A review on the driving forces of water decline and its impacts on the environment in Poyang Lake, China
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ABSTRACT

The recession of water levels of natural lakes and their associated impacts on wetland ecosystems is a serious issue worldwide. Poyang Lake (the largest freshwater lake in China) has experienced a heightened and prolonged water decline since the year 2000, which causes concern for associated ecological impacts. In particular, climate change, operation of the Three Gorges Dam (TGD), and high magnitude sand mining appear to be well-correlated with the occurrence of water decline in Poyang Lake. Though the above factors have been analyzed in previous studies, a comprehensive summary has never been compiled. This paper provides a detailed literary review highlighting the driving forces and possible impacts of the consistent water decline in Poyang Lake. We conclude here that the operation of TGD is a fundamental cause for the lake water decline, aggravated by climate change and sand mining. The water decline has caused a deterioration of water quality, as well as having given rise to a potential threat to the habitat of migratory birds and Yangtze finless porpoises. The paper intends to offer constructive references that can be used in decision-making for effective protection of water resources and lake ecosystems.

Key words | climate change, migratory birds, sand mining, TGD, Yangtze finless porpoise, water decline

HIGHLIGHTS

- This study provides the first review of driving forces of the water decline in Poyang Lake and its impacts.
- We have chosen climate change, operation of Three Gorges Dam and sand mining to discuss the driving forces of water decline.
- We have chosen four elements (water quality, landscape, migratory birds, and Yangtze finless porpoises) as representative examples to reveal severe influences on the water decline.

INTRODUCTION

It is a well-recognized fact that lakes and their associated watersheds have unique hydrological and biogeochemical cyclical processes, and also provide crucial functions for both local environments and communities, such as biodiversity maintenance, fresh water supply, flood mitigation, agriculture and recreation (Mitsch et al. 2005; Zedler & Kercher 2009). However, the maintenance of the natural hydrological regime of many lakes tends to be at odds with globalization, meaning that many lake basin ecosystems are confronting severe challenges (Pekel et al. 2016; Srinivasan et al. 2017). Under the influence of 21st-century global climate change and intensified human activities such as enhanced anthropogenic disturbances, hydrological issues facing lake systems have been characterized by water
level decline, over-exploitation, frequent floods and droughts, increased eutrophication and pollution, disruption of aquatic ecosystem equilibrium, lake degradation or even extinction (Jiang 2009; Carpenter et al. 2011; Paerl et al. 2011). One of the most severe lake-related tragedies is the irreversible shrinkage of the Aral Sea in Central Asia (Micklin 2007). In the context of severe changes, the scope of UNESCO's International Hydrological Programme has recognized five major elements as an important multidimensional complex of promoting sustainable development: water resources, biodiversity, ecosystem services, resilience, and culture (Zalewski et al. 2016).

The Yangtze River in China is the largest and longest river in South Asia, with a water discharge of 900 km3/yr and a sediment load of 470 Mt/yr, ranking 5th and 4th in the world respectively (Yang et al. 2011). To meet the needs of social-economic development, more than 50,000 dams have been established on the river and its tributaries for the purpose of flood prevention, hydroelectric generation and irrigation (Yang et al. 2005). Such artificial interference has certainly changed the hydrological conditions of the Yangtze River Basin. Hence, many natural lakes in the Yangtze River Basin have faced growing conflicts between socioeconomic development and aquatic environments (Jiao 2009). For instance, the lake systems attached to the Yangtze river basin have historically accounted for 21.2% and 24.1% of the country's lake area and the total number of lakes, distributed on both banks of the Yangtze River. In the middle reaches of the Yangtze River, watershed, marshes, multiple river channels and thousands of lakes are found in the plains, forming a unique and comprehensive ecosystem of rivers and lakes. These lakes are used to supply water to regional agriculture, and also are efficient reservoirs, which are important for flood control (Nakayama & Watanabe 2008; Yu et al. 2009; Ma et al. 2010). Nevertheless, over the past half century, a great number of lakes have vanished due to human disturbances such as the reclamation of lakes and hydraulic engineering projects. As a consequence, Dongting Lake and Poyang Lake are the only remaining large lakes that still maintain a natural connection with the Yangtze River in the middle and lower reaches (Du et al. 2011). Dongting Lake was once the largest freshwater lake in China with a maximum surface area of about 6,300 km², but due to the adverse land conversion and the establishment of water conservancy facilities, the area of the lake has been reduced by approximately 60% (3,800 km²). Many studies have analyzed this dynamic interaction by way of administration, exploitation, and protection of Dongting Lake, though the trend of shrinkage and fragmentation is still ongoing (Li et al. 2004; Zhao et al. 2005; Sun et al. 2012; Ou et al. 2014; Wang et al. 2015).

Poyang Lake is now the largest fresh water lake in China, and has thus received more recent attention (Jiao 2009; Shankman et al. 2006; Guo et al. 2012; Zhang & Werner 2015; Wang et al. 2019a). Poyang Lake is part of the first batch of the Ramsar Convention List of Wetlands of International Importance, and is also on the list of globally important ecological areas designated by the WWF (World Wide Fund For Nature) (Liu & Liu 2022). As one of the most precious wetland ecosystems in China, the particular characteristics of Poyang Lake are summarized as follows:

First, Poyang Lake is principally fed by five major tributaries within its basin, and it is connected with the Yangtze River through one outflow. The basin area of Poyang Lake is approximately 162,000 km², accounting for 9% of the total area of the Yangtze River Basin. The average annual outflow to the Yangtze River is 14.6 billion m³, accounting for 17% of the average annual runoff of the Yangtze River (Zhu 1997).

