Sediment movement on steep slopes to the Mekong River: an application of remote sensing

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Abstract We utilize archived satellite images for studying erosion and sediment movement on steep slopes of the middle Mekong River basin in Lao PDR. Such images enable rapid evaluation of a large area as well as monitoring change over time which is otherwise difficult. In this paper we have traced the seasonal pattern of erosion and sediment storage and transfer for about 225 km^2 of steep terrain drained by one of the world's largest rivers. The first several weeks of the wet season is the period of maximum erosion and sediment transfer on slopes which are then covered with vegetation, although sediment transfer continues for the rest of the wet season in the channels. We have also observed the changes over 8 years of data. We submit that information in the form of archived satellite images can be used to significantly extend current observations on accelerated erosion and sediment storage and transfer.

Key words satellite images; Mekong River; erosion; sediment transfer and storage

INTRODUCTION

A number of studies (Anderson & Spencer, 1991; Gupta, 1996; Gupta & Krishnan, 1994; Gupta & Chen, 2001) have discussed storage and transfer of large volume of sediment on the slopes and in the channels of Southeast Asia, sediment which ultimately ends up in coastal waters (Milliman & Syvitski, 1992). This aspect of environmental degradation is usually related to vegetation removal and unwise land-use practices on steep slopes, which experience high annual rainfall with a strong seasonal component. Two constraints limit the applicability of these studies. First, most approaches are field-based and necessarily limited to data from a small area which are then extrapolated to represent a large region. Second, it is not always possible to extend the findings over time. We submit that information in the form of archived satellite images can be used to extend observations on accelerated erosion and sediment storage and transfer, at least to identify trends, over large areas.

We demonstrate the application of satellite images for erosion and sediment monitoring for an area in the middle Mekong basin in Lao PDR. We use SPOT 20 m multispectral satellite images archived in the Centre for Remote Imaging, Sensing and Processing (CRISP), Singapore, and one Landsat image from 1992 for reference, as CRISP started receiving images from September 1995. The images have been supplemented with (a) field observations and (b) hydrological and morphological information received from the Mekong River Commission. Previous work in this area (Chen *et al.*, 2000; Gupta, 1998) identified the general vulnerability of the slopes to vegetation removal. This paper indicates: (a) the seasonal distribution of accelerated erosion and sediment transfer and storage, (b) the processes involved, and (c) the pattern of change over a number of years.

THE STUDY AREA

The pan-shaped 795 000 km^2 basin of the Mekong drains into the South China Sea across six countries: China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam. The Mekong is the eighth and tenth largest river in the world for mean discharge and average suspended sediment load respectively (Meade, 1996). We have examined 13 969 km^2 of the middle Mekong basin (Fig. 1) using four SPOT satellite scenes (Gupta *et al.*, 2002). This is an area of steep-sided ridges and valleys, with the ridge tops rising to more than 1000 m and the Mekong flowing below 250 m only 5 km away. Palaeozoic folded sedimentary and metamorphic rocks and Mesozoic sedimentary rocks occur in this area along with extrusive rocks associated with an ancient suture zone. The NNE structural trend is followed by a set of faults, and in general, by the river and the ridges, although the Mekong in places has changed course abruptly to flow across the structural trend. Within this approximately 14 000 km^2, an area of 225 km^2 is examined in detail in this paper, mostly steep slopes that drain directly to the Mekong River.

Annual rainfall is heavy over most of the Mekong basin, 2000–4000 mm, although the raingauges in the study area record annual rainfall figures of around 1500 mm. The rain, associated with the southwestern monsoon is strongly seasonal, 85–90% falling between May and October. Some of the Mekong's runoff is also caused by summer snowmelt in eastern Tibet. The Mekong has an extremely seasonal discharge, with 80% of the annual flow between June and November. September alone accounts for 20–30% of the annual flow. Large floods, like those of 1966, 1998 and 2000, occur in the wet season. The steep rainfed tributaries, especially the smaller ones, are even more seasonal. They tend to peak earlier than the Mekong, July against late August–September, in the study area (Mekong River Commission, various dates).

In the study area, the course of the river ranges between 700–800 m wide steep-sided reaches cut in rock with a >10 m deep inner channel and 1–1.5 km wide sections where the inner channel is less prominent and exposed bedrock is covered by sand accumulation. The local relief in the channel, in the form of rock protrusions, controls sediment accumulation to a large extent, and in the dry season the wide sections of the Mekong are a mosaic of sand, rocks, and pools of ponded water. The gradient of the river averaged over the study reach varies between 0.0002 and 0.0003, although the step-pool nature of the rock bed indicates that considerable variation exists on a local scale.

