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Long-term and inter-monthly dynamics of aquatic vegetation and its relation with environmental factors in Taihu Lake, China

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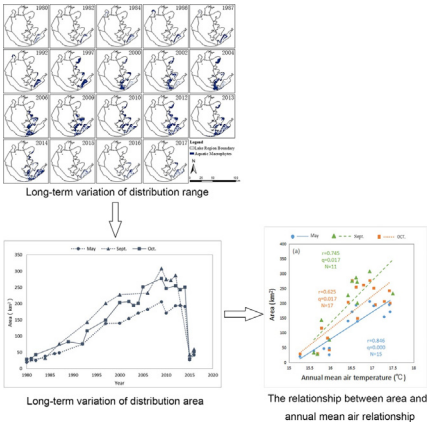
HIGHLIGHTS

- Long-term spatio-temporal variations in aquatic macrophytes in Taihu Lake
- Inter-monthly spatio-temporal variations in aquatic macrophytes in Taihu Lake
- Relationship between the aquatic macrophytes area and environmental factors

GRAPHICAL ABSTRACT



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ABSTRACT

This paper discussed the long-term and inter-monthly variation in the distribution area of aquatic macrophytes in Taihu Lake, as well as the relationship between these variations and environmental factors. The findings were of great significance to the protection and environmental remediation of lake ecosystems. This paper presented data from 92 periods during 1980 to 2017 on the distribution area of aquatic macrophytes (including submerged macrophytes and floating-leaved macrophytes, but excluding emergent macrophytes) in Taihu Lake. Data were acquired by remote-sensing and subsequent image interpretation. The analysis of the inter-monthly variation indicated that the area occupied by aquatic macrophytes first increased and then decreased from January to December. Specifically, the distribution area was very small from January to March, began to increase gradually from April to August, reached its maximum in September, and decreased gradually from October to December. The analysis of the long-term variation showed that the distribution and area of aquatic macrophytes experienced two stages during the years 1980 to 2017: 1) gradual increase, 2) sharp decrease. In the first stage (1980 to 2014), the area occupied by aquatic macrophytes increased by 9 times, the maximum distribution area was 206.27 km^2 (in May), 307.92 km^2 (in September) and 277.33 km^2 (in October). In the second stage (2015 to 2017), the distribution area of aquatic macrophytes decreased sharply to 50 km^2 or less. The distribution area of aquatic macrophytes during the months of January to December had a significant positive correlation with monthly average temperature, COD_{Mn} value, secchi disk depth(SDD), area of cyanobacteria and chlorophyll-*a*

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(Chl-*a*) concentration, a significant negative correlation with water quality indices such as dissolved oxygen (DO) value and NH_3-N concentration, but no significant correlation with water quality indices such as pH values and total suspended matter (TSM) concentration. The distribution area of aquatic macrophytes from 1980 to 2017 had a significant positive correlation with annual average temperature, annual minimum water level, pH value, SDD, area of cyanobacteria and Chl-*a* concentration, but no significant correlation with water quality indices such as DO value, COD_{Mn} value, NH_3-N concentration and TSM concentration. The sharp decrease in the distribution area of aquatic macrophytes in 2015 and subsequent years was primarily due to the mechanized salvage of aquatic plants.

1. Introduction

As an important type of plant in a lake ecosystem, aquatic macrophytes are able to change the physical and chemical environments of lake water (Meerhoff et al., 2003; Agostinho et al., 2007; Carr et al., 2015). Specifically, aquatic macrophytes serve to change the quality of lake water, retard stormy waves, immobilize bottom mud, increase water transparency, and suppress the growth and reproduction of algae (Miranda et al., 2000; Pelicice et al., 2005). Therefore, aquatic macrophytes play a regulatory role in lake evolution and the ecological balance of lakes (Phiri et al., 2011). China abounds with lakes; water resources in lakes are among the most important freshwater resources of China, and are of vital importance to China's socioeconomic development. Due to the overdevelopment of lake basins and aggravation of pollutants after China's reform, some lakes have been confronted with severe eutrophication and the frequent occurrence of phytoplankton blooms (Guo, 2007). These factors pose a severe threat to the quality of life for people near lake regions. In addition, lake environments have changed due to water level regulations, aquiculture, aggravated water eutrophication, and global climate change. This produces a severe influence on the growth of aquatic macrophytes and the distribution of aquatic communities, thus causing a variation in the distribution area of aquatic macrophytes. In view of this, it is necessary to study variations in the distribution and area occupied by macrophytes, as well as the relationship between the variations and environmental factors. The findings presented here will serve as a guide to reasonable development and utilization of aquatic macrophytes in lakes, as well as governance and environmental remediation of lake ecosystems.

