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Detection of illicit sand mining and the associated environmental effects in China's fourth largest freshwater lake using daytime and nighttime satellite images

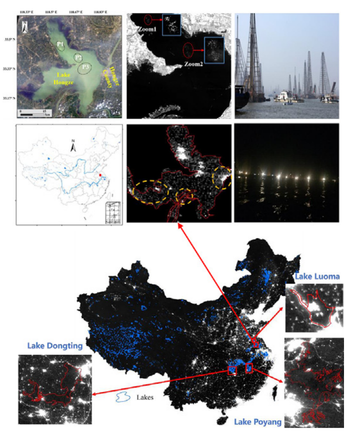
Hongtao Duan [a,*], Zhigang Cao [a,b], Ming Shen [a,b], Dong Liu [a], Qitao Xiao [a]

[a] Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- VIIRS DNB NTL data were used to monitor illegal sand mining activities in Lake Hongze.
- Nighttime dredging activities were found to have significantly disturbed the lake water.
- A method of evaluating the dredging intensity was proposed using daytime and nighttime satellite data.
- The effectiveness of government policies was scientifically evaluated.

GRAPHICAL ABSTRACT



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ABSTRACT

Illegal sand mining activities are rampant in coastal and inland water around the world and result in increased water turbidity, reduced water transparency, damage to fish spawning sites and adverse effects on the health of aquatic ecosystems. However, many sand dredging vessels hide during the day and work at night, rendering conventional monitoring measures ineffective. In this study, illegal sand dredging activities and the associated aquatic environmental effects were investigated in Lake Hongze (the fourth largest freshwater lake in China) using both conventional daytime satellite data, including MODIS/Aqua and Landsat TM/ETM data as well as VIIRS Day/Night Band (DNB) nighttime light (NTL) data, the following results were obtained. (1) The Landsat data revealed that sand dredging vessels first appeared in February 2012 and their number (monthly average: 658) peaked in 2016, and sand dredging stopped after March 2017. (2) The VIIRS NTL data were satisfactory for monitoring nighttime illegal dredging activities, and they more accurately reflected the temporal and spatial distribution characteristics of dredging vessels due to their high frequency. (3) Observations from the MODIS data acquired since 2002 showed three distinct stages of changes in the suspended particulate matter (SPM) concentrations of Lake Hongze that were consistent with the temporal distributions of sand dredging vessels. (4) The contribution of dredging vessels to the increases in SPM concentration was quantitatively determined, and nighttime sand dredging activities were found to have disturbed the waters more significantly. (5) The effectiveness of government measures implemented at various stages to control illegal sand dredging activities were

* Corresponding author.
E-mail address: htduan@niglas.ac.cn (H. Duan).

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scientifically evaluated. This study provides technological support for government monitoring and the control of illegal sand dredging activities and can serve as a valuable reference for water bodies similar to Lake Hongze worldwide.

1. Introduction

Sand mining is widespread in most developing and developed countries (Larson, 2018; Padmalal and Maya, 2014) because yellow sand found in river and lake sediments is used in high-quality building materials. However, sand mining activities, particularly uncontrolled sand mining activities, pose relatively large threats to the ecological environments of water bodies, the quality of drinking water sources and the safety of maritime transport and dams. Therefore, both central and local governments in most countries restrict sand mining operations. In China, governments at various levels have formulated laws and regulations to prohibit illegal sand mining. However, because sand mining generates high profits, illegal sand mining activities are rampant in regions such as the Yangtze River Basin, the Yellow River Basin, the Pearl River Basin and the Huaihe River Basin (Lai et al., 2014; Meng et al., 2018; Zeng et al., 2018; Zhao et al., 2015). Illegal sand mining activities are typically covert, mobile and random; therefore, they are difficult to detect. Some illegal sand dredging vessels hide during the day and work only at night. Thus, it is difficult for government administrations to enforce the relevant laws.

Satellite remote sensing is characterized by wide coverage, periodicity and easy data acquisition and can be used to satisfactorily monitor sand mining activities. Currently, relatively high-resolution (≥30 m) optical satellite data such as those acquired by the Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Operational Land Imager (OLI) series sensors and the charge-coupled device (CCD) cameras on board Chinese Huan Jing satellites (HJ-1-A/B) are used to monitor sand dredging vessels and their activities. Relevant information is primarily extracted based on the significant differences among sand dredging vessels and their locations in normal water bodies using the near-infrared or shortwave infrared bands (Barnes et al., 2015; Li et al., 2014; Wu et al., 2007). Sand dredging vessels are generally approximately 10–20 m in length; therefore, moderate-resolution (≥250 m) data such as those acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) cannot be directly used to monitor sand dredging vessels. Nevertheless, because sand dredging often results in significant increases in suspended particulate matter (SPM) concentrations in the relevant areas, sand dredging activities and their effects can be indirectly analyzed through observations of turbid plumes (Cao et al., 2017; Kutser et al., 2007). Some illegal sand dredging vessels mainly work at night to evade government control; therefore, daytime satellite data such as Landsat data are ineffective in identifying such operations.

