Quantifying the impacts of compounding influencing factors to the water level decline of China's largest freshwater lake

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Abstract: As a large open lake that connects to the lower Yangtze River, the Poyang Lake, China has persisted dramatic water-level decline since 2003. For better management of lake water resources and ecosystem, this study quantitatively examined the contributions and spatiotemporal differences of compounding influencing factors to this hydrological change. Attempts were achieved through the reconstruction of lake water level series by two combined neural network models. Results indicate that with reference to the period 1980-1999, the average contributions of lake bottom topography change, the operation of the Three Gorges Dam (TGD), climate change and other human activities over the Yangtze River basin were 50%, 18% and 32% respectively to lake decline during 2003-2014. The response of the lake water level to the three factors shows obvious spatiotemporal differences due to different influencing mechanisms. It is worth noting that the effect of lake bottom topography change is still growing across the lake. In addition, the

22 reduction of precipitation in the Yangtze River basin should be highly addressed to the water level
23 decline of the lake. From the perspective of maintaining a certain water level of the lake and
24 preventing continuous decline and shrinkage, the construction of the proposed water control
25 structure would be an effective solution.

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27 **Keywords:** climate change; changes of lake bottom topography; Three Gorges Dam (TGD); water
28 level decline; the Poyang Lake

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Introduction

Lake is one of the most important landscapes in the world which plays an irreplaceable role in maintaining regional hydro-ecological security. Hydrological condition is known to be the most fundamental factor that affects all the related hydro-ecological functions of lakes (Mitsch and Gosselink 2000). Changes in lake hydrological regimes have been widely recognized across the world during the past decades, resulting in various problems in regional water supplies and ecological health (e.g. Ma et al. 2010; Wang and Hejazi 2011; Desta et al. 2012; Li et al. 2013). However, hydrological alteration in those large open lakes that have complex composition of water system is often driven by compounding influencing factors from inside and outside the lake catchment. Quantifying the net impact of different influencing factors on hydrological changes is a challenging but important task for the management of regional water resources and ecosystem.

In China, the middle-lower Yangtze River basin (YRB) is one of the major regions that clustered by thousands of freshwater lakes. Unfortunately, this region is experiencing drastic hydrological changes. The most prominent example of hydrological changes is the water level decline of the Poyang Lake in the last decade (Min and Zhan 2012; Liu et al. 2013; Zhang et al. 2012). The Poyang Lake located at the south bank of the middle-lower reaches of the Yangtze River is the largest freshwater lake in China (Figure 1a). The lake receives water inflows from five major tributaries in the catchment and discharges to the Yangtze River at Hukou (Figure 1b). As one of the only two large lakes that still naturally connects to the Yangtze River, the Poyang Lake plays an important role in floodwater storage, water supply and providing habitats for many rare and endangered species (Kanai et al. 2002). The Lake catchment belongs to a subtropical monsoon climate with annual precipitation of 1200 mm. Every year, the lake water level starts to rise in

February and peaks in July due to increasing precipitation, and then drops some 9 m to the minimum in December according to the arrival of dry season. Seasonal water level variation of the lake shows a spring raising period, summer flood period, autumn recession period and winter dry period in a year. The lake surface can expand to 3000 km² in summer flood season, but shrinks to less than 1,000 km² in winter dry season due to large water level fluctuations (8-18m) (Feng et al. 2012). The significant seasonal water level fluctuation in the lake creates a distinctive ephemeral floodplain wetland ecosystem of some 3000 km² (Wang et al. 2013). As an important Global Eco-region, the Poyang Lake is considered to need priority conservation by the World Wildlife Fund (WWF).

Recent decline of the Poyang Lake has raised wide concerns about the increasing risk of regional water and ecological security. What are the major causes to this hydrological change is the most concerned question. Because most of these hydrological drought events in the lake were occurred after the Three Gorges Dam (TGD) operation in 2003, this coincidence made the impact of TGD to be the focus of debate and was even blamed for the extreme low water levels (Qiu 2011). Among the previous studies, most concluded that the operation of the TGD significantly exacerbated the severe hydrological droughts that occurred in late September to November because of water impoundment (e.g. Wang et al. 2011; Zhang et al. 2012; Guo et al. 2012; Zhang et al. 2014). However, this couldn't explain for the lake decline in the other months of the dry season (October-March). Some studies attributed the recent lake decline to the lower regional precipitation and hydro-climatic influences (Feng et al. 2012; Lai et al. 2014a; Liu and Wu 2016). Recently, Lai et al. (2014b) revealed that intensive sand mining in the Lake should be blamed to the abnormal low water levels in the dry season, because the prevalent of sand mining since 2000 has increased the discharge potential due to widened and deepened outflow channel in the lake. Yao et al. (2018)

pointed out that the the water level reduction was enhanced due to lower water levels. However, these studies mainly focused on one influencing factor and the result was not quantitatively compared with the other influencing factors under different spatiotemporal scales.

