Suspended Sediment Load Monitoring Along the Mekong River from Satellite Images

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Abstract  
The Mekong River has recently been suffering from environmental degradation despite its global significance of biodiversity. The monitoring of important components of ecosystems is critical for implementing effective environmental management. Meanwhile, the application of remote sensing to assess inland water quality has recently escalated due to its scanning wide water bodies within a short time period. In this study, the applicability for monitoring suspended sediment load (SSL) in the Mekong River over temporal and spatial dimensions was investigated. Landsat scenes captured between 1988 and 2000, including 110 Thematic Mapper (TM) images and 21 Enhanced Thematic Mapper Plus (ETM+) images, were analysed in correspondence with ground observations. The three visible and near infrared bands were included in the analysis. The polynomial relationship of the NIR exoatmospheric reflectance, band 4 wave length: 760-900 nm, to SSL based on the ground observations at 9 sites along the river demonstrated the best agreements (overall R2, 0.76). Subsequently, the equation enables us to reasonably estimate the suspended sediment load longitudinal profiles and its temporal changes. Thus, the results confirmed a high applicability of satellite image for monitoring SSL in relatively large rivers such as the Mekong River.

Keywords: Suspended sediment; Mekong river; Satellite image; Longitudinal profile; Temporal change

Introduction  
The monitoring of important components of ecosystems is critical for implementing effective environmental management [1]. However, due to the spatial and temporal heterogeneity of water bodies coupled conventional sampling methods often result in inadequate monitoring and characterization of water quality [2]. Meanwhile, the application of remote sensing to assess inland water production has escalated recently because its capability of scanning wide water bodies within a short time period [3]. Consequently, a combined approach utilizing the spatial and temporal coverage of remote sensing with conventional water sampling provides potentially effective solution to monitoring fresh water ecosystem [4]. In relation to water quality, sediments transport and erosion is a complex natural process that is strongly affected by human activities such as deforestation, agriculture and urbanization. In particular, sediment play a key role in controlling water quality and it can cause a major reduction on stream capacity for handling flood waves [5]. Sediment is the most common constituent both in weight and volume in surface waters of fresh water systems. Thus, especially for turbid rivers, the effect of the other optical active substances on the satellite data is negligible [6].

The Mekong River is Asia’s third largest river in terms of length and sediment load [7]. It receives enormous public attention in Asia because the river runs through six countries and approximately 60 million people live on or dependent on the Mekong basin [8]. The Mekong has recently been suffering from environmental degradation due to population increase, economic development, deforestation, and intensified meteorological extremes [9,10]. Especially, the dam construction and land use change within the basin are expected to alter hydrological process and sediment transport [11]. Therefore, adequate monitoring of sediment load is needed if prospective plans for basin development and management were under taken or current plans are continued.

Sediment has been recognized as the important contaminant affecting the Mekong water [12]. Besides its direct role in determining water clarity, bridge scouring, and reservoir storage, sediment serves as a vehicle for the transport of many binding contaminates, including nutrients, trace metals, semi-volatile organic compounds, and numerous pesticides [13]. Over the past three decades, remotely sensed images have been widely used in the assessment of suspended sediment [9,10]. Relative to large water bodies, such as lakes and reservoirs, water in rivers are more immediately sensitive to and more directly influenced by the characteristic of the river bank, human activities, and other external forces [14]. Therefore, the successful application of remote sensing technology to suspended sediment load monitoring of rivers could be a very useful tool for management and development at basin scales [15].

The present study aims to investigate the applicability of satellite images for monitoring suspended sediment load (SSL) in the Mekong River over temporal and spatial dimensions. Based on the generated observations, the empirical equation to estimate SSL was then applied to construct suspended sediment load profiles over the Mekong length and its temporal changes.

Materials and Methods

Study area

The Mekong is the largest trans-boundary river in Asia. It originated at Tibet in China and flows down to Southern Vietnam, a distance of more than 4600 km (Figure 1). It delivers approximately 160 million tons of sediment and 475 km³ of fresh water per year into the South China Sea [8]. Compared to other major rivers of the world, the Mekong is...
The Mekong River basin is experiencing rapid economic and population growth. Increasing demand for hydropower and fresh water leads to the construction of more and more dams and reservoirs along the main stream, which will inevitably change the water/sediment discharge downstream. The most controversial hydropower project on the Mekong River so far is the Lancang Cascade within China's Yunnan Province in the upstream area. Since the completion of the Manwan Dam (the first of 14 dams in total) in 1993, arguments have been raised about its positive and, especially, negative impact on the Lower Mekong Basin. The Lancang Cascade within China's Yunnan Province is the first of 14 dams in total in the Lower Mekong Basin. dam is the sediment and runoff source; Zone 2, the main river channels as a transfer component; and Zone 3, the alluvial floodplains, fans, deltas, etc., as zones of deposition. Zone 1 can be further divided into upland areas, lateral areas, and small stream channels. Considered together, these three elements form the watershed [8].

