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Spatial distribution of sediment discharge to the coastal waters of South and Southeast Asia

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Abstract South and Southeast Asia have been identified as areas with very high rates of erosion and sediment production (Milliman & Syvitsky, 1992). This could be attributed to both natural (plate margin tectonics, volcanic deposits, steep slopes, high and intense rainfall) and anthropogenic (deforestation, urbanization) factors. However, only a few sediment-related measurements are available from a small number of rivers. Attempts are made to use a surrogate measure by mapping sediment plumes in coastal waters using AVHRR imagery for the area between the east coast of India and the island of Borneo. Although the data are based on surface reflection from suspended sediment-laden coastal waters, it has been possible to (a) map the distribution of sediment plumes over a very large area, (b) identify the areas with above normal sediment production, and (c) hypothesize whether such high sedimentation rates are natural or due to anthropogenic modification of the land.

INTRODUCTION

High rates of erosion and sediment production emerge from the few case studies that exist on drainage basins of South and Southeast Asia. Based on good evidence, such rates have been generally attributed to anthropogenic alteration of the land cover and land surface features (Bruijnzeel, 1990; Douglas, 1978; Douglas *et al.*, 1992). In a recent paper on worldwide sediment discharge to the oceans – the latest of this genre which includes Holeman (1968), Milliman & Meade (1983) and Walling & Webb (1983) – Milliman & Syvitski (1992) attributed unusually high sediment yields to the rivers draining Southern Asia and the archipelagoes and peninsulas of Southeast Asia. The yield figures, in their estimation, could be as high as 3000 t km^{-2} $year^{-1}$. The log-linear function of sediment yield with basin area and maximum elevation tends to be modified in South and Southeast Asia by the effect of human activities, climate and geology. Sediment fluxes from small mountainous rivers, frequently draining into active plate boundaries, have been greatly underestimated by earlier studies. Recurring tectonic activities of active plate margins which resolve into earthquakes, volcanic eruptions, mass movements and steep slopes are behind such high figures (Milliman & Syvitski, 1992).

In this paper, part of this area with high sediment yield is examined at a regional scale. Direct measurement of sediment load is available only for some rivers and a few instrumented sites. The instrumented sites have usually been designed to monitor disturbances due to anthropogenic activities, such as deforestation or urbanization, rather than to reflect the natural environment. Figure 1, which is based on data listed

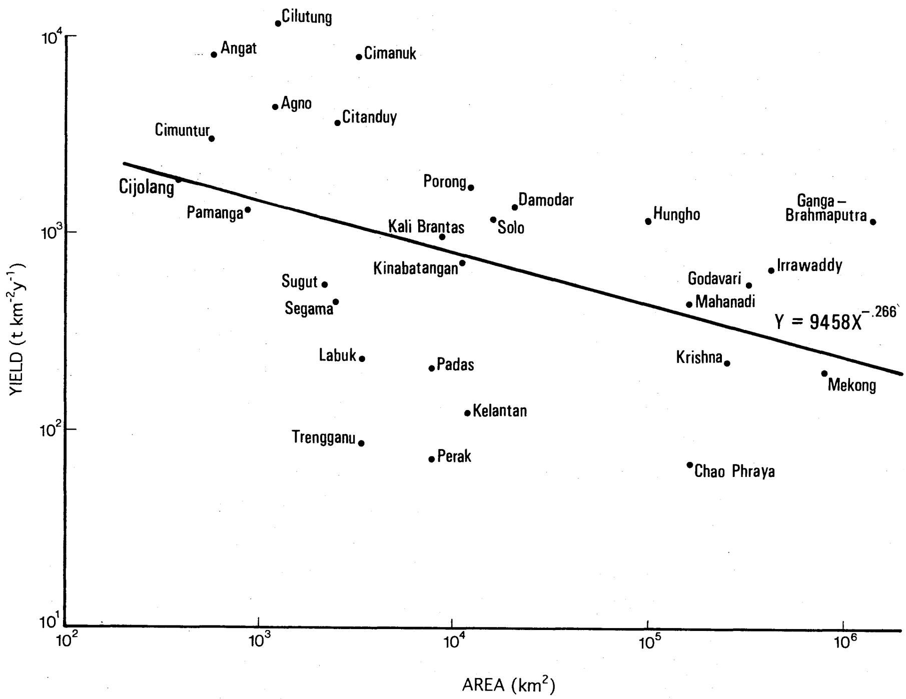

Fig. 1 Deviation in sediment yield from area based regional expectation. Data from Hoekstra (1989), Milliman & Meade (1983), Milliman & Syvitski (1992) and Murtedza & Ti (1993).

in Milliman & Syvitski (1992), supplemented with information from a few other sources, summarizes the available information, and indicates considerable variations within the region.

