Human Impact on Erosion and Sedimentation (Proceedings of Rabat Symposium S6, April 1997).
IAHS Publ. no. 245, 1997

The impact of hill land clearance and urbanization on runoff and sediment yield of small catchments in Pulau Pinang, Malaysia

WAN RUSLAN ISMAIL
Section of Geography, School of Humanities, Universiti Sains Malaysia, 11800 Pulau Pinang, Malaysia

Abstract The 285 km^{-2} granitic island of Pulau Pinang, Malaysia, is undergoing rapid development and recently the development has encroached upon the hillslopes of Penang Hill. A space-time substitution approach has been used to establish the relative importance of changes in the steep headwaters and on the lower footslopes. Monitoring stations were established to gauge stream discharge and suspended sediment output, in the steep headwaters and on the lower footslopes of the Sg. Relau catchment. To assess the effects of active urbanisation on this river, the relatively undisturbed Sg. Air Terjun catchment was also monitored. The runoff from urban areas in the disturbed lower catchment was much higher than from the upper catchment of Sg. Relau, reflecting the impact of urbanization. Runoff in the Sg. Relau is more extreme than in the Sg. Air Terjun. Quickflow, was higher for Sg. Relau than for the Sg. Air Terjun, reflecting the role of impervious surfaces in promoting higher runoff during storms. Runoff from the undisturbed catchment was higher than the disturbed catchment reflecting the role of forest cover in regulating flow and runoff. The annual sediment yield was much higher in the more disturbed lower Sg. Relau compared to other stations. Quarrying and construction sites in the lower Sg. Relau were responsible for much of the sediment supply in the catchment. Storms account for the bulk of sediment output.

INTRODUCTION

The rapid urbanization and industrialization of Penang Island has accelerated its impact on the hydrology and geomorphology of the island. The rapid increase in the population of the island due to internal migration and the influx of people from other countries such as Indonesia and Bangladesh, seeking for jobs in the island's industries, have caused an increased need for more land for development of housing estates. The intention of the State Government to make Penang the leading industrial state in Malaysia has also caused more flatland to be developed for industrial use. Due to it small size (285 km^2) and lack of flatland, development has encroached on the hillslopes of the island. The study reported in this paper was carried out to assess the impact of hillslope development on erosion and sediment transport.

THE APPROACH AND THE STUDY CATCHMENTS

In assessing the impact of hillslope development on soil erosion and sediment yield, two catchment areas were selected. The first, the Sg. Relau catchment (Fig. 1), was affected by hillslope development and urbanization in the lower section of the catchment. A space-time substitution approach was used to establish the relative importance of changes in the steep headwaters and on the lower footslopes. Two monitoring stations were established to gauge stream discharge and suspended sediment output, one in the steep headwaters and one in the lower footslopes of the catchment. Another relatively undisturbed catchment, the Sg. Air Terjun, was selected for comparison. Raingauges were installed in the Sg. Relau catchment to measure the amount and intensity of rainfall. Raingauges operated by the Drainage Irrigation Dept. Malaysia on Penang Hill at Bukit Bendera were used for the Sg. Air Terjun catchment. Continuous water level recorders and automatic liquid samplers were installed at the two gauging stations, located upstream (RA) and downstream (RB) in Sg. Relau, and at the Waterfall Treatment Plant weir (WA) in Sg. Air Terjun.

Storms samples were collected by the automatic liquid samplers, which were activated by a float switch set at a pre-determined depth. Low flow samples were collected manually using a modified USDH 48 sampler at RB and by means of 1 litre plastic bottles from the lips of the weirs at RA and WA. Streamflow gauging was carried out at RB using the velocity area method as suggested by Richards (1982).

The disturbed Sg. Relau catchment (Fig. 1) has an area of 11.52 km^2 above the downstream station (RB). The 0.55 km^2 tributary catchment in the upper Relau (RA) has been cleared for agriculture and orchards, with some road construction. The lower part of the catchment is rapidly undergoing transformation, with new land being cleared for urban construction. The percentage forest cover is only 3.1%, while the percentage area represented by urban related areas is 21.8% for the whole catchment above the lower station. The relatively undisturbed Sg. Air Terjun catchment, which was selected for comparison, has a catchment area of 4.75 km^2 and comprises 94% relatively "undisturbed" forest.

