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Effects of local climate and hydrological conditions on the thermal regime of a reservoir at Tropic of Cancer, in southern China

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ABSTRACT

Thermal regime is strongly associated with hydrodynamics in water, and it plays an important role in the dynamics of water quality and ecosystem succession of stratified reservoirs. Changes in both climate and hydrological conditions can modify thermal regimes. Liuxihe Reservoir (23°45′50″N; 113°46′52″E) is a large, stratified and deep reservoir in Guangdong Province, located at the Tropic of Cancer of southern China. The reservoir is a warm monomictic water body with a long period of summer stratification and a short period of mixing in winter. The vertical distribution of suspended particulate material and nutrients are influenced strongly by the thermal structure and the associated flow fields. The hypolimnion becomes anoxic in the stratified period, increasing the release of nutrients from the bottom sediments. Fifty-one years of climate and reservoir operational observations are used here to show the marked changes in local climate and reservoir operational schemes. The data show increasing air temperature and more violent oscillations in inflow volumes in the last decade, while the inter-annual water level fluctuations tend to be more moderate. To quantify the effects of changes in climate and hydrological conditions on thermal structure, we used a numerical simulation model to create scenarios incorporating different air temperatures, inflow volumes, and water levels. The simulations indicate that water column stability, the duration of the mixing period, and surface and outflow temperatures are influenced by both natural factors and by anthropogenic factors such as climate change and reservoir operation schemes. Under continuous warming and more stable storage in recent years, the simulations indicate greater water column stability and increased duration of stratification, while irregular large discharge events may reduce stability and lead to early mixing in autumn. Our results strongly suggest that more attention should be focused on water quality in years of extreme climate variation and hydrological conditions, and selective withdrawal of deep water may provide an efficient means to reduce internal loading in warm years.

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1. Introduction

Water temperature and heat budgets have a significant influence on the water quality and ecological characteristics of lakes and reservoirs (Wetzel, 1983). Vertical density gradients (mainly due to thermal stratification in freshwater systems) act to resist water column mixing (Moreno-Ostos et al., 2008), thus influencing the vertical distribution of particulate and dissolved substances (Yu et al., 2010). In the period of stratification, the thermocline weakens the replacement of oxygen in deeper water layers, creating a hypolimnetic oxygen deficit. In productive lakes and reservoirs in tropical regions this can lead to anoxic conditions over most of the year (Branco et al., 2009).

The thermal/mixing regime also strongly affects nutrient availability. This is shown directly or indirectly in the dynamics of the phytoplankton community, particularly in well-stratified reservoirs with low epilimnetic nutrient concentrations (Becker et al., 2009). The timing of stratification affects the seasonal dynamics in phytoplankton (Chen et al., 2009; Seip and Reynolds, 1995; Chien et al., 2009; Becker et al., 2010). Furthermore, the thermocline depth and its stability impact on the available light energy for phytoplankton photosynthesis and, consequently, the net primary production (Thebault et al., 1999).

Variations in natural environmental or anthropogenic factors (e.g. climate change and hydrological operation schemes) affect the thermal structure of reservoirs. Climate impacts on the physical characteristics of lakes, including temperature structure and mixed layer depth, summer and winter heat budgets, timing of the onset and breakdown of stratification, drainage basin storage and flushing rates (Hauer et al., 1997). These factors in turn influence nutrient fluxes, sediment transport, biological production and food-web dynamics (Firth and Fisher, 1992). Global warming has been predicted to affect most deep lakes by reducing vertical exchange, resulting in an extended period of hypolimnetic anoxia (Sahoo and Schladow, 2008), and potentially amplifying the effects of eutrophication (Matzinger et al., 2007; Trolle et al., 2011). These effects have been investigated in many temperate and subarctic lakes in Europe and North America (Effler et al., 1986; Fee et al., 1996; Snucins and Gunn, 2000; Livingstone, 2003; Stefan et al., 1998) but less so in reservoirs where thermal dynamics are more variable due to fluctuations in water storage volume, operational variability and, generally, higher flushing rates (Moreno-Ostos et al., 2008). Operational drawdown, for example, can change the length of summer stratification and modify the heat budget (Nowlina et al., 2004).

Density differences across the thermocline are generally substantially lower in subtropical or tropical lakes than in temperate lakes despite warmer temperatures, leading to a stronger response to climate changes in tropical lakes during periods of stratification (Lewis, 1973). Local climatic conditions such as higher air temperatures reduced seasonality also create certain conditions that promote algal blooms (Jones and Poplawski, 1998); the ecosystems may therefore respond more sensitively to climatic and hydrological perturbations than temperate lakes.

Most reservoirs in southern China are located in the transition zone from tropical to subtropical (21–24°N). Reservoirs in this zone supply about 40% of the total water demand for China (Lin et al., 2003a). The water quality in many of these reservoirs had declined over the last 20 years, mostly due to increasing trophic status (Lin et al., 2003b; Xu et al., 2004). These reservoirs are strongly influenced by the monsoon climate and have distinct seasonal variation in hydrodynamics, which strongly influence phytoplankton populations (Han et al., 2006) and their succession (Xiao et al., 2011). Understanding of the thermal regime in response to changing climate and hydrological conditions is critical in developing strategies to adaptively manage water quality in tropical and subtropical reservoirs.

In this study, we applied a hydrodynamic model to quantify the way in which the thermal regime and hydrodynamics of a large and stratified reservoir respond to changes in local climate and hydrological conditions. The model simulations were conducted to study the onset/end time of stratification, surface and outflow temperature, thermal stability, and assess the impacts of probable external changes on the ecosystem to gain an understanding of the thermal regimes of reservoirs in southern China.

2. Material and methods

2.1. Study site

Liuxihe Reservoir (23°45′50″N; 113°46′52″E) is a large canyon-shaped reservoir located in a tropical to subtropical transition zone about 90 km north-east of Guangzhou city in Guangdong Province, southern China (Fig. 1). This impoundment, initially filled in 1958, is an important source of drinking water to residents in downstream areas, including Guangzhou city (population >14 million). The lacustrine zone has dendritic complexities, and the dam is located at its south-western end. When full, this reservoir has a surface area of 14.9 km^2, with a mean and maximum depth of 22 and 73 m, respectively. Generally, the high water level is 235 m above sea

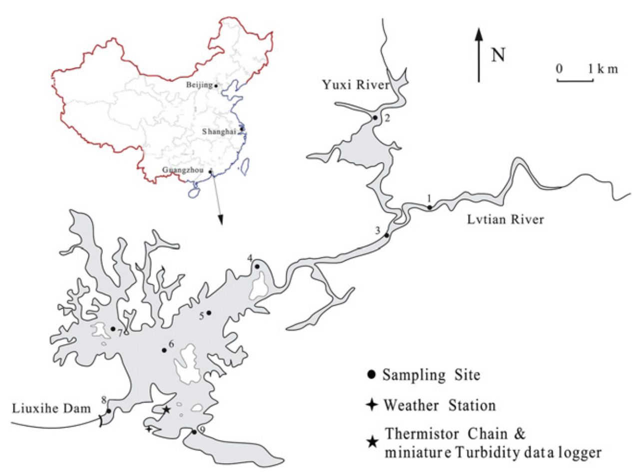

Fig. 1 – Illustration of Liuxihe Reservoir showing the location of sampling and monitoring sites.