Second, the total population in the Poyang Lake region is over 10 million, with a GDP of more than 500 billion RMB, having increased by 400 billion in the past decade alone. Due to the flat terrain around Poyang Lake (Figure 1), this area has been known as ‘the land of plentiful rice’ since ancient times. The preservation of Poyang Lake is facing challenges from high-speed urbanization and the collaborative development of industrialization and agriculture in the surrounding areas.

Third, Poyang Lake provides unique and critical habitats and rich food resources for rare species, including the Yangtze finless porpoise, swan goose, and nearly 95% of the entire world population of the endangered Siberian crane (Wu et al. 2009; Dronova et al. 2011). Therefore, the variations in the hydrological situation of Poyang Lake not only affect the development of the social economy in surrounding areas, but also determine the regional biodiversity and ecological balance.
Poyang Lake is a unique system, much different from other large lake systems of the world. For example, the Great Lakes in North America are much larger and deeper than Poyang Lake and include a larger watershed with more input tributaries feeding them. Classically, the water levels and area of the Great Lakes are typically much more constant than Poyang Lake as the latter may fluctuate by a large amount seasonally due to a relatively shallow water depth. However, recent developments in the Great Lakes have included excessive low level events in the 2000s, caused by increased water temperature (enhanced evaporation) due to a significant decrease in winter ice cover (Assani et al. 2016). Conversely, the past few years have shown a reversal of this trend, with historical record high water being observed. Yet, the overall water levels and area of the Great Lakes, even during extreme events, only vary by a small amount when compared to the overall depth and area, and while some elements of the ecology are under greater threats due to these dynamical changes, the overall health of the Great Lakes is strong (Assani 2016).

The ecohydrology stability of Poyang Lake is more fragile under the interference of climate change and human activities. On one hand, the frequent large floods in Poyang Lake have caused extensive damage to the wetland ecosystem and the social economy (Yu et al. 2009). Statistics indicate that from 1950 to 2010, there were 17 years that can be considered major flood events (when the Poyang Lake water level exceeded 20 m), and there were six years that can be defined as severe floods (when the Poyang Lake water level exceeded 21 m) (Li et al. 2015). It was also found that all of these severe floods happened during or shortly after El Niño events, which shows that the flood phenomenon is closely related to climate change, especially precipitation (Shankman et al. 2006).

On the other hand, since the beginning of the 21st century, the persistent shrinkage of the lake area and continuous decline of the water level have been well documented (Feng et al. 2012a; Lai et al. 2014a; Yao et al. 2018). Previous research has detailed two important events after 2000 that have led to extreme changes in the hydrology conditions in Poyang Lake. First was the establishment of the Three Gorges Dam (TGD; Figure 1), which began operation in 2003. Second is the extensive sand mining which began in 2001 after dredging was banned in the Yangtze River (Wu et al. 2007; Guo et al. 2012). In the past decade, many studies...
have studied the water level decline of Poyang Lake which have obtained diverse results. However, the issue of determining the exact nature and contributions of the dominant driving forces is still a subject of strong debate. For instance, some studies illustrated that the enhanced dry season was primarily driven by climate changes while others pointed out that impoundment of water by the TGD rather than precipitation was the major cause of the shrinkage of Poyang Lake (Ye et al. 2014; Zhang et al. 2014, 2015a). Meanwhile, other studies revealed that the pervasive sand mining in Poyang Lake has increased the discharge factor. Numerous efforts have investigated the cause of drought in Poyang Lake, yet few studies have done a comprehensive analysis of the impact of this constant water decline. In 2019, Poyang Lake has faced the most severe drought conditions in recent history, and the occurrence of the dry season has significantly advanced (by approximately 30 days), according to hydrology department data (Figure 1). Therefore, proper management strategies of Poyang Lake should be based on careful analyses of hydrological parameters. Our review is mainly based on papers published since 2000, aiming to establish a link between the water decline and its impact on the lake. We examine the current perception of the relevant issues and highlight promising directions for further research. The review attempts to answer the following critical questions:

1. What is the extent of the water decline in Poyang Lake in the past decade?
2. What are the primary mechanisms responsible for the water decline of Poyang Lake?
3. What is the impact of the water decline, and what aspects of future research should be pursued to better understand and mitigate this issue?

**DESCRIPTION OF POYANG LAKE**

Poyang Lake (at a latitude of 28°24′ to 29°46′N and a longitude of 115°49′ to 116°46′E) is located in the middle reaches of the Yangtze River (Figure 1) (Lai et al. 2014a). The Yangtze River is the longest river in China and the longest river on the Eurasian continent, and plays an important role not only in the maintenance of the wetlands ecosystem, but also in the social and economic development of China (Du et al. 2011). It originates in the Tibetan Plateau and flows eastward through central China (Zhang et al. 2016a). Poyang Lake lies in southeastern China and is connected to the Yangtze River through a narrow channel in Hukou county. The lake receives surface runoff from five major tributaries: Xiushui, Gan jiang, Fuhe, Xinjiang and Raohe, and the total catchment area of the lake accounts for 97% of the territory of Jiangxi Province, home to 46.6 million residents, and classified as a subtropical monsoon climate (Dronova et al. 2011).