In the study area, the steep slopes are generally under either forest (including a substantial amount in the degraded state) or shifting cultivation (mostly hill rice with vegetables such as long beans and cucumbers). Plots are cleared at the beginning of the dry season in December–January and the biomass on the ground is burnt towards its end in April–May. The rural population density is low (tens per km^2) in the highlands but the cultivated slopes can be steep. Nearly a quarter of the land cleared between

1996 and 1998 was on slopes of more than 25º (Chen *et al*., 2000). Clearances tend to follow valleys associated with geological lineations. Starting as small patches on the side slopes of tributary valleys, the clearances tend to coalesce.

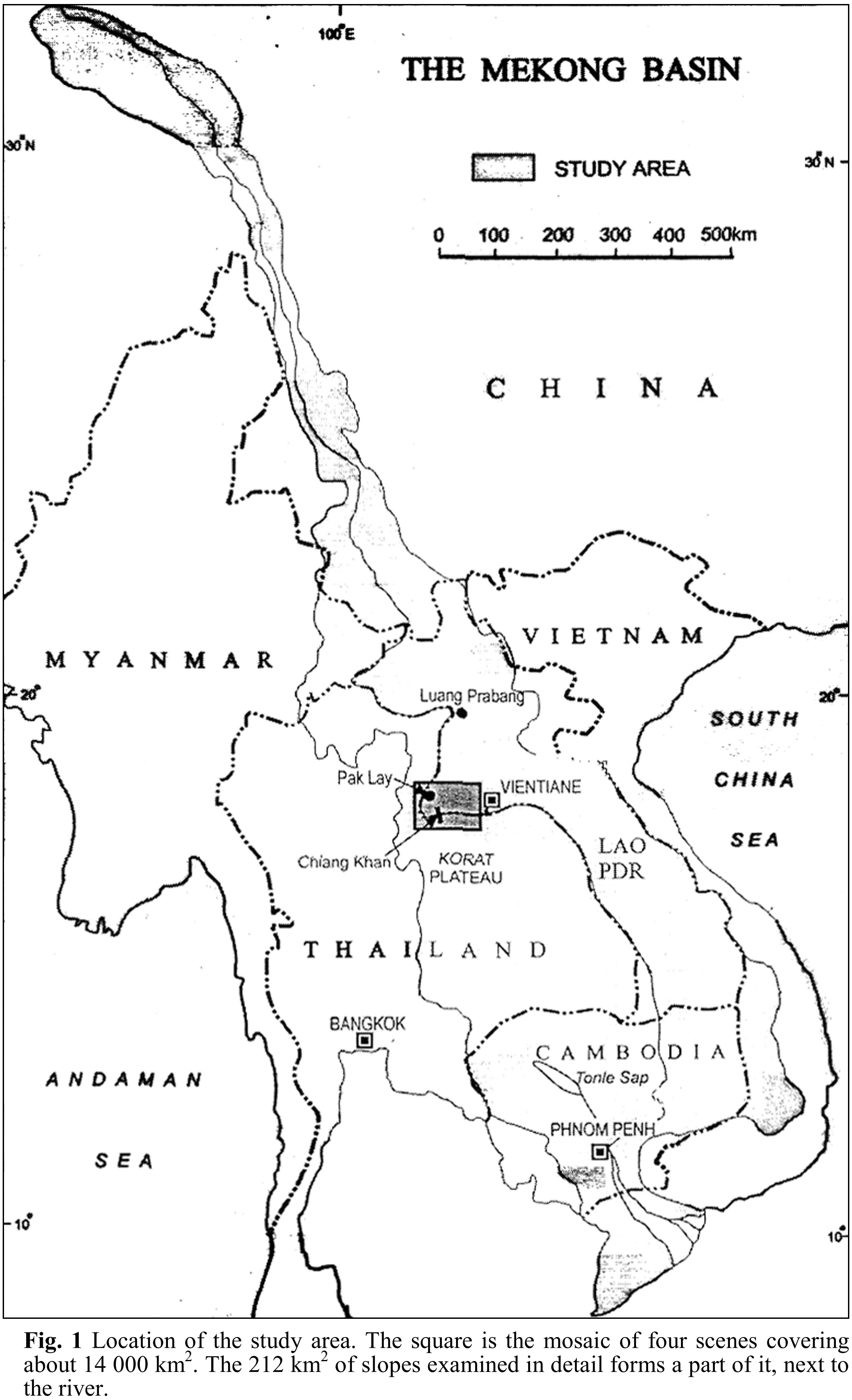

Fig. 1 Location of the study area. The square is the mosaic of four scenes covering about 14 000 km^2. The 212 km^2 of slopes examined in detail forms a part of it, next to the river.

