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Monitoring the river plume induced by heavy rainfall events in large, shallow, Lake Taihu using MODIS 250 m imagery

Yunlin Zhang [a,*], Kun Shi [a], Yongqiang Zhou [a,b], Xiaohan Liu [a,b], Boqiang Qin [a]

[a] Taihu Laboratory for Lake Ecosystem Research, State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China

[b] University of Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Knowledge of stormwater river plume dynamics is important for the management of lake water quality because river discharge associated with rainstorms can be a major source of pollutants for lake waters. Total suspended matter (TSM) derived from the discharge of sediment-laden rivers is highly variable over a wide range of time and space scales. In the present study, the first use of remote sensing to monitor the river TSM plume was conducted to investigate the effects of heavy rainfall events on Lake Taihu by the largest inflowing river (Tiaoxi River) based on a calibrated and validated model using daily 250 m MODIS imagery in band 1 (620–670 nm). From 2004 to 2013, 48 MODIS images of 20 heavy rainfall events were obtained, showing that the area of the TSM plume significantly increased in the waters adjacent to the inflowing river, reflecting runoff input. The TSM concentration of the river plume after heavy rainfall was significantly higher than that before rainfall (ANOVA, $p < 0.001$). A significantly positive correlation between the TSM plume area and the rainfall amount in heavy rainfall events ($p < 0.01$) was also observed. The heaviest rainfall event, in October 2013, caused a river plume with an area of 302.8 km^2, which lasted for more than 10 days. The significant increase in the frequency and rainfall amount of rainstorms and large rain in the past 50 years (1965–2014) in Lake Taihu under global warming indicated an important role of remote sensing in monitoring the river plume resulting from heavy precipitation. The present study demonstrates that remote sensing tools can be valuable instruments in the detection and tracking of the effect of heavy rainfall events on the distribution and diffusion of the TSM concentration in the lake. The results obtained from the present study are valuable for further hydrological research on the Tiaoxi River, particularly for the immediate assessment of flood impacts on soil erosion of the catchment.

1. Introduction

River plumes are the major route through which nutrients, sediments and other land-based pollutants, such as heavy metals and organic contaminants, are transported into lake waters (Qin, Xu, Wu, Luo, & Zhang, 2007; Rao & Schwab, 2007). Thus, river plumes play a fundamental role in the physical processes and biogeochemical cycles in lakes (White et al., 2009). The effects of river plumes on lake water quality and ecosystem structure and function can be considered from several aspects. (1) By inputting a large amount of nutrients from domestic, industrial and agricultural effluents, fluvial discharges modify the concentrations and ratios of nutrients in waters near the river mouth (Corcoran, Reifel, Jones, & Shipe, 2010). The over-enrichment of nutrients promotes phytoplankton growth, determines phytoplankton species distribution, and is detrimental to water quality (Grosse, Bombar, Doan, Nguyen, & Voss, 2010). (2) High concentrations of total suspended matter (TSM) and chromophoric dissolved organic matter (CDOM) discharged through the river plumes result in increased turbidity and decreased light penetration and submerged aquatic vegetation (SAV) growth (Cannizzaro, Carlson, Yarbro, & Hu, 2013; Ondrusek et al., 2012). (3) High concentrations of TSM, associated with bacteria and metallic pollutants and pesticides originating from industrial discharges and intensive agriculture or forestry plantations, affect lake water quality and human health (Kannan et al., 2012). (4) River plumes alter the nearshore thermal structure, and affect the vertical exchange of nutrients and the vertical migration of phytoplankton, zooplankton and fish (Rao & Schwab, 2007; Wang, Qian, Han, Luo, & Hamilton, 2012). Therefore, monitoring rainfall and overflows in rivers is important to determine their effects on water quality for sustainable lake management.

The effects of river plumes are best known for those caused by the high discharge following heavy rainfall (Chen, Huang, Chen, & Wang, 2011; Lahet & Stramski, 2010; Nezlin & DiGiacomo, 2005). However, these effects are typically limited when discharge is small. River plumes produced by stormwater discharge are easily distinguished from

* Corresponding author at: Yunlin Zhang, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, China.
E-mail address: ylzhang@niglas.ac.cn (Y. Zhang).

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ambient coastal waters based on the high concentration of TSM that changes the color of the water surface. Although storm river plumes are typically studied using data collected from buoys and research vessels, the spatiotemporal variations of river plumes are typically too dynamic and broad; thus, these water bodies are not easily and effectively observed through shipboard monitoring (Nezlin, DiGiacomo, Stein, & Ackerman, 2005; Zawada et al., 2007). Another approach is to use hydrodynamic models in combination with estimated pollutant loads discharged from rivers to estimate the dispersal of pollutants (Hu, Jørgensen, & Zhang, 2006). However, this approach requires significant expertise and computational resources, and in most cases, the computed results have not been validated against in situ data.

Remote sensing technology overcomes the problems of conventional monitoring techniques and can be applied to the study of river plumes. Remote sensing using optical determination facilitates the identification of river plumes and provides a better understanding of TSM distribution and transport compared with conventional monitoring techniques. Although remote images seldom replace conventional sources of information for water resources, these images can supplement field data by revealing broad-scale patterns not recognizable at the surface, recording changes over time, providing data for inaccessible regions, and decreasing data acquisition costs (Lihan, Saitoh, Iida, Hirawake, & Iida, 2008; Warrick et al., 2007). However, a limitation of using remote sensing imagery is that cloud cover leads to missing data, and cloudiness is a common occurrence after a heavy rainfall (Petus et al., 2014).

