral-derived calcium, magnesium, sodium and silica. The 50 cm throughflow trough water had lower concentrations than the overland flow, possibly because important decomposition interactions between plant material and other biota and soil minerals are taking place at the surface, whereas the mineral matter beneath had already been highly leached. The 100 cm trough water has higher concentrations of silica than water from shallower depths, indicating the role of mineral water interactions in the deeper pathways. Such interactions may also explain the higher concentrations of calcium and potassium in the 160 cm trough.

(*b*) *Solute loads*

If the annual quantities of water moving though the different sectors of the vegetation and the soil are considered, a generalized first approximation of the chemical transfer through the rain forest system may be obtained (table 2). This has to be treated with caution as storm period weighting has not been considered.

The pattern of chemical element transfer in the East Ridge area of the Danum Valley is similar to that of many previous tropical rain forest studies (Douglas & Spencer 1985; Anderson & Spencer 1991): only a small part of the elements washed down to the forest floor being lost to the drainage system by runoff in the upper layers of the soil profile. The bulk of the water movement to streams takes place by movement along deeper pathways than those intercepted by the troughs in the throughflow pit represented in table 2. More nutrient matter is likely to be evacuated by this deep circulation. Of the elements in the table, silicon provides the largest single component of the solute transport below 50 cm depth, again indicating the greater importance of mineral breakdown than decomposition of vegetation as a control of soil water chemistry.

Table 2. *Quantities of chemical elements (in tonnes per square kilometre per year) transferred through components of the vegetation soil system at East Ridge, Danum Valley*

	Ca	Mg	Na	Si	P	K
rainfall	1.76	0.56	0.16	0	0.64	1.44
throughflow	5.87	4.50	0	4.22	2.11	41.16
stemflow	0.18	0.0076	0.003	0.18	0.02	1.25
overland flow	0.65	0.22	0.20	0.44	0.01	1.02
50 cm depth	0.20	0.12	0.15	0.27	0.02	0.38
100 cm depth	0.04	0.04	0.05	0.36	n.d.[a]	0.07
160 cm depth	0.05	0.02	0.03	0.15	0.01	0.07

[a] n.d. = no data.

Thirty times as much potassium is washed down from the vegetation by throughfall and stemflow than is carried out by overland flow and throughflow (table 2). Although the potassium carried in throughflow at Danum appears higher than in other tropical sites, the quantities of magnesium and calcium are of the same order as elsewhere. The generalized nutrient budget here suggests that, as indicated elsewhere (Nye & Greenland 1960; Kenworthy 1971; Anderson & Spencer 1991), under natural forest the surface soil, organic material and decaying litter of the forest floor make up an important store for many plant nutrients.

5. REMOVAL OF SEDIMENT BY OVERLAND FLOW AND THROUGHFLOW

The annual sediment losses for the three undisturbed plots on the East Ridge were: plot 2, 19.7 t km^{2} y^{-1}; plot 3B, 15.5 t km^{2} y^{-1}; and plot 4B, 29.3 t km^{-2} y^{-1} (figure 3). The higher sediment yield from the gentler 7° slope, plot 4B, than from the 20° slope, plot 3B, is probably due to the difference in soil faunal activity between the two plots. Counts were made on three dates of the number of small, chimney-like mounds on each plot (table 3). Plot 4B had more chimneys than any other plot, including the adjacent plot 4A from which the understorey had been removed. The loosening of the soil by the termites, cicadas, earthworms, or other insects building the chimneys provided an increased bare soil area on which raindrop splash could operate.

The first count of soil chimneys was made on 6 April 1990 during a dry period when sediment yields were low. After that period, yields from 4B remained relatively low and were less than from 3B in June 1990. Lack of chimney counts earlier in the study period makes it impossible to say whether or not it is reasonable to endorse the suggestion that soil erosion on the forest floor is, at least in part, a function of soil faunal activity.

Just as approximately 75% of the total rainfall was derived from storms of more than 30 mm, so roughly the same proportion of the sediment yield from the plots came from such events. Plot 4B had 88.9% of its sediment yield during such storms, whereas plot 3B had only 75.9%, and 4A 82.0%. Probably the higher organic matter content and greater volume of organic activity of the plot 4B surface account for the resistance of the plot to lower rainfalls and greater susceptibility to high energy rains. The results together indicate that sediment loss is a function of cover and soil organic matter. As cover is lessened, smaller, lower energy rainfalls are able to erode sediment. Thus in a bare soil plot established on an abandoned logging track (plot 5) only 65.5% of the sediment yield was propelled by the storms of over 30 mm. Even here