A surrogate is needed for direct measurement in order to present the pattern across this large region. This need was met by using the Advanced Very High Resolution Radiometer (AVHRR) imagery, which has low resolution, but covers a large area. AVHRR imagery was used to (a) map the distribution of sediment plumes across the study region; (b) identify areas with above normal sediment production; and (c) determine from knowledge of the area and published material, whether such high rates of sedimentation were natural or were related to anthropogenic modification of drainage basins.

THE NATURE OF THE AVHRR IMAGERY

The AVHRR image used was a mosaic of 38 afternoon pass images recorded by NOAA-11 along 10 different orbits between 12 November 1990 and 3 March 1991 received from GRID-Bangkok. The area covered was from 81° to 120°E and from 29°N to 10°S. From east to west it extends from the island of Borneo to the east coast of India, and from north to south from India and Myanmar to the south coast of the Indonesian islands of Sumatra and Java. The spatial resolution was 1.1 km. Only the extract images of the first two bands were used: band 1 (visible) and band 2 (near infrared). Variable cloud cover was present in the composite mosaic which created problems in plume identification over parts of the area, especially in the Strait of Malacca. On the unclassified composite image only the large sediment plumes were visible. A simple masking of the land features considerably improved the image and more plumes appeared clearly. However, neither an unsupervised cluster analysis nor a principal component analysis was very effective in further improving the image. A cloudfree subset covering parts of the Bay of Bengal was extracted, including the deltas of the Ganga-Brahmaputra and the Irrawaddy, the Sittang and the Salween systems. A simple unsupervised cluster analysis of this subset produced good results, improving the clarity of the sediment plumes. Masking of the land improved this subset image even further and local differences could be seen within the plumes. Sediment plumes show up clearly on AVHRR imagery when the area is cloudfree, but for this very large study area extending across the equator it is not usually possible to get an entirely cloudfree scene. The number of AVHRR images which could be used for mapping sediment plumes in the study area is therefore extremely limited, which hinders comparison between images at different seasons or between images taken several years apart. For example, it was originally intended to carry out a comparative study of the size of the plumes from different parts of the study area during the two monsoon systems, but it was not possible to do any measurement or significant image enhancement as cloud cover and reflection existed for at least one of the two images for most of the coastal area.

A high concentration of suspended sediment in water causes increased scattering of incoming radiation and strong spectral radiance (Bhargava & Miriam, 1991). Measurements of direct or derivative spectral reflectance have been used to estimate suspended sediment concentration in laboratory experiments or small bodies of water. Given the size and environmental variability it was not possible to do so for the study area. Instead the area was mapped for sediment plumes (Fig. 2), and the size of the plumes was used as an indicator of erosion and sediment yield from the drainage basin concerned. Such plumes have been mapped off the mouth of the Amazon and along the Brazilian coast (Amaseds Research Group, 1990). In Southeast Asia this has been done for the Bangkok Bay and off the Mekong Delta (Tanchotikul, 1987).

THE SPATIAL DISTRIBUTION OF SEDIMENT

Basically, Fig. 2 is a map of the coastal waters where the sediment concentration at the surface or near surface is high enough to produce a bright reflectance. Because the spatial resolution of an AVHRR image is 1.1 km, any area that shows up has a high sediment-producing drainage basin inland. A problem arises from the temporal variability in sediment production and sediment release. Slugs of sediment released either by natural or anthropogenic causes often take time to reach the coast if the river is long, and therefore such sediment outpourings may not yet be visible when the image is taken. For a small basin which has undergone an event of catastrophic sediment production, the plumes may be highly visible or enlarged for several years, but then return to a more common smaller size. This happens following a major volcanic eruption, as demonstrated by the events following the eruption of Mount St Helens in the State of Washington, USA (Meade & Parker, 1985). Similarly, the increase in sediment production following deforestation near Bengkulu in Sumatra lasted only for a limited number of years (Collins *et al.*, 1991; J. R. Giardino, personal communication).