METHODS

We located 17 nearly cloud-free multispectral images between 22 December 1992 and 16 January 2000. Of these, eight were for 1998, thereby allowing us to monitor changes in land use and sediment transfer through a calendar year. These images were used to document: (a) seasonal changes and (b) changes over time, specifically between 1992 and 2000.

Geometric correction was initially carried out for each image in order to analyse land cover changes over different years or different months in the same year. This was followed by masking of clouds and the river on the image. The normalized difference vegetation index (NDVI) images were generated from each multispectral scene in order to highlight vegetation. The vegetated and cleared areas were identified from the NDVI image through thresholding method. The extent of vegetated and cleared areas was then calculated for each classified image.

Using a multiplier of average sediment yield we then estimated how much sediment would be removed from the slopes in a particular month. Our objective was to determine approximately the intensity of erosion and the amount of sediment transfer through the year. This approximation was necessary, because although rainfall and discharge data are available from gauges maintained in the vicinity of the study area by the Mekong River Commission, we could not find any field measurement of sediment transfer from these slopes. Two surrogate measures were available: (a) the average of a number of measurements for forested land and land under shifting cultivation in Southeast Asia, and (b) values for forests and shifting cultivation on similar topography in Thailand (Gupta, 1996; Gupta & Krishnan, 1994). We used a multiplier of 100 and 1500 t km^{-2} year^{-1} for vegetated and bare ground respectively. We determined the areas under vegetation and shifting cultivation from the scenes in km^2, and then calculated the contributed sediment from such areas by adjusting for the rainfall received in that particular month. A sample of the results is given in Table 1. These numbers should be interpreted as trends and comparative values rather than exact measurements. The results will be more accurate when local field measures are available.

We then looked at the variations in monthly sediment yields during 1998 in order to establish the seasonal pattern. The same was done for either December or January (beginning of the dry season, comparative conditions) of 1992, 1996, 1998 and 2000 to determine whether there has been a progressive change in erosion on the slopes and sediment accumulation in the channels. We also checked the 5 February image for 1999, a little further into the dry season.

Table 1 Estimated monthly erosion and sediment transfer: slope to channels.

Month	Vegetated area (km^2)	Clear area (km^2)	Sediment from vegetated area (t)	Sediment from cleared area (t)	Total sediment (t)
Dec. 1992	149.99	61.80	1237	7648	8 885
Jan. 1998	134.37	77.41	43	372	415
Mar. 1998	102.92	108.87	93	1470	1 563
May 1998	175.25	36.54	3000	9383	12 313
Oct. 1998	207.10	4.71	706	359	1 065

SEASONAL CHANGES

Eight scenes from 1998 (7 January, 18 February, 8 March, 24 April, 16 May, 27 August, 25 October and 22 December) were used to determine seasonal changes; two scenes are shown in Fig. 2. It should be noted that 1998 was an El Niño year, and both rainfall and cloud cover were strikingly below average. This possibly