RESULTS AND DISCUSSION

Annual runoff

From November 1993 to August 1994, the Sg. Air Terjun catchment had a higher water yield than Sg. Relau. The highest yield was recorded in the upstream sub-basin of Sg. Air Terjun (WA) with 1092.9 mm. The coefficients of total runoff at WA and RB were almost similar at 61% and 62% respectively. However, a lower coefficient was observed at RA (49.4%). The high water yield and runoff coefficient at WA is undoubtedly a reflection of the high rainfall input to the hill, and the steeper gradient of Sg. Air Terjun compared to Sg. Relau. However, the higher runoff at RB compared to RA, (even though RA is steeper than RB) reflects the anthropogenic activities in the catchments. There is general agreement that the annual runoff from urban areas is greater than that from the same area under natural conditions. In regions where annual runoff depends primarily on storm rainfall, the annual runoff from urban areas may be 2 to 2.5 times greater than that from natural areas (Kuprianov, 1977). In this study the runoff at RB (urban) was only 1.25 times greater than from RA. The runoff coefficient at RA is lower than that at RB with values of 49.4% and 62.1% respectively. There was an increase of total runoff from 661.4 mm at RB due to the increase in storm runoff (Kuprianov, 1977).

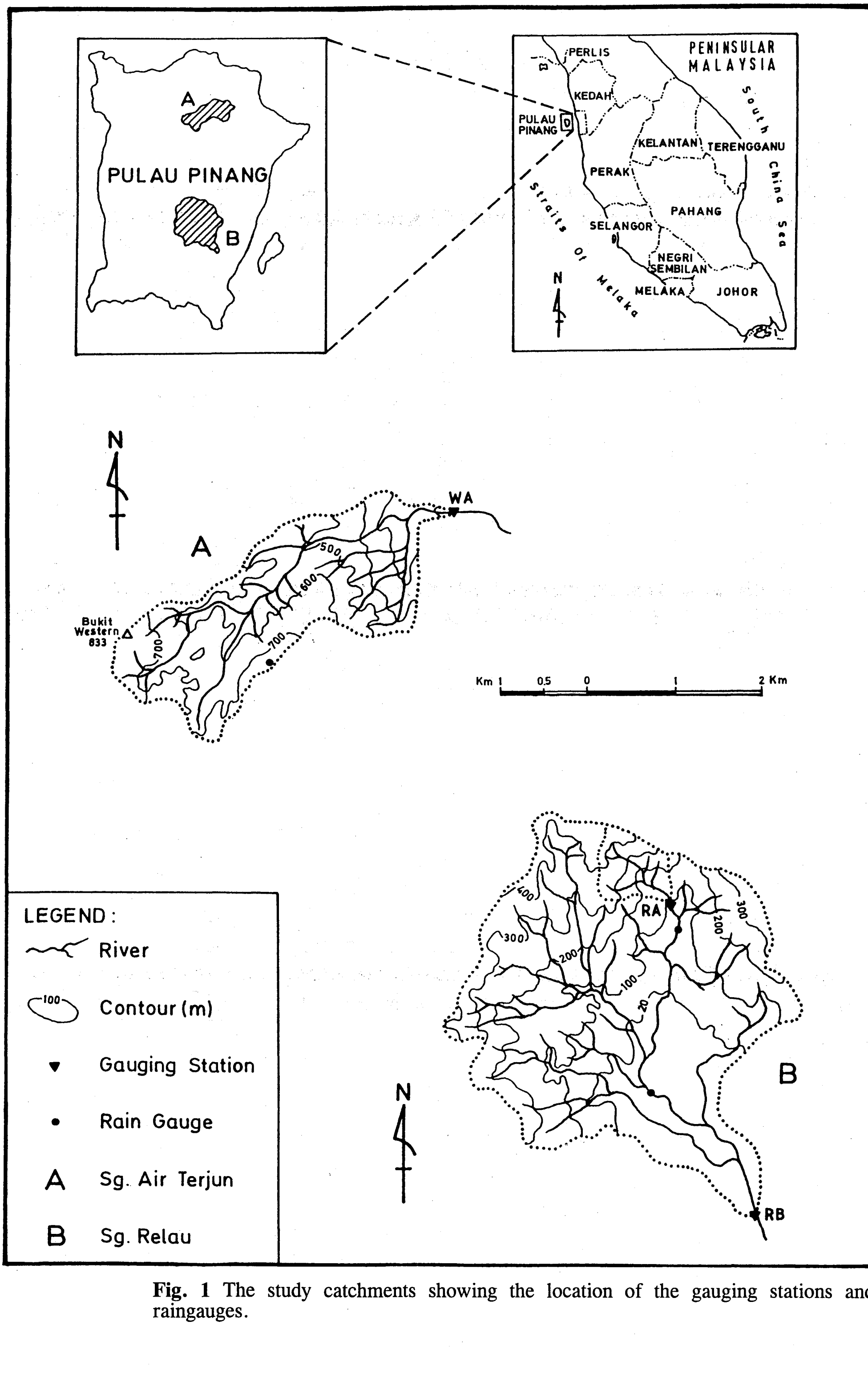

Fig. 1 The study catchments showing the location of the gauging stations and raingauges.

Monthly variation in runoff

In the Sg. Relau catchment runoff coefficients greater than 100% were recorded in the dry months of December, January and July when runoff exceeded rainfall. This could be due to baseflow carried over from the previous wet months of October, November and June. Another possible contribution to the baseflow during the dry months of December 1993 and January 1994 at RB, could be due to the continual output of waste water discharges from urban outflows and the quarrying industry. However, this amount could not be quantified. In the dry months runoff was higher at WA than at RB (Fig. 2). Groundwater storage in the Penang Hill catchment with its deep weathering profiles must be large and supplies a baseflow adequate for the water supply for which it has been tapped since the early 1900s.

