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The impact of land-use changes, especially logging, shifting cultivation, mining and urbanization on sediment yields in humid tropical Southeast Asia: a review with special reference to Borneo

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Abstract The Southeast Asian region provides an excellent range of tectonic styles within the humid tropics against which to test ideas of geologic and climatic controls of sediment yields in tropical forests and in which to examine the increase in sediment yield following clearance. The available data on sediment yields for Southeast Asian catchments are diverse and varied, with many reliant on spot samples and estimation of storm-period yields from rating curves. Recent data obtained using automatic sampling during storms may give better estimates. Volcanic activity and associated mass movements undoubtedly greatly affect sediment yields, but landslides are also a significant contributor to sediment yields in natural forests on the Tertiary sedimentary rocks of Borneo. Malaysian data shows increases in sediment yield under logging regimes of up to 20 time the undisturbed rate. Shifting cultivation does not increase sediment yields significantly, largely because so much organic debris is left on the ground. Urbanization and mining increase sediment yield in stable terrain by two to three orders of magnitudes in catchments of several km^2, but yields from construction sites can exceed those from the most unstable, tectonically active natural environments in Southeast Asia.

INTRODUCTION

Major controls on regional denudation rates (or sediment yields) include climate and geology, with human activity becoming increasingly important in the twentieth century. While much has been written about the climatic controls of denudation (Fournier, 1960; Douglas, 1967; Strakhov, 1967; Walling & Webb, 1983) the geologic influences have seldom been analysed in a regional context. Geology is expressed through the rocks of the catchment area and the tectonic style of the terrain on which the catchment is developed. The highest sediment yields occur in tectonically active areas, where earth tremors trigger frequent mass movements which supply large volumes of sediment to rivers. The lowest sediment yields are on old land surfaces of low relief and deep weathering profiles. The contrast quantitatively is the difference between yields of the order of 10 000 t km^2 year^{-1} in mountains of New Guinea, Taiwan and the South Island of New Zealand (Pickup *et al.*, 1981; Shimen Reservoir Authority, 1975; Griffiths, 1979) and yields of around 100 t km^2 year^{-1} in Africa (Milliman & Meade, 1983). These differences emerge in tropical and temperate rainforest climates where small mountainous rivers discharge great volumes of sediment per km^2 of catchment area, but are largely ignored in global sediment budget calculations (Milliman & Syvitski, 1992). The Southeast Asian region provides an excellent range of tectonic styles within the humid tropics against which to test ideas of geologic and climatic controls of sediment yields in tropical forests and in which to examine the increase in sediment yield following clearance. While the older, more stable land surfaces such as Peninsular Malaysia have stable regimes with rivers carrying low sediment loads under natural conditions (Chong, 1985), they also tend to have deeply weathered regoliths which potentially can yield large quantities of sediment once disturbed. Do such landscapes provide more sediment after disturbance than less stable landscapes with higher natural denudation rates, but thinner soils and shallow weathering profiles?

For Southeast Asia, deductive arguments suggest that sediment yields of the order of 10 000 t km^2 $year^{-1}$ occur in the most tectonically active parts of the island arcs, with around 1000 t km^2 $year^{-1}$ on the weak Tertiary mud rocks of eastern Borneo and 50-100 t km^2 $year^{-1}$ on the deeply weathered Mesozoic granites of the Thai-peninsular Malaysia-Bangka intrusive complex (Douglas, 1992; Curtis & Douglas, 1993). The critical examination of the evidence from catchment studies, particularly in Borneo, presented here seeks to test this hypothesis and to examine the impacts of different forms of disturbance.

DATA AVAILABILITY

The available data on sediment yields for Southeast Asian catchments are diverse and varied, with many reliant on spot samples and estimation of storm-period yields from rating curves. Wide ranges of values occur, for example estimated soil erosion rates for 79 watersheds in Thailand vary from 7 to 3873 t km^2 $year^{-1}$ (Jantawat, 1985). However, recent data using automatic sampling during storms may give better estimates, for example the highest values in columns A and B of Fig. 1 which are for the Sg. Air Terjun, Pulau Pinang and Sg. W8S5, Sabah catchments respectively (Wan Ruslan, 1995; Douglas *et al.*, 1992). Even so, few catchments have been studied for more than three years and events with a recurrence interval rarer than 1:10 years have probably not been sampled. Long-term natural sediment yields therefore cannot be stated with confidence.