We focused on the Mekong River from the upstream of Chiang Sean to the downstream of Phnom Penh, which is 2,365 km long (Figure 1). In situ measurements of SSL from January 1988 to December 2000 along the Mekong were collected, Mekong River Commission [8]. The spatial resolution of TM and ETM+ data is 30 m (except for band 6 of the thermal infrared channel with 120 m). The images were acquired from the different seasons of the year from the Landsat archive from the United States Geological Survey (USGS) (http://glovis.usgs.gov). The three visible and near infrared bands were included in the analysis. These data were combined with in situ measurements for determination of statistical relationships between reflectance of different TM and ETM+ bands and SSL. The monitoring cases from 1988 to 2000 were used to illustrate the longitudinal profiles and the temporal change of SSL of the Mekong.

Satellite reflectance

Suspended sediments increase the radiance emergent from surface waters in the visible and near infrared (NIR) proportion of the electromagnetic spectrum [3]. The Landsat TM and ETM+ visible and NIR bands, 1-4, are optical bands recording electromagnetic radiation of 0.45-0.52, 0.52-0.60, 0.63-0.69 and 0.76-0.90 μm, respectively. Cloud-free pixels in the middle of the river width, counting the information only from water surface but not from land, were used to estimate SSL. Since analysis was carried out for individual image with quite a small angular range, the atmospheric correction has a little effect on correlation analysis [23]. Thus, the atmospheric correction was neglected. The analysis involved transformation of the raw Landsat TM and ETM+ digital numbers (DNs) to physical values of 1 radiance using in-flight sensor calibration parameters [24],

\[ L_\lambda = \left( \frac{L_{\text{sat}} - L_{\text{min}}}{255} \right) \times DN + L_{\text{min}} \]  

(1)

where, \( L_\lambda \) is spectral radiance measured over band width \( \lambda \) (m W \( \text{cm}^{-2} \text{sr}^{-1} \text{μm}^{-1} \)); DN is digital number value recorded, \( L_{\text{max}} \) is radiance measured at detector saturation (m W \( \text{cm}^{-2} \text{sr}^{-1} \text{μm}^{-1} \)); and \( L_{\text{min}} \) is lowest radiance measured by detector (m W \( \text{cm}^{-2} \text{sr}^{-1} \text{μm}^{-1} \)). Then, exoatmosphere reflectance for each band width computed [24],

\[ \rho_\lambda = \frac{L_\lambda}{L_\lambda \cos \theta} \]  

(2)
where, ρλ is reflectance as a function of band width λ; d is Earth-sun distance correction; Eo is exoatmospheric spectral irradiance; and θs is solar zenith angle. In this study, some regression methods including linear, exponential and log formulations were used to examine the relationships between SSL analysed in the laboratory and remote sensing reflectance data in TM and ETM+ bands 1-4.

Results and Discussion

Suspended sediment load models

Because of the nonlinear behaviour of the observations, the polynomial regression method to relate SSL to exoatmospheric reflectance of the visible bands 1-3 and NIR band 4 was chosen. The Landsat scenes and the corresponding in situ measurements of SSL at the monitoring sites were used. The polynomial graphs were developed by 49 data points (29 points during the dry season and 19 during the winter season). The relationships were obtained with optimized curve-fitting, (Figures 2a-2d). The results showed R² values of 0.436, 0.358, 0.566, and 0.76 for band 1, band 2, band 3, and band 4, respectively. Overall, the best relationship was obtained for Landsat TM and ETM+ band 4 per,

\[ \rho_4 = -493.37 \rho_4 - 5.72 \]

where, SSL is suspended sediment load (t y⁻¹×10⁻⁶); ρ4 is exoatmospheric reflectance of band 4. The best wavelengths for satellite assessment of suspended sediment load are found in the NIR, which is in line with previous research conclusions [3] (Figure 2).

Scatter plot of predicted values from equations (3) versus measured values of SSL is shown in Figure 3. The correlation coefficient and the Root Mean Square Error (RMSE) are 0.76, and 81.5 t y⁻¹×10⁻⁶. The
results indicate that predicted values of SSL and measurements are in a reasonable agreement.

**Longitudinal profiles and temporal changes of suspended sediment load**

In order to illustrate the longitudinal profile of suspended sediment load for different seasons we select four longitudinal profiles, where there was extensive satellite coverage of the Mekong. Two profiles represent the variation of SSL for dry season, winter (December to February) and spring profile (March to May), and the other two for rainy season, summer (June to August) and autumn profile (September to November). The polynomial model based on the NIR data, equation (3), was applied to estimate SSL. Results of the SSL model were in reasonable agreement with the measurements, as shown in Figures 4a-4d. The Root Mean Square Error (RMSE) between the observed and estimated SSL were 4.41, 11.1, 38.73 and 17.45 t y\(^{-1}\)*10\(^{-6}\) for winter, spring, summer and autumn profiles, respectively.