Different from the slow effect of climate change over a long time period, the impacts of human activities are normally occurred in a short time period and cause quick modification of lake hydrology. However, it is quite difficult to quantitatively distinguish the influence of the two driving factors as both the effects on lake water system are often interact and occur simultaneously (Wang and Hejazi 2011). Especially, for those large open lakes that have complex composition of water system, the responses of lake hydrology to climate change and human activities are sometimes not sensitive and not significant (Arias et al. 2012). The Poyang Lake is a typical open water-carrying lake. The regime of lake hydrology is not only affected by the lake inflow tributaries, but also controlled by the variations of Yangtze River discharge (Hu et al. 2007). The background causes for lake water level variations may include the internal factor from the change of lake bottom topography and external factors of climate change over the YRB. Furthermore, the operation of the Three Gorges Dam (TGD), the world's largest hydroelectric project has also added to this complexity. All these compounding influencing factors make the thorough understanding of the background mechanism of hydrological changes in the Poyang Lake more challenging. So far, the debate about the causes of the lake decline is still continuing. In this case, the objectives of this study are: (1) to quantify the impacts and spatiotemporal differences of compounding influencing factors (including the change of lake bottom topography, the TGD regulation, climate change and other human activities) on the water level decline of the Poyang Lake since 2003; (2) to explore the background mechanism of specific influencing factor on the hydrological changes in the lake and (3)

to highlight the possible implications for local water resources planning and management.

Material and methods

Available data

Daily discharges and water levels at Yichang and Hankou stations during 1980-2014 were collected from Hydrological Bureau of the Yangtze River Water Resources Commission. In addition, daily inflow and outflow series of the Three Gorges Reservoir were downloaded from China Three Gorges Corporation (<http://www.ctg.com.cn/inc/sqsk.php>) and cover the period of 2003–2014. Daily water level data during 1960–2014 at four gauging stations (Hukou, Xingzi, Duchang and Kangshan) were selected to represent spatial differences of Poyang Lake water level (Figure 1b). Meanwhile, observed daily lake inflows during 1980–2014 were collected from the 6 gauging stations that located at the lower reaches of major tributaries (Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui Rivers) (Figure 1b). The quality of all the hydrological data was well controlled before delivery and no missing data exists. Because the analysis of this study was based on monthly scale, all the daily data were averaged for each month to get monthly time series for further application.

In addition to the above hydrological data, quality-controlled monthly precipitation data from weather stations across the YRB (see Figure 1a for station distribution) were obtained from National Climate Centre of China Meteorological Administration (<http://data.cma.cn/>). Among these weather stations, there are 30 weather stations distributed in Hanjiang River sub-basin and Dongting Lake sub-basin in the middle reaches of the YRB. In addition, there are also 20 representative weather stations located in the upper reaches of the YRB and 12 across the Poyang Lake sub-basin. All these weather stations have complete data series during 1980-2014.

Two scenarios of Digital Elevation Model (DEM) of the lake during 1998 and 2010 with a resolution of 1: 10,000 were collected to calculate the change of lake bottom topography.

Model simulation

Due to high efficiency and great accuracy, the technique of artificial neural network has been widely applied for river flow and water level prediction during the past decades (e.g. Cigizoglu 2003; Shrestha et al. 2005; Panda et al. 2010; Chen et al. 2012; Li et al. 2015). Taking the advantage of the recent advancement of neural network, a method of combined two back-propagation neural network (BPNN) models is proposed to explicitly quantify the relative contributions of different influencing factors at different time and space scales. The first one is used for the reconstruction of Hankou discharge that without the effect of TGD regulation, and the second one is used for the simulation of lake water level variations. The predicted discharge from the first model was used as the input variable in the second model after the discharge was converted to river water level according to the rating curve between river discharge and water level at Hankou station (Figure 2).

