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Fifteen-year monitoring of the turbidity dynamics in large lakes and reservoirs in the middle and lower basin of the Yangtze River, China

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A B S T R A C T

The Middle and Lower Yangtze River (MLY) basin holds the most freshwater in East Asia; however, the conditions of basin-scale water turbidity remain unknown. In this work, a remote sensing algorithm was developed to estimate the concentrations of the total suspended sediments (TSS) in large lakes and reservoirs over the MLY basin and was based on a band ratio between 555 nm and 645 nm of the atmospherically corrected surface reflectance of the Moderate Resolution Imaging Spectroradiometer (MODIS). In situ samples used to calibrate the algorithm were collected from 58 lakes and reservoirs with a TSS range of 1 to 300 mg L^{-1}, and the uncertainty of this algorithm was 30–40%. The algorithm was subsequently applied to a total of 102 lakes and reservoirs located in the MLY basin to derive TSS maps from 2000 to 2014 at a 250 m spatial resolution, and the first comprehensive document of the TSS distributions and dynamics of large inland waters of the MLY basin was created. The seasonal patterns among the selected water bodies were similar, with the largest TSS concentrations occurring in the first and fourth quarters in a year and the lowest values occurring in the third quarter. In contrast, spatial heterogeneities were revealed by the 15-year long-term mean TSS climatology information. Although most lakes downstream of Poyang Lake were turbid with 15-year TSS climatology values of 45–100 mg L^{-1}, waters between Poyang and Doting Lake were relatively clearer with TSS climatology values of 15–45 mg L^{-1}, and the clearest waters (<15 mg L^{-1}) were found in reservoirs. The turbidity of 64.5% (e.g., 49/76) for lakes in Class II exhibited a decreasing trend over the 15-year period, and the Three Gorges Reservoir (TGR) and Dongting Lake in Class I also showed significant TSS declines. Analysis with meteorological data shows that the intra-annual variations appear to be significantly correlated with local precipitation, with a time lag of two months for TSS. The prominent TSS decreasing trend of the lakes in Class II was probably linked to the significant NDVI increase in the MLY basin, whereas the TSS decrease in the TGR and Dongting Lake is likely to be attributed to the impoundment of the Three Gorges Dam. The TSS environmental data record (EDR) of large inland waters presented in this study serves as an important reference for future water quality monitoring and evaluation in the MLY and in China.

1. Introduction

Lakes not only supply a large amount of surface freshwater accessible for human consumption but also play an important role in maintaining regional ecological and environmental functions, such as the hydrological cycle, agricultural irrigation, flood control, and fishery, among others (Street-Perrott and Harrison, 2013; Wang et al., 2014; Zhong and Chen, 2005; Wu et al., 2005). However, due to anthropogenic activities and climate change, numerous lakes throughout the world have shrunk or disappeared in recent decades (Schindler, 2009; Larsen, 2005; Ravilious, 2016), and others have also faced severe water quality problems such as large-scale algal blooms (Nakamura, 1997; Donald et al., 2002; Lewitus et al., 2003; Matthews et al., 2010). Inland lakes in China are not immune to these changes. For example, Ma et al. (2010) showed that 243 large lakes with >1 km^2 surface area in China have vanished since the 1960s. A net decline in the inundation areas was also observed in the middle and lower basin of the Yangtze River Basin (hereafter referred to as the MLY basin) using 12-year remote sensing observations from 2000 to 2011 (Wang et al., 2014). Serious eutrophication has been observed in the waters of Taihu Lake and Chaohu Lake (Duan et al., 2009; Xu et al., 2005), which are the third and fifth largest freshwater lakes in China, respectively.

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The total suspended sediment (TSS) concentration (or water turbidity) is one of the key water quality parameters that play a critical role in shaping the physical landscape and regulating ecological systems (Knighton, 1998). Water turbidity can influence underwater light transmission, thus altering the productivity of water-column phytoplankton and the living conditions of both aquatic animals and vegetation (Moore et al., 1997; Havens, 2003). Moreover, suspended sediments are considered important carriers for pollutants and heavy metals of terrestrial origin and impact the health of underwater environments (Erftemeijer and Robin Lewis, 2006; Moore et al., 1997; Novotny and Chesters, 1989; Tabata et al., 2009). Therefore, knowledge of spatial and temporal TSS patterns is essential for evaluation of water quality and associated environmental functions.

In practice, it is often technically challenging to monitor the TSS distributions of a large water surface, let alone numerous freshwater systems across the entire Middle and Lower Yangtze River (MLY) basin. The transitional ship-based sampling method is insufficient on both the spatial and temporal scales and prohibits statistically meaningful measurement because TSS concentrations are significantly heterogeneous in terms of space and time. For example, episodic events (such as heavy rain or high wind) could trigger mass sediment resuspension, leading to a high TSS of the surface water for a short time period (Gavin, 2007). Thus, overcoming the challenge of documenting TSS concentrations in a comprehensive manner appears to be the first step in revealing turbidity changes.

With synoptic and frequent observations, remote sensing has been used to monitor water turbidity since the 1970s (Ritchie et al., 1976; Holyer, 1978). The fundamental theory is that the visible spectrum (especially red and Near-Infrared) is significantly elevated with increasing sediment due to the associated back-scattering (Feng et al., 2012; Petus et al., 2010; Miller and McKee, 2004). Over the past several decades, various satellite remote sensing data have been used to quantify the TSS concentrations on large and regional scales, such as the ocean colour sensors of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS) (John et al., 1998; Tassan, 1994; Feng et al., 2012; Zhang et al., 2010b; Duan et al., 2014; Sokoletsky et al., 2014; Shen et al., 2010). Additionally, high spatial resolutions and large dynamic ranges allow land-based instruments to be used in water turbidity applications, including the Satellite Pour l'Observation de la Terre (SPOT), the Landsat series and many others (Doxaran et al., 2002; Zheng et al., 2015).