Generally, the Mekong exhibited a downstream decrease in the SSL. The longitudinal gradient was not linear and SSL changes occurred along the fluvial continuum. The SSL shows no steady trend along the Mekong, as illustrated in Figures 4a-4d. Walling explained this phenomenon as a convergence losses associated with sediment storage starting from approximately 50 km upstream of Chiang Sean [25]. The highest SSL variations here were close to Vientiane and Nakhon Phanom. The SSL was raised along this part because the maximum precipitation in the Mekong basin is documented at Nakhon Phanom with a mean rate of 2298.7 mm y\(^{-1}\) (1953-2005) and this section is mainly under forest [12]. Subsequently, intensive soil erosion was occurred carrying high sediment load to the river along this part. The summer profile showed the highest SSL values along the Mekong varies from 288.15 t y\(^{-1}\)*10\(^{-6}\) at Chiang Sean to 25.5 t y\(^{-1}\)*10\(^{-6}\) at Phnom Penh, while the lowest SSL values was varied from 7.9 t y\(^{-1}\)*10\(^{-6}\) at Chiang Sean to 3.1 t y\(^{-1}\)*10\(^{-6}\) at Phnom Penh, for winter profile as shown in Figures 4a and 4c. Thus, the load of suspended sediment was higher in the rainy

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**Figure 4:** Suspended sediment load profile of the Mekong (a) winter profile (December 1995 to February); (b) spring profile (March to May); (c) summer profile (June to August); (d) and autumn profile (September to November).

**Figure 5:** Temporal change in the SSL (a) upper region station (Chian Sean); (b) middle region station (Khong Chiam); (c) lower region station (Kampon Cham).
season than the dry season. This can be attributed to the intensive soil erosion coincident with the heavy precipitation. The average SSL at Phnom Penh, the start of Mekong Delta, were estimated to be 3.1, 2.96, 25.54, and 25.57 t \( y^{-1} \times 10^4 \) in winter, spring, summer and autumn seasons, respectively. This was the lowest among the studied stations due to the sediment deposition behaviour in the Delta region, which decrease the SSL in the water phase.

The annual sediment loads of the Mekong River were relatively stable in the past 40 years [25]. However, there is a significant seasonal change in the SSC among the year seasons. The polynomial model based on the NIR was applied to estimate this temporal change in SSL at the monitoring stations. Figures 5a-5c shows the trend of seasonal SSL change for one of upper region stations (Chian Sean), one of the middle region stations (Khom Chiam), and one of the lower region stations (Kampam Cham) with observed and estimated SSL values of 18.11, 40.42, and 37.46 t \( y^{-1} \times 10^4 \), respectively. The seasonal SSL was fairly well estimated at the main stream stations of the Mekong in all three regions. Thus, the SSL model represented observed data satisfactorily describe the seasonal cycle of suspended sediment load in the Mekong, which can be applied to estimate the future SSL in the basin.

Based on the estimations, the average SSL was higher in the rainy season than the dry season. That is due to the intensive soil erosion coincident with the heavy precipitation. The result reveals a decreasing trend in SSL along the three regions. This longitudinal decrease was due to the decrease in the main stream water velocity, which increases the sediment deposition and the SSL become lower.

The average SSL at Kampam Cham was the lowest among the studied stations due to the sediment deposition behaviour in the Delta region, which decrease the SSL. The results provided average decrease in SSL post Manwan Dam at Chiang Sean. However, the effect of the dam at the other downstream stations was negligible. That can be because the heavily precipitation in the middle region and the deposition behaviour in the Mekong Delta are the control factors for the SSL in the river at these stations compared to the effect of the upstream dams (Figure 5).

**Conclusion**

An effective combination of Landsat TM and ETM+ images with conventional in situ measurements was found to monitor SSL along the Mekong River. The analysis composed transformation of the raw Landsat TM and ETM+ digital numbers (DNs) to physical values of radiance and to exoatmosphere reflectance. Regression methods were used to examine the statistical models between SSL analyzed in the laboratory and remote sensing reflectance values in TM and ETM+ bands 1-4. A polynomial model based on the NIR data was chosen to predict the SSL along Mekong because of its higher correlation. The model fairly represented field satisfactorily at the main stream stations of the Mekong in all three regions and would be used to estimate the future SSL in the basin. Generally, the Mekong River exhibited a decrease in the SSL downstream. The longitudinal gradient was not linear and SSL changes occurred along the fluvial continuum. The highest SSL variations, rising, were close to Vientiane and Nakhon Phanom. The suspended sediment load was higher in the rainy seasons than the dry seasons. The lowest SSL was estimated at the start of Mekong Delta, due to the sediment deposition behaviour in the Delta region, which decreased the suspended sediment concentration in the water. The approach introduced here shows suitability of monitoring SSL at large basin scales like the Mekong. Thus, it can be applied not only for the Mekong but also for other large basins since suspended sediment is the common constituent in surface waters.

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**References**