Based on the theoretical driving mechanism of lake water level variation, but not just the simulation ability of a machine learning technique, all potential influencing variables were considered in the models. For the Hankou discharge BPNN model, monthly discharge of Yichang station and precipitation from 30 weather stations in the middle reaches of the YRB were used as the input variables and Hankou discharge was used as output variable. For the lake water level BPNN model, monthly water level of Hankou station and discharge of other 6 gauging stations from the major tributaries across Poyang Lake basin were used as the input variables, monthly lake

water level data at the four gauging stations in the lake were used as output variables. Due to large regulation function of the lake, variations of the lake water levels may be affected by the catchment inflows and Yangtze River water level dozens of days earlier. Therefore, the Yangtze River water level and the lake inflows of the former month that would have impacts on lake water level variations were also incorporated in the BPNN model. Finally, 14 input variables were considered for the lake water level simulations.

A standard three-layer feed-forward BPNN was applied for both the models (Figure 2). Because during the period 2000–2002 sand mining in the lake was just begun and the Three Gorges Dam is about to run, the lake-river relationship was entering into the adjustment period, therefore, the data series of this period was discarded in our analysis. In addition, we selected the data series during 1980–1999 as the training and validation periods of lake water level BPNN model due to the change of lake bottom topography was relatively small in this period. A simple cross-validation approach was applied for the model optimization. That is we use the data during 1980–1985 to validate the calibrated model by using the data of during 1986–1999, and then we use the data during 1994–1999 to validate the calibrated model by using the data during 1980–1993. The same is true for Hankou discharge BPNN model. The most sensitive parameter, the number of hidden layers, in the BPNN model was obtained by the method of trial and error. The selected training algorithm and the other parameters, such as momentum coefficient and learning rate were referred to Ye et al. (2018). The performance of the two BPNN models was evaluated by determination coefficient (R^2) and mean-relative-error (MRE). Statistical result show that calculated R^2 for the four water level hydro-stations are ranging in 0.92–0.99 and MRE ranging in 0.06%–2.41% during the cross-validation processes, indicating a very high accuracy of model performance for lake water

level simulations. In case of Hankou discharge simulations, R^2 are ranging in 0.82–0.93 and MRE ranging in 0.38%–1.21% during the cross-validation processes. After cross-validation, the optimal model was selected for the prediction of lake water level during 2003–2014.

Attribution analysis

As an open lake water system, the causes for the variations of Poyang Lake water level mainly include the internal factor from the change of lake bottom topography, and external factors such as the TGD regulation, climate change and other human activities over the YRB. The established lake water level BPNN model during 1980–1999 reflects the complexities of Yangtze River water level and catchment inflow on lake water level variations under the average condition of lake bottom topography of that period. The effects of climate change and other human activities over the YRB on the Poyang Lake hydrology mainly through the influence of the mainstream discharge of the Yangtze River. As a first step, we consider these effects as one influencing factor; further investigation of the two components is discussed in the later section.

In this study, we select the observed lake water levels during 1980–1999 as the reference series, denoted as H_{obs}^0 . In contrast, the observed lake water levels during 2003–2014 were considered to be the series that was impacted by the compounding influencing factors, and marked as H_{obs}^1 . Quantitative assessment of the above three driving factors was decomposed into the following five steps:

First step: reconstruct the monthly discharges of Yichang station during 2003–2014 that without TGD impact.

$$Q_{YC-rec} = Q_{YC} + \Delta Q_{TGD} \quad (1)$$

where Q_{YC-rec} is the reconstructed discharge; Q_{YC} is the observed discharge during 2003–2014; and ΔQ_{TGD} is the difference between the outflow and inflow of the Three Gorges Reservoir during 2003–2014.

Second step: reconstruct the monthly discharges of Hankou station during 2003–2014 that without TGD effect according to established Hankou discharge BPNN model.

$$Q_{HK-rec} = Q_{HK} + \Delta Q_{HK} \quad (2)$$

$$\Delta Q_{HK} = Q_{HK-sim}^0 + Q_{HK-sim}^1 \quad (3)$$

where Q_{HK-rec} is the reconstructed discharge; Q_{HK} is the observed discharge during 2003–2014; Q_{HK-sim}^0 is the simulated Hankou discharge based on observed Yichang discharge; Q_{HK-sim}^1 is the simulated Hankou discharge based on reconstructed Yichang discharge.