Throughout Southeast Asia, rapid development during the last few decades, has led to great increases in river sediment discharge. Consequently, problems of soil erosion and sediment discharge have emerged as matters of national concern (Chong, 1985). Many agencies have collected sediment data and several have promoted small catchment experiments, especially to examine the effects of forestry management practices. The range of Malaysian data for disturbed catchments (columns D, E and F on Fig. 1) shows increases in sediment yield under logging regimes of up to 20 times the undisturbed rate. Results across the region however are inconsistent. From an examination of data for catchments in northern Thailand, Alford (1992) argues that the runoff coefficient is low at 20 to 25% and that sediment yields at around 100 t km^2 $year^{-1}$ are also low. He claims that time series analyses of the existing data bases show no evidence that streamflow or sediment regimes have changed significantly since the 1950s. There is no empirical substantiation for the hypothesis that land-use practices have altered the hydrologic

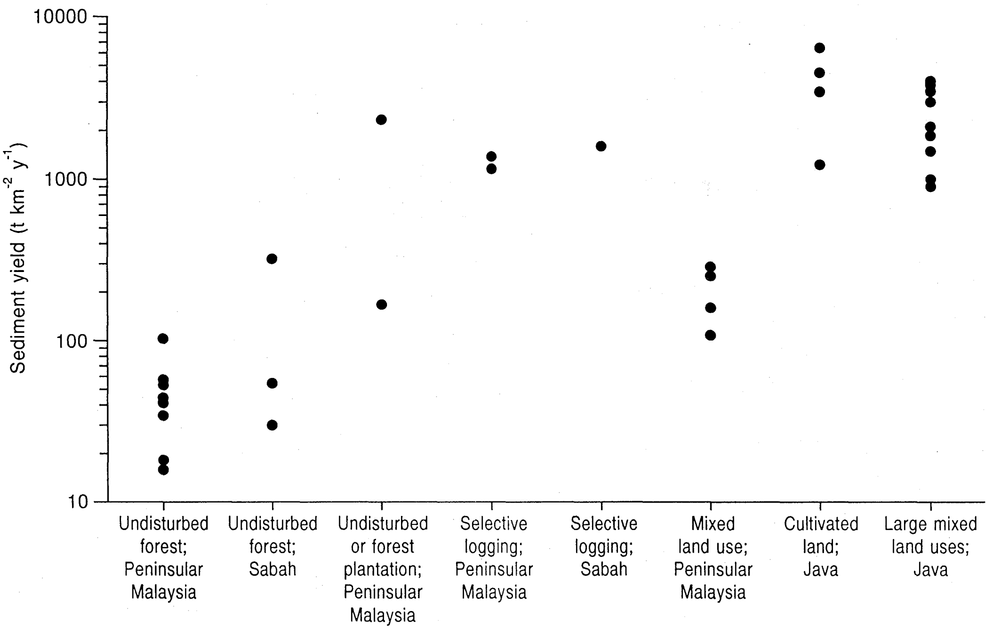

Fig. 1 Pattern of sediment yields from Southeast Asian catchments of differing tectonic style and land uses.

regime of these basins, or have contributed to an increase in the sediment loads of the rivers. On the other hand, experimental land-use manipulations on two small grassland watersheds using the paired-watershed experiment at Angat, Bulacan, Philippines (Fig. 1) showed that no-burning and reforestation resulted in increased water yield (9.5%, 11.5%) and decreased suspended sediment yield (59% for no-burning and 72% for reforestation) when compared to an annually-burned Imperata grassland (Dano, 1990).

THE INFLUENCE OF GEOLOGY ON EROSION IN UNDISTURBED AREAS

Volcanic catchments in Java have high erosion rates even under forest, as the Cilutung catchment (the highest point in column C in Fig. 1) illustrates. At 2250 t km^2 year^{-1} (Van Dijk & Vogelzang, 1948), the sediment yield here is more than seven times that in the Borneo W8S5 catchment on the Miocene Kuamut mudrocks and melange formation. However, the Borneo catchment has a yield three times higher than the Sg. Air Terjun catchment draining the granite Penang Hill. However, other data, such as that for the Cijambu catchment (lower point in column C, Fig. 1) suggest that there are conditions in Java under which erosion is considerably less than on the volcanic slopes.