As a natural lake connected to the Yangtze River, the comprehensive effects of the Yangtze River outflow, the inflow of its five tributaries, and various climate conditions form a strongly seasonal characterized water regime of Poyang Lake. Poyang Lake has an inundation area and maximum length which fluctuates from less than 1,000 to over 3,000 km² and from 74 to 173 km, respectively, between the summer flood season (June–September) and the relatively drier winter dry season (November–March) (Feng et al. 2011). As the water level varies from approximately 8 to 22 m every year, the lake is a large floodplain in flood season, and transforms into different landscape types in the dry season including isolated small lakes, meadows, mudflats, and shoals (Qi et al. 2016). This regular seasonal pattern not only provides abundant water resources in the catchment, but also makes Poyang Lake an excellent habitat for rare animals such as 95% of the global Siberian crane population, 57% of the global oriental white stork population, and the endangered Yangtze finless porpoises (Zhao et al. 2008; Jia et al. 2013). Currently, six national and provincial nature reserves have been established to insure the continued protection of the Poyang Lake wetland system (Figure 2).

**PATTERNS OF WATER DECLINE AND SHRINKAGE IN POYANG LAKE**

A general consensus about the low water level seen in Poyang Lake can be reached from previous studies. After the start of the 21st century, the dry season of Poyang Lake has advanced and been prolonged and the water decline in the retreat period has accelerated. The lake area
has severely diminished in the dry season, which has led to advanced exposure of marshland, and the long-term ecological water shortage in the dry season has been enhanced (Li et al. 2008; Min & Zhan 2012; Lai et al. 2014b; Cheng et al. 2019). This phenomenon has resulted in water supply and irrigation problems for the 12.4 million inhabitants of the region. For example, in 2003, 3.89 million hectares of arable lands were affected with an economic loss of 1.15 billion CNY (Chinese Yuan equivalent to 188 million USD) (Zhang et al. 2014).

Different studies have applied different data and analysis methods to quantify the decline of water level in Poyang Lake. However, due to the different perspectives of these analyses, their results were not the same. Min et al. (Min & Min 2010) first noticed the drought problem in Poyang Lake by analyzing hydrological data from Duchang which was gathered from 1952 to 2011, and the data were analyzed on a decadal scale to distinguish the average value of the lowest water level. It was found that since the 1980s, the lowest water level has shown a decreasing trend, with the period of 2000–2010 being the lowest decadal value on record (Min & Zhan 2012). Duchang station is located in the center of Poyang Lake, so some other studies have agreed that the water level at this location may accurately reflect the overall decline of the lake as a whole. Mei et al. (2015a) also analyzed the water level data of Duchang station and compared the daily water level from 2003–2012 with 1992–2002. Their results revealed that the occurrence of extremely low lake levels (below 10 m) has increased dramatically from 4% to 25%, while occurrences of extremely high levels (over 22 m) have ceased. However, it may not be sufficient to characterize the entirety of Poyang Lake by using the water level data of one hydrological station. Due to the huge differences in hydrological characteristics of Poyang Lake in different seasons, the key period of research should be differentiated. Zhang et al. (2014) collected water level data from three different hydrological stations in Poyang Lake, located in the downstream, center, and upstream, respectively, and compared the decadal average values of daily water levels. It was observed that since 1953–2010, the minimum value of the annual average water level occurred in the 2000s. In addition, the annual variations in outflow and the catchment inflow have both decreased during the last decade.

By utilized water level data from the 1950s–2012 at four stations (Hukou, Xingzi, Duchang, and Kangshan) and the inflow data at water level stations of major tributaries from the same period. Lai et al. (2014a) demonstrated that the mean lake level in dry season (December to February) from 2001 to 2012 decreased by 0.8 m at Duchang and 0.5 m at Xingzi when compared to previous decades (1961–2000). Statistical results of Ye et al. (2018) indicate that the average decline of water levels were about 0.60 m, 0.80 m, 0.95 m, 0.54 m and 0.41 m, respectively during 2000–2014 for the five previously listed observation stations in Poyang Lake.

These studies reached a consensus that the water level of Poyang Lake has decreased drastically as compared with long-term averages. However, another important issue concerns the shorter-term variation during this extended dry period seen during the past decade. Previous studies used
MODIS images between 2000 and 2010 to visually analyze the inundation patterns. Significant seasonality and interannual variability were found in the monthly and annual mean inundation areas; both the annual mean and minimum inundation areas showed statistically significant declining trends (−30.2 km² yr⁻¹ and −23.9 km² yr⁻¹) (Feng et al. 2012a), and the cumulative inundation areas of Poyang Lake decreased by 55% (Wu & Liu 2016). The application of remote sensing technology provided accurate data for studying hydrological changes in Poyang Lake; unfortunately, it has not been possible to completely understand the significance of the lake shrinkage in the 2000s as compared to earlier periods. To better understand the mechanisms behind the water level decline, Li et al. (2016a) used a physically based mathematical model (MIKE 21) to establish the relationship between the lake area and water level. These results showed that the decadal average lake area in the 2000s (950 km²) decreased by more than 124 km² as compared to that obtained from 1961 to 2000. In addition, the minimum lake area varied from 1,259.7 km² (1997) to 702.8 km² (2009) resulting in a large difference of 550 km². Wang et al. (2018) applied the Standardized Precipitation Evapotranspiration Index to analyze meteorological drought parameters in the Poyang Lake basin from 1961 to 2015, and pointed out that Poyang Lake has entered a relatively dry period since the 2000s. In general, previous studies indicated that the decline of lake water level as well as the declining inundation trend have been significant (Figure 3). Hence, the general consensus is that the prolonged drought, enhanced low water level and shrinkage of the inundation area have all placed immense pressure on water utilization and wetland ecosystem protection of Poyang Lake.