Third step: reconstruct the monthly water level of Hankou station during 2003–2014 by using the reconstructed monthly Hankou discharge according to the river discharge-water level rating curve of 1980–1999. This reconstructed monthly water level series represents the variation of river water level that without TGD impact.

Fourth step: simulate monthly lake water level during 2003–2014 with observed Hankou water level and basin inflows according to established lake water level BPNN model. With comparison to the period of 1980–1999, this simulated monthly lake water level series represents the scenario that under the impacts of TGD regulation as well as climate change and other human activities but excludes the impact of lake bottom topography change. We marked this series as H_{sim}^0 .

Fifth step: simulate monthly lake water level during 2003–2014 with reconstructed Hankou water level and observed basin inflows according to established lake water level BPNN model. With comparison to the period of 1980–1999, this simulated monthly lake water level series

represents the scenario that under the impacts of climate change and other human activities but excludes the impact of TGD regulation as well as lake bottom topography change. We marked this series as H_{sim}^1 .

Based on the outputs of the fourth and fifth steps, we can then distinguish the effect of specific influencing factors:

$$\Delta H_{bott} = H_{obs}^1 - H_{sim}^0 \quad (4)$$

$$\Delta H_{TGD} = H_{sim}^0 - H_{sim}^1 \quad (5)$$

$$\Delta H_{clim-hum} = H_{sim}^1 - H_{obs}^0 \quad (6)$$

where ΔH_{bott} is the effect of lake bottom topography change; ΔH_{TGD} is the effect of TGD regulation; $\Delta H_{clim-hum}$ is the effect of the climate change and other human activities over the YRB.

Results

Recent decline of lake water level

Figure 3 shows the annual variation of average water levels at the four hydro-stations during 1960–2014. It is clear from visual inspection that lake water level of the Poyang Lake has experienced a dramatic decline since 2000. The decline of the lake water level during this period well coincides with the initial of sand mining in the lake and the operation of TGD. Persisted low water events increased significantly especially in the following years during 2006–2009, and reached the extreme in 2011. For the Hukou, Xingzi, Duchang and Kangshan hydro-stations, it is revealed that average declines of lake water levels were about 0.75 m, 1.00 m, 1.18 m and 0.54 m during 2003–2014 with reference to the period of 1960–1999.

Figure 4 shows the exceedance of probability distribution of daily water levels at the four hydro-stations under the three periods. The result demonstrates an overall decline of the lake, not only for high water levels, but also for those moderate and low water levels. On average, except for the higher exceedance probability of some extreme low water levels at Hukou station, the exceedance probability of lake water levels was generally lower during 2003–2014. Especially for Duchang station, the decline is particularly prominent for lake water levels lower than 14m. The declines of lake water levels are bigger when compared with the data series during 1980–1999.

Quantification of the influencing factors

It is clear from the Figure 5 that monthly effects of the three influencing factors are spatially different across the lake. The change of lake bottom topography plays an important role on reducing lake water level all the year. The reduction of average monthly lake water level is most prominent at Duchang (0.28 m–1.57 m), followed by Xingzi (0.24 m–1.13 m), Hukou (0.20 m–0.63 m) and Kangshan (0.09 m–0.52 m). In terms of seasonal variations, the reduction of lake water level is particularly obvious during the winter dry season, the maximum value was about 0.34 m–1.57 m. During the spring and the autumn seasons, the reduction of lake water level is about 0.09 m–1.00 m and 0.24 m–1.14 m, respectively. However, during summer flood season, the maximum reduction of lake water level is smaller than 0.60 m (see in Table 1). Generally, seasonal contributions of lake bottom topography change on lake water level decline were about 20%–132% at Hukou, 25%–113% at Xingzi, and 32%–128% at Duchang and Kangshan. The decline of lake water level in winter was almost totally driven by this effect.

The effect of TGD regulation is mainly reflected by reducing lake water levels all over the

year except for a marginal rising in February and May. Most obviously reduction of water levels happens during the flood season of July–August and the recession period of September–October, while the effects are slight in the other months. In addition, the effect of TGD regulation shows the largest at Hukou, and weakened upstream the lake. Average reduction of monthly lake water level during September–October is about 0.69 m–1.03 m at Hukou, followed by 0.69 m–0.94 m at Xingzi, 0.63 m–0.76 m at Duchang and 0.42 m–0.48 m at Kangshan. Statistical result indicates that the contribution of TGD regulation on the decline of lake water level was about 33%–42% across the lake during the impoundment period of September–October and 26%–36% for the whole autumn season.