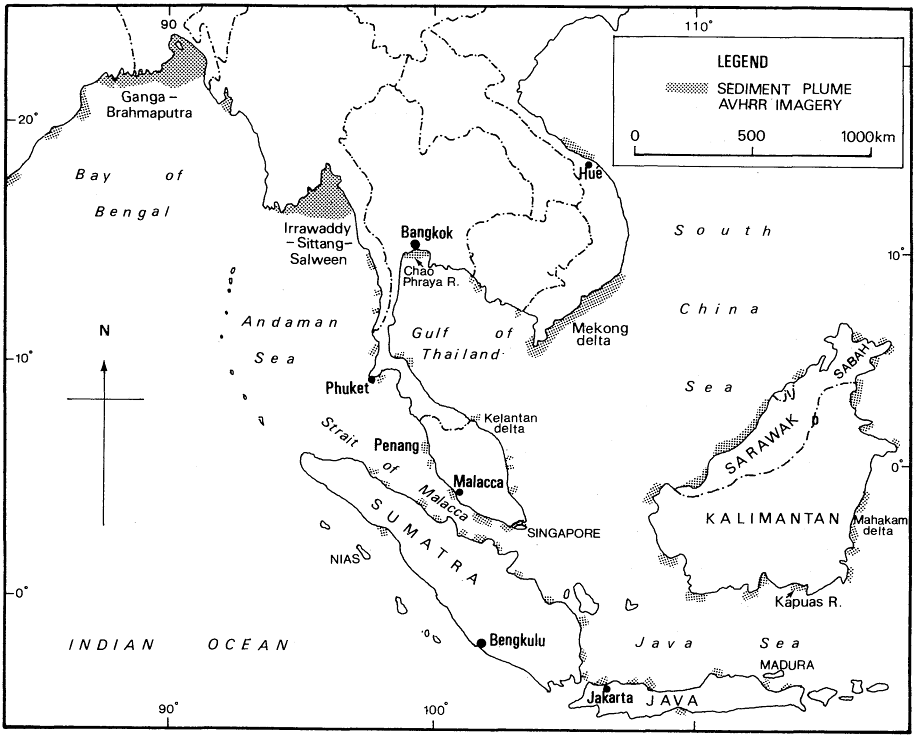

Fig. 2 Coastal areas with high sedimentation, parts of South and Southeast Asia.

It may be concluded that a map like Fig. 2 will show the regional pattern, and include the major plumes, but the inclusion of the minor ones could be a random phenomenon.

Sediment discharge into the sea is far from uniform. Some areas have few or no plumes. In other areas a patchy distribution is seen. Some of the plumes can be very large (Irrawaddy-Sittang-Salween) or extend along the coast for hundreds of kilometres (Sarawak coast). A sediment plume is naturally expected off the mouth of a large river and such examples do occur, but the coastal waters in a number of areas are also unusually murky, indicating a number of drainage basins undergoing considerable erosion.

Certain general conclusions can be reached. Very large sediment plumes are seen off the deltas of some of the major rivers: Ganga-Brahmaputra, Irrawaddy, Salween, Mekong, Kelantan and Mahakam. In comparison, the plume of the Chao Phraya is conspicuously small, which matches the findings of Milliman & Syvitski (1992) from direct sediment measurement. Large plumes (in places coalescing and stretching for hundreds of kilometres along the coast) occur along the Tenasserim coast, east of Phuket, between the island of Penang and the Malaysian mainland, near Malacca and southwest Johore, near Surat Thani, at the head of Bangkok Bay, and along the Vietnam coast near Hué. On the islands, large sediment plumes occur along parts of eastern coast of Sumatra, and on the north coast of Java (near Jakarta, Cirebon, Tanjong Bugel) and between the islands of Java and Madura. Widespread sediment discharges occur around the island of Borneo except the extreme north. Almost the entire Sarawak coast is releasing sediment but the plumes are bigger off the mouths of large rivers such as

Kapuas and the Mahakam, both in Kalimantan. In contrast, there are only two areas of sediment accumulation in the coastal waters off the southwestern coasts of Sumatra and Java. Sediment accumulation along the Gulf of Thailand is also rather patchy.

The size of the plumes was measured by counting pixels, and the results are shown in Table 1. Only a certain number of plumes could be measured, but the figures in Table 1 and the map (Fig. 2) are in accordance with the conclusions of Milliman & Syvitski (1992). Certain generalizations regarding the location of conspicuous sediment plumes are possible. Large plumes are seen off the mouth of large rivers (except the Chao Phraya), in sheltered bays where small rivers end, and between an island and mainland or between two islands. Except the Ganga-Brahmaputra delta and the accumulations along the coasts of Myanmar, large sediment plumes occur on shallow shelf seas and are absent from active plate margins associated with subsidence.

