

Sediment Released to Coastal Waters of Southeast Asia: Seasonal and Spatial Distributions

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Introduction

The amount of sediment going out to the coastal waters of the world has been investigated and mapped several times (Fournier, 1960; Holeman, 1968; Milliman and Meade, 1983; Walling and Webb, 1983; Milliman and Syvitski, 1992; Meade, 1996; Hovius, 1998). Milliman and Syvitski (1992) explored the causes behind variation in amount of sediment released to coastal waters. Statistical relationships were established between sediment load and basin characteristics. Hovius (1998) indicated that sediment yield in large catchments are associated with erosion rates in the upper basins. In certain large rivers such as the Amazon or the Orinoco, nearly 90 percent of the sediment is derived from tectonically active steep source areas of headwaters (Warne et al., 2002; Meade, in press). In many river basins, natural rates have been tremendously accelerated by anthropogenic alteration of land use. This is particularly true for Southeast Asia (Gupta, 1996), where part of the region carries a very high rate of $3000 \text{ tkm}^{-2}\text{yr}^{-1}$ naturally (Milliman and Meade, 1983; Milliman and Syvitski, 1992).

Milliman and Syvitski, in their 1992 paper, asked “What is the sediment flux to the sea?” and concluded that we do not yet know the answer to that question. In this paper we propose a methodology based on remote sensing that provides part of the answer to this question for a sector in Southeast Asia. We, however, are not able to provide volumetric measurements, as transformation from remotely sensed images to calculation of sediment volumes in water involves a very large number of variables that change locally and thus difficult to determine over a large area.

We use MODIS images for sediment measurement. The work has been carried out at the Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore. This type of work has been attempted earlier, using AVHRR for Southeast Asia and other sensors for smaller locations (see Gupta and Krishnan, 1994 for a discussion). MODIS, however, provides better images for sediment mapping because of higher resolution (250-1000 m, depending on the band used) and a much larger choice of bands. The technique and its follow-up interpretation are still being developed but currently the methodology is at a stage where offshore sediment plumes can be repeatedly mapped with reliability.

Methodology

We use MODIS Level IB 500-m granules which provide calibrated and geolocated radiances at apertures for MODIS Spectral bands. The area covered at present measures 2330 x 2030 km and includes parts of Kra Isthmus, the Malay Peninsula, Sumatra, Java, Bali, Lombok, Borneo, the neighbouring smaller islands, and the southwestern part of the Mekong delta. The MODIS temporal coverage is almost twice daily and the data are available by direct broadcast to CRISP by NASA-EOS Gateway.

Sediment-laden waters reflect strongly in the green and red bands and are commonly mapped using reflectance. Extensive field measurements are needed to derive the statistical relationship between reflectance values and sediment volume using either regression analysis or supervised classification methods. These can be done at pre-selected stations. A long range of field measurements are required at many locations to do this over a large area, a demanding task.

We, however, mapped the particle backscattering coefficients, which measure the amount of light scattered back to the sensor by suspended particles in water. This physical quantity is directly related to the measured reflectance. High particle backscattering coefficients are indicative of high sediment loads. We used the input of MODIS calibrated reflectance for Band 1 (red), Band 2 (NIR), Band 3 (blue), and Band 4 (green). The values were corrected for ozone absorption and Rayleigh scattering. The land was masked out. The NIR channel was used as a measure of reflectance from aerosol and water surface. Finally, using ocean colour model (quasi-analytical algorithm), particle backscattering coefficients were extracted for Band 1 (red).

The selection of the scenes had to be done carefully as most of the scenes are either cloud-or sun-glint contaminated. It required obtaining information from various scenes to build-up a complete spatial distribution at a regional scale. We mapped the maximum particle backscattering coefficients for each month. At present this has been completed for each month over the period February-December 2004. The project will continue and further monthly information will be added to the collection.

The sediment maps

Sediment maps were prepared at two levels. First, coastal areas were mapped for a 4.7×10^6 km rectangular sector as described earlier. This large area was mapped for each month between February and December 2004 showing the maximum sediment released for each month. This area will henceforth be referred to as the 'large area'. Three smaller areas within this rectangle were then presented at a larger scale for each of these months. The areas are (1) the southwestern corner of the Mekong Delta, illustrating sediment release and distribution off the mouth of a large river, (2) southwestern corner of Kalimantan indicating sediment off a coastal marsh and two small rivers, and (3) part of the northwestern coast of Sumatra (magmatic arc mountains), the Mantawai Strait (fore-arc basin), and part of the island of Nias (fore-arc ridge) as an example of sediment input from steep inland basins and its disposal in a tectonic setting.

In all cases, sediment plumes were seen to change over time. We have not explored the possible accounting of the time-sequence of changes or the distribution yet, but some explanations are obvious.

The pattern of sediment distribution and disposal

The large area mapping indicates that plumes tend to occur in certain areas at this scale. Such plumes may be persistent but they tend to vary in size depending on the direction of the monsoon. We have so far mapped sediment release for the southwestern monsoon (approximately June to October, continues longer in certain areas) and the relatively dry period preceding the southwestern monsoon.

It is apparent that in Southeast Asia, transfer of sediment to the coast follows seasonal (monsoon) rainfall. The supply of sediment depends on the volcanic and tectonic aspects of river headwaters. Recently anthropogenic disturbances have also

drastically increased sediment yield (Table 1). Sediment accumulation and movement in coastal waters, however, depend on a host of factors: offshore topography, coastal currents, wind direction, etc. At this stage we are mapping the changes in sediment release and explaining variations in sediment discharge to coastal waters have not been systematically attempted. We, however, highlight certain factors as possible explanations of coastal sediment fluxes.

We used the three smaller locations in different environments to illustrate sediment fluxes. The monthly maps of the Mekong Delta illustrate the accumulation of coastal sediment with the monsoon and sediment transport along the delta-face towards the southwestern corner of the Ca Mau Peninsula and its sudden disappearance beyond. This raises several questions such as whether the Lower Mekong Basin experiences more storminess towards the end of the southwestern monsoon or there is a clear time lag. Does the southwestern transport indicate currents, or the presence of a structural depression beyond Ca Mau? And do these patterns influence delta-building of the Mekong?

In southwestern Kalimantan, where the coast surveyed is backed by a swamp and two small rivers, increase in sediment flux with the monsoon is seen again, although the sediment plumes are not so prominent and end much earlier. In the tectonic setting of Sumatra and adjoining areas, the sediment plumes are smaller; the monsoon effect is repeated; and sediment plumes enlarged by land use changes inland are persistent, although they also increase in size in the monsoon.

Conclusion

So far we have mapped sediment plumes from MODIS imagery. We intend to look into the environmental constraints of plumes and their fluxes, including both natural

and anthropogenic causes in future. It should be noted that sediment fluxes may have a long-term pattern but disruptions are also imposed on such patterns from anthropogenic changes and high-magnitude low-frequency events such as the 26 December tsunami in the Indian Ocean.

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Types of land use	Sediment yield ($\text{tkm}^{-2}\text{yr}^{-1}$)
Forest	$10^0 - 10^2$
Logging, early stage	10^3 , max. recorded 15000
Shifting cultivation	10^3 (plot measurement) 10^2 (from entire basin)
Agriculture	$10^2 - 10^3$, depending on conservation methods used
Urban construction	10^3
Large river basin (mixed land use)	$10^2 - 10^4$, mostly 10^3

Table1. Sediment yield from different types of land cover
(data collected from published accounts in South and Southeast Asia)