As mentioned above, the rainfall in December 1993 was low, but the runoff was greater due to the water storage from previous wet months. There appears to be a lag in runoff due to groundwater storage and baseflow. The forest plays a major role in this water retention and slow release in the Sg. Air Terjun catchment. In the Sg. Relau, however, the effect of waste water discharges throughout the year could be the main cause of runoff exceeding rainfall during low rainfall months at RB.

High discharges occur more often in Sg. Air Terjun than Sg. Relau but the forer has a higher minimum flow. One hundred percent of the flows at WA exceed 0.025 $m^3 s^{-1} km^{-2}$, but the equivalent values are only 84.1% at RB and 75% at RA (Fig. 3). The percentage of time that discharge exceeds 0.20 $m^3 s^{-1} km^{-2}$ at WA is only 0.8% while the values for RA and RB are 1.4% and 2.5% respectively. Thus the Sg. Relau has a more extreme and more flashy regime than the Sg. Air Terjun. This is to be expected, because the more disturbed catchment will experience more extremes, with discharge greater than 0.3 $m^3 s^{-1} km^{-2}$, for example, occurring 0.6% of the time at RA, 1.6% of the time at RB and never at WA. In the Sg. Relau catchment the rapid runoff originates primarily from urban areas close to the lower station.

Storm runoff quickflow

The mean monthly quickflow contribution in the Sg. Air Terjun catchment (WA) is 14.6%, with values for individual months varying from 0.1% in dry months to 24.1% in months with high rainfall and storms. Much of the runoff at WA is dominated by the baseflow contribution which accounts for an average of 85.4% of the total runoff. The stormflow contribution in the Sg. Relau catchment is higher than in the Sg. Air Terjun catchment. The impermeable surfaces in the Sg. Relau have undoubtedly contributed to the higher runoff at RA, which has a mean monthly quickflow of 22.4%, with values for individual months ranging from 0.7% to 33.8%. The lower catchment of Sg. Relau which has undergone massive transformations experiences the highest quickflow contribution, with a mean monthly value of 34.4% and values for individual months ranging form 3.6% to 58.7%.