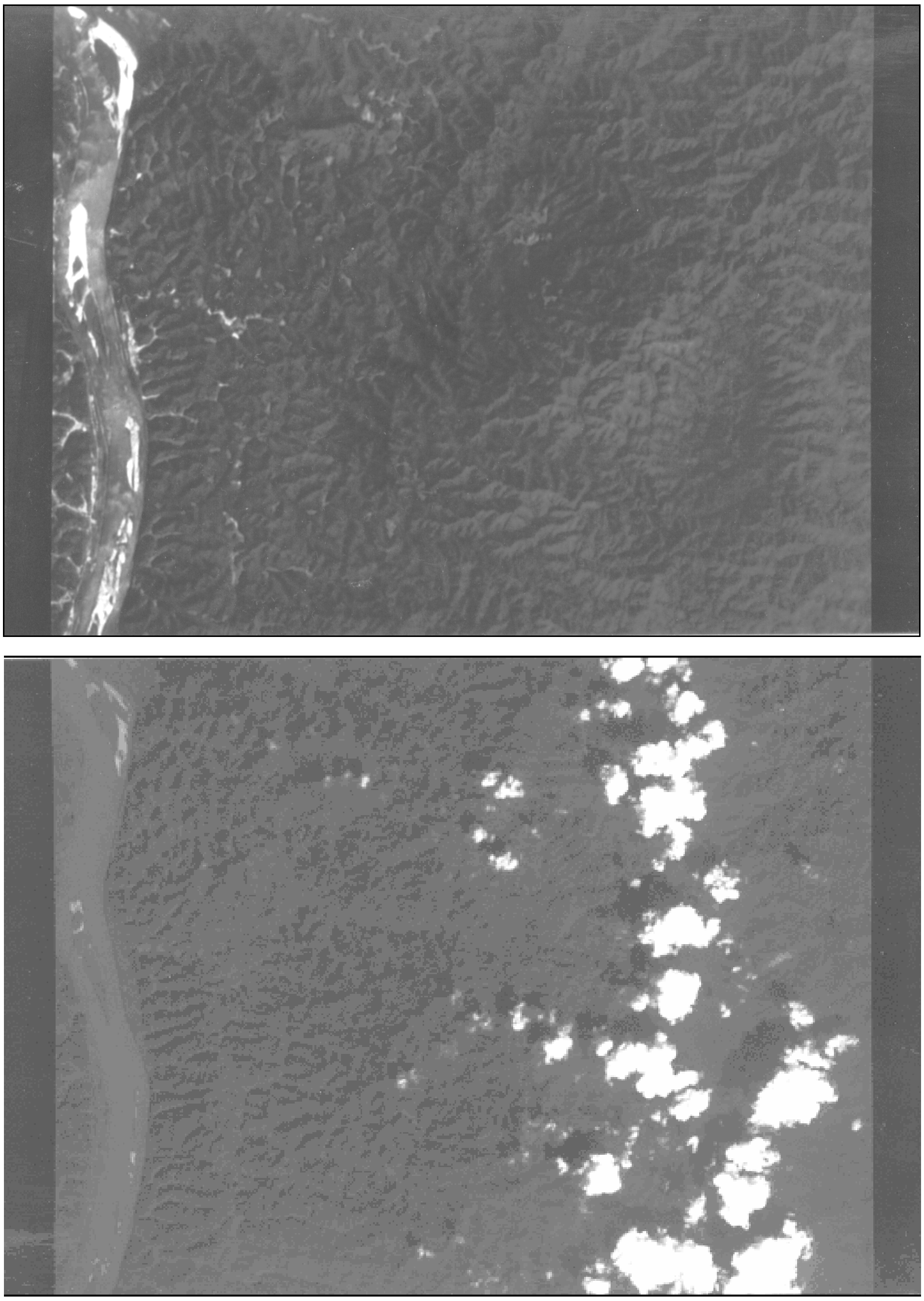

Fig. 2 Vegetated and cleared land in the study area: (*top*) March 1998, (*bottom*) October 1998. Note the vegetation cover in the late wet season and the difference in stage in the Mekong with associated changes in power and sediment transport. The images used for this paper are similar.

Table 2 Seasonal erosion and sediment transfer: middle Mekong basin.

Period	Slopes	Tributaries	The Mekong
December–April Dry, a few showers	Increasing clearance; very little erosion or sediment transfer due to lack of rainfall	Low flow; past sediment stored mainly on bed, as insets and at confluences	Sediment stored on bed, as insets, around rock protrusions and at confluence with major tributaries; gradually falling stage and diminishing sediment transport
May Rains start, rising discharge	Slopewash, gullies, small debris flows; sediment transfer to channels	Sediment pulses transferred following showers; sediment from slopes	Increased flow velocity and transport of channel sediment; increased competence
June–July (?) Early wet season	Major erosion and sediment transfer to channels via processes described above	Transfer of channel sediment to the Mekong; more sediment from slopes; confluence accumulation	Erosion of bed material, insets, and bars; increased competence; critical and supercritical flow in places; water tens of metres deep in inner channel
August–November Late wet season	Vegetation growth; little erosion; very little sediment transfer	Continuous transfer of channel sediment; confluence accumulation	Continued erosion of bed material, insets, and bars; local critical and supercritical flows; bedrock erosion; deep water in inner channels; sediment accumulation at channel confluences