Lakes, ponds, and reservoirs are intensively distributed in the MLY basin area (5900 in number or ~15,000 km^2 in area) (Wang et al., 2014), serving as critical roles in supporting the water resources for agricultural production and socioeconomic development in this region. Previous studies have examined the TSS concentrations and dynamics of several lakes in this region, such as Poyang Lake (Feng et al., 2012), Taihu Lake (Shi et al., 2015), and Donting Lake (Zheng et al., 2015), etc. However, no systematic efforts have been conducted to establish a decadal environmental data record (EDR) of the water turbidity for the lakes or reservoirs in the entire region or to understand the changes and their potential driving forces. Given the urgent need for accurate information on the TSS distributions and dynamics in the MLY basin, we used long-term MODIS surface reflectance products from 2000 to 2014, in situ measurements, and other auxiliary data to fill the knowledge gap with the following specific objectives:

1. Development of a robust TSS algorithm using in situ data from 58 different lakes and reservoirs with which reliable TSS concentrations of large water bodies in the MLY basin can be obtained using MODIS surface reflectance data;
2. Documentation of the temporal and spatial dynamics of the TSS for the studied lakes and reservoirs using long-term MODIS observations and determination of the potential driving forces of the short- and long-term TSS variations;
3. Establishment of a TSS EDR for the large inland water bodies in the MLY basin areas to serve as important information for evaluating the inland water quality for this region or even all of China.

2. Study area and datasets

With a coverage area of ~785,000 km^2, the MLY basin contains approximately 5900 freshwater lakes, reservoirs and ponds, and the areal sizes of these water bodies range from under 0.01 km^2 to over 2000 km^2 (Wang et al., 2014). These freshwater lakes supply the local population with essential water resources and promote local economic development, and certain river-connected lakes even play an important role in regulating the water level of the Yangtze River. However, under the influence of human activities, many lakes in this region have experienced dramatic degradation over the past decades, and the lakes still currently connected with the Yangtze River are Poyang Lake, Dongting Lake and Shijiu Lake (Wang et al., 2014). Certain lakes have even suffered from serious water quality problems (Duan et al., 2009; Xu et al., 2005; Feng et al., 2012). Water quality issues can lead to a series of problems such as drinking water shortages (Guo, 2007), decreasing fish population (Zhong and Chen, 2005), and reducing productivity of wetland vegetation (Wu et al., 2005), etc. However, to date, no reports are available on the long-term water turbidity conditions for this region, which appears to be critical information for water monitoring and restoration efforts.

The long-term remote sensing data used to derive the TSS distributions were the MODIS 8-day surface reflectance data composites, and the spatial resolutions are 250 m (MOD09Q1 and MYD09Q1) and 500 m (MOD09A1 and MYD09A1). Terra data from 2000 to 2014 and Aqua data from 2002 to 2014 were obtained from the NASA Land Processes Distribution Active Archive Center (https://ladsweb.nascom.nasa.gov/), and a total of 2516 composites were downloaded. The 500 m data were re-sampled to 250 m using the sharpen method (Pohl and Genderen, 1998). Additionally, MODIS daily surface reflectance data (MOD09GQ and MYD09GQ) concurrent with the field sampling dates were also downloaded. In general, each pixel of the 8-day composites represents the best possible observation during an 8-day period (e.g., high observation coverage, low viewing angle, absence of clouds or cloud shadows and aerosol loading). A Quality Control (QC) flag is associated with the quality of each pixel, with which data with potential artifacts (such as atmospheric correction failure) can be excluded for TSS estimations.

Water field measurements were performed in 58 lakes and reservoirs from 13 July of 2009 to 10 October of 2013 by cruise surveys with a total of 363 sampled stations. The 58 sampled water bodies were distributed along the Yangtze River (see locations in Fig. 1), and the sampling stations (see Table 1) ranged from turbid to clear waters (TSS of 1–300 mg L^{-1}), suggesting that these waters could satisfactorily represent the turbidity conditions of the lakes and reservoirs of the MLY region. For each station, water samples were collected and filtered immediately on a pre-weighted Whatman filter (GF/F or Cellulose Acetate Membranes) with a diameter of 47 mm. The filter was stored in a desiccator, burned at 550 °C for 3 h, and weighed again in the laboratory. The TSS concentration was determined according to the weight difference normalized by the filtered water volume. The filter was weighed on an analytical balance with a precision of 0.01 mg. At each station, the longitude and latitude coordinates were obtained using a global position system receiver (Garmin eTrex Legend HCx).

Lakes with a surface area of >8 km^2 and reservoirs with a capacity of >0.1 km^3 in the MLY region were selected in this study, considering the relatively low spatial resolution of MODIS data. The values of 8 km^2 in inundation area for lakes and 0.1 km^3 in capacity for reservoirs are the thresholds to classify large lakes and reservoirs in China (Yang and Lu, 2013). The area and capacity information was obtained from the China Lake Scientific Database (http://www.lakesci.csdb.cn/), *Chinese lake catalogs* (Wang and Dou, 1998) and the Water Conversancy Information System (http://218.249.40.251/tpi/WebSearch/Search_