General suspended sediment behaviour

The extent of anthropogenic activities on each catchment is clearly reflected in the

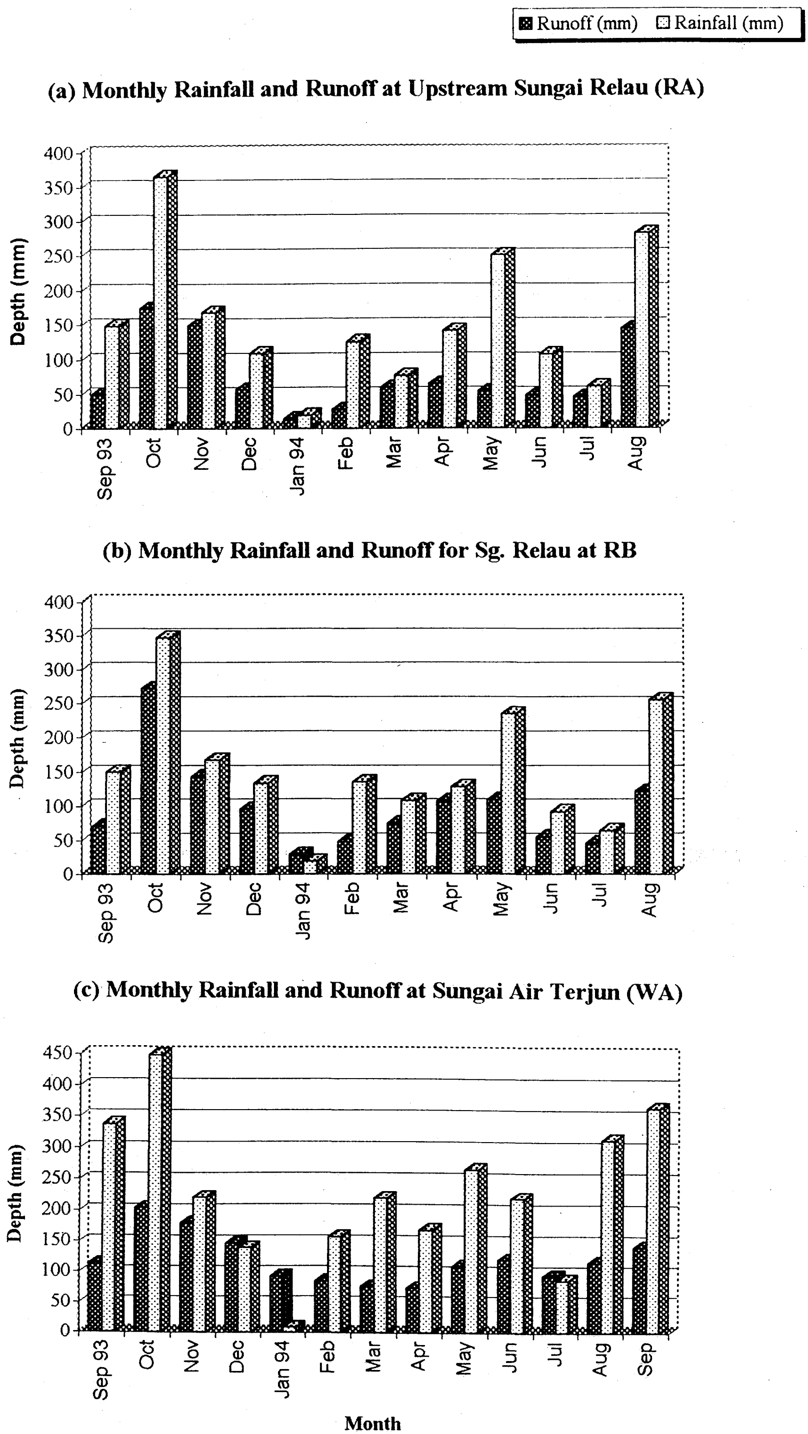

Fig. 2 Monthly rainfall and runoff for each station during the study period.