**DRIVING FORCES OF HYDROLOGICAL REGIME VARIATIONS IN POYANG LAKE**

The above problems are of great concern for governments and local residents. In order to understand if the recent decline is a continuous trend affected by specific factors, it is of critical importance to clarify the mechanisms responsible for these changes. Previous studies have generally focused on the following aspects: Regional climate change, the impact of the Three Gorges Dam, and the impact of sand mining. We will summarize and discuss these factors below.
Regional climate change

Under the background of global warming, an uneven distribution of precipitation and increased extreme weather events has caused major global changes. Many scholars have postulated that the impact of climate change on river runoff, especially floods and droughts, is of much larger magnitude than the impact of land use change (Bronstert et al. 2002; Kundzewicz 2002; Huntington 2006). The Poyang Lake basin has also been affected by abnormal climate, resulting in frequent flood and drought disasters (Guo et al. 2006). The frequency of floods increased significantly in Poyang Lake area before 2000, as four severe floods occurred within eight years, but after 2000, episodes of extreme drought have occurred more frequently (Min 2002; Min & Min 2010). Runoff of the tributaries that feed Poyang Lake is directly affected by regional climate change (including precipitation, temperature, relative humidity, sunshine duration, vapor pressure and wind speed) and this can directly affect the water level of Poyang Lake. To address the relationship between climate and hydrological processes in the Poyang Lake basin, runoff and precipitation data from different gauging stations throughout the lake basin were analyzed to demonstrate a general increasing trend of annual streamflow, precipitation and a significantly decreasing trend of evapotranspiration from 1950 to 2003. (Zhao et al. 2010) Further studies have confirmed this result, and correlation analyses indicated that variations in streamflow were more related to precipitation changes than evapotranspiration (Sun et al. 2015). Another statistical analysis determined that the annual precipitation and potential evapotranspiration of Poyang Lake Basin have shown a long-term increase and decrease, respectively. Additionally, the variations of mean annual runoff have been principally affected by climate change, which resulted in an increased annual runoff of 75.3–261.7 mm. (Ye et al. 2013).

The precipitation and runoff in the Poyang Lake basin before 2000 exhibited an increasing trend, however, the situation changed after 2000. Zhang et al. (2016b) found a notable conclusion after an extension of the research duration to 2009. The time period of the 2000s witnessed a decrease in precipitation and an increase in potential evapotranspiration, which induced a decrease in annual streamflow. This result is opposite to what was seen before 2000. Consequently, studying the long-term fluctuations of meteorological factors and tributary runoff may explain the water shortage of Poyang Lake. The Standardized Precipitation Evapotranspiration Index (SPEI) analysis was applied to analyze the temporal variability and spatial distribution characteristics of meteorological drought over the Poyang Lake basin. Statistical results revealed that by the 2000s, the Poyang Lake basin had entered a high-frequency drought period, during which the occurrence frequency of severe droughts reached a maximum value, while autumn was the most frequent drought-affected season (Wang et al. 2018). Furthermore, the correlation between lake level and SPEI was best in winter and worst in autumn, and the correlation coefficients increased from north to south within Poyang Lake. Two concepts are worth mentioning: 1. In winter, the climate conditions are the main influencing factor for lake levels, while in autumn this influence was weakened by other factors. 2. The closer the distance to the Yangtze River, the weaker the interaction between climatic conditions and lake water level.

With these factors in mind, several questions can be asked. Will the continuous drought in Poyang Lake after 2000 be a short-term climate disturbance? And how will the water level change under future climatic conditions? A distributed hydrological model (WATLAC) was applied to bridge this knowledge gap and clarify the water level evolution under climate change in the future. These simulation results demonstrate that changes in climate conditions will result in an increase of lake water level of 0.10–1.34 m from February to July and a decrease of 0.32–1.31 m from September to February during 2011–2050 (Ye et al. 2011).

This alarming result suggests that there may be increases in the frequency and severity of flooding and droughts in the Poyang Lake catchment as climate conditions worsen in the future. Other research has investigated the connection between hydrological features and climatic elements such as evapotranspiration and wind effects of Poyang Lake (Ye et al. 2014b; Yao et al. 2019). However, when studying the relationship between hydrology and climate change at a basin scale, the interference of human activities is the biggest uncertainty, as different periods have witnessed different degrees of human activity disturbance and climate change on hydrological condition changes. Therefore,
integrating multiple climatic factors should be the preferred approach, and the interrelationship between climate and the hydrological cycle must be reflected on an appropriate time scale.

**Impact of Three Gorges Dam**

As discussed above, the correlation between climate change and water level in autumn is not obvious, and another question can be raised: Are there other driving forces that dominate the water level of Poyang Lake in autumn? One study proposed a perspective that the recent lake water decline was not a long-term trend, as no significant correlation was seen between precipitation and outflow discharge; instead, the shrinkage was considered as a regime shift that coincided with the stage decrease of the Yangtze River (Liu et al. 2013). Model simulations suggested that the Yangtze River was the dominant cause for enhanced recession in Poyang Lake during 2001–2010, specifically, the Yangtze River flow conditions have a much greater effect on the autumn (September–October) dryness of the lake (Zhang et al. 2014). Zhang et al. (Yao et al. 2016) explored the influence of the Yangtze River and lake catchment on water level based on two typical years, and also demonstrated that the influence of the Yangtze River was the critical factor for the autumn dryness. Yet another question is still unanswered: Why did the hydrological conditions of the Yangtze River change suddenly after 2000? An answer to this might be found by considering the construction of the Three Gorges Dam (TGD), which was initially started in 1994, and completed by 2006. TGD is the largest hydropower project in the world, located in the upper reaches of the Yangtze River (Figure 1). The first impoundment was initiated in 2003, which raised the water level to 139 m. The second impoundment (which started in 2006), raised the water level to 156 m, and the final impoundment raised the water level to 172.8 m in 2008. In order to maximize the potential flood control capability, a historic high water level of 175 m was reached in 2010 (Zhang et al. 2016a). The regulation pattern of the TGD reduces the reservoir water available during flood season (June-September) and stores water for electricity generation between October to May. Inevitably, this regulation has complicated the hydrological regime of the Yangtze River (Mei et al. 2015b). However, to fully understand the effect of the TGD, comparative studies of hydrological data of the middle to lower Yangtze River before and after the dam’s construction is required. Lai et al. (2014b) analyzed the water level change between 2006–2011 and 1956–2002 to find that the TGD’s operation has substantially reduced water levels in the middle-lower Yangtze River during impoundment from September to November. To further investigate the influence of the TGD on the middle-lower Yangtze river conditions, Tian et al. (2019) extended the research time frame (1956–2016), and obtained the result that the TGD not only advanced the dry season in the middle-lower reaches of the Yangtze River, but also increased the probability of the occurrence of minimum water levels.

