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Seasonal and spatial distributions of euphotic zone and long-term variations in water transparency in a clear oligotrophic Lake Fuxian, China

Q3 Q2 Qichao Zhou[1,2], Yunlin Zhang[1,*], Kaidi Li[2,3], Licheng Huang[2], Fengle Yang[2], Yuanyang Zhou[2,3], Junjun Chang[3]

1. 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 210008, China. E-mail: qchzhou@gmail.com

2. Yunnan Key Laboratory of Pollution Process and Management of Plateau Lake-Watershed, Yunnan Institute of Environmental Science (Kunming China International Research Center for Plateau Lake), Kunming 650034, China

3. School of Ecology and Environmental Science, Yunnan University, Kunming 650091, China

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ABSTRACT

To assess the seasonal and spatial variations and long-term trends in water optical properties in Lake Fuxian, investigations based on field work in four seasons and a long-term analysis of data from 1980 to 2014 were conducted. The results show that there was no significant variation in the euphotic depth (Z_{eu}) across the four seasons, and no significant correlations between Z_{eu} and potential influencing factors in seasons other than summer, suggesting that the water itself may be a major factor regulating the Z_{eu} in general. Nevertheless, significant differences in Z_{eu} between the north region (NR) and the south region (SR) were observed in all seasonal tests except spring. This finding relates to a higher abundance of chromophoric dissolved organic matter (CDOM) in the NR due to runoff, especially in the rainy seasons (summer and autumn). CDOM and its terrigenous component had an important impact on Z_{eu} in summer, with the highest precipitation, and impacts from suspended solids and non-algal particles were also found in the NR in summer. The Secchi disk depth in the lake decreased clearly over the years, with significantly negative correlations with the increasing permanganate index and air temperature, implying that organic contaminants (CDOM and/or phytoplankton) are important regulators of water transparency. We estimate that the combined effects of climate warming and changes in land use and land cover are also indirect regulating factors. These findings should be considered in the protection of Lake Fuxian, owing to the importance of light penetration in aquatic ecosystems.

Introduction

Solar radiation has an important effect on the thermal regime, biogeochemical cycles, primary productivity, population dynamics and community structure in aquatic ecosystems. Estimating the depth of the euphotic zone and measuring water transparency are two common methods used to characterize water optical properties, especially for photosynthetic active radiation (PAR, 400–700 nm). The euphotic zone can be defined as the water layer that supports net primary productivity; its lower end

* Corresponding author. E-mail: ylzhang@niglas.ac.cn (Yunlin Zhang).

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is the compensation depth, at which the amount of organic carbon fixed by photosynthesis is equal to that emitted by respiration, and its thickness (euphotic depth, Z_{eu}) is generally defined as the depth at which the downwelling irradiance of PAR falls to 1% of that just below the water's surface (Kalff, 2002; Kirk, 2011). The Secchi disk depth (SDD) is the most straightforward parameter used to represent water transparency and evaluate light penetration, as well as to indicate the value of Z_{eu} indirectly through conversion (Luhtala and Tolvanen, 2013; Zhang et al., 2012).

Water optical properties will experience significant shifts due to the effects of climate change and allochthonous inputs from catchments (Modenutti et al., 2013; Pienitz and Vincent, 2000), as well as changes in phytoplankton biomass (Wu et al., 2015), especially in alpine clear lakes (Laurion et al., 2000; Rose et al., 2009; Sommaruga and Augustin, 2006). Alpine clear lakes, the water optical properties of which differ from other lakes (Rose et al., 2009; Zhang et al., 2011), are considered sentinels of environmental change owing to their extreme sensitivity (Mladenov et al., 2011; Sommaruga-Wograth et al., 1997). Lake Fuxian, the third deepest freshwater lake in China, is a clear oligotrophic plateau lake and provides various natural resources for the local inhabitants. Unfortunately, the lake is at risk due to climate warming (Tao et al., 2013), eutrophication (Zhang et al., 2015) and other severe environmental changes (*e.g.*, population surges, increases in contaminant discharge, and variations in land use and land cover (LULC)) in the catchment (Dai et al., 2017; Gao et al., 2013), which could have significant impacts directly or indirectly on water optical properties. Moreover, several studies have revealed temporal and spatial variations in light conditions in other aquatic environments (Belzile et al., 2004; Brandão et al., 2016; Luhtala et al., 2013; Wu et al., 2015; Zhang et al., 2006; Zhou et al., 2014), but more research is needed in Lake Fuxian (Pan et al., 2008; Zhou et al., 2016b), because of the seasonal and spatial heterogeneity and significant changes in the environmental conditions within the watershed.

