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Effects of lake-basin morphological and hydrological characteristics on the eutrophication of shallow lakes in eastern China

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ABSTRACT

The Yangtze River floodplain contains numerous oxbow or riverine lakes, all of which were openly connected with the Yangtze River or its major tributaries prior to 1950s. However, stresses resulting from human settlement and utilization of catchment resources have exerted great pressures on these lake ecosystems changing their morphology, connectivity and trophic state lakes. This study examined the interaction of these changes and their impact on eutrophication for 90 shallow lakes in eastern China in 2008 to 2011. TN and TP in the study lakes had negative relationships with mean water depth (Z_{mean}), but no single lake-basin characteristic was found to dominate chlorophyll-a (Chl-a) growth. Instead, water depth and surface area were found to interactively affect Chl-a concentrations in smaller lakes. That is, Chl-a concentration in the lakes with $Z_{mean} > 2$ m and surface area (SA) ≤ 25 km^2 was significantly higher than that in relatively larger lakes with $Z_{mean} > 2$ m and SA > 25 km^2 (p-value ≤ 0.038). Chl-a concentration was higher in the lakes located within the lower Yangtze River basin which had longer retention times, than in the lakes located within the middle Yangtze River basin, where flow velocity is relatively larger. As expected, the water quality was found to be better in the lakes hydraulically connected with rivers than in those isolated from the river. This study revealed that lake-basin morphology and hydrology dominated algal blooms in the highly eutrophic shallow lakes in eastern China.

Introduction

Eutrophication of lakes, especially shallow ones, is a worldwide environmental concern because it threatens ecosystem health and species diversity (Zhai et al., 2010). Shallow lakes are easily shifted to a new trophic state due to their: 1) polymictic and dimictic nature (Havens et al., 2001); 2) high concentration of suspended solids from continuous circulation (Ishikawa and Tanaka, 1993; Vicente et al., 2012); 3) lack of long-term, stable thermal stratification (Muraoka and Fukushima, 1981; Padisák and Reynolds, 2003; Read et al., 2011; Verbruggen et al., 2011); and 4) substantial internal loading of nutrients migrating from sediments into the water column (Goda and Matsuoka, 1986; Søndergaard et al., 1992; 2013). Thus, water quality [e.g., total nitrogen (TN) and total phosphorus (TP)] of shallow lakes is sensitive to human activity as well as to climatic and hydrological conditions.

In the past decades, extensive studies have been conducted to better understand mechanisms of algal blooms in shallow, eutrophic lakes. These studies have taken into account how climate change (Chen et al., 2012; Fragoso et al., 2011; Gerten and Adrian, 2001; Mooij et al., 2007; Straile and Adrian, 2000), external nutrient load, and/or in-lake process (e.g., temperature stratification) (Huang et al., 2009; Sas, 1989) affect trophic structure. Study designs have included long-term observations (Aizaki and Otsuki, 1987; James et al., 1995a,b; Spears and Jones, 2010; Spears et al., 2012), site-specific experiments (Moss et al., 1996; Roessink et al., 2010; Yvon-Durocher et al., 2010), analysis of nutrient cycling and trophic dynamics (Fukushima et al., 1987; Kokfelt et al., 2010; Olila and Reddy, 1993), and model simulation (James et al., 1997; Janse et al., 2008; Kelly et al., 2012; Mooij et al., 2010).

For a shallow lake, water quality is susceptible not only to climate change and human activity but also to the size of the lake basin and its hydrologic characteristics. Köiv et al. (2011) analyzed phosphorus retention rate as a function of external load, hydraulic residence time, surface area (SA), and relative depth (Z_{rel}) using published data for 54

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lakes and reservoirs located in different climate regions around the world. Those authors found that water bodies with a longer hydraulic residence time tended to retain a larger proportion of external phosphorus, and that the correlation between phosphorus load and hydraulic residence time was much stronger in the lakes with SA > 25 km^2 than in the lakes with SA ≤ 25 km^2. Carvalho et al. (2009), who analyzed data from 466 lakes in 12 NW European countries, found that chlorophyll-a (Chl-a) concentration increased with increase in color and alkalinity, but it decreased with lake water depth and geographic location. Both of these studies concluded that lake ecosystems were severely restricted by lake-basin morphology, as characterized by water depth, SA, shape, and wind fetch, and that background nutrient concentrations were higher in shallow lakes than in deep ones. In addition, for floodplains, in which shallow lakes are usually located, there has been an increasing awareness of influences of lake-basin morphology on nutrient load and transport as well as how unwanted morphological change may alter structures and functions of a lake ecosystem.