Since Poyang Lake is naturally connected with the middle-lower Yangtze River, it is highly suggested that due to the operation of the Three Gorges Dam, there will be two significant changes in Poyang Lake water levels. The first aspect is that in order to increase the storage capacity for flood mitigation, the TGD water release from May to June will increase the water level of the Yangtze River and inevitably constrain the discharge of Poyang Lake to Yangtze River, called the enhanced blocking effect. The second aspect is that in order to generate power, the rapid water impoundment of TGD from September to November will lower the water level of the Yangtze River, which may accelerate the drainage from Poyang Lake, known as the enhanced empty effect. The empty effect is usually thought to intensify the drought during the dry season of Poyang Lake (Zhang et al. 2012a). However, it was pointed out by Guo et al. (2012) that the strength of this impact depends on the practical impound and release rates of TGD.

In this regard, numerous studies have explored whether the operation of the TGD is the main driving force for the water decline in Poyang Lake. By comparing the two extreme drought periods during the past 60 years (the 1960s and the 2000s), evidence that the impoundment of the TGD was the main factor in water level decline during dry season was discussed by Wang et al. (2019b), who found that in late September, early October, and mid-October, the contributions of water storage of the TGD to the decline in the water level of Poyang Lake reached 68.85%, 59.04%, and 54.88%, respectively. Zhang et al.
showed that, regardless of the blocking time or the amount of water intrusion from the Yangtze River to Poyang Lake, the values seen in the 2000s were much lower than in the 1960s. Shockingly, almost no water intrusion from the Yangtze River to Poyang Lake in the 2000s was seen; this result highlights an interesting fact that the decrease of streamflow in the upper Yangtze reaches has caused a decrease of the blocking effect and an increase of the enhanced empty effect, and the impoundment of water by the TGD has induced a water level decline of 0.5–1.5 m at Hukou station.

On the other hand, the TGD has also had a huge impact on sediment transport in the Yangtze River (Zhang et al. 2006; Dai et al. 2011; Wang et al. 2013). Though the TGD discharges clean water, the turbulent water stream quickly washes away the riverbed and causes large amounts of sediments to move downstream, causing an elevation change of the riverbed. On top of this, Mei et al. (2015b) found that the maximum and minimum water levels downstream of the TGD both have shown a decreasing trend, which was caused by channel erosion. Accordingly, severe erosion of the main channel of the Yangtze River has led to the scouring of the river bed, which has increased the elevation difference at the junction of Poyang Lake and the Yangtze River, further weakening the blocking effect and enhancing the empty effect (Zhang et al. 2016a). The erosion of the deeper channel has accelerated the decline of the water level of Poyang Lake and has led to about 10% to 20% of the water level decline in the dry season (Wang et al. 2019b).

Other studies have found different conclusions. Wang et al. (2017) focused on the lake shrinkage during 2000–2011, and suggested that climate variables (e.g., precipitation and mean air temperature) was the dominant driving force on the lake level decline, while the TGD played an marginal role (less than 5%). Other studies have contested the reasoning that the TGD has caused the severe drought because no significant change in the inundation-runoff relationship could be seen, and concluded that the link between drought of Poyang Lake and the operation of the TGD was quite small (Feng et al. 2012b). There has been some additional controversy as to whether the climate conditions and the TGD are the main reason of the water decline in Poyang Lake. Feng et al. (2015) combined MODIS data with meteorological and hydrological observations to investigate the impact of the TGD on inundation area shrinkage in Poyang Lake. Their results showed that decreasing inundation area and decreasing lake drainage were linked to the operation of TGD. Song et al. (Song & Ke 2014) raised some questions about this study concerning three aspects: 1. Satellite images cannot indicate reliable changes in long-term behavior; 2. Correlation analyses suggested that changes in water levels of the two lakes are strongly related to precipitation during 1993–2010; 3. The results of some typical years cannot be the conclusive verdict about long-term trends.

It is our hypothesis here that there is firm evidence that the Three Gorges Dam has a significant impact on the decline of Poyang Lake, especially for the continuous low water level seen during the dry season. The impoundment of water by the TGD has led to a huge outflow of 760.6 million m$^3$ day$^{-1}$, which has caused a loss of 7,864.5 million m$^3$ of water from Poyang Lake just in one year (Feng et al. 2011). While a statistically significant decrease of 3.3%/year in the Poyang Lake inundation areas has been determined (Feng et al. 2014). Overall, the TGD has affected the lake water budget through changing runoff and riverbed erosion in the middle-lower Yangtze River, and the recent water decline in Poyang Lake should therefore not be viewed as a long-term natural trend but as a regime shift (Liu et al. 2013).