Satellite imagery, including the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Moderate Resolution Imaging Spectrometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS), and Landsat Thematic Mapper (TM), has been widely used to monitor TSM transport and distribution from river plumes in estuarine and coastal waters (Guneroglu, Karsli, & Dihkan, 2013; Lahet & Stramski, 2010; Nezlin et al., 2005; Shen, Zhou, Li, He, & Verhoef, 2013). However, to our knowledge, there are few remote sensing studies on the effect of river plumes resulting from heavy rainfall on the transport and distribution of TSM in lakes (Binding, Greenberg, & Bukata, 2012; Lathrop, Vande Castle, & Lillesand, 1990). Typically, studies of river plumes in lakes are based on in situ measurement and numerical modeling (Churchill, Ralph, Cates, Budd, & Urban, 2003; He, Rao, Howell, & Skafel, 2006; McCullough & Barber, 2007; Pavlac et al., 2012; Rao & Schwab, 2007).

In Lake Taihu, the third largest freshwater lake in China, previous studies concerning the effects of temporal and spatial patterns on TSM concentration have used remote sensing estimation models (Sun et al., 2013; Wang, Shi, & Tang, 2011; Zhang, Shi, Liu, Zhou, & Qin, 2014). In these studies, attention is paid to the effects of lake topography, wind-driven sediment resuspension, and SAV distribution on TSM concentration (Zhang et al., 2014). However, there are no remote sensing studies associating the distribution of TSM concentration with river plumes and hydrological processes. This knowledge gap can be partially attributed to the lack of synchronous TSM distribution and hydrological and meteorological data and a failure to recognize the important role of river plumes in lake ecosystems due to the relatively low discharge of rivers flowing into lakes compared with the large discharge of rivers flowing into estuarine and coastal waters. For example, the Tiaoxi River, the largest inflowing river of Lake Taihu, has an annual inflow of 2.7 billion m^3 (Liu et al., 2011), which is substantially lower than some large rivers inflowing to the estuary and ocean (Bai et al., 2014; Petus et al., 2014; Thomas & Weatherbee, 2006).

To address this knowledge gap, in the present study, we present a methodological approach for monitoring the dispersion and effect of a river plume in a large shallow lake using remote sensing during heavy rainfall events. Specifically, the aims of the present study were to 1) quantify the areas and intensities of the river plumes for each heavy rainfall event from 2004 to 2013; 2) determine the persistence of the river plumes (i.e., determine how long the discharge signal is retained in the lake); and 3) determine the relationship between rainfall amount and TSM plume area using remote sensing.

2. Materials and methods

2.1. Study region

Lake Taihu, the third largest freshwater lake in China, has a complicated river and channel network, with 219 rivers or channels connecting to the lake (Qin et al., 2007). Most of the water enters the lake from west and flows out to the east, primarily through Eastern Taihu Bay. According to the inflow and outflow, the rivers associated with Lake Taihu are simplified to thirteen inflowing rivers in the western and northern areas and one outflowing river (Taipu River) in the eastern part of the lake (Fig. 1).

The Tiaoxi River exhibits the maximum inflow, and the associated river plume was the focus of the present study. The Tiaoxi River has an annual inflow of 2.7 billion m^3, contributing approximately 60% of the total water for Lake Taihu (Liu et al., 2011). The main stream of the Tiaoxi River is 158 km, and the catchment area is approximately 4576 km^2 with 90% vegetation cover. The width of the Tiaoxi River and average water depth are approximately 350 m and 2.5 m, respectively. The multi-year average precipitation amount of the Tiaoxi River catchment is approximately 1460 mm. Topography types of the catchment include hills (88%) and plains (12%). The upstream part of the river flows through agricultural areas, while the downstream part flows within the urban district of Huzhou and is subject to industrial inputs. The river collects waters from a population of approximately one million inhabitants, primarily located in moderately sized cities along the river continuum.

2.2. MODIS data and TSM estimation model

We used MODIS data to estimate the concentration of TSM in Lake Taihu. These data, available since 2002, have a spatial resolution of 250–1000 m. We used 250 m resolution MODIS imagery in band 1 (620–670 nm), which has been widely used to estimate TSM concentration or turbidity in diverse aquatic ecosystems (Chen, Hu, & Muller-Karger, 2007; Feng, Hu, Chen, & Song, 2014; Lahet & Stramski, 2010; Petus et al., 2010; Petus et al., 2014), and this technique is sufficiently accurate for Lake Taihu with a water area of 2338 km^2 (Shi et al., 2015; Wang et al., 2011). More importantly, the high frequency images (1/day) facilitated the monitoring of the turbid plume from the Tiaoxi River throughout heavy rainfalls. The MODIS-Aqua Level 1A data were obtained from NASA Goddard Space Flight Center and processed to Level 2 format using the NASA SeaWiFS Data Analysis System (SeaDAS version 5.1.6).

From January 2003 to December 2013, we set the criterion for matching the satellite data and the in situ observations to ≤3 h (the time interval between the in situ measurements and the corresponding MODIS-Aqua data) to produce 300 in situ TSM satellite-derived R_{rs} "matches", i.e., data pairs of MODIS-Aqua images represented by the same pixel. The 300 TSM satellite-derived *R*rs "matches" were randomly divided into calibration and validation datasets: 150 pairs were used to calibrate a TSM estimation model, and 150 pairs were used to validate the model. An empirical algorithm was calibrated and validated to estimate TSM concentration using MODIS band 1 in Lake Taihu based on the calibration and validation datasets (Fig. 2) (Shi et al., 2015). The detailed description including band optimization choice, atmospheric correction, model calibration and validation, and time series analysis of the TSM concentration from 2003 to 2013 has been previously elucidated (Shi et al., 2015). Thus, in the present study, we focused on the effect of the river plume resulting from heavy rainfall events in Lake Taihu using the TSM estimation model.