

Lake hydrology, water quality and ecology impacts of altered river–lake interactions: advances in research on the middle Yangtze river

Guishan Yang, Qi Zhang, Rongrong Wan, Xijun Lai, Xia Jiang, Ling Li, Huichao Dai, Guangchun Lei, Jianchi Chen and Yongjun Lu

ABSTRACT

Water and mass exchange between rivers and lakes are key processes that maintain the health of the ecology of river–lake systems. Alteration to river–lake interactions have great impacts on water and mass balances. Naturally connected to the middle Yangtze River are the Poyang Lake and Dongting Lake, which are the largest and the second largest freshwater lakes in China. The operation of the Three Gorges Dam (TGD) in the upper Yangtze River was found to have substantial impacts on the middle Yangtze river–lake system. In the past decade, unusual seasonal dryness was evident in the two lakes. Considerable deviations in lake water quality and wetland ecosystem were also detected. In order to explore and distinguish the causal factors influencing the river–lake system, the Ministry of Sciences and Technology (China) launched a research project in 2012, the National Basic Research Program of China (973 Program) (2012CB417000). This article provides an overview of advances in this research, including the evolution of the river–lake interactions, the impacts of the TGD, and the influences on lake hydrology, water quality, and ecosystem. The 20 papers in this issue deliver part of the research outcomes of this project.

Key words | Dongting Lake, middle Yangtze River, Poyang Lake, river–lake interaction, Three Gorges Dam

Guishan Yang
Qi Zhang (corresponding author)
Rongrong Wan
Xijun Lai
Nanjing Institute of Geography and Limnology,
Chinese Academy of Sciences,
73 East Beijing Road, Nanjing 210008, China
and
Key Laboratory of Watershed Geographic Sciences,
Chinese Academy of Sciences,
73 East Beijing Road, Nanjing 210008, China
E-mail: qzhang@niglas.ac.cn

Xia Jiang
Chinese Research Academy of Environmental
Sciences,
8 Anwai Beiyuan Dayangfang,
Chaoyang District, Beijing 100012, China

Ling Li
Huichao Dai
Hohai University, 1 Xikang Road,
Nanjing 210098, China

Guangchun Lei
Beijing Forestry University,
35 East Qinghua Road, Haidian District,
Beijing 100083, China

Jianchi Chen
Hydrology Bureau of Changjiang Water Resources
Commission,
Ministry of Water Resources,
1863 Jiefang Avenue, Wuhan 430010, China

Yongjun Lu
Nanjing Hydraulic Research Institute,
Ministry of Water Resources, 223 Guangzhou Road,
Nanjing 210029, China

INTRODUCTION

The exchange relationships of water, sediments, dissolved constituents, and energy between rivers and lakes significantly influence the geomorphology, water regime, water

quality, and aquatic and riparian ecosystems of river–lake systems (James 1999; Kneis *et al.* 2006; Elisa *et al.* 2010; Milner & Robertson 2013). The Yangtze River is the largest river in China and the third largest in the world, with an average annual runoff of $9,970 \times 10^8 \text{ m}^3$, accounting for about 40% of the total river runoff volume in China. Located in the middle Yangtze River are the Poyang and the

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Dongting Lakes, which are the largest (3,960 km²) and second largest (2,740 km²) freshwater lakes, respectively, in China. The total capacity of the two lakes exceeds $506 \times 10^8 \text{ m}^3$ (Wang & Dou 1998). The middle Yangtze River system is characterized by complex hydrological interactions between the river and the adjoining lakes, in a manner that is regarded as unique in the world (Hu *et al.* 2007; Yin *et al.* 2007).

River–lake exchanges of water and sediment are considered to be critical for flood mitigation and the maintenance of water resources and aquatic and terrestrial ecosystems in the middle Yangtze River region (Dai *et al.* 2005; Xia & Pahl-Wostl 2012; Li *et al.* 2015c). The construction and operation of large hydraulic reservoirs in the upper Yangtze River, such as the Three Gorges Dam (TGD), has significantly altered river–lake interactions (Guo *et al.* 2012; Zhang *et al.* 2012; Lai *et al.* 2014c) within the past decade. In addition, climate variability and rapid socio-economic development in local lake catchments has also affected the hydrological regime of the lakes, and has subsequently modified hydrologic connections to the Yangtze River.