implies less runoff and erosion than in most other years, leading to less sediment transport. On the other hand, in a year with normal rainfall, cloud cover would generally prevent detailed examination of any wet season scene and only scenes from the dry months could be used. The degree of dissection, the steep slopes, and the high local relief preclude the use of radar for mapping vegetation cover. We therefore propose to use the data from 1998 for trend identification, with the suggestion that even a year with average rain will cause more runoff, erosion, and sediment transport than these figures. The sequence of events is described in Table 2, starting with the early dry season in January (7 January 1998 image) and finishing with the next dry season (5 February 1999 image). Land under any kind of vegetation cover and land that is bare was measured for 212 km^2 of each scene (the total area minus the river).

Table 1 indicates that erosion and sediment transfer are directly related to both vegetation cover removal and rainfall. Most of the sediment comes off the slope during the early weeks of the rainy season before the extremely fast vegetative regrowth covers the cleared fields. It is therefore the first 6–8 weeks of the rainy season (determined from the date of the images) when the slopes are significantly eroded. Field visits indicated that this erosion takes place via slopewash, gullies, and debris flows down first- and second-order channels. Continuing into the rainy season, the vegetative cover on the slopes restricts erosion in spite of large volume of rainfall but the sediment which is already in the channels of the tributaries and the Mekong is transferred downstream. The few available measurements of suspended sediment load in the Mekong indicate the same pattern (Mekong River Commission, various dates). It should be noted that in a year of normal rainfall, considerable sediment might move as indicated by the data for December 1992 (Table 1). Preventive measures that restrict sediment transfer from slopes for the first 6–8 weeks of the rainy season could provide useful protection.

CHANGES OVER TIME

The percentages of cleared land within the 212 km^2 study area in the early dry season for 22 December 1992, 8 January 1996, 7 January 1998, 5 February 1999 and 16 January 2000 were 29.18, 22.61, 36.55, 23.45 and 18.30 respectively. As expected from shifting cultivation on steep slopes, this indicated a fluctuation but not a progressive trend. On all images the clearance was along small valleys and midslopes on both sides of the river. The sediment yield may not necessarily have a linear relationship with these figures as it is also dependent on rainfall. We can however, make three observations at this stage. First, the land, at least near the valleys, will tend to follow a rotation of secondary vegetation, cleared plots, and pioneer growth. Second, erosion takes place via slopewash, gullying, and small debris flows down first- and second-order channels. Sediment generated is stored in tributary channels as insets and channel bars, and at confluences with the Mekong. This periodically mobile sediment is identifiable by its colour and its unconformable position on top of gravel and rocks exposed in channel beds. Third, on each of the five days listed above, the level of the flow in the Mekong was different. This is visible on the images and also shown by the gauging records of the Mekong River Commission (Mekong River Commission, various dates). The days with lower stages display considerable more sediment which is stored in the channel of the Mekong, presumable waiting to be transported during the high flows of the next wet season. The sediment is stored as insets and on rock shoulders, where an inner channel is present and backed against rock protrusion and transverse ribs where the Mekong cuts across the geological structure in a widened channel.

CONCLUSION

We have shown the application of archived remote sensing images in monitoring erosion and sediment yield in large areas with difficult terrain and over time. It is possible not only to map the area undergoing change but also to determine numerical estimates of sediment yield. The processing of information requires some exposure to the field conditions and availability of hydrological data, but that may not be impossible to acquire. It is certainly extremely difficult, if not impossible, to undertake this kind of work based entirely on fieldwork. The estimates generated are nowhere near the highest sediment transfer recorded for the Mekong basin (Gupta *et al.*, 2002). It is also possible to trace the passage of sediment from the slopes to the main river. We are currently investigating the extent to which satellite images may provide information on the pattern of sediment storage and transfer in a large river channel, using the Mekong as an example. This study also shows that a large volume of sediment is present in the channel of the Mekong that (a) increases early in the wet season as pulses enter from the slopes and tributary channels and (b) may be expected to show a dramatic increase if the vegetation on the slopes is progressively destroyed due to increasing population pressure or logging. As dams and reservoirs and other engineering projects have been proposed for this section of the Mekong from time to time, such information has a relevance and utility.

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