As studies of lake macrophytes deepen, the traditional manual survey method can no longer satisfy the needs of large-scale and long-term monitoring in large lakes (for example, Taihu Lake). Instead, remote sensing technologies can be used to monitor the growth and distribution of aquatic macrophytes (Han and Rundquist, 2003; Gullström et al., 2006; Laba et al., 2010; Szantoi et al., 2013; Gao et al., 2017; Liang et al., 2017; Hou et al., 2018). So far, some scholars had used remote sensing technologies to interpret and identify aquatic macrophytes distributed in Taihu Lake. They had also analyzed the periodic variations in aquatic macrophytes distributions over long time periods (Ma et al., 2008; Zhao et al., 2012; Zhao et al., 2013; Luo et al., 2016; Luo et al., 2017). However, the scope of their studies was limited to local lake regions, and the time series data were relatively short. In terms of the study objectives, the existing studies covered all aquatic macrophytes in local lake regions as a whole, but did not focus specifically on the long-term or inter-monthly variations for any specific types of aquatic macrophytes (such as submerged macrophytes and floating-leaved macrophytes) (Ma et al., 2008; Zhao et al., 2012; Zhao et al., 2013; Luo et al., 2016; Luo et al., 2017). Other scholars studied how environmental factors influence the long-term variations in distribution area of aquatic macrophytes in the eastern region of Taihu Lake (Zhao et al., 2012; Zhang et al., 2016). However, they did not study Taihu Lake as a whole. Moreover, their studies mainly focused on interannual variations rather than inter-monthly variations. Therefore, there had not been any studies on the interannual or inter-monthly variation in distribution area of aquatic macrophytes (including submerged macrophytes and floating-leaved macrophytes only) across the entirety of Taihu Lake, nor had the relationship between these variations and environmental factors as well as the managed removal of the vegetation been studies.

Therefore, the objective of this paper was to discuss the following issues: 1) inter-monthly variation in the distribution area occupied by aquatic macrophytes (including submerged macrophytes and floating-leaved macrophytes, but excluding emergent macrophytes) from January to December; 2) long-term variation in the distribution area occupied by aquatic macrophytes over nearly 40 years; 3) the relationship between the interannual and inter-monthly variation and environmental factors, and the possible impacts on interannual and inter-monthly variation exerted by environmental factors and human activities such as vegetation salvage and enclosure culture, which was extremely interesting and potentially novel.

2. Materials and methods

2.1. Study area

Taihu Lake is China's third largest freshwater lake and is located in the Taihu Plain in the southern part of the Yangtze River Delta. Geographically, Taihu Lake stretches from 119°53′49″ to 120°35′25″ EL, and from 30°55′32″ to 31°32′50″ NL (as shown in Fig. 1). It is a typical shallow lake with a total area of 2338 km^2, an average depth of 1.89 m, and a maximum depth of 2.6 m. According to historical survey data, Taihu Lake abounded with aquatic macrophytes (Duan et al., 2009; Luo et al., 2016). The submerged macrophytes mainly included *Curly Pondweed*, *Myriophyllum spicatum*, *Elodea canadensis*, *Vallisneria natans*, *Ceratophyllum demersum*, *Nymphoides peltatum*, *Potamogeton malaianus*, *Potamogeton pectinatus*, *Potamogeton maackianus* and *Hydrilla verticillata*. The floating-leaved macrophytes mainly included *Hydrocharis dubia*, *Nymphoides peltate* and *water chestnut*. These aquatic plants were primarily distributed in the eastern bays, in the neighboring region between Xishan and Dongshan, and in the neighboring region between the eastern and southern regions (Lei et al., 2009; Li et al., 2014). Taihu Lake was divided into nine regions, which is consistent with the zoning result of Taihu Basin Authority of Ministry of Water Resources, as shown in Fig. 1,they were respectively the Wuli Bay, Meiliang Bay, Gonghu Bay, Eastern Region, East Taihu Bay, Southern Bay, Western Bay, Zhushan Bay and Central Region.

2.2. Satellite data

The long-term and inter-monthly variation in aquatic macrophytes populations in Taihu Lake was primarily analyzed according to data acquired through remote-sensing and image interpretation. The remote-sensing data used here included Landsat and HJ-1A/B remote-sensing images. Taihu Lake region is cloudy and rainy, which resulted that many remote-sensing images covered by cloud can't be used. In addition, the remote-sensing data used covered as much as possible years and months. Moreover, only one image was selected for each month