

Erosion and sediment yield in Southeast Asia: a regional perspective

AVIJIT GUPTA

Department of Geography, National University of Singapore, Singapore 119260

Abstract Southeast Asia is potentially a region of high erosion and sediment transfer due to several environmental factors, including tectonic movements and volcanism associated with skirting subduction trenches, steep local relief, the mountainous interior of the islands and peninsulas and a very high annual rainfall. The actual erosion rates over most of the region are, however, much lower than expected due to the natural forest cover of this assemblage of peninsulas and archipelagos. Currently, destruction of this cover due to deforestation, expansion of agriculture, urbanization, and implementation of large-scale resettlement schemes has increased the annual sediment yield from <100 to several $1000 \text{ t km}^{-2} \text{ year}^{-1}$. This paper (a) identifies current areas of high erosion, (b) locates related active sediment sinks, (c) reviews existing sediment yield, and (d) discusses the possible effects of sediment loading on channel forms and processes. The data consist of satellite imagery at various resolutions and existing field records of sediment yield from mainly Indonesia, Malaysia, Singapore, and Thailand.

INTRODUCTION

The archipelagos and peninsulas of Southeast Asia are perceived as areas of active erosion and high sediment yield, an observation borne out by a substantive part of the instrumented case studies from the region. Milliman & Syvitski (1992) have estimated the sediment yields to be as high as $3000 \text{ t km}^{-2} \text{ year}^{-1}$, the physical manifestation of which are the large sediment fluxes travelling down small mountainous rivers. The natural explanations for the high erosion rate include location near active plate margins, pyroclastic eruptions, steep slopes, and mass movements (Milliman & Syvitski, 1992). Furthermore, parts of Southeast Asia display striking anthropogenic alteration of the landscape resulting in accelerated erosion rates, although such acceleration may be only temporary, operating on a scale of several years. The combination of anthropogenic alteration and fragile landforms gives rise to very high local yields. Sediment yields of more than $15\,000 \text{ t km}^{-2} \text{ year}^{-1}$ have been estimated from such areas (Ruslan & Menam cited in Lal, 1987). It is even possible to map areas with high sediment yield on a regional scale using low resolution satellite imagery (Gupta & Krishnan, 1994).

The very high rates of sediment yield reported for Southeast Asia have prompted an investigation of the effect of such sediment on channel form and behaviour; its effects on deltas, beaches, mangroves and coral reefs; and whether it leads to a general lowering of environmental quality. The area covered is western Southeast Asia, consisting of parts of Myanmar, Thailand, Lao PDR, Cambodia, Malaysia, Singapore

and Indonesia (Fig. 1). The data used consist of satellite imagery at various resolutions and existing field records of sediment yield collated from a number of sources. This paper (a) identifies current areas of high erosion, (b) locates active sediment sinks, (c) reviews existing sediment yield figures, and (d) discusses the possible effect of sediment loading on channel form and processes.

PHYSICAL ENVIRONMENT OF SOUTHEAST ASIA

Geologically, Southeast Asia is a stable cratonic core surrounded by a seismically active outer arc system. Scattered inland basins of sedimentary rocks and deposition of Quaternary sediments along the coasts and offshore complete the picture. The geological background has given rise to the mountainous islands of Indonesia with their steep volcanic slopes and intermontane basins flanked by flat coastal plains of varying width. Elsewhere the coastal plains generally surround rolling granitic hills and steep mountains, and scarp and vale topography developed on sedimentary rocks. Plains in the interior are formed by several large rivers. Except for northern Thailand, eastern Indonesia, and most of Indochina, the annual rainfall exceeds 2000 mm, rising to over 4000 mm locally. A significant part of the rain may arrive in either the northeastern or the southwestern monsoon. The rain also falls with very high intensity.

Where a vegetation cover still exists over the plutonic and volcanic rocks, a thick regolith is normally found. As many studies in the rainforest have shown, sediment yields from these areas are low (Anderson & Spencer, 1991). Large volumes of sediment are, however, released either naturally on the volcanic islands or because of anthropogenic modification of the land. The anthropogenic modifications are related to deforestation, agricultural expansion, resettlement of population in area of low population density, and urbanization. All these activities have greatly increased in the second half of this century and the superimposition of these on the natural environment of thick weathered material, steep slopes, short swift streams, and intense and heavy rainfall is reflected in the current high sediment release. Such rates, usually decline after several years, but they continue to remain much above the original level.