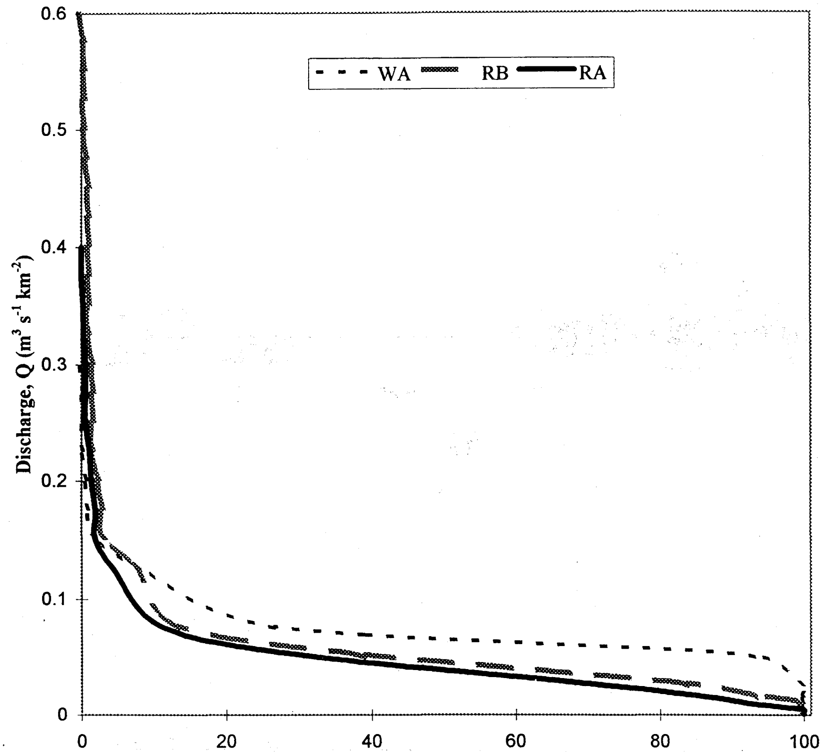

Fig. 3 Flow duration curves for each station for the study period.

suspended sediment concentration data (Table 1). Sg. Relau, which is heavily urbanized and the most disturbed catchment, had the highest mean concentration of suspended sediment. The data were further separated into storms and baseflow concentration. Even after the separation, the low flow concentrations were still highest at RB. The concentrations at RA were also considerably greater than at WA. These concentration data clearly show that the most disturbed, urbanizing lower catchment of Sg. Relau has concentrations approximately twice those of the disturbed upper catchment gauged at RA and 25 times greater than the relatively undisturbed upper Sg. Air Terjun catchment monitored at WA.

During storms, the suspended sediment concentrations on the rising limb of the hydrograph differ from those on the falling limb. For both the Sg. Relau stations, mean concentrations were higher on the falling stage than on the rising counterpart, but, when the maximum concentrations are considered, the trend is reversed in the case of RA. For RB the mean concentrations differed little between the rising stage and the falling stage. However, the maximum suspended sediment concentrations were much greater during the falling stage compared to the rising stage (Table 1). Sg. Air Terjun, on the other hand, exhibits a completely different behaviour wherein the falling stage suspended sediment concentrations were consistently greater than the rising stage concentrations.

Table 1 Descriptive statistics of suspended sediment concentration (mg l^{-1}).