**Impact of sand mining**

Another important factor that is a likely influence on Poyang Lake water levels comes from sand mining. Sand mining was banned within the main stream of the Yangtze River in 2001, in consideration of the serious threats to the river embankment and ecosystem. Afterwards, an increasing number of dredging operations turned to Poyang Lake for sand resources (Wu et al. 2007). Globally, the demand for sand is growing, especially for developing countries, such as China, as large cities like Shanghai and Shenzhen have huge demand for sand and gravel for infrastructure construction and renewal. (de Leeuw et al. 2010; Calle et al. 2017; Kondolf 1997). Because of the possible alterations in the physical, chemical and biological properties of natural aquatic ecosystems, many studies have argued that sand mining should be regarded as a crucial anthropogenic
interference of global environment variation (Nayar et al. 2005; Hossain et al. 2004; Gavriletea 2017). Therefore, understanding the magnitude of sand mining in Poyang Lake is a critical issue. By estimating the number of vessels operating in Poyang Lake, it was calculated that that the sand extraction in the lake was 236 million m$^3$ year$^{-1}$ during 2005–2006, equal to 17.9% of the total sand production in the USA in 2006, and exceeded the total production of Germany in the same year (de Leeuw et al. 2010). Sand mining in Poyang Lake was originally concentrated in the northern part of Poyang Lake, but has expanded southwards since 2009 (Li et al. 2014). Qi et al. (2014) found that the rate of extraction of sand and gravel in Poyang Lake is possibly the largest single operation in the world. Digital elevation models (DEMs) of Poyang Lake from 1:10,000 maps surveyed in 1998 and 2010 were used to describe the topography changes which concluded that the lake bed erosion in the northern channel was an average of 5 m (Yao et al. 2018). The question that followed is whether such a huge magnitude of sand mining could be a significant mechanism contributing to the water decline in Poyang Lake.

The mean water level at the outlet of Poyang Lake to the Yangtze River during the dry season has remained approximately constant (8.5 m) from 2001 to 2012, so the changes in the Yangtze River discharge failed to explain the abnormal water decline in the dry season. Lai et al. (2014a) illustrated that intensive sand mining has altered the outflow channel of Poyang Lake, which has caused a 1.5–2 times increase in the discharge ability, and they suggest this as the main reason for the low water level phenomenon. Furthermore, a total volume of $1.54 \times 10^8$ m$^3$ year$^{-1}$ of net change in lake bottom topography occurred 2000–2011, 97% of which was directly caused by sand mining. This extensive change has increased the average annual lake outflow by 182.74 m$^3$ s$^{-1}$ and decreased the water levels of the lake by 0.23 m–0.61 m (Ye et al. 2019).

The impact of sand mining on the water level of Poyang Lake is likely to strengthen with increasing demand of sand and gravel. Another impact of increased mining is that the sediment balance of Poyang Lake is changing significantly. After 2000, Poyang Lake no longer receives significant loads of sediment from the Yangtze River. (Gao et al. 2014). Consequently, the sediment load of the Yangtze River entering the sea now contains increasingly more sediment from Poyang Lake. Thus, Poyang Lake has been converted from a depositional to an erosional system with a gross sediment loss of 120.19 Mty$^{-1}$.

Thus, it is highly suggested that topography changes caused by sand mining will bring increased impacts to the hydrological features of Poyang Lake such as water level and flow velocity (Qi et al. 2019). The net sediment flux converted from positive to negative after 2000, and the decreased sediment concentrations in Poyang Lake is clearly attributed to sand mining (Wang et al. 2019c). The current changes in the topography of the lake were mainly concentrated in the northern channel of Poyang Lake which contributes to the water decline in dry season by enhancing the empty effect. However, as sand mining has recently extended into the central part of the Poyang Lake and even to the channels of major tributary rivers, it will pose an increasing threat to the water regime of Poyang Lake (Ye et al. 2018). Thus, new methods of effective resource management on the sediment balance of Poyang Lake should be analyzed in greater detail in the near future.

**IMPACTS OF THE DRAMATIC RECESSION IN POYANG LAKE**

The majority of recent research on the water decline of Poyang Lake has mainly focused on the driving forces, and little focus has been given to its impact on different aspects of the environment. Yet this is an important consideration, as it can significantly affect the availability and quality of fresh water, causing eco-environmental problems to emerge, thereby triggering modifications to the biota of Poyang Lake. We thereby chose four elements of the Poyang Lake wetland ecosystem (water quality, landscape, migratory birds, and Yangtze finless porpoises) as representative metrics of the direct and indirect impacts of the water decline in Poyang Lake.

**Water quality**

The primary factor that can be affected by the variation of hydrological conditions is water quality. In China, water quality impairment has been severe in certain regions,
with important consequences for ecology as well as sustainable economic and social development (Duan et al. 2016).

There have been many studies on the water quality of Poyang Lake, but most of these involved sampling analyses of certain positions. The reduction of Poyang Lake’s water level will inevitably affect the transport and spread of pollutants and alteration of water residence time. These changes may cause serious ecological damage, such as eutrophication, which has affected many lakes located in the middle and lower Yangtze River. It has been recognized that the seasonal dynamics of TN (Total Nitrogen), TP (Total Phosphorus) and other water quality parameters in Poyang Lake showed similar variations, with the lowest concentrations found in the flood season and the highest concentrations found in the dry season (Li et al. 2017). A study carried out by Li et al. (2018a) revealed that the eastern part of the lake was subject to high levels of pollution and the water decline could result in a maximum increase of TN and TP concentrations by 25.6% and 23.2% respectively.