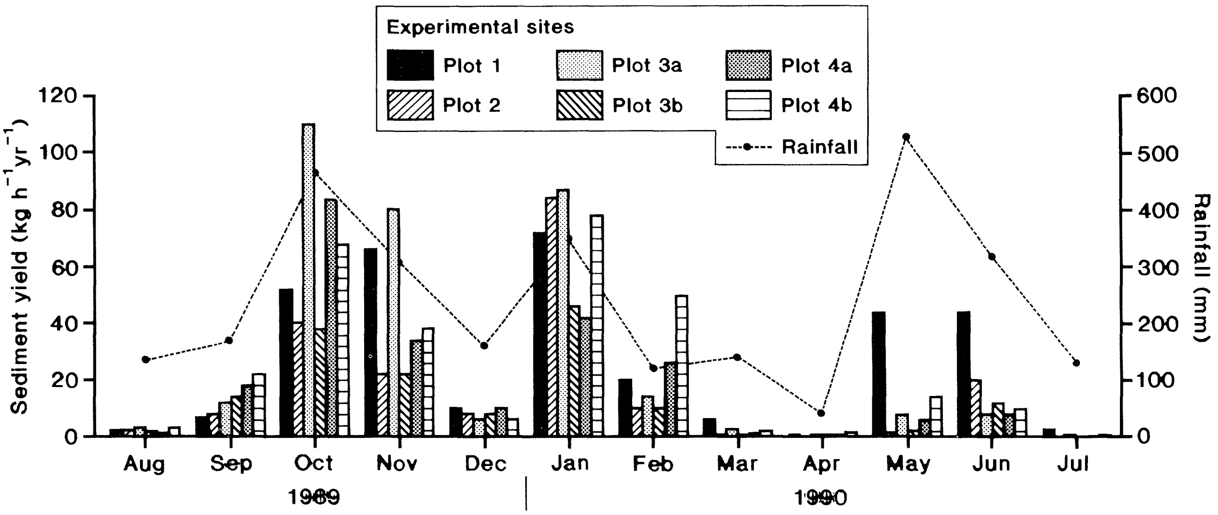

Figure 3. Sediment yield from the forest runoff plots at Danum Valley.

sediment yield decreased through time as vegetation grew over the track (figure 4). These results confirm that the biggest storms will be effective in causing erosion even under undisturbed dense forest.

6. CONCLUSIONS: ROLES OF THE BIOTA AND EXTREME EVENTS

The wide differences in throughfall amounts collected at different sites on the East Ridge trail confirm the importance of canopy structure and density in regulating how rainfall reaches the ground. The stemflow observations emphasize how different species yield varying amounts of water and chemical elements, emphasizing the validity of findings from the cyclone-affected rain forests of North Queensland (Herwitz 1986*a*, *b*). Plant material and invertebrates together influence surface water movement and soil loss. Removal of the vegetation changes the proportion of the water that reaches the forest floor that runs off as overland flow from about 5% to over 50% on compacted surfaces. The hydrologic role of termites is well known from arid and savanna environments (Boyer 1959; Aloni 1975, 1978; Elkins *et al.* 1986; Williams 1968) but is less understood in tropical rain forests. In particular, the way in which invertebrate–hydrology interactions might change with forest disturbance is poorly known.

Much of the erosive activity of rainfall, even in the vegetation-moderated environment of the rain forest, occurs during the biggest storms. These are the occasions when the available energy and water exceed the resistance offered by the canopy and ground cover and the infiltration capacity of the forest soils. Thus

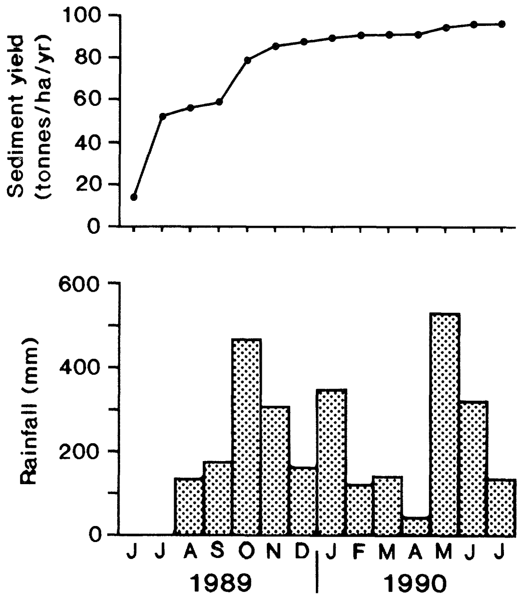

Figure 4. Sediment yield and rainfall for the 5 m × 1 m runoff plot on an abandoned logging track near the Sungai Sapat Kalisun at Danum Valley, showing the decrease in sediment supply as vegetation grew back over the track.

Table 3. *Number (percentage) and distribution of soil pillars (chimneys) on the forest runoff plots*

plot number	date	upper third of plot	middle third of plot	lower third of plot
1	06.4.90	11 (61)	3 (17)	4 (22)
	24.6.90	9 (45)	6 (30)	5 (25)
	18.8.90	14 (34)	15 (36)	12 (29)
2	06.4.90	292 (42)	226 (33)	173 (25)
	24.6.90	287 (50)	153 (27)	137 (24)
	18.8.90	62 (16)	189 (50)	124 (33)
3a	06.4.90	19 (48)	14 (35)	7 (17)
	24.6.90	37 (48)	23 (30)	17 (22)
	18.8.90	66 (49)	35 (26)	33 (25)
3b	06.4.90	15 (25)	33 (55)	12 (20)
	24.6.90	57 (46)	43 (35)	23 (19)
	18.8.90	87 (38)	83 (36)	60 (26)
4a	06.4.90	46 (44)	38 (37)	20 (19)
	24.6.90	94 (54)	47 (27)	34 (19)
	18.8.90	129 (42)	95 (31)	82 (27)
4b	06.4.90	136 (27)	200 (39)	170 (33)
	24.6.90	213 (38)	187 (34)	150 (28)
	18.8.90	289 (39)	258 (35)	187 (25)

even over the short timescale of this study, the notion that rain forest structure and dynamics can be related to a scale of natural disturbance regimes (Spencer & Douglas 1985) has some validity. Two practical lessons emerge: (i) short-term process investigations of a few weeks or months reveal little of the temporal variability of hydrologic processes in tropical rain forests; (ii) any attempts to forecast or model the natural dynamics or the consequences of disturbance of tropical rain forests must cope with the magnitude, frequency and duration of rainfall events.

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