	Sg. Relau: RA	Sg. Relau: RB	Sg. Air Terjun: WA
All data			
Mean	1465.72	2862.43	111.04
Maximum	15 441.04	22 140.0	668.69
Minimum	4.04	46.54	0.53
Standard deviation	2317.55	2525.2	118.67
n	425	634	704
Baseflow			
Mean	29.61	1550.56	11.36
Maximum	177.04	13 942.04	60.53
Minimum	4.04	46.54	0.5
Standard deviation	30.18	2059.0	12.14
n	115	116	89
Storms			
Mean	2013.81	3137.8	125.5
Maximum	15 441.04	22 140.05	668.7
Minimum	91.54	46.54	11.0
Standard deviation	2520.7	2529.1	120.22
n	307	524	615
Rising stage			
Mean	1925.32	2763.415	116.02
Maximum	15 441.04	13 942.04	577.04
Minimum	91.54	46.54	11.0
Standard deviation	2555.79	2287.02	109.24
n	133	275	326
Falling stage			
Mean	2071.14	2818.74	135.00
Maximum	10 359.02	22 140.05	668.69
Minimum	78.04	46.54	16.04
Standard deviation	2476.06	2502.13	130.04
n	219	312	294

Stormflow sediment behaviour

It is well known that the bulk of annual sediment transport commonly occurs during a limited number of high rainfall events (Douglas, 1967; Sarma, 1986; Amphlett, 1988; White, 1990; Gellis, 1993). Based on such evidence, stormflow periods are very important in controlling sediment transport and sediment yield. Storms accounted for the bulk of the sediment output in the study catchments. In Sg. Relau, 98% of the sediment output at RA was transported during storms and 83.8% at RB. In Sg. Air Terjun only 60.9% of the sediment yield was transported by storms at WA.

Monthly variation of sediment transport in Sg. Relau

Upstream station (RA) The monthly sediment transport at RA was highest in October 1993 (301.41 t km^{-2}) followed by November 1993 (267.31 t km^{-2}). These two months which account for 63% of the total load observed during the monitoring period experienced the most intense rain and highest rainfall energies. The lowest yield was recorded in January 1994, with 0.27 t km^{-2} which can be considered negligible compared to the total load. The wet months of September, October, November and August accounted for 89.5% of the total suspended sediment output from this station during the study period.

Downstream station (RB) At RB, the highest monthly sediment yield was recorded for September 1993, with 1393.98 t km^{-2}, followed by October 1993 with 453.98 t km^{-2} and November 1993 with 374.99 t km^{-2}. The sediment output during these three months was 2222.95 t km^{-2} or 71.9% of the total load during the study period. The wet months of September, October, November and August were again the major contributor to annual sediment load, accounting for 79.78% of the total load during the study period. September alone accounted for nearly half of the total load (45.1%) and 96.0% of the September load was associated with storm events. Because of the preceding dry conditions the infiltration during September was far greater than October, causing less runoff and thus less overland flow. Thus one possible reason for the high sediment load during September is the abundant source of sediment supply near the channel and in channel sediment being reworked by even the smallest rainfall event. Furthermore, the increase in sediment load when compared with that from RA is far greater than in other months, suggesting either remobilization of dry, loose sediment or important newly exposed local sources. An increase in soil erodibility caused by land clearance always leads to an increase in sediment yield.

Monthly variation of sediment transport in Sg. Air Terjun

The highest monthly sediment load recorded at this station during the study period was 57.61 t km^{-2} in November 1993. October and November 1993 were the most productive months, accounting for 64.5% of the total load, with November alone accounting for 52.35%. The storm contribution for these two months was 44.08% of the total load. The remaining months of the study period had a sediment output of less than 10 t km^{-2} per month, with values ranging from the lowest output of 0.5 t km^{-2} in January 1994 to 5.6 t km^{-2} in August 1994. Monthly storm contribution varied from 18.68% in January 1994 to 92.74% in June 1994.

Sediment yield

The more urbanized and disturbed Sg. Relau catchment had estimated annual sediment yields of 910.5 t km^{-2} and 3100.6 t km^{-2} at RA and RB respectively (Table 2). These values are respectively about 9 and 30 times greater than the undisturbed Sg. Air Terjun at WA. The estimate for RB is 2.5 times greater than the maximum tolerable limit of erosion of 250-1250 t km^{-2} $year^{-1}$ (Lal, 1984). However, the upstream sediment output falls in the range cited by Lal (1984). The sediment yield for the Sg. Relau catchment at the lower monitoring station was previously

Table 2 Summary of suspended sediment load values at each station.