AREAS OF HIGH EROSION AND ACTIVE SEDIMENT SINKS

Mapping of coastal areas with high sediment concentrations at or near the water surface has been carried out for South and Southeast Asia by Gupta & Krishnan (1994), using Advanced Very High Resolution Radiometer (AVHRR) imagery. The original AVHRR image covered a larger area from which a small section has been selected for this paper (Fig. 1). Sediment plumes large enough to show up on the AVHRR imagery are generally absent from the southwest and southern coasts of Sumatra and Java. Only two plumes could be identified, one in Sumatra and the other in Java. Both are associated with river systems, the Simpang in Sumatra and the Citanduy in Java, flowing into sheltered bays and lagoons. It has not been possible to collate any information regarding sediment transfer by the Simpang, but the Citanduy has long been recognised as a river with high sediment load (Hardjowitjtro, 1981). A description of its behaviour and pattern of sediment transport is also available (Stevens, 1994).

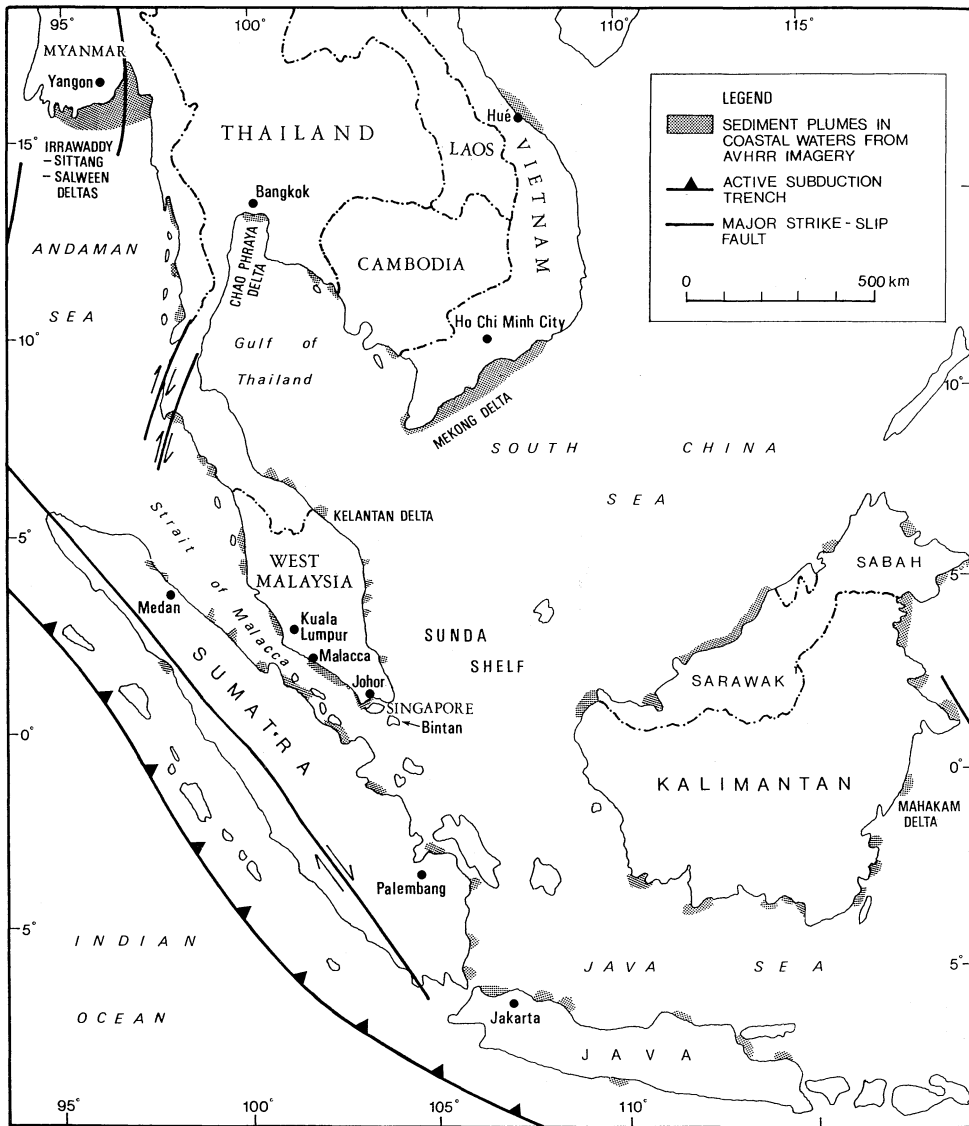


Fig. 1 Coastal sediment plumes, part of Southeast Asia. Mapped from AVHRR mosaic with 1.1 km resolution. plume areas approximate.