Links between changes to river–lake interactions and the seasonal shortage of water resources, deterioration of water quality, eutrophication, and ecosystem degradation within the lakes has become a major subject of debate. In particular, the potential impact of the TGD has been widely debated (Stone 2008; Qiu 2011; Feng *et al.* 2013; Lai *et al.* 2014b), across various levels of government, media, and the scientific community. Plans to further modify the region's hydrology through engineering works (Li 2009) warrant urgent additional analysis to explore river–lake interactions and the associated mechanisms that give rise to potential impacts from hydraulic engineering. An improved understanding of these processes will provide significantly improved scientific bases to develop regulation strategies for the optimization of water and sediment exchanges between rivers and lakes. Research into the hydrological performance of the middle Yangtze River basin will not only lead to enhanced water security and ecosystem functioning, but will resolve persistent research questions that remain unresolved within the scientific community and have an important bearing on the uncertainty of future predictions of hydrological trends of this region.

Supported by the National Basic Research Program of China (973 Program) 'Evolution of river–lake relationship in middle Yangtze River and impacts on water quality and ecology and regulation strategies' (2012CB417000) (<http://www.yangtze973.ac.cn/>), the Chinese Academy of Sciences and Ministry of Water Resources teamed together several research institutes and universities to conduct this research. The 20 papers included in this issue are part of the research outcomes of this project.

OVERVIEW OF RESEARCH ADVANCES OF THIS PROJECT

The evolution and mechanism of river–lake interactions

The water and sand transfer properties between the Yangtze River and the Dongting Lake and Poyang Lake are regarded as typical river–lake interactions. Dongting Lake receives water from four tributaries (Xiangjiang River, Zishui River, Yuanjiang River, Lishui River) of the catchment and three inlets of the Yangtze River (Songzi River, Hudu River, Ouchi River), and then discharges into the Yangtze River at Chenglingji outlet (Yuan *et al.* 2015). Poyang Lake receives water from five tributaries (Gan River, Fu River, Xin River, Rao River, Xiu River) of its catchment, and interacts with the Yangtze River at Hukou outlet, where the emptying and blocking effects greatly influence the hydrological conditions in the lake (Zhang *et al.* 2014). Under a certain condition of a relatively high stage of the Yangtze River, backflow from the river to the lake may even occur (Li *et al.* 2016e).

TGD is a super large water project with multiple functions, including flood control, power generation, and navigation improvement. The storage capacity of the reservoir reaches 393 m^3 at its normal impoundment level of 175 m (above sea level). The operation of impoundment alters the natural flow regime downstream (Lai *et al.* 2016a), and thus influences the process and flux of water and sediment exchange between the Yangtze River and the two lakes. It demonstrates different effects on the river–lake interaction during different seasons. The decrease in reservoir level in the dry season (from December to March) and pre-flood releasing (from April to May) increase the discharge of the

Yangtze River, and thus raise water level downstream to a certain degree. In-flood regulation and after-flood impoundment (from June to November) decrease the discharge and the water level downstream (Guo *et al.* 2012; Lai *et al.* 2016a) and accelerate lake drainage (Huang *et al.* 2014; Zhang *et al.* 2014). Moreover, the influence of in-flood regulation on lake outflow is the greatest for wet years, and becomes smaller for dry years. The after-flood impoundment has only a minor impact in wet years. Larger impacts occur in normal and dry years, which is one of the main reasons for earlier dry seasons, extended dry periods, and lower water levels for the two lakes in the past decade. The increased river flow in the dry season and the release of water at pre-flood times enhance the blocking effect of the Yangtze River on lakes, and result in reduced water exchange rates between the lakes and the Yangtze River during high lake water level periods.

Influences of alteration of river–lake interactions on lake hydrological regime

Lake hydrological regime is affected by the combination of catchment runoff and Yangtze River flow, and demonstrates a strong seasonal variation (Guo *et al.* 2012). Alteration of river–lake interaction has affected the relative forcing of the catchment and Yangtze River on the lake, and subsequently affected the hydrological and hydrodynamic conditions of the lake. It has been found that during rising and low lake level periods, runoff from the local catchment is the dominant factor that controls the lake hydrological regime. However, the Yangtze River flow has a greater influence on lake water level during its recession period (Guo *et al.* 2012; Zhang *et al.* 2014).

Since 2003, the average annual water level of Dongting Lake has been generally lower than that for 1956–2002. A decrease of 0.19–0.4 m was found in different parts on an annual basis. Changed water level magnitudes in different seasons are also evident. During the dry season, an increase of 0.21–0.63 m of water level was found across the lake, with the largest value in East Dongting Lake. Decreased water level was evident during the rising, high, and recession periods. In particular, an average drop of 1.07–1.77 m water level was found in October, with the largest decrease in East Dongting Lake (Lai *et al.* 2013, 2014c).

Similar to Dongting Lake, the average annual water level in Poyang Lake for 2003–2014 was found to be lower than that for 1956–2002. A decrease of 0.33–1.12 m was found across the lake, with larger values at Hukou (downstream) and smaller ones in the south (upstream). During the dry season, an elevated water level of 0.33–0.57 m was found in Hukou lake region. The magnitude decreased from Hukou to the upstream area. Decreased water level was evident during the rising, high, and recession periods. A significant magnitude of 1.05–1.88 m water level decrease occurred in October to November (Lai *et al.* 2014a, 2014c).

