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Estimation of suspended sediment concentrations using Terra MODIS: An example from the Lower Yangtze River, China

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ABSTRACT

Traditional measurements of suspended sediment concentrations (SSC) through in-situ sampling in rivers are expensive and time-consuming to perform. Thus, these methods cannot provide continuous SSC records. Although remote sensing has been used for SSC estimation, little research has been undertaken on inland rivers, especially for highly turbid rivers like the Yangtze. Previous studies have proposed Landsat TM/ETM+ Band 4 as a spectral SSC indicator for the Yangtze, but its limitation on temporal resolution is insufficient for the study of dynamic changes of sediment. This paper presents a method of estimating SSC of the Yangtze at Jiujiang using time-series satellite data of high temporal resolution Terra MODIS. It was found that differences in water reflectance between Band 2 and Band 5 could provide relatively accurate SSC estimation even when in-situ atmospheric conditions were unknown. After cross-validation, mean absolute relative error (ARE) and relative root mean square error (RRMSE) were relatively low (*i.e.*, 25.5% and 36.5%, respectively). This empirical relationship was successfully applied to the estimation of SSC at Datong in the Lower Yangtze River, although the SSC values were generally underestimated. This study suggests that Terra MODIS could be used to estimate SSC in large turbid rivers, although some influencing factors require further study to improve the accuracy of SSC estimation.

1. Introduction

To study sediment-associated environmental changes such as alterations of river channel morphology, degradation of water quality and negative effects on aquatic ecology, it is necessary to accurately monitor transport and discharge of suspended matter in rivers (Schiebe et al., 1992; Collins and Walling, 2004; Ouillon et al., 2004). However, this task is constrained by severely limited spatial and temporal samplings of suspended sediment concentration (SSC) due to the high cost and time-consuming methods currently used for in-situ measurement (Gao and O'Leary, 1997). As Syvitski et al. (2000) indicated, most rivers in the world have either not been gauged or their sediment data are not readily available.

Satellite remote sensing has been used to retrieve SSC data because it has wide spatial coverage and high temporal repeatability, and various visible and NIR bands have been proposed as SSC indicators in previous studies (e.g., Ritchie and Cooper, 1988; Li, 1993; Reddy and Srinivasulu, 1994; Dekker et al., 2002; Doxaran et al., 2002; Ouillon et al., 2004; Chen et al., 2004; Wang et al., 2004; Milier and Mckee, 2004; Binding et al., 2005; Ma and Dai, 2005; Zhou et al., 2006). These studies have focused mainly on coastal, estuarine, lagoon, lake and reservoir environments. Previous studies on rivers, such as Islam et al. (2001) on the Ganges–Brahmaputra Rivers and Onderka and Pekarova (2008) on the Danube River, involved short river reaches within the coverage of a single Landsat image, and images from only one or two days were used. Moreover, these studies focused on moderately or mildly turbid waters. For instance, Onderka and Pekarova (2008) studied samples with 0–60 mg l^{-1} only. Islam et al. (2001) indicated that their algorithm was suitable for the SSC range of 0–1200 mg l^{-1}, but they used only five samples. Wang et al. (2007) found that SSC could be estimated from Landsat ETM+ images directly, and their study involved SSC samples within 22–2610 mg l^{-1} at 10 stations along the Upper Yangtze River. Wang et al. (2009) later used 16 ETM+ images covering 16 stations along the Upper and Middle Yangtze River to estimate SSC. Both studies found that the ETM+ Band 4 (NIR) was the best indicator of SSC.

Temporal resolution of Landsat TM and ETM+ is 16 days. Hence, to accurately monitor dynamic changes in a river system, higher temporal resolution images are required. Terra MODIS (or Moderate Resolution Imaging Spectroradiometer) may be a viable option. The Terra satellite was successfully launched on December 18, 1999, with Terra MODIS aboard (NASA MODIS Website, online: http://modis.gsfc.nasa.gov/index.php). Terra MODIS, passing from north to south across the equator in the morning, views the entire surface of the Earth every 1 or 2 days, acquiring data at 36 spectral bands within a range of 405–14,385 nm. Spatial resolutions are 250 m for Bands 1–2, 500 m for Bands 3–7 and 1000 m for Bands 8–36, respectively. Spatial resolutions of Bands 1–7 make them likely to be useful for large rivers such

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as the Lower Yangtze. This study aimed to investigate whether Terra MODIS with higher temporal and spectral resolutions could be used to estimate SSC in a large river system.

2. Study area

The 6300 km-long Yangtze River, the third longest river in the world, originates in the Tibet Plateau and flows eastwards into the East China Sea (Fig. 1). The upper river reach covers an area 4500 km upstream to Yichang, Hubei Province, and the middle and lower reaches flow across a huge, gently sloping plain where the river channel widens. The middle and lower reaches of the river are dominated by a subtropical monsoon climate with a large proportion of annual precipitation in the wet season. The Three Gorges Dam (TGD), the largest dam in the world, is located 37 km upstream from Yichang (Nilsson et al., 2005). Due to the sediment deposition in this reservoir, SSC of water passing through the downstream main river channel has been declining since operation of the dam began in 2003 (Dai et al., 2008). Changes in sediment load along the Yangtze River may cause adverse environmental problems in the Middle and Lower Yangtze River basin, which is one of the most critical regions in China in terms of economic development. Along the Lower Yangtze River, Jiujiang and Datong are the only two gauging stations that measure sediment. Jiujiang is at the junction of the middle reach and the lower reach of the Yangtze River. Datong is the lowest station on the Yangtze River, so its sediment data were often used to estimate this large river's sediment flux into the sea. The channel width was around 1.5–2 km in wet seasons at Jiujiang and Datong, and the water depth was around 5–6 m at the two sites.