The effect of climate change and other human activities (i.e. other influencing factors in Table 1) over the YRB increased Hukou water level from January to March and the other three stations in January. Average increase of lake water level at Hukou was about 0.21 m–0.53 m. However, in the other months, this effect mainly resulted in reducing water levels across the lake. Especially in October, average reduction of lake water level is about 1.29 m, 1.26 m, 1.12 m and 0.56 m at Hukou, Xingzi, Duchang and Kangshan, respectively. During the flood season of July–August, this effect is also much prominent, which can lead to an average decrease of water level of 0.75–0.91 m across the lake. The contribution of this effect on the lake water level decrease was about 48%–54% in summer, and 34%–43% in autumn (Table 1).

On annual basis, the three effects are much different across the lake (Figure 6). The effect of TGD regulation reduced an average annual water level of 0.11–0.29 m across the lake. The relative contribution of this effect was about 13%–27%. The effect of lake bottom topography change in reducing lake water level is most prominent among the three influencing factors. Especially, this

effect is remarkably increased at Xingzi and maximized at Duchang. The reduced average annual water levels due to lake bottom topography change were 0.67 m and 0.87 m at the two stations, which account for 51% and 60% of the total changes. The effect of climate change and other human activities over the YRB on the lake decline is relatively uniform at Hukou, Xingzi and Duchang stations (0.37 m–0.40 m), but slight weakened at Kangshan (0.27 m). For the whole lake, the average contribution of lake bottom topography change was 50% to the lake decline, while the contributions of TGD regulation and climate change and other human activities over the YRB was 18% and 32%, respectively (Figure 6).

Figure 7 further shows the change trend of the three effects. As shown in Figure 7a, only in 2010 during the past 12 years, observed annual lake water levels at Hukou, Xingzi and Kangshan were higher than that of the averaged condition in 1980–1999. A long-term increasing trend can be observed for the effect of lake bottom topography change. The linear trends at Xingzi and Duchang stations are significant ($p<0.05$), while not significant at Hukou and Kangshan stations. For all the four stations, the effect of TGD regulation just shows a slight decreasing trend but not significant. Overall, the effect of climate change and other human activities over the YRB plays a role of reducing annual lake water levels except for 2003, 2005, 2010 and 2014, and shows large fluctuation during 2003–2014. The effect was particularly prominent in 2011. However, almost no trends can be observed.

Discussion

Influencing mechanism of lake bottom topography

Our result revealed that the change of lake bottom topography is essential on recent decline of lake

water levels, especially in winter season it has become the dominant driving factor. The change of lake bottom topography in the Poyang Lake was mainly caused by sand mining activities in recent years (Wu et al. 2007; Lai et al. 2014b). Based on the two DEM scenarios of the Poyang Lake in 1998 and 2010, a total volume of $1.154 \times 10^9 \text{ m}^3$ lake basin change can be calculated during this period. In addition, a significant scouring zone can be observed along the main waterway from Duchang to Hukou in the lake.

The effect of sand mining on lake water level is mainly through increasing the lake outflow ability and lake volume due to widened and deepened water channel in the lake (Lai et al. 2014b; Yao et al. 2018). Lai et al. (2014b) found that the outflow ability of Poyang Lake at low water levels has increased to 1.5–2 times the values before the initiation of extensive sand mining. Meanwhile, average water level at Xingzi decreased by 0.66 m in the dry season (October–March) during 2008–2012 with reference to 1955–2000. Our assessment is highly consistent with this result. In addition, our observation also shows that the reduction of lake water level at Duchang is the most across the lake. The causes should be attributed to the spatial differences of relative changes of lake bottom topography according to south move of the sand mining dredges during the past decade. It can also be observed from Figure 3 that since 2009, the average water levels at Hukou, Xingzi and Duchang were almost the same, indicating no gradient differences of lake bottom topography in these areas due to sand mining activities.