From this we can speculate that under conditions of increasing discharge into the Yangtze River, the water quality will likely deteriorate further and cause severe consequences such as eutrophication. There have been only a few reports of eutrophication in Poyang Lake in recorded history, however, an increasing interference of human activities in the basin in recent years has caused a considerable accumulation in nitrogen and phosphorus discharge, and the risk of eutrophication is thus increasing (Deng et al. 2011). It was found by Wu et al. (2013) that the dominant species within the phytoplankton community is Bacillariophyta, with a larger biomass found in the southern part of the lake. Additionally, the phytoplankton biomass associated with the nutrient concentration has shown an increasing trend. A long-term sampling effort during 2009–2018 illustrated that both water level and water temperature were critical parameters affecting phytoplankton populations (Wu et al. 2019a). We now consider the temperature conditions in the watershed. Poyang Lake underwent a highly significant warming trend from 1980 to 2018, with an annual mean air temperature warming rate of 0.44 °C/decade (Li et al. 2020a). These trends suggested a potential increased risk of eutrophication. Since Poyang Lake is a shallow lake, the thermal regime of the lake has not received a great deal of research attention. However, Li et al. (Li et al. 2018b) found that the lake is generally stratified during summer and early autumn, and classified as partially mixed and fully-mixed during winter and spring, respectively. Subsurface light penetration and thermal stratification will also likely change with the decline of water level, and research into this aspect should be strengthened. Another crucial parameter affecting water quality is water residence time, which can indicate the transport process of nutrients. The regional differences of water residence time may cause different risks of water quality deterioration in different areas of the lake (Li et al. 2010; Gao et al. 2018). In most areas of the lake, the water residence time ranged from 10 to 30 days, while it reached more than 300 days in the eastern lake and some enclosed channels of the southern lake (Qi et al. 2016). In addition, Wang et al. (2015b) and Wu et al. (2014a) reached a similar conclusion by investigating the chl-a concentration of Poyang Lake, finding that the eastern part of Poyang Lake may have greater risks of water quality deterioration. Therefore, the impact of the water level changes on residence time should be observed more rigorously in order to monitor the possibility of water pollution and eutrophication in Poyang Lake.

The Poyang Lake Basin is undergoing rapid industrial and agricultural development. The tributaries of Poyang Lake import not only water and sediment, but also carry contaminants such as heavy metal, polycyclic aromatic hydrocarbons (PAHs), and microplastic. These contaminants pose high risks to the condition of both the ecosystem and human populations in the Poyang Lake region, and this issue has received more attention lately (Feng et al. 2019). Studies have shown that heavy metal contaminants in Poyang Lake such as copper and cadmium may be contributed by anthropogenic activities like mining and fertilizer usage. Furthermore, concentrations of manganese, aluminum and lead have exceeded safe limits in some samples of groundwater around Poyang Lake, which makes the water unsuitable for drinking (Dai et al. 2018; Liao et al. 2018). Differences in the distribution of contaminants in different regions of Poyang Lake is another important concern. Niu et al. (2019) showed that the eastern areas of Poyang Lake had higher concentrations of heavy metals, which has led to a higher toxicity of sediments in the eastern areas. The condition of PAHs in Poyang Lake
has been shown to be due to combustion products of fuel oil as well as other pyrogenic sources (Zhi et al. 2015; Wan et al. 2020). The spatial distribution patterns of PAHs sources in Poyang Lake was analyzed by Li et al. (2018c), and their results indicated that petroleum combustion from urbanization and shipping petroleum-related contaminants was the main source of PAHs in the southern and northern areas of Poyang Lake, respectively. These contaminated sediments might be released and cause secondary pollution as the water level of the lake experiences further variations in the future. Additionally, Liu et al. (2020) showed that soil acidification in the Poyang Lake Basin has deteriorated. As the water level of Poyang Lake continues to decline, the surface and underground hydrological connectivity may also be altered significantly, and the relationship between this alteration and water quality should be researched in greater detail.

Though the current water quality of Poyang Lake is shown to be steady, a deteriorating trend has been observed at the interannual scale in the last decade. This is particularly true in the dry season, as the probability of serious deterioration of water quality has reached 50%–70% (Wu et al. 2017). This suggests that the water decline is a direct mechanism of water quality deterioration.

**Landscape, vegetation and migratory birds**

If Poyang Lake’s low-water conditions continue, the temporal pattern of wetland submergence or emergence at different elevations will subsequently change, which will in turn alter the spatial landscape structure of the Poyang Lake wetland system, and modify the wetland vegetation belt and dominant communities. These conditions are critical to the sustainabilty of habitats and feeding locations for wintering migratory birds in Poyang Lake. Therefore, studying the response of the spatio-temporal changes of landscape types such as shoals, mud-flats, and meadows to the water level variation can help improve the stability of the wetland ecosystem of Poyang Lake as well as provide informed suggestions for better protection of wintering migratory birds.

Vegetation is the most extensive class seen during the dry season of Poyang Lake, occupying 41.2–49.3% of the total area, followed by water, mudflats and shoals. (Dronova et al. 2011). Feng et al. (2016) showed that Carex was the dominant and most widely distributed species in the Poyang Lake wetland. Carex communities can survive in a relatively wider variety of hydrological conditions in Poyang Lake, due to its adaptation ability to longer inundation duration and depth conditions (Zhang et al. 2012b; Zhiqiang et al. 2016). However, as the water level has declined at an average rate of 0.16 m per year during 2000–2010, the total area of vegetation coverage has shown an increasing trend (You et al. 2017). This was further confirmed by Wu et al. (Wu & Liu 2017) who found that the vegetation area increased by 58.82 km² in the dry season, with the most significant changes occurring in the estuary deltaic regions of the tributaries.

