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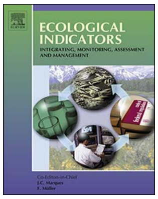

Original Articles

When and where to reduce nutrient for controlling harmful algal blooms in large eutrophic lake Chaohu, China?

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ABSTRACT

Nutrient reduction was an important but costly strategy to control harmful algal blooms (HABs) in eutrophic lakes. It is still unclear that when and where to reduce nutrients for controlling HABs in a large eutrophic lake. This study proposed a nutrient loading contribution index (NLCI) to evaluate the contribution of nutrient loading on HABs in a large eutrophic lake (Lake Chaohu, China). The index was calculated using a hydrological, hydrodynamic and water quality model. A multi-site and multi-variable calibration revealed that the coupled model captured the spatio-temporal pattern of chlorophyll *a* in the lake representing HABs. The evaluation results revealed that effective HABs controlling in the lake depended on reducing P loading. Both internal and external P loading contributed significantly to HABs in the lake. Nanfei and Hangbu Rivers were the hot spots for external P reduction. Aug., May and Jul. were the hot moments for external P reduction. The new index (NLCI) can be potentially used in other large eutrophic lakes to make a better strategy for nutrient reduction in water management practice.

Model availability

Model name: Xinanjiang Model
Model download: http://www.escience.cn/people/elake/index.html
Programming language: Python
Model name: Environmental Fluid Dynamics Code (EFDC)
Model download: http://sourceforge.net/projects/snl-efdc/
Programming language: FORTRAN

1. Introduction

Harmful algal blooms (HABs) caused by excessive nutrient loading in freshwater systems have been a global problem for decades. Examples of severe HABs included Lakes Taihu and Chaohu in China (Kong et al., 2017; Qin et al., 2010), Lake Erie in North America (Michalak et al., 2013; Watson et al., 2016), Lake Winnipeg in Canada (Schindler et al., 2012; Ulrich et al., 2016). These HABs caused the harmful impacts of oxygen depletion, fish kills, liver damage by toxins, biodiversity loss and water quality degradation (Catherine et al., 2013; Clark et al., 2017; Paerl and Huisman, 2008). Reducing nitrogen (N) and phosphorus (P) loadings can limit excessive phytoplankton growth (Brookes and Carey, 2011), and had achieved great success for controlling HABs in many freshwater lakes, such as Lake Erie in North America (Smith et al., 2015). However, decision-making on nutrient reduction was challenging for a large lake due to the following unaddressed questions.

(1) Whether one or both nutrients should be reduced for controlling HABs? Inspired by Liebig's minimum law, worldwide limnologists have been trying to identify the most limiting nutrient for phytoplankton growth in eutrophic lakes. P was found to be the growth-limiting nutrient, and P controlling was thus strongly recommended (Hecky and Kilham, 1988; Imboden and Gachter, 1978; Thomas, 1972; Vollenweider, 1976). This conclusion led to widespread of P loading

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Abbreviations: NLCI, nutrient loading contribution index; HABs, harmful algal blooms; EFDC, environmental fluid dynamics code; Q, flow discharge (m^3/s); WL, water level (m); TP, total phosphorus (mg P/L); TN, total nitrogen (mg N/L); NH_4^+, ammonia nitrogen (mg N/L); CHL, Chlorophyll *a* (μg/L); DO, dissolved oxygen (mg/L); WT, water temperature (°C)

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reductions in North American and European lakes and consequent improvements in water quality (National Research Council, 1992). However, a dual (N and P) nutrient reduction was proposed in some lakes that were dominated by non-N_2-fixing cyanobacteria, and had a rapid P recycle between water and sediment (Conley et al., 2009). Although hot debates among N or P reduction to control HABs are continuing (Conley et al., 2009; Schindler, 1974), there is a consensus that an appropriate strategy for nutrient (N or P) controlling can be determined by investigating N:P ratios using Redfield ratio (Abell et al., 2010; Schindler et al., 2008), that was originally proposed by Alfred C. Redfield in 1934 (Arrigo, 2014).

(2) When and where to reduce nutrients for controlling HABs? Nutrient reduction is one of the most effective strategies to control HABs for a eutrophic lake (Schindler et al., 2016). However, either internal or external nutrient loading reduction is time-consuming and costly. Therefore, learning the nutrient contribution to HABs in the lake can help water managers to make a priority list on nutrient reduction. Successful cases to investigate the response of HABs/phytoplankton to nutrient conditions were implemented in many aquatic ecosystems, such as Lake Taihu (Huang et al., 2016), Lake Dianchi (Wu et al., 2017) and the Bay of Quinte, Lake Ontario (Shimoda et al., 2016). However, for large lakes, a specific nutrient reduction strategy (e.g., P reduction from one inflow) may alleviate HABs in different areas to different extents. Therefore, it is helpful for water managers to know when and where to reduce nutrients for controlling HABs in the most concerned area (e.g., drinking water intake). To our knowledge, this question was scarcely investigated for a large shallow lake due to its multiple nutrient sources and complex mass transport processes.

The hypothesis of this study was that nutrient reduction in different inflows and during different periods would result in different spatio-temporal patterns of HABs in a large shallow lake. To test above hypothesis, a large shallow eutrophic lake (Lake Chaohu) in China was used as an example. A new nutrient loading contribution index (NLCI) was proposed to evaluate nutrient loading contribution to spatio-temporal pattern of HABs. NLCI had the advantage of describing HABs and nutrient transport in the large lake using a hydrological, hydrodynamic and water quality model. Based on the evaluation results using NLCI, the contribution of nutrient sources (inflows and sediment fluxes) for spatio-temporal pattern of HABs in the lake was accounted for.

2. Materials and methods

2.1. Study area and data

Lake Chaohu (surface area, 768 km^2; mean depth, 2.7 m), the fifth largest freshwater lake in China, is located in central Lake Chaohu watershed (13,555 km^2) (Fig. 1). The main connecting rivers of Lake Chaohu include six inflows (Hangbu, Baishitian, Zhao, Zhegao, Nanfei and Pai Rivers) and one outflow (Yuxi River) connecting with Yangtze River. A sluice at H3 was used to control water level of Lake Chaohu since Dec. 1962, and resulted in a long water retention time of 207 d, and a large water level fluctuation from 8.11 m to 10.04 m above sea level (Wusong datum) during 2011–2014. Lake Chaohu was well-known for its scenic beauty and rich aquatic products before the 1960s. However, due to rapid population growth and economic development during past few decades, Lake Chaohu showed a decreasing trend of wetland area, macrophyte coverage, and an increasing trend of algal biomass (Xu et al., 1999). HABs occurred from May to November since 1980s. During the past decade, a series of measures (e.g., improving wastewater treatment) have been taken by government to control eutrophication in Lake Chaohu. However, HABs coverage, frequency, and duration showed an increasing trend during 2000–2013 (Zhang et al., 2015). The phytoplankton was dominant by cyanobacteria (99.5% of total phytoplankton biomass) (Jiang et al., 2014). Nutrients (phosphorus and nitrogen) and HABs in western Lake Chaohu were significantly higher than those in eastern Lake Chaohu (Zhang et al., 2016). Nonpoint source pollution from agricultural farmlands was found to be the primary nutrient sources for the lake (Zhou and Gao, 2011).

A measured dataset was collected during 2010–2014 for modeling HABs in Lake Chaohu (Table 1). This dataset included land use, meteorological, hydrological and water quality data. The land use data were derived from satellite images (the moderate-resolution imaging spectroradiometer, MODIS) in 2010. The daily meteorological data were collected from six national weather stations and a hydrological station. The daily hydrological data including flow discharge (Q, m^3/s) and water level (WL, m). Q data were collected from three hydrological stations of H1, H2 and H3. WL data were collected from the hydrological station of H3. Water quality data included the variables of total

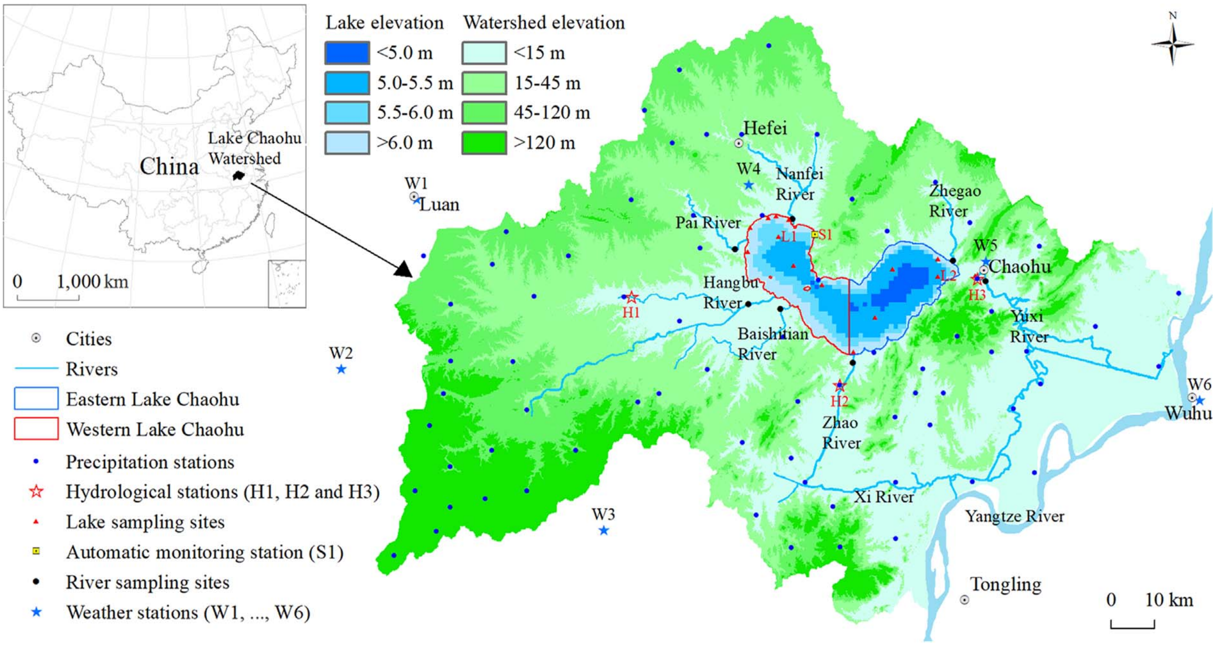

Fig. 1. Locations of Lake Chaohu watershed, elevation above sea level (Wusong datum), river network, water sampling sites, weather and hydrological stations.