Even when satellite images with a resolution of 50 m are examined, no other plume shows up on these coasts. This is surprising, given the combination of steep volcanic slopes, high annual rainfall, and disturbances associated with the convergent plate margin location. It is possible that strong wave action along this coastline prevents large accumulations of sediment at river mouths. The prevalence of straight coasts, coastal sand dunes, and the absence of large protruding deltas at river mouths support this hypothesis.

In contrast, the coasts of the shallow cratonic South China Sea indicate the presence of a large number of sediment plumes of various sizes, a number of which show up on AVHRR imagery (Fig. 1). Sediment accumulation is expected to, and does, occur at the mouths of large rivers to form deltas, although the size of the deltas vary. The Chao Phraya, for example, has a delta the size of which is much below the regional norm for a river basin of its size (Gupta & Krishnan, 1994). Elongated river mouth plumes, coalescing and stretching for hundreds of kilometres along the coast occur in Tenasserim, Malacca, Southwest Johore, off the Vietnam coast near Hué, along the coasts of northeast Sumatra, north Java, Sarawak and, in a discontinuous pattern, around the rest of the island of Borneo. The occurrence and magnitude of most of these plumes is difficult to explain in terms of the natural environment of the drainage basins, and anthropogenic disturbances are suspected to be the main cause. In most of this area of hilly peninsulas and archipelagoes, the upper parts of small rivers commonly drain a coastal range. A good example is the Sarawak coast (Fig. 1) where a number of short rivers drain the coastal hill ranges. The sediment plumes at the mouths of these rivers have coalesced laterally to extend for about 800 km. Given the small basin area, the geology, and the low population density the suspected explanation for excessive sediment production, transfer and deposition is deforestation of the slopes. Such deforestation is clear for many areas, even from small-scale forest cover maps (Collins *et al.*, 1991). On-going timber extraction, extension of agricultural land, establishment of plantations, large development projects such as *transmigrasi* in Indonesia and FELDA in Malaysia, along with rapid urbanization, continue to destroy natural vegetation on slopes. Collins *et al.* (1991) determined that in the 1980s most of the countries of Southeast Asia had an annual deforestation rate of thousands of km².

Figure 1 shows the coastal sediment sinks, and by implication the approximate areas of accelerated erosion which release the sediment. It does not, however, indicate the inland sinks such as alluvial fans, flood plains and channel features. The occurrence of sediment sources and sinks is even more widespread than shown in Fig. 1.

MEASURES OF SEDIMENT YIELD

Sediment yield estimates have been produced for various areas using methods as different as sediment sampling of streams, calculation of ground lowering from small erosion plots, or determination of the rate of extension of a delta into the sea over a number of years. Slope, geology, land use and rainfall vary widely in these studies. The data examined for this paper come mostly from Malaysia and Java (Indonesia). Only published information has been used. Some of the published figures are in t km⁻² year⁻¹ whereas others are in m³ km⁻² year⁻¹. Even when converted into the same unit of measurement no single figure can represent any set of rock types or land use. For example, for small plots undergoing active urbanization, the sediment yield figures range from 1050 to 1500 t km⁻² year⁻¹. The data have been grouped according to land use types, but the frequency for individual categories only reaches a reasonable size for two classes of land use: (a) forests, and (b) relatively large river basins with mixed types of land use. Published information on sediment yield for anything else is sparse.

The sediment yield data from forests range from nil to 460 t km⁻² year⁻¹ (Anderson & Spencer, 1991; Douglas *et al.*, 1992; Douglas *et al.*, 1993; Greer *et al.*, 1994; Lai,

1993; Law *et al.*, 1989; Leigh & Low, 1973; Malmer, 1990; Murtedza & Ti, 1993; Peh, 1981; Ruangpanit, 1985; Ruslan & Menan in Lal, 1987; Shallow, 1956; Sinun *et al.*, 1992; Weera & Kittipong, 1987; Wiersum, 1984; Zulkifly *et al.* cited in Douglas *et al.*, 1993). The distribution of yield figures is skewed to higher values, with the mean at $69.55 \text{ t km}^{-2} \text{ year}^{-1}$ and a median of 34.3. If the values more than two standard deviations higher than the mean are removed, the mean drops to $45.2 \text{ t km}^{-2} \text{ year}^{-1}$ and the standard deviation is almost halved. The annual sediment yield from the forested slopes of Southeast Asia is therefore generally low, and only tens of t km^{-2} , but under special situations it can rise to much higher figures. Such figures are, however, not high enough to build extensive depositional features. It is likely that the sediment will travel downstream in pulses, being stored intermittently as part of the channel features or the flood plain. With the destruction of the forest the sediment yield increases, at times dramatically.