Therefore, the aim of this study was to assess the seasonal and spatial variations and long-term trends in water optical properties (euphotic depth and water transparency) and their potential regulating factors. SDD was selected to describe long-term variations in water transparency due to a large number of missing historical data about the diffuse attenuation coefficient (K_d) and Z_{eu} in Lake Fuxian, the limitation of sample size for predicting the K_d or Z_{eu} through SDD in the lake at present, as well as the conversions available between SDD and K_d or Z_{eu} across aquatic ecosystems and over time (Luhtala and Tolvanen, 2013; Padial and Thomaz, 2008; Zhang et al., 2012).

1. Materials and methods

1.1. Description of Lake Fuxian

Lake Fuxian (24°21′–24°38′N, 102°49′–102°57′E; Fig. 1) is a warm monomictic fault lake located in the middle of the Yungui Plateau in southwestern China (Yuxi City, Yunnan Province). The lake is characterized by a central subtropical, plateau, semi-humid, monsoon climate. The lake area is 211.0 km^2, the mean depth is 89.6 m, the maximum depth is 155.0 m, and the water storage is 189.0×10^8 m^3 at a water level of 1771.0 m. More than 100 rivers flow into the lake, and the lake has a dozen or more species of submerged macrophytes distributed in the littoral zone. The lake serves as a drinking water source for the local inhabitants. Although the average water quality of the lake meets Grade I of the China National Water Quality Standard (*i.e.*, GB3838-2002), it has been reported that since the 1980's, the lake's water quality has decreased (Gao et al., 2013), and the aquatic ecosystems have been changed (Liu et al., 2014).

1.2. Field sampling and measurement

Sixteen sites (Fig. 1) were chosen in the lake for field sampling in autumn (October 2014), winter (January 2015), spring (April 2015) and summer (July 2016). Sampling sites 1 to 9 were classified as being within the north region (NR), and the others (from 10 to 16) were classified as being within the south region (SR). The underwater downwelling irradiance of PAR at different depths from 0 to 3.3 m in the mixing layer was measured using a UV–visible Radiation Meter (PUV-2500, Biospherical Instruments Inc., USA) at all sampling sites. For optically homogeneous water, the K_d of the underwater irradiance (PAR in this study) was calculated using the following equation (Kirk, 2011):

$$K_d(\lambda) = -\frac{1}{z}\ \ln\frac{E_d(\lambda, z)}{E_d(\lambda, 0)} \quad (1)$$

where $E_d(\lambda,z)$ and $E_d(\lambda,0)$ are the values of downward irradiance at z m depth, and just below the surface, respectively.

The value of Z_{eu} was derived from K_d according to the $Z_{1\%}$ calculation method, as follows (Kirk, 2011):

$$Z_{1\%}(\lambda) = 4.605/K_d(\lambda) \quad (2)$$

The vertical profiles of water temperature (WT), electrical conductivity (EC), pH and dissolved oxygen (DO) were measured using a Multiparameter Water Quality Sonde (6600, Yellow Springs Instruments, USA). At the same time, water samples were collected at a depth of 0.5 m in the surface water column to determine other parameters.

Water samples were filtered through GF/F membranes (Whatman, UK), after which the concentration of dissolved organic carbon (DOC) was determined using a TOC-VCPN analyzer (SHIMADZU, Japan). Chlorophyll *a* (Chl-*a*), total nitrogen (TN), total dissolved nitrogen (TDN), total phosphorus (TP), total dissolved phosphorus (TDP), the permanganate index (I_{Mn}; *i.e.*, chemical oxygen demand by Mn, COD_{Mn}) and suspended solids (SS) were analyzed according to the standard methods described by the Editorial Board of Water and Wastewater Monitoring and Analysis Methods of the Ministry of Environmental Protection of the People's Republic of China (2002). Phytoplankton fixed with Lugol's solution were identified and enumerated by microscope to determine the algal densities, and the phytoplankton biomass was converted from the algal densities, in which the conversion coefficients of different algae species were according to Zhao (2005). We estimated the concentration of non-algal particles (NAPs) as being approximately equal to the amount of SS minus the phytoplankton biomass.

Additionally, the same sixteen field sampling sites were used in January 2017 to measure the relative contributions of the absorption coefficients of chromophoric dissolved organic