During nighttime operation, sand dredging vessels often gather closely, forming a well-lit area. This characteristic provides the possibility for nighttime light (NTL) monitoring based on remote sensing. Satellite NTL data, including those acquired by the Operational Linescan System from the first-generation satellite of the Defense Meteorological Satellite Program and those acquired by the Visible Infrared Imaging Radiometer Suite Day/Night Band (VIIRS DNB) sensor onboard the Suomi National Polar-orbiting Partnership satellite—a new-generation of NTL image products—have traditionally been used to monitor nighttime city scenes and study the spatial expansion and economic development of cities (Hu et al., 2017; Wang et al., 2017). For example, satellite NTL data were used to study seasonal changes in the nighttime brightness of cities. One study found that monthly changes in nighttime brightness were positively correlated with monthly changes in snow cover and albedo and negatively correlated with monthly changes in the normalized difference vegetation index (NDVI) (Levin, 2017). In addition, satellite NTL data have been used to monitor the gross domestic products: the total radiance derived from a smoothed annual image exhibited a high correlation with gross domestic product at the state level (Zhao et al., 2017). Thus far, satellite NTL data have rarely been used to monitor vessels (Kanjir et al., 2018). Satellite NTL data were used to monitor fishing boats (Elvidge et al., 2015b) and the movements of commercial icebreakers in Arctic shipping routes to indirectly estimate ice thicknesses along the shipping routes (Straka et al., 2015). In addition, NOAA's Earth Observation Group (EOG) has worked since 2014 on algorithms to report the locations of boats detected based on light in global VIIRS DNB images (https://www.ngdc.noaa.gov/eog/viirs/download_boat.html). Currently, however, no studies have reported using NTL data to monitor sand dredging vessels in inland lakes.

Situated in northern Jiangsu Province, China, at the junction of the middle and lower reaches of the Huaihe River, Lake Hongze (33°06′–33°40′N, 118°10′–118°52′N) (Fig. 1) is the fourth largest freshwater lake in China (Wang and Dou, 1998). Lake Hongze is not only a primary source of drinking water for nearby cities (e.g., Huai'an) but also an important hub in the Eastern Route of the South–North Water Transfer Project (SNWTP). The water quality of the lake plays a vital role in the transfer of clean water from the Yangtze River to the North China Plain. A large amount of high-quality yellow sand was discovered in the bed of Lake Hongze in 2012, and this finding was soon followed by the appearance of a large number of sand dredging vessels. These sand dredging activities pose a threat to safe drinking water and damage the original ecological environment of the lake and the lakebed, resulting in increased turbidity in the lake and the deaths of fish and shrimp (Yan, 2015). More importantly, they also pose a severe threat to the safety of the dam along the eastern shore of the lake, directly endangering the safety of the 20 million residents and the productivity of the 2000 km^2 of farmlands in the five cities downstream of the lake (including Huai'an, Yangzhou and Taizhou). Therefore, illegal sand dredging constitutes an extensive safety hazard. In fact, the central and local governments have introduced multiple policies intended to control sand dredging operations. However, no method has been developed to effectively determine whether such policies produce an immediate effect.

In this study, daytime and nighttime multisource satellite data were used to analyze sand dredging activities in Lake Hongze, China. The main objectives were to: (1) use Landsat OLI and VIIRS DNB data to monitor sand dredging vessels around the clock; (2) use Aqua MODIS data to reveal the characteristics of changes in the SPM concentrations between 2002 and 2017 and analyze the effects of sand dredging activities on lake turbidity; and (3) evaluate the effectiveness of the policies implemented to control sand dredging operations. This study has the potential to provide support for monitoring illegal sand dredging activities and for scientific lake management worldwide through multisource satellite data.

2. Materials and methods

2.1. Dredging ships retrieved from VIIRS DNB

The newest-generation satellite with nighttime light-observing sensors, NPP-VIIRS DNB, was successfully launched on October 28, 2011. This satellite's increased spatial resolution (15 arc sec, 742 m × 742 m), low light-imaging detection limits (~2×10^{-11} $W \cdot cm^{-2} \cdot sr^{-1}$) and high