Influencing mechanism of the TGD regulation

As the world's largest hydropower project, it is undeniable that TGD operations, including impounding and releasing water affected considerably the seasonal variation of discharge and water

levels of the Yangtze River (Guo et al. 2012; Zhang et al. 2014). The TGD regulation has modified the interaction between the River and Poyang Lake by weakening the River's blocking effect on the Poyang Lake, and thereby increasing lake discharge during July–September (Guo et al. 2012). In comparison with our results, some previous studies magnified the TGD effect on reducing Hukou water level during impoundment period due to the ignorance of sand mining influence in recent years (e.g. Guo et al. 2012; Zhang et al. 2012). In addition, the increase of Yangtze River discharge by TGD regulation during December–May didn't leads to the synchronously rise of lake water level. Background reason lies in the strong riverbed erosion of Middle-Lower Yangtze River induced by TGD regulation. Dai and Liu (2013) pointed out that suspended sediment discharge and suspended sediment content in Middle-Lower Yangtze River have been reduced significantly since TGD operation in 2003. Thalweg depths in the middle Yangtze River have been lowered significantly after the initial impoundment of TGD in 2003 (Ye et al. 2017).

This big change of riverbed erosion will have influence on water level variations. It is clear from Figure 8 that the fitting curve during 2003–2014 is obviously lower than that during 1980–1999, indicating river water level at Hankou has been lowered in the later period under the same river discharge. Furthermore, the figure also indicated that the decline of river water level is much bigger under the conditions of low river discharge than that of under high river discharge conditions. For example, the calculated average monthly decline of river water level is 0.55 m under the monthly river discharge of $1.0 \times 10^4 \text{ m}^3/\text{s}$, and 0.25 m under the monthly river discharge of $3.0 \times 10^4 \text{ m}^3/\text{s}$. Wang et al. (2013a) also realized the effect of riverbed erosion and their study revealed that the average winter water level increase due to increased river discharge was completely counteracted by its deep channel scouring at Hankou station, resulting in a net level

change of -0.11 m in winter. Also the spring ‘blocking effect’ for Poyang Lake was partially alleviated as indicated by the erosion-induced level drops at Hukou.

Generally speaking, the TGD effect, including the seasonal river discharge regulation and riverbed erosion, to some extent, exacerbates the water-level drop of Poyang Lake. The TGD effect of reducing lake water level at inter-annual timescale was mainly resulted from riverbed erosion of the Middle-Lower Yangtze River as the TGD regulation doesn’t change the total amount of annual river discharge in normal years. The slight decreasing trend of the TGD effect (see in Figure 7b) is possibly due to the stable of riverbed erosion after the long-term operation of TGD.

Influencing mechanism of climate change and other human activities in YRB

The effect of climate change and other human activities over the YRB on lake water level variations needs to be highly addressed. Due to large fluctuations, this effect can dominate the change of lake water levels in some years, such as 2006 and 2011. Seasonally, this effect on reducing lake water level in summer flood season is much more prominent with comparison to the other two driving factors. Even during the following autumn recession period, this effect at least exerts equivalent influence to the decline of lake water level. The effects of climate change and other human activities over the YRB on the Poyang Lake water level are mainly through the influence of Yangtze River discharge and catchment inflow. However, Yangtze River discharge is significantly correlated with regional precipitation. Correlation analysis indicates that the Pearson correlation coefficient between annual precipitation and annual discharge is 0.79 at Yichang station and 0.88 at Hankou station. In this sense, the effect of climate change over the YRB mainly refers to the impact of precipitation change.

During the period 1980-2014, annual precipitation of the YRB showed a long term decreasing trend but not significant. Accordingly, river discharge across the Yangtze River also showed a decreasing trend. With comparison to the period 1980-1999, precipitation in the upper reaches of Hankou station reduced 4.6% during 2003-2014 and river discharge decreased 7.6%. This result well explained the negative effect of regional precipitation on the change of lake water level. Furthermore, this result indicates that precipitation reduction of the YRB can explain at least 60% decrease of the Yangtze River discharge. This estimation is quite consistent with the report of Yang et al. (2015) that precipitation change accounts for 61% of river discharge decrease of the entire Yangtze Basin (upstream of Datong). Some of previous studies have noted the impacts of local precipitation changes on the lake decline. For example, Lai et al. (2014a) realized the effect of remarkable decrease of inflows to the middle and lower Yangtze River on recent low water levels of Poyang Lake caused by precipitation changes.