Enormous populations of migratory waterbirds travel to this region during winter for the rich food resources provided by emergent and submerged aquatic plant diversity. Almost 95% of the entire world population of the endangered Siberian crane and other important migratory birds (e.g., swans, Anseriformes) winter at this lake and forage on the tubers of the submerged aquatic macrophyte, Vallisneria spiralis L. Changes in the landscape pattern and vegetation distribution will inevitably affect the habitat and foraging habits of these migratory birds (Wu et al. 2009). It seems natural to infer that the water decline of Poyang Lake during the dry season will increase the area covered by vegetation, and thus increase the habitat of migratory birds. Tang et al. (2016) found that long-term lake shrinkage in low-water periods may provide more suitable habitats for migratory waterfowl, and a recent survey from 1997 to 2013 showed an increasing trend of Anseriformes population. Likewise, Wu et al. (2014b) indicated an increasing trend in migratory bird populations as well as in avian biodiversity. However, there were also negative discussions. A changing diet of migratory birds may be simply a survival strategy during extremely adverse conditions. Therefore, sudden changes in habitat and food selection may indicate the deterioration of the habitat quality. Recently, large numbers of Siberian cranes have been observed to forage a different plant (Potentilla limprichtii) in wet meadows (Jia et al. 2013). This observation might suggest that the changes in the bird’s food resources may have been caused by hydrological disturbances. However, this is still under debate and more studies are needed to assess the question as to whether

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a significant increase in wetland exposure and an observable shift in the seasonal timing of dryness will seriously degrade the wetland system and threaten the endangered birds.

Another important reason for studying the changes of wild bird habitats in Poyang Lake regards the prevention of avian influenza, which is especially in focus with the advent of the new coronavirus (COVID-19) affecting many places around the world. The total detection rate of avian influenza antibodies in wild birds in southern China is 56.8%, which is significantly higher than that in other regions (Chen et al. 2019). Poyang Lake is the most important bird habitat in southern China, so ensuring the continued health of avian populations is of critical importance. Sampling research has revealed that wild birds and poultry in the Poyang Lake area have different carrier potential levels of the avian influenza virus (Prosser et al. 2015, Li et al. 2016b). Due to the comprehensive system of wetland, farmland and poultry farming in the Poyang Lake area, the risk of avian influenza outbreaks through cross-species transmission is very high (Fearney 2015). By studying variations of wetland landscapes and bird habitats under the influence of water decline, it may be possible to preemptively understand the risk of avian influenza transmission between wild birds and poultry to better maintain the ecological safety of Poyang Lake.

Therefore, the response of various migratory birds to the change of the landscape patterns of Poyang Lake is a direction that should be studied in the future, using a combination of biology, ecology, geography, and even epidemiology study methodologies.

The Yangtze finless porpoises

Poyang Lake is an ideal habitat and foraging place for the Yangtze finless porpoises whose populations are threatened (Turvey et al. 2007). The Yangtze finless porpoise (Neophocaena asiaeorientalis asiaeorientalis) is endemic to China and it was once distributed throughout the middle and lower reaches of Yangtze River, but it is now listed as endangered by IUCN (Zhao et al. 2008). As the baiji (Lipotes vexillifer) is functionally extinct, the Yangtze finless porpoise is the only cetacean inhabiting the Yangtze River Basin (Kimura et al. 2010). However, illegal fishing, pollution, vessel traffic and sand mining have all contributed to the decline of the porpoise population over the last four decades, to a point where this species is classified as Critically Endangered on the IUCN Red List of Threatened Species (Huang et al. 2020). It was recently announced that the number of remaining individuals was down to approximately 1,800 in 2006, and the species was decreasing then at a rate of 5% per year (Wang 2009). Recent studies reported that there were only 505 porpoises still inhabiting the main stream of the Yangtze River in 2012 (Mei et al. 2014).

Huang et al. (2017) showed that the mean predicted time for the extinction of Yangtze finless porpoises was 25–33 years in the Yangtze River and 37–49 years overall in the wild at the current rate of decline. With this concern, a study on the relative abundance of the porpoise by field survey proposed that the existing protected reserves of Yangtze finless porpoises was not enough and reasonable, some additional areas should urgently be designated as new protected areas given their high porpoise density (Zhao et al. 2015). The number of Yangtze finless porpoises in Poyang Lake accounts for about half of the total number (400–500), and Lake Poyang is known as the last refuge for Yangtze finless porpoises (Liu et al. 2016; Huang et al. 2020). Interestingly, ship traffic, bridges and sand mining operations do not seem to significantly affect the presence of porpoises in Poyang Lake, but the distribution of porpoises has a strong temporal difference (Kimura et al. 2012). An open question thus remains: if human activities have little effect on the occurrence of Yangtze finless porpoises in Poyang Lake, is the driving force for the distribution of finless porpoises in Poyang Lake in different seasons due to seasonal changes in the hydrological conditions?

The author of this paper participated in two joint finless porpoise field surveys in Poyang Lake, one in flood season and one in dry season, which was led by the Department of Agriculture and Rural Affairs of Jiangxi Province. The fishery bureaus of 12 counties and cities along the lake set off at different places at the same time so that the survey domain essentially covered all the important waters of Poyang Lake, while largely avoiding double-counting. The result of the