Volcanic activity undoubtedly greatly affects sediment yields. Many rivers in Indonesia and the Philippines originate in regions where volcanic eruptions cause enormous flows of ash and lava into these rivers. This debris is easily eroded and often turns into lahars after rain. Lahars erode the sediment of river beds and banks and achieve considerable size and enormous energy, causing considerable damage (Legowo, 1981). At least 59 rain lahars have occurred on Mayon Volcano, on the Philippine island of Luzon, since its last eruption in 1984. The Mabinit Channel, 5 km long, 15 to 70 m wide, and 2 to 22 m deep, was formed by lahars on the southeastern slope of the volcano during the eruption. In 1985, the channel was drastically modified by a lahar triggered by a typhoon. Sediment-budget calculations from surveys conducted in 1985 and 1986 corroborate inferences from other volcanoes that lahars can grow significantly in volume by eroding their channels (Rodolfo, 1989). Monitoring from 1985 to 1990 noted sixteen debris flows. Each was triggered by a rainfall that lasted at least 1.4 h, delivered a minimum of 40 mm of rain at an overall rate of 11 mm h^{-1} or more, and included at least one 10 minute interval during which at least 10 mm fell (Rodolfo & Arguden, 1991). Mudflows and lahars from Mount Pinataubo were still causing severe damage in 1995, shifting large volumes of sediment four years after the eruptions. Such events lead to frequent extremely high sediment yields in the affected catchments.

The relative roles of volcanicity and human activity are difficult to separate for larger catchment areas (column H on Fig. 1), but all these Javanese sediment yields are higher than those in Borneo or Peninsular Malaysia. Human activity, especially road construction and clearance for urbanization greatly accelerates mass movement, creating major new sediment sources. However, mass movements occur throughout tropical steeplands and are by no means confined to tectonically active areas. Landsliding contributes about 16.5% of the annual erosion rate in natural forests on the Tertiary sedimentary rocks of Borneo as Alan Dykes (1995) found at Ulu Temburong. Major slips are readily visible from aerial photos of the Upper Rajang and Ulu Segama catchments. However, logging road construction both reactivates old landslides and causes new movements, some of which do not occur until several years after roads have modified drainage and pore water pressures.

The mass movement problems associated with lahars are not the only sources of extreme sediment yields. Tropical cyclones (typhoons) play a major role away from the equator in Southeast Asia. In the Philippines, tropical cyclones are the events which erode and transport most sediment (White, 1990). Even away from the main cyclone tracks, major storms cause mass movements. On 20-23 November, 1988, a three-day total rainfall of 885 mm triggered large scale landsliding with debris avalanches and debris flows transporting approximately 107 t km^2 in a catchment of 92 km^2 in the Nakhon Si Thammarat Range of Phipun District in southern Thailand (Harper, 1995). Land-use change from rainforest to rubber plantation may have contributed to the landsliding. The minimum annual erosion rate in this area with this sort of landsliding every 150-300 years would be 356-712 t km^2 $year^{-1}$.

SHIFTING CULTIVATION

Shifting cultivation has far less impact on sediment yield than many people claim. Excellent plot studies over 11 years in Sarawak, Borneo (Table 1) show that while traditional cultivation of pepper in rows produces sediment yields 200 times greater than those under natural forest, shifting cultivation does not increase them significantly, largely because, despite the burning, the organic debris left on the ground prevents long rills or channels for sediment movement from developing.

Table 1 Data on erosion rates under forest and shifting cultivation for Sarawak after Ng & Teck (1992) and Teck (1992).

Land use	Location	Slope (degrees)	Period (years)	Soil loss (t km^2 year^{-1}) mean	Soil loss (t km^2 year^{-1}) range
PRIMARY FOREST	Niah F.R. Semongkok	25-30 25-30	4 11	19 24	8.3-31 7-77
SECONDARY FOREST					
(a) logged 10 years previously	Niah F.R.	25-30	4	23	11-36
(b) with hill padi	Semongkok	25-30	11	10	2-17
(c) 2 month old lallang and scrub	Semongkok Niah F.R.	25-30 33	11 3	10 100	2-17 450-1800
HILL PADI/SHIFTING CULTIVATION					
(a) normal	Kg. Benuk	25-30	1	18	
(b) terraced with cover	Semongkok	20	11	120	21-246
(c) bush fallow	Semongkok	16-26	3	23.3	6-45
(d) bush fallow	Tebedau	25	2	34	22-46
TRADITIONAL PEPPER	Semongkok	25-30	11	8944	5118-13912