Figure 9 further shows the comparison of monthly precipitation changes in different regions of YRB. From the figure, it is clear that in most time of a year, precipitation in the whole upper-middle reaches of Yangtze River was decreasing. During the period of TGD impoundment, the decrease of precipitation in the Hanjiang basin, Poyang Lake basin is obvious. The decrease of precipitation in summer was mainly found in the upper reach of YRB the Dongting Lake basin and the Poyang Lake basin and contributed to the decline of lake water level.

In addition to the effect of precipitation reduction, human activities play a secondary role in the decreasing of river discharge. In consideration of the long term decreasing trend of potential evapotranspiration in the YRB during the past decades (Wang et al. 2006; Wang et al. 2013c; Xu et al. 2006), the effect of human activities accounts for less than 40% decrease of the Yangtze River

discharge. Chen et al. (2014) pointed out that annual runoff in the Yangtze River shows little response to the major changes (dam volume, population and GDP) occurring in the basin during the period 1955-2011, the changes in the basin explained less than 20% of the runoff variance. Ye et al. (2013) further revealed that due to the intensified water utilization, the decrease of streamflow in the Fuhe River sub-basin in 2000s was primarily affected by human activities.

It must be pointed that the effect of climate change and other human activities is spatially different in the lake. Because the Kangshan station is located in the upstream of the lake, lake water level at the station is much more affected by the lake inflow, while the other three stations are also affected by the Yangtze River discharge. That's why the effect of climate change and other human activities over the YRB is relatively uniform and larger at Hukou, Xingzi and Duchang stations but slightly weakened at Kangshan (see in Table 1).

Implication for water resources planning and management

Our investigation revealed that the internal factor from sand mining induced change of lake bottom topography has become the dominant influencing factor for the water level decline of the Lake. From this perspective, the prohibition of sand mining in the lake is the first consideration to mitigate the decline of lake water level. Fortunately, local government of the Jiangxi Province has realized the importance of controlling sand mining activities. A regulation on centralized management and total volume control of sand mining has been established in 2017 (see in www.jxsl.gov.cn). However, the effect of lake bottom topography change on lake water level decline is still growing as sand mining activities in the lake has continued to move from the north waterway to the center and even to the south parts of the lake. In consideration of the sedimentation

processes, reestablishment of a pre-mining sediment budget in the lake is quite difficult in a short time period, even though sand mining activities in the lake is completely prohibited.

The operation of TGD exacerbates the water-level drop of the Poyang Lake, especially the impoundment in September-October will worsen the autumn dryness of the lake. As the lowering of lake water level is most serious in the dry season in winter, it is important to increase the TGD discharge to raise the water level of the lower Yangtze River, which can reduce the outflow and raise water level of the lake. Our analysis indicates that an increase discharge of 1000 m³/s from the TGD can raise lake water level of 0.2 ~ 0.5 m at Hukou station during the winter dry season, regardless of the river bed down cutting of the lower Yangtze River. If the down cutting effect of the Yangtze River is taken into account, the effect of increasing TGD discharge on raising lake water level will be greatly reduced. However, the role of increasing TGD discharge in the dry season is still cannot be neglected, because it is very important to maintain a certain water area of the lake in those extreme climate droughts. In view of regional climate change, it is necessary to adjust the dispatching mode of the TGD in flexible manner.

In response to the potentially decreasing of lake levels, especially during the dry season, the proposal of a control structure at the lake outlet has being considered by the Jiangxi Provincial government (Lai et al., 2014; Zhang et al., 2014) (Figure 1). The proposed control structure is designed to allow unobstructed flow of the lake into the Yangtze River during the summer wet season while restricting discharge during the winter dry season to maintain the lake level higher than would otherwise occur at this time of year (Lai et al., 2014). Results of our investigation agree that the construction of Lake control structure will be an effective solution to maintain lake water level. It is anticipated that sand mining in the lake will be continued, more dams will be built in the

upper reach of the Yangtze River, and also the risk of extreme climate will increase in the future, the construction of lake control structure is important for improving the carrying capacity of water resources of the Poyang Lake. In the dry season, the proposed control structure will enlarge lake water surface and increase the water depth, which will alleviate the ecological water shortage of the wetland and improve the habitat of wild waterfowl and migratory birds. However, the construction of the control structure will change the hydrological and hydrodynamic processes of the Lake, and subsequently affect the water quality, wetland vegetation and the migration of aquatic species (Zhang et al., 2014). The potential ecological threats due to the partition of natural connectivity between the lake and the Yangtze River of this structure are the most realistic problem that requires substantial further research (Harris and Zhuang, 2011).