Description	Sg. Relau: RA	Sg. Relau: RB	Sg. Air Terjun: WA
Area (km^2)	0.55	11.52	4.75
Period (days)	362	364	395
Total load (t)	499.36	35 630.24	522.71
Total yield (t km^{-2})	903.01	3092.10	110.04
Annual yield (t km^{-2} $year^{-1}$)	910.49	3100.60	101.68
Storm output (t)	489.41	29 859.94	318.73
Storm yield (t km^{-2})	885.01	2591.33	67.1
Annual storm yield (t km^{-2} $year^{-1}$)	892.34	2598.45	62.0
Percentage storm output of total load	98.0	83.8	60.9

estimated to be 2701 t km^{-2} $year^{-1}$ (Wan Ruslan & Zullyadini, 1994) based on a short study period between May and September 1991. The current estimate is 1.15 times higher than the previous estimate.

SUMMARY

The influence of human activity in the catchment areas is clearly shown by the amount and behaviour of their sediment output. Sg. Relau at RB had a sediment yield about 30 times greater and at RA about 9 times greater than the undisturbed Sg. Air Terjun at WA, with 3100.6 t km^{-2} $year^{-1}$ and 910.5 t km^{-2} $year^{-1}$ respectively. The readily available sediment sources due to land clearance for agriculture and exposure of ground for construction sites and quarrying have had an important impact on the amount of sediment output. The important role of storms has also been highlighted with 99.2% of the total yield at RA in November 1993 being attributed to storms. The wet months of August, September, October and November had the highest percentage of storm output per month at all stations, ranging from 70% at WA (July 1993) to 99.4% at RA (September 1993). The average percentage of storm yield per month for each station was 81.5% at RA; 53.2% at WA and 59.7% at RB.

Acknowledgements Thanks are extended to those who participated in the fieldwork carried out in Penang; to Professor Ian Douglas, University of Manchester, UK for his supervisions, guidance and comments during the final stages of my doctoral study at Manchester, and to USM for granting study leave.

REFERENCES

Amphlett, M. B. (1988) A nested catchment approach to sediment yield monitoring in the Magat catchment, central Luzon, the Philippines. Paper presented at the 5th International Soil Conservation Conference (Bangkok, 18-29 January 1988).

Douglas, I. (1967) Natural and man made erosion in the humid tropics of Australia, Malaysia and Singapore. In: *Symposium on River Morphology* (Proc. General Assembly of Bern, September-October 1967), 17-30. IAHS Publ. no. 75.

Gellis, A. (1993) The effects of Hurrican Hugo on suspended sediment loads, Lago Loiza Basin, Puerto Rico. *Earth Surf. Processes and Landforms* **18**, 505-517.

Kuprianov, V. V. (1977) Urban influences on the water balance of an environment. In: *Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality* (Proc. Amsterdam Symp., October 1977), 41-47. IAHS Publ. no. 123.

Lal, R. (1984) Soil erosion from tropical arable lands and its control. *Adv. Agron.* **37**, 183-248.

Richards, K. S. (1982) *Rivers: Form and Processes in Alluvial Channels*. Methuen; London, UK.

Sarma, J. N. (1986) Sediment transport in the Burdhi Dihing River, India. In: *Drainage Basin Sediment Delivery* (ed. By R. F. Hadley) (Proc. Albuquerque Symp., August 1986), 199-215. IAHS Publ. no. 159.

Wan Ruslan Ismail & Zullyadini A. Rahaman (1994) The impact of quarrying activity on suspended sediment concentration and sediment load of Sungai Relau, Pulau Pinang, Malaysia. *Malaysian J. Tropical Geogr.* **25**(1), 45-57.

White, S. M. (1990) The influence of tropical cyclones as soil eroding and sediment transporting events. An example from the Philippines. In: *Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Steeplands* (ed. by R. R. Ziemer, C. L. O'Loughlin & L. S. Hamilton) (Proc. Suva, Fiji, Symp., June 1990), 259-269. IAHS Publ. no. 192.