A representative figure for land under shifting cultivation or continuous agricultural operations is difficult to ascertain, as the number of sediment yield measurements are limited. Douglas *et al.* (1993) have remarked that the only valid soil erosion data for the effect of shifting cultivation in Malaysia are the measurements by Hatch on 40 m^2 plots. Some of his figures are high, such as those for pepper cultivation in traditional fashion, but, given the small size and temporary nature of the operation, the total erosion figures are less significant. The figures for shifting cultivation determined by Weera & Kittipong from Thailand are comparable and sediment yields of around a few thousand $\text{t km}^{-2} \text{ year}^{-1}$ can be expected so long as the fields are open and no proper conservation measures are adopted. When entire basins are considered (parts of which have remained forested), the values may drop to hundreds of tonnes (Murtedza & Ti, 1993). The few measurements of sediment yield from agricultural areas show a wide range, from hundreds to thousands of tonnes mostly determined by the presence or absence of conservation measures (Douglas *et al.*, 1993; Shallow, 1956; Weera & Kittipong, 1987). With logging, as expected, the figures are very high for the first 2-3 years and can be in thousands of tonnes; the two highest figures in the literature were over $7000 \text{ t km}^{-2} \text{ year}^{-1}$ from Sabah (Greer *et al.*, 1994) and more than $15\,000 \text{ t km}^{-2} \text{ year}^{-1}$ from Java (Ruslan & Menan, in Lal, 1987). The number of observations are insufficient for statistical calculations, but we may arbitrarily assume a conservative figure of annual sediment loss of 1500 t km^{-2} . This sediment will progressively move downstream, and if from small coastal basins, will reach the sea within a few years. If logging continues in the basin, the pattern will persist. Rapid urbanization in Southeast Asia is producing sediment at rates comparable to logging (Balamurugan, 1991; Douglas, 1978; Leigh, 1982). Its storage and transfer are similarly both temporary.

The sparse sediment yield data make it difficult to estimate how much extra sediment will travel downstream once the natural vegetation is removed. Erosion plot based studies have indicated that the change can be extreme. Anderson & Spencer (1991) have referred to an increase of 53 times in Java, from 30 to $1590 \text{ t km}^{-2} \text{ year}^{-1}$. It is debatable, however, whether figures from erosion plots or single gauging stations should be regionally extrapolated. Perhaps the best estimate of the volume of sediment being generated due to anthropogenic activities in Southeast Asia lies in the figures available for large basins (area in hundreds to thousands km^2) with a combination of land use in their catchment areas. Data of this type exist for Indonesia, Malaysia, and Thailand (Aitken, 1981; Balamurugan, 1991; Hardjowitjtro, 1981). The densely populated

Cimanuk basin has extensive rice fields in the lower plains, whereas the upper slopes are in upland crops, rice, and forest or scrub with volcanoes marking part of the divide (Aitken, 1981). The 42 basin measurements produce a mean of $4051.2 \text{ t km}^{-2} \text{ year}^{-1}$ and a median of 2932. This is also a skewed distribution. Interestingly, most of the load carried by the rivers is less than 0.05 mm in size.

THE EFFECT OF THE SEDIMENT

Under natural conditions, it is only on the volcanic islands of Southeast Asia that river channels can be choked with sediment arising from pyroclastic flows followed by lahars. Lavigne & Thouret (1995) reported 20 rain-triggered lahar events in the Boyong River draining the southern slopes of the Merapi Volcano in Java where about 10^6 m^3 of material was delivered in six months, completely filling up the channel. Takanashi