Conclusion

The current study presents an investigation on quantifying the compounding influencing factors on water level decline in China's largest freshwater lake. The magnitude and trend of three major influencing factors were explicitly clarified, and the background mechanisms were discussed. Several findings can be obtained as follows:

(1) Our assessment revealed that the average contributions of sand mining induced change of lake bottom topography and TGD regulation in the upstream Yangtze River were about 50% and 18% respectively to the lake decline on annual basis during 2003-2014, while the contribution of climate change and other human activities over the YRB was 32%.

(2) The effect of sand mining induced change of lake bottom topography on lake water level decline is still growing across the lake. The effect of TGD operation in the upper Yangtze River is

about to account for 33%–42% of the average water level decline during the impoundment period of September-October, but much weakened in the other seasons. The reduction of precipitation in the YRB should be highly addressed to the water level decline of the Poyang Lake.

(3) The responses of the lake water level to the three influencing factors are not consistent and show great spatial and temporal differences due to the background driving mechanism of the three influencing factors are much different.

(4) The prohibition of sand mining in the lake is the first consideration to mitigate the decline of the Poyang Lake water level. However, from the perspective of maintaining a certain water level of the lake and preventing continuous decline and shrinkage, the construction of the proposed water control structure would be an effective solution.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

- (1) Monthly discharge and water level data at Yichang and Hankou stations during 1980–2014;
- (2) Monthly inflow and outflow series of the Three Gorges Reservoir during 2003–2014;
- (3) Monthly water level data of the four gauging stations in the lake during 1960–2014;
- (4) Monthly discharge of the 6 gauging stations from the lake catchment during 1960–2014;
- (5) Monthly precipitation data of 62 weather stations across the YRB during 1960–2014;
- (6) Reconstructed the monthly discharge of Yichang station during 2003–2014;
- (7) Reconstructed the monthly discharge and water level of Hankou station during 2003–2014;
- (8) Reconstructed monthly lake water level of the four gauging stations during 2003–2014 (H_{sim}^0)

which represents the scenario that under the impacts of TGD regulation as well as climate change and other human activities but excludes the impact of lake bottom topography change.

(9) Reconstructed monthly lake water level of the four gauging stations during 2003–2014 (H_{sim}^1) which represents the scenario that under the impacts of climate change and other human activities but excludes the impact of TGD regulation as well as lake bottom topography change.

(10) The proposed two combined neural network models.

Acknowledgements

This work was financially supported by the Fundamental Research Funds for the Central Universities (XDJK2019B074). Cordial thanks are extended to Prof. Qi Zhang, Dr. Xianghu Li, Yunliang Li and Jing Yao from the Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, China for their constructive comments and data support.

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Fig.1. (a) River networks in the Yangtze River basin with the Three Gorges Dam, the Poyang Lake and the locations of meteorological and hydrological stations are marked. The grey part shows the combined Hanjiang River sub-basin and Dongting Lake sub-basin in the middle reaches of the Yangtze River basin. Sub-plot at bottom left shows the TGD's operational water levels. (b) The Poyang Lake water system and hydrological stations. Sub-plot at upper right shows the variation of lake inflow, Yangtze flow (Hankou) and corresponding water level at Xingzi station. (c) The TGD operation rule and (d) The monthly variation of lake water level according to catchment inflow and Yangtze flow.

(a) Hankou discharge BPNN model

(b) Lake water level BPNN model

Fig. 2. Architectures and flow charts of the two combined BPNN models

Fig. 3. Hydrographs and annual variations of average water level at Hukou, Xingzi, Duchang and Kangshan stations. The vertical grey lines indicate the starting of sand mining in the lake (2000) and the TGD operation (2003)

Fig. 4. Comparison of exceedance probabilities of daily water levels at Hukou, Xingzi, Duchang and Kangshan under the two different periods.

Fig. 5. Detail effects of lake bottom topography change, TGD and climate change on monthly lake water level changes during 2003-2014 (with reference to 1980-1999).

Fig. 6. Spatial differences of average annual effect of the three influencing factors

Fig. 7. Annual variation and linear trends of water level total changes and the effects of the three influencing factors during 2003–2014 (with reference to 1980–1999)

Fig. 8. Comparison of the changes of monthly river discharge and water level rating curves under the two different time periods.

Fig. 9. Comparison of precipitation changes in different regions of the Yangtze River basin.