The sizes of plumes at river mouths are directly proportional to the basin area. In most cases the upper parts of the rivers concerned drain basins backed by a coastal range. On the Sarawak coast a number of rivers, one or two hundred kilometres long, drain out of a mountain range parallel to the coast, producing plumes which have merged with each other along the coast for nearly 800 km. There is no natural explanation for such widespread sedimentation which is probably due to the deforestation on the slopes. Deforestation along such valleys extends into the hills beyond the coastal plains, as shown even by the small-scale national forest cover maps of Collins *et al.* (1991). The congregation of sediment plumes to the east coast of

Table 1 Areal size of selected sediment plumes in parts of South and Southeast Asia.

Location	Area of deposition	Plume area (km^2)
Ganga-Brahmaputra	large delta	40 444.3
Irrawaddy-Salween	large deltas	40 645.1
Mekong	large delta	14 180.0
Kelantan	delta	863.9
Penang, east coast	narrow strait	666.7
Perak coast	strait	294.0
Pekanbaru coast	narrow strait	989.8
Telok Labuk, Sabah	small bay	1 088.7
Telok Darvel, Sabah	small bay	5 581.7
Tidung, Kalimantan	delta	1 377.0
Mahakam, Kalimantan	delta	1 160.4
Adang, Kalimantan	small bay	1 040.6
Kapuas, Kalimantan	delta	733.3
Sarawak coast	delta and coast	7 257.6
Telok Branai, Sabah	small bay	500.9

Note: The figures refer to the area of the sediment plumes. Only plumes which were large and cloudfree enough to be measured are included.

Sumatra could be due to the presence of a shallow strait in contrast to the deep water over the active subduction trenches of the west coast, but it is also probably due to the widespread forest destruction in the eastern parts of this island. Tectonics, relief and rainfall pattern no doubt have in combination determined which river basins will be extensively eroded, but deforestation and settlement have also accelerated erosion of the mountains beyond the coastal plain. The pattern of the sediment plumes of Fig. 2 is indicative of such a background.

A remarkable similarity exists between Figs 1 and 2. If their size is big enough, the rivers above the line of best fit display plumes on AVHRR imagery. Only very large rivers, such as the Mekong, may show plumes and still plot below the line. In the case of the Mekong, however, the correct interpretation from Fig. 1 should be that it is producing the regional average, and the regional average is high. The small basins on Fig. 1 above the line are rivers in Indonesia and the Philippines, and could be expected to be undergoing considerable erosion and sediment production both due to natural and anthropogenic causes. The small basins below the line are of rivers from parts of eastern and western Malaysia which still have a considerable part of their basin area forested and are away from active plate margins. The difference between the two figures is that the map from AVHRR imagery can be produced in about a week, and is thus very useful for identifying problem basins quickly, especially for areas from which data on sediment production are not easily available. A map like Fig. 2, which provides the regional picture, is extremely difficult and time-consuming to prepare from the field data.

Pixel size is a very important factor in plume determination. As part of this project, smaller areas have been examined using Landsat TM with 30 m resolution. At that level, river mouth plumes appear more widespread and the effect of local disturbances are clearly seen. This work is continuing but it is too early to report on the results. It should be stated, however, that even with that high resolution, plumes are not visible at each river mouth. The areas identified on AVHRR resolution imagery as regionally low in sediment production show either small plumes or none. At the same time greater details could be picked up for the high yield areas.

Although it does not produce direct measurements of sediment yield, AVHRR imagery, which can be acquired at the cost of a computer tape, can very quickly produce a regional picture of erosion and sedimentation. If cloudfree scenes are easily available, it should be possible to see the seasonal changes in sedimentation by comparing two images at different periods, or even to record a time-sequence of changes in sediment production over years. It is therefore an excellent tool for reconnaissance study, as has been attempted for parts of South and Southeast Asia.

CONCLUSIONS

Using AVHRR imagery one could quickly (a) establish the location of sediment plumes in the study area, (b) identify areas with above normal sediment production, and (c) determine some of the factors which cause high rates of erosion and sedimentation. It has not been possible to measure the volume of sediment derived from the drainage basins, but a surrogate measure, sediment plume size, has been used for comparison between the plumes.

It is therefore possible to quickly determine areas undergoing extensive erosion on a regional scale. Though the accuracy is limited to pixel size, the importance of such mapping is twofold. First, this leads to the identification of basins undergoing high erosion which need better land management; and second, also to the depositional areas where excessive sediment might cause ecological problems by affecting beaches, coral reefs and mangroves.

Such mapping has been carried out for South and Southeast Asia. In areas where cloudfree images are more readily available, it should also be possible to compare between seasons regarding the amount of sediment reaching the coastal seas, and furthermore, to study erosion and sedimentation over time.

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