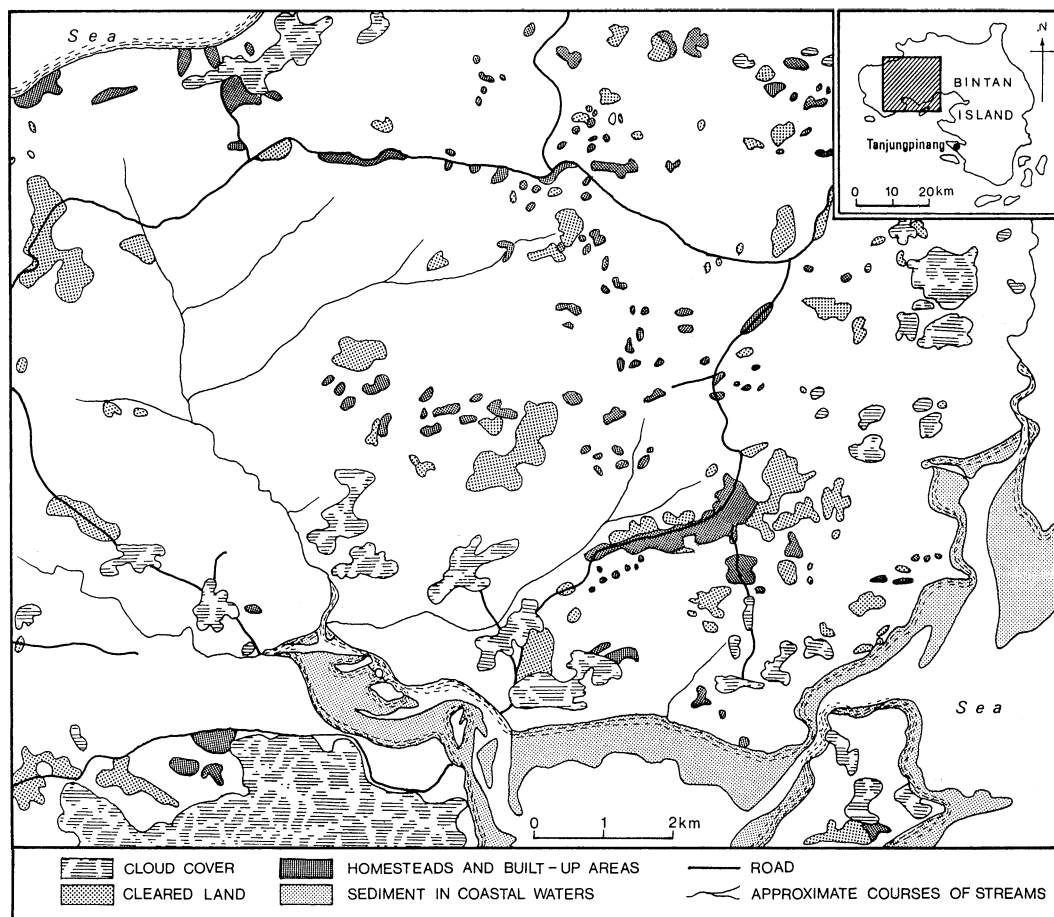


Fig. 2 Pulau Bintan, Riau Archipelago. Sediment sources, transfer, and sinks mapped from Landsat TM imagery.

(1981) has described similar deposition of volcanic material from the Kelud Volcano in the channel of the Brantas River in Java. The river channel downstream shows evidence of carrying large amounts of both bed and suspended load (Voskuil & Zuidam, 1982), and unless anthropogenically removed, becomes flood-prone (Takanashi, 1981). In comparison, anthropogenic modification of the forest cover increases the sediment load in all areas of Southeast Asia, particularly in areas which are either steep or underlain by erodible rock formations.

Koopmans (1972) described the early deposition of coarse bed load by rivers flowing out of the granitic Main Range of Malaysia. The extensive flood plains of the lowlands are primarily built by deposition of finer suspended load. Increased sediment yield will further load the streams with fine sediment thereby locally increasing the flood potential. Small rivers draining coastal ranges will bring this suspended sediment to the coastal waters. For example, the rapid urbanization of the Pontian coast in Johore, Malaysia has resulted in coastal plumes which show up even on AVHRR imagery. Sediment is seen to travel from source to sink when high resolution Landsat images of this area are enhanced. Figure 2 is an example of a similar situation on Bintan Island (Indonesia), south of Singapore, where several km long streams are transferring sediment from land which has been cleared to the waters of sheltered bays. In larger rivers, sediment transport following deforestation in the basin may have only local manifestations, except during large floods (Douglas *et al.*, 1993).

The huge increase in sediment yield gives rise to bar formation, raising of the channel bed, increased flooding, accelerated flood plain formation, and possibly changes in channel pattern. Such changes are expected but do not always follow, as Stevens (1994) has shown for the Citunduy River (Java) which aggrades due to both anthropogenic modifications of the land use and volcanic eruptions in the upper basin. In spite of this, the Citunduy remains stable because of its tough clay banks and bed. The sand is transported above the clay bed.

Considerable amounts of sediment are, however, reaching the coastal waters of Southeast Asia leading to delta formation (Aitkens, 1981; Hadisumarno, 1979; Koopmans, 1972), beach building, and (probable) degradation of mangroves and corals reefs. Research in general, however, is still mostly involved with measuring sediment yield in experimental stations. It is time to establish the regional picture and also to determine the effects of accelerated sediment discharge to the streams and coastal waters.

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