3. Data and methods

3.1. SSC data and Terra MODIS

At Jiujiang, the daily SSC data measured at gauging stations were point-integrated samples collected at 0.2, 0.6 and 0.8 water depths from ten verticals in the cross-section. The water samples were treated following the national standard (Ministry of Water Resources of China, 1992). The current study focused on the wet season (May–October) with tremendous temporal and spatial variations in SSC. The daily SSC ranged from 45 to 909 mg l^{-1} at Jiujiang during the entire wet season in 2005.

This study used geocoded Terra MODIS L1B images received by the Tokyo receiving station and the Bangkok receiving station, respectively. These geometrically corrected images were downloaded free from the MODIS Data Service Center website, Institute of Industrial Science, University of Tokyo, Japan (Online: http://webmodis.iis.u-tokyo.ac.jp/). Bands 1–7 were used in this study, and spatial resolutions at Bands 1–2 had been re-sampled to 500 m by the two receiving stations. MODIS images were checked before being downloaded to exclude cloudy days. Daily quick-look images are available at MODIS Rapid Response System of NASA (online: http://rapidfire.sci.gsfc.nasa.gov/realtime/?calendar).

3.2. Top-of-atmosphere (TOA) radiance and reflectance extraction

The pixels were selected according to the stations' geographic coordinates (Fig. 2). To facilitate selection of the pixels, Band 2 or band combination RGB = 765 was used for image display because it clearly

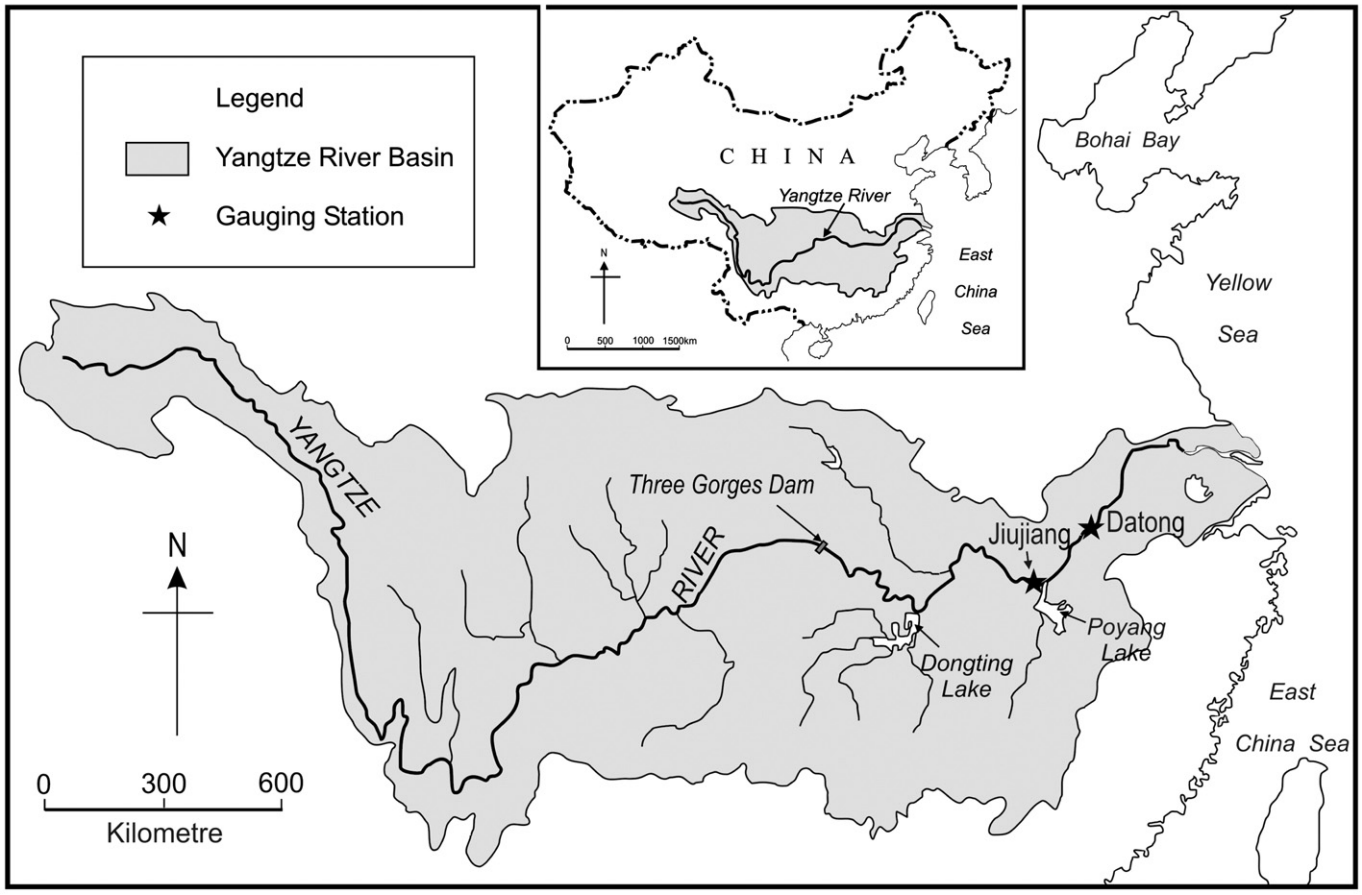

Fig. 1. Map of the Yangtze River basin showing the locations of Jiujiang and Datong, the only two gauging stations with sediment records along the Lower Yangtze River.