EFFECTS OF LOGGING

The rapid economic growth in Southeast Asia, in particular mining and logging operations, is causing serious erosion problems, increasing the sediment loads of rivers, and aggravating flooding (Pushparajah, 1985). Logging (Columns D and E in Fig. 1) may increase sediment yields at the catchment scale by 10 to 20 times. Such increases in sediment yield persist for several years (Fig. 2) but when roads and log extraction (snig) tracks are carefully designed and sediment yield to streams is regulated by buffer strips (supervised catchment in Fig. 3) the sediment yield is much less. Roads and snig tracks play a major role in increasing sediment production, as shown in the Huay Ma Feung stream in Thailand during the rainy season of 1983. Storms produced simultaneous peaked suspended sediment concentration and discharge hydrographs with

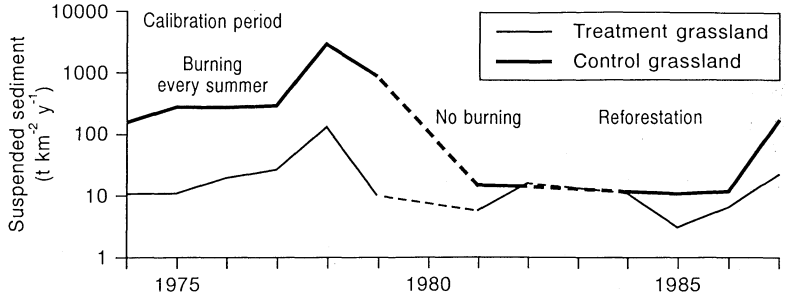

Fig. 2 Measured sediment yield in grassland catchments, Angat, Philippines.

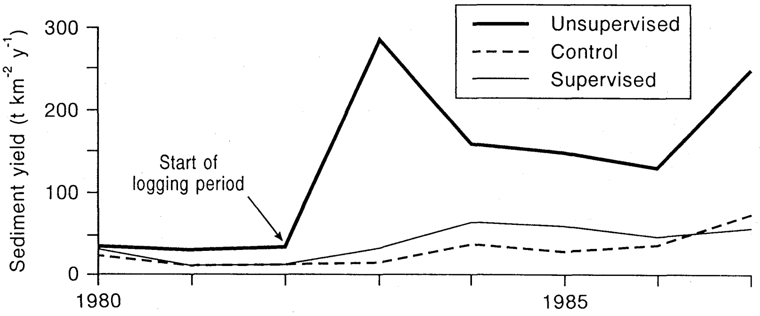

Fig. 3 Type of logging and sediment yield in the Berembun catchment.

maximum values at 28 000 mg l^{-1} and 1.46 m^3 s^{-1}, respectively. Bed load accounted for more than 80% of the total load of 10 494 t km^2. Sedimentological evidence and prevailing soil hydraulic properties indicated that the bulk of sediment originates from roadside gullies, slumps and landslides (Henderson & Witthawatchutikul, 1985). Selective logging of the Sg. Lawing catchment on the deeply weathered granites of the Main Range of peninsular Malaysia led to a twenty-fold increase in sediment yield (from 54 to 1129 t km^2 $year^{-1}$, Lai *et al.*, 1995). In the Sg. Steyshen Baru catchment of Sabah, the increase was 18 times (columns D an E compared with column A in Fig. 1).

MINING

Mining and quarrying in Southeast Asia ranges from the huge open-cut excavations of metallic ore and coal seeking transnational corporations to the shallow alluvial workings of peasant gold prospectors. All mines and quarries in this spectrum contribute, in their different ways, to increased fluvial sediment yields. Good management of waste heaps and mine tailings is essential, but increasing concern is being felt over the residues left when mines close and maintenance of spoil tips ceases, as in the old tin mine tailings which still affect streams near Kuala Lumpur (Sg. Jinjang in Table 2). Past disasters associated with alluvial mining include the gradual burial of the old town of Kuala Kubu in Selangor, Malaysia by sediment carried by flood flows from tin workings on the hillsides upstream.

URBAN EROSION

Wherever rapid urban development has occurred on deep humid tropical regoliths in Southeast Asia, severe erosion and high sediment yields have occurred. Urbanization causes a temporary and extreme rise in sediment production from a drainage basin. On cleared and graded slopes, sheet flow moves high concentrations of sediment with peak values of nearly 50 000 mg l^{-1}, mainly in the form of clays, silts and fine sands, to the rills. Rills carry high sediment concentrations of 10 000-15 000 mg l^{-1} at the beginning of a storm, but the concentration falls as the storm continues. Rill sediments tend to be coarse. The material is frequently transported to drains and natural channels close to the

Table 2 Results of urban catchment studies in Peninsular Malaysia.

