Journal of Environmental Management 151 (2015) 33–43

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Remote sensing estimation of the total phosphorus concentration in a large lake using band combinations and regional multivariate statistical modeling techniques

Yongnian Gao [a,*], Junfeng Gao [a], Hongbin Yin [a], Chuansheng Liu [b], Ting Xia [c], Jing Wang [d], Qi Huang [a]

[a] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China
[c] College of Environment, Nanjing University of Technology, Nanjing 210002, China
[d] Jiangsu Institute of Land Surveying and Planning, Nanjing 210024, China

ARTICLE INFO

Article history:
Received 12 September 2014
Received in revised form
17 November 2014
Accepted 29 November 2014
Available online

Keywords:
Total phosphorus
Remote sensing
Band combination
Regional statistical modeling
Lake Chaohu

ABSTRACT

Remote sensing has been widely used for ater quality monitoring, but most of these monitoring studies have only focused on a few water quality variables, such as chlorophyll-a, turbidity, and total suspended solids, which have typically been considered optically active variables. Remote sensing presents a challenge in estimating the phosphorus concentration in water. The total phosphorus (TP) in lakes has been estimated from remotely sensed observations, primarily using the simple individual band ratio or their natural logarithm and the statistical regression method based on the field TP data and the spectral reflectance. In this study, we investigated the possibility of establishing a spatial modeling scheme to estimate the TP concentration of a large lake from multi-spectral satellite imagery using band combinations and regional multivariate statistical modeling techniques, and we tested the applicability of the spatial modeling scheme. The results showed that HJ-1A CCD multi-spectral satellite imagery can be used to estimate the TP concentration in a lake. The correlation and regression analysis showed a highly significant positive relationship between the TP concentration and certain remotely sensed combination variables. The proposed modeling scheme had a higher accuracy for the TP concentration estimation in the large lake compared with the traditional individual band ratio method and the whole-lake scale regression-modeling scheme. The TP concentration values showed a clear spatial variability and were high in western Lake Chaohu and relatively low in eastern Lake Chaohu. The northernmost portion, the northeastern coastal zone and the southeastern portion of western Lake Chaohu had the highest TP concentrations, and the other regions had the lowest TP concentration values, except for the coastal zone of eastern Lake Chaohu. These results strongly suggested that the proposed modeling scheme, i.e., the band combinations and the regional multivariate statistical modeling techniques, demonstrated advantages for estimating the TP concentration in a large lake and had a strong potential for universal application for the TP concentration estimation in large lake waters worldwide.

1. Introduction

Because of the increasing discharge of nutrients into water from various pollution sources, the quality of the lakes, reservoirs and other surface water have deteriorated and eutrophication has become a severe water pollution problem in many countries over the past few decades. (Kondratyev and Pozdnyakov, 1998; He et al., 2008; Li et al., 2009; Smith et al., 1999; Sherwood and Qualls, 2001; Gao et al., 2011). Numerous studies have suggested that phosphorus is one of the main nutrients limiting eutrophication of aquatic ecosystems (e.g., Edmondson, 1970; Dillon and Rigler, 1974; Vollenweider, 1976; Schindler, 1977; Tyrrell, 1999; Guildford and Hecky, 2000; Wu et al., 2010). Monitoring phosphorus changes is

* Corresponding author. 73 East Beijing Road, Nanjing 210008, China. Tel.: +86 25 86882127; fax: +86 25 86882124.
E-mail address: yngao@niglas.ac.cn (Y. Gao).

http://dx.doi.org/10.1016/j.jenvman.2014.11.036
0301-4797/

important for controlling eutrophication in lakes, reservoirs and other surface water (Seker et al., 2003).

The current in situ techniques for measuring and monitoring the phosphorus concentrations in lakes and reservoirs are time-consuming and do not provide a synoptic view of a water body across the landscape (Wu et al., 2010; Bilge et al., 2003; He et al., 2008). Fortunately, remote sensing may provide a tool for phosphorus monitoring because it has been used successfully to monitor other water quality variables, such as temperature (e.g., Alcântara et al., 2010), chlorophyll-a (e.g., Yacobi et al., 2011; Le et al., 2009; Bresciani et al., 2011), turbidity (e.g., Nellis et al., 1998), and total suspended solids (e.g., Bistani, 2009), with a higher precision for lakes and reservoirs (Lillesand et al., 1983; Lathrop and Lillesand, 1989; Wu et al., 2010) around the world (Bistani, 2009). However, most of the studies on the water quality remote sensing have mainly focused on optically active variables (He et al., 2008). Few studies have focused on non-optically active compounds in water, such as total phosphorus (TP) (e.g., Wu et al., 2010; Santaella and Campos, 2008), total nitrogen (TN) (e.g., He et al., 2008), dissolved oxygen (DO) (e.g., Xie et al., 2007), the chemical oxygen demand (COD) (e.g., Wang et al., 2004; Yang et al., 2011) and the biochemical oxygen demand (BOD) (e.g., Wang et al., 2004). Although remote sensing has the potential to generally estimate the water quality variables, it presents a challenge in estimating the phosphorus concentration. In theory, remote sensing estimation of the phosphorus concentration is difficult using a physical model (Wu et al., 2010). However, the TP concentration may be highly correlated with the chl-a concentration, the chromophoric dissolved organic matter (CDOM) or the total suspended solids (TSS) concentration value (Schindler, 1977; Carlson, 1977; Heiskary and Wilson, 2005; Wu et al., 2010; Li and Xiao, 2011; Miao et al., 2011). The chl-a, CDOM and TSS have direct optical properties and spectral characteristics and can be estimated by remote sensing. Therefore, the TP concentration can be expressed according to the following relationship:

$$TP \propto f(\mathrm{chl-a,\ CDOM,\ TSS\ or\ others}) \tag{1}$$

The chl-a concentration, CDOM and TSS values can be expressed through the remote sensing reflectance ρ according to the following expression:

$$f(\mathrm{chl-a,\ CDOM,\ TSS\ and\ others}) \propto \rho \tag{2}$$

According to these two equations, the TP concentration can be expressed as follows:

$$TP \propto \rho \tag{3}$$

In Lake Chaohu, it was found that the correlation coefficient value between the TP and the chl-a concentration was 0.707, and they were highly significantly correlated at the $p < 0.01$ significance level. The study by Schindler (1977) has also shown that 74% of the variability in the chlorophyll concentration among lakes could be explained by the variation in the phosphorus concentration (Wu et al., 2010). These findings have suggested that the optically active compounds strongly correlated with surface reflectance, such as chl-a concentration, may serve as a proxy for the phosphorus concentration. Therefore, the logical deduction, which is the assumption of this study, is that there is a correlation between the remote sensing observations and the TP concentration in a water body (Wu et al., 2010) in the form of the reflectance $\rho = f(\mathrm{chl-a,\ CDOM,\ TSS\ and\ others}) = f(\mathrm{TP})$.

To date, attempts to estimate the phosphorus concentrations in lakes and reservoirs have achieved limited success. Using the correlations between the ground-truth data and combinations of spectral bands from the remotely sensed data, spectral indices have been developed that could be used to estimate the phosphorus content. Slightly refined spectral indices for phosphorus have been required in the new environmental setting (Bistani, 2009). Ellyson and Ecker (2005) have demonstrated that a principal component analysis of more than 20,000 remote sensed pixels can be used in a regression analysis to accurately predict the total phosphorus levels in Casey Lake at three distinct times during the summer of 2004. In the study by He et al. (2008), a water quality retrieval model has been established and has been used to analyze for TP using the Landsat 5 Thematic Mapper (TM) data and multiple regression algorithms, and the TP concentration was retrieved within a 30% mean relative error. Wu et al. (2010) have developed an empirical remote sensing model using the Landsat TM data to estimate the phosphorus concentration and to characterize the spatial variability of the phosphorus concentration in the mainstream of the Qiantang River. According to the results of the case studies (e.g., Ellyson and Ecker, 2005; He et al., 2008; Wu et al., 2010; Santaella and Campos, 2008), the TP in the lakes was estimated from remotely sensed observations, primarily using the simple individual band ratio or their natural logarithm and statistical regression method based on the field TP data and the spectral reflectance. However, when a lake is very large, has a spatial variability of the water quality and has obvious concentration gradients between the different parts of the lake, full-lake statistical modeling based on the band ratio and other simple methods can not reflect the spatial heterogeneity of the TP; thus, multivariate statistical modeling-based lake segmentation may be an effective method for lake segmentation could be a solution to fit each part of large lake.

The objectives of this study were as follows: (1) to develop an empirical remote sensing model to estimate the TP concentration of a large lake using band combinations and regional multivariate statistical modeling techniques, (2) to test the applicability of the spatial modeling algorithm to a large lake, such as Lake Chaohu, using the field TP data, and (3) to characterize the spatial variability of the TP concentration in Lake Chaohu.

2. Materials and methods

2.1. Study area

Lake Chaohu, the fifth largest freshwater lakes in China, is located in the center of the Anhui Province in China (117.16°–117.51° E and 31.43°–31.25° N) (Fig. 1). Lake Chaohu has a surface area of 770 km^2 and an average water depth of 2.7 m (Wang and Dou, 1998; Liu et al., 2011). Laoshan Island is situated within the lake. The lake is now one of China's most polluted lakes (Wikipedia, 2011) and one of the three most eutrophic lakes of China. The eutrophication state of the lake's western part is more serious than that of the eastern part, primarily because the former is the final destination of industrial and municipal wastewater from Hefei City, the capital of the Anhui Province (Shang and Shang, 2007).

2.2. Field measurements

2.2.1. Sampling sites

In this study, thirty-eight water-sampling sites were established, as shown in Fig. 1. The water was sampled at the thirty-eight sampling sites in Lake Chaohu on July 30 and August 2, 2010. The samples were obtained at depths of 0–0.2 m. Each sampling site was geographically located using a Global Positioning System (Garmin, GPSMAP 60 CSx) with a precision of 3–6 m (Chen et al., 2008). Among the sites, there were fourteen sampling sites in eastern Lake Chaohu and twenty-four in western Lake Chaohu. The water samples were acid preserved immediately in a portable