There are numerous shallow lakes in eastern China, most of them located within the middle and lower Yangtze River basins (Qin, 2002). In the Yangtze River floodplain, hundreds of lakes are of oxbow or riverine types and had open hydrologic connections with the Yangtze River or its major tributaries prior to 1950s (Yang et al., 2002). The maintenance of natural hydrologic connectivity is of great importance to the ecological equilibrium of these lake ecosystems (Liu and Wang, 2010). However, their environmental health has been adversely impacted by stresses resulting from human occupancy and overexploitation of catchment resources during the past half century (Jin, 2003). Consequently, most of the lakes in this area have become reservoir-type due to modified flows and susceptible to algal blooms partially due to undesirable alterations of lake-basin morphology and hydrology. Addressing the worsening eutrophication problems being faced by these shallow lakes requires a better understanding of the complex interactive effects of lake-basin morphology and hydrology; however, such understanding to date is insufficient in existing literature and there is room for improvement.

The shallow lakes in eastern China have been facing threats of discharges with high concentration of nutrients as China's economy has grown. Since the 1990s, eutrophication has become a major environmental concern for these lakes. Although several previous studies (e.g., Chen et al., 2012; Fragoso et al., 2011; Gao and Zhang, 2010; Huang et al., 2009; Jin, 2003) intended to address such concerns, only one lake or two were analyzed in a given study. Also, only a few of those studies assessed effects of hydrological conditions on eutrophication of the studied lakes. Thus, those studies have limited value in developing corrective measures for solving such a regional eutrophication problem. The objective of this study was thus to determine the effects of lake-basin morphology and hydrology on eutrophication for 90 typical shallow lakes in eastern China. The parameters of lake-basin morphology considered are water depth (Z_{rel} and mean depth Z_{mean}) and SA, while the hydrological parameters include both hydrologic connectivity and drainage characteristics (e.g., stagnated versus turbulent fast flow). We hypothesized that eutrophication of shallow lakes is mainly affected by both lake-basin morphology and hydrology. Unlike previous work on Chinese lakes, we report on 90 shallow lakes distributed across several provinces (Fig. 1). Our work provides a perspective and synthesis of research on Chinese shallow lakes not previously provided in the scientific literature.

Materials and methods

Study area

In the middle and lower Yangtze River basins, there are 651 lakes with SA > 1 km^2 and 18 lakes with SA = 100 to 3841 km^2 (Jin et al., 1995). Most of the lakes are shallow and have a water depth ranging from 1.31 to 23.5 m. The total water surface area of all these lakes is > 21,000 km^2, accounting for 25% of the overall water surface area of all lakes in China. In terms of data availability and geographical distribution, this study selected 90 typical lakes (Fig. 1) from the available lakes. The descriptive statistics of the 90 lakes, including the largest lakes of Poyang, Dongting, Tai, Hongze, and Chao (listed in descending order

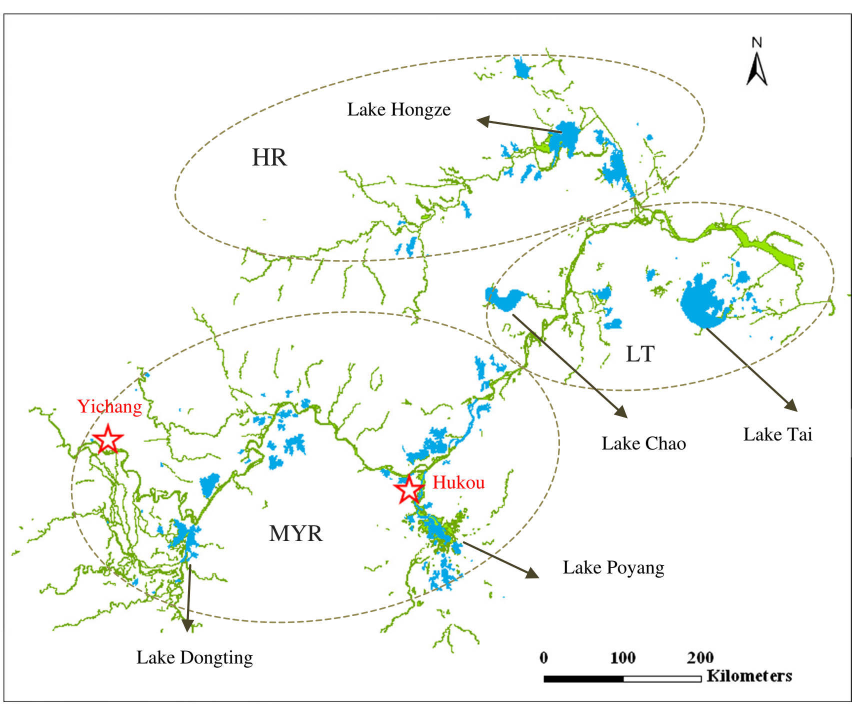

Fig. 1. Map showing the distribution of the 90 study lakes located within basins of the Middle Yangtze River (MYR), the region of the lower Yangtze River upstream of Lake Tai (LT), and the Huaihe River (HR). The five largest lakes and two major cities (Yichang and Hukou) are also shown.

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