Catchment	Land use	Area (km^2)	Altitude range (m)	Rainfall (mm)	Sediment yield (t km^2 $year^{-1}$)	Source
Sg. Air Hitam, Penang	Tropical rainforest	4.75	80-810	2580	74.49	Wan Ruslan (1995)
Sg. Air Hitam, Penang	Tropical rainforest in upper part, stable urban area in low	8.87	30-810	2580	376.59	Wan Ruslan (1995)
Sg. Relau, Penang	Disturbed forest and semi-urban	0.553	50-520	1830	911.09	Wan Ruslan (1995)
Sg. Relau, Penang	Rapidly urbanizing, quarrying, construction	11.523	20-520	1830	3102.73	Wan Ruslan (1995)
Sg. Jinjang (1)	Newly urbanizing	10.3	30-120	2400	1056	Balamurugan (1991)
Sg. Jinjang (2)	Tim mining and urbanizing	27.1	25-120	2300	2283	Balamurugan (1991)
Sg. Kelang (1)	Newly urbanizing	14.2	35-590	2400	1480	Balamurugan (1991)
Sg. Kelang (2)	Newly urbanizing and mature urban	29.0	25-590	2300	1372	Balamurugan (1991)
Sg. Keroh	Urban and industrial	35.9	30-90	2200	1759	Balamurugan (1991)
Sg. Batu	forest and urban	145	35-610	2400	1265	Balamurugan (1991)
Sg. Gombak Jln Pekililing	forest and urban	140	25-620	2200	1157	Douglas (1978)

construction site. Control measures are related to increasing channel capacity or diverting the runoff to a new outlet (Gupta, 1982).

The widely documented environmental effects of urban growth in the Kuala Lumpur and Pulau Pinang areas include severe urban erosion (Table 2). Peak flows per km^2 in the city have increased by 4.23 times over natural flows. The increase in runoff volumes by an average of 252% (Ben-Ithnin, 1988) and severe channel aggradation have produced major flash flooding problems. Areas undergoing construction usually experience sediment yields 2 to 3 orders of magnitude greater than those under natural forest. In such catchments, the importance of extreme events is often more marked than under natural conditions, with between 35 and 80% of the annual load being carried in a single month at the Penang stations listed in Table 2.

Federal government legislation enabling local authorities to exert greater control over the lay-out and management of construction sites, and an urban drainage design standards and procedures manual for Peninsular Malaysian conditions appear to have encouraged developers in the Federal Territory of Kuala Lumpur to take a more responsible approach to building site lay-out and management (Leigh, 1982). However, suburban development just outside the territory has moved onto steeper slopes with severe erosion and even occasional lethal landslide problems, such as that at UK Heights at the end of 1993.

One of the major nuisances is when streams that have been diverted for highway or other forms of construction cause erosion in localities formerly considered safe. Frequent accounts of such bank erosion episodes occur in the Southeast Asian press. In June 1995, for example a Malaysian newspaper reported the concern of a family at the way a diverted stream carrying extra runoff from a new highway had eroded laterally for 9 m and was threatening to undermine the family's house.

The highest catchment sediment yields associated with urbanization in the stable, but deeply weathered terrains of Peninsular Malaysia (Sg. Relau and Sg. Jinjang in Table 2) are of the same order of magnitude as those for disturbed and large catchments in Java (columns G and H in Fig. 1). The economics of land development and housing construction in Malaysia still encourage the clearance of large areas at one time, instead of phased development which maintains a vegetation cover for as long as possible. While such a policy remains, the use of steeper land will lead to even more siltation problems in the future.

CONCLUSION

Geologic influences on sediment yield must be taken into account when discussing erosion in Southeast Asia. Under natural conditions, the severest problems arise where volcanic debris is converted into lahars and mudflows by rains from typhoons. Natural erosion rates in undisturbed forests range over at least three orders of magnitude. Disturbance raises catchment sediment yields by 1 to 2 orders of magnitude, selective logging causing 15-20 fold increase, but urbanization leading to increases of over 40 times the natural yields. Where deep weathering provides a major sediment source, erosion of bare land becomes extreme causing massive channel aggradation downstream.

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