Influences of altered river–lake interactions on lake hydrology also depend on the meteorological and hydrological conditions of the lake catchment. The influences of the Yangtze River are enlarged for a relatively dry condition of the catchment, while the emptying effect of the Yangtze River will be weakened for a wet catchment condition. Regulation of the Three Gorges reservoir during flooding seasons can effectively lower the water level in the lakes, and hence reduce the flood risk in lake regions.

Influences of river–lake interactions on trophic environment of lakes

Changes of hydrologic or hydrodynamic characteristics, sediment transportation and migration, and ecological conditions have been caused by evolution of river–lake interactions. The transportation, spatial distribution, and nutrient status between Dongting and Poyang Lake were also influenced. As a consequence, the water environmental capacity of the lakes, the size of the area of water bloom, and the associated sensitive periods may also be substantially affected.

The trophic level index of Dongting Lake has shown a rising trend in recent years. The degree of eutrophication in East Dongting Lake was higher than other lake areas, and the nitrogen concentration increased significantly while the phosphorus concentration decreased gradually. The algal biomass was 2.35 times as much as before the operation of the TGD. The area of Daxiao Xihu in East Dongting Lake had a high value of algal biomass and long period of water bloom (from April to August) (Xie *et al.* 2015). Simulation of a hydrodynamic water quality model indicated that the flow velocity for the low lake level and a rising period in the main lake area increased after the

operation of the TGD. However, the flow velocity was still below 0.1 m/s (critical flow velocity) in East Dongting Lake, which was the sensitive area of water bloom.

Compared to Dongting Lake, Poyang Lake has had a relatively better water quality in recent years. However, the concentration of nitrogen and phosphorus demonstrated an increasing trend in the lake water. The amounts of species and genus of cyanobacteria increased and the southern Poyang Lake had a higher algal biomass. The operation of the TGD may increase the flow velocity in high water level periods, which could improve the water quality and increase the environmental capacity. The prolonged low water level in the recession period (from September to November) caused a longer exposed time of the sediments, and subsequently resulted in a higher concentration of total phosphorus, organic phosphorus, and reactive phosphorus. The risk of direct and potential phosphorus release from sediments to lake water also increases (Wang *et al.* 2012; Ni *et al.* 2015).

Influences of river–lake interactions on lake and wetland ecology

The biomass variations of each phytoplankton species in Poyang Lake are closely linked to the water level fluctuations. The interrelationship between the Yangtze River and the lake has undergone changes. In particular, earlier arrival of the dry season with a continuously declining water level has led to an abrupt shift of wet to dry seasons. As a result, cyanobacteria distributed in the inner embayment of Poyang Lake and Weilv District (Cuoji Lake and Nanji Wetland) flow into the main channel, converge at the Duchang cross section, and form band-shaped cyanobacteria clusters that extend from the slow-flow zone near the bank side to the channel center (Liu *et al.* 2015). The variations of the hydrological regime induce changes of the flow field in the lake, which in turn, affect the sediment composition in the bed. The density, biomass, and diversity of benthic animals exhibit an increased tendency from sandy sediments to muddy sediments and then to sand–mud mixed sediments (Cai *et al.* 2014).

The hydrological regime is a key factor in determining the vegetation pattern, community dynamics, and plant growth in the wetland. Over the past 20 years, the interaction between river and lake has changed greatly. The

water levels in both Dongting Lake and Poyang Lake have become relatively low. In particular, the rapid decline of water level during the recession period has led to the earlier appearance, longer duration and lower water levels of the dry season. As a consequence, the vegetation patterns at Dongting Lake and Poyang Lake have changed significantly, showing a trend of positive succession (Xie *et al.* 2015). Specifically, the area of woodland and reed has increased while that of lake grass decreased sharply. The area suitable for the growth of lake grass declined and moved to the low elevation zone, while the suitable area for the growth of woodland and reed expanded. The increase of woodland area has improved the biodiversity of undergrowth species, especially an increase in the proportion of neutrophilous and heliophilous species, but a reduction in the proportion of hygrophyte (Li *et al.* 2014, 2015a, 2015b).

The water level fluctuations in natural ecosystems maintain the biodiversity and health of ecosystems. The large areas of grass beach, mud flat, and shallow waters of Dongting Lake and Poyang Lake during the dry season provide the wintering aquatic birds, featuring the Anatidae as the dominant species, with abundant food and habitat (Wang *et al.* 2013). As the interrelationship between river and lake changed during the recession period from September to November, the water level started to decline earlier and the duration of the dry season became longer, thereby favoring the food supply for the wintering aquatic birds. During the water-rising stage from April to May, the water level rose and thus affected the plant growth of both lakes, possibly resulting in food scarcity for the wintering aquatic birds.

Evaluation and optimization of river–lake interactions

Evaluation of the river–lake interactions

In regard to flood control, water supply, water quality, and lake/wetland ecosystem health, the multi-criteria water security evaluation index system was developed. A 10-day maximum average water level was selected to evaluate the flood control security; a 10-day minimum average water level and a 10-day minimum average water level during the retreating season were chosen as indicators of water supply security. Dissolved oxygen, total nitrogen, total phosphorus, chemical oxygen demand, and ammonia nitrogen were selected to evaluate

the water quality. Finally, the ratio of cyanobacteria and diatoms, biotic index of macroinvertebrates, Shannon–Wiener index of macroinvertebrates, and the area ratio of Phragmites and Carex belt in wetland were selected to characterize lake ecosystem health (Zhang *et al.* 2016a). The overall state of lake water security was evaluated using weighted fuzzy comprehensive analysis. Based on the results of river–lake interaction index, as well as the investigation of associations between lake water security and lake hydrological conditions, a random forest model was used to simulate the relationship of river–lake interaction index and lake water security. The state of river–lake interaction was then evaluated for Dongting Lake and Poyang Lake from 1980 to 2013.

Compared with Dongting Lake, the state of the river–lake interaction for Poyang Lake has been relatively worse, especially for the past ten years. Under the dual influence of decreased precipitation and the impoundment of the TGD, the dry season has become prolonged and extremely low water levels frequently recorded. The worsening of the river–lake interaction of Poyang Lake and the potential impacts on the lake ecosystem cause great concerns for the local management authorities.

Optimization of river–lake interactions

An optimization model was developed for the operation of a multi-reservoir system, including the TGD and major reservoirs on the tributaries of Dongting and Poyang Lake (Dai *et al.* 2013). The optimal target is the pursuit of attaining a relative desirable river–lake interaction state for the storage period and the dry period.

In the storage period, the optimal scheduling is to appropriately store water in advance under the premise of guaranteeing the security of flood control; that is, on the basis of regular scheduling, to decrease the discharge of the reservoir system in mid-August and at the end of the storage period (mid-October to late-October) to gradually increase discharge to secure lake ecosystem health. This scheduling can basically minimize the adverse effects of the reservoir filling on river–lake interaction in normal years and wet years. It can also improve the river–lake interaction state in dry years to some extent, although the effect is relatively limited.

In the dry period, the optimal scheduling is to meet the environmental water demand of lakes to the maximum

extent under the premise of normal operation of reservoirs. It is effective in appropriately increasing discharge from the reservoir system to maintain the environmental water demand of the Yangtze River-connected lakes in dry years.

ABOUT THE PAPERS IN THIS ISSUE

The topics of the papers in this issue can be divided into three parts. The first part deals with the hydrological processes and modeling (eight papers), the second part studies the impacts of TGD on water and sand transportation (six papers), and the third part investigates the influences of the changes in mass of water and sand transport on lake ecology and environment (six papers). The first part studies the water balance of the Yangtze River based on satellite products (Zhang *et al.* 2016c), with a focus on characteristics of long-term water level changes during low water level periods for Poyang Lake (Li *et al.* 2016d) and the identification of the influencing factors of low water levels for typical years (Yao *et al.* 2016). Studies on the prediction of lake water level using statistical methods and the simulation of catchment runoffs using spatially distributed models are also reported. A comparison between the different methods is also offered (Li *et al.* 2016b). The flooding mechanism of Poyang Lake (Li *et al.* 2016c) and the projected catchment runoff under future climate scenarios are investigated using hydrological models (Li *et al.* 2016a). The second part investigates sand movement in the Yangtze River (Liu *et al.* 2016b), with a focus on the impacts of the TGD on hydrological flow regimes in the stem of the river (Lai *et al.* 2016a) and associated sediment transport in typical reaches (Zhang *et al.* 2016b), and subsequently, the influences on the water flows of the Jingjiang's three inlets of the Yangtze River into Dongting Lake. Moreover, assessment of the possible impacts of the construction of the Poyang Lake hydraulic engineering project on lake hydrology and hydrodynamic is performed (Lai *et al.* 2016b). The third part mainly focuses on the influences on lake wetland eco-hydrological processes. Correlations between lake water level, soil organic carbon, and spatial distribution of vegetation communities are studied (Wang *et al.* 2016). Phosphorus transport across the lake sediment–water interface in Dongting Lake (Huang *et al.* 2016) and variations of

water quality (Liu *et al.* 2016a) and the species of phytoplankton (Cao *et al.* 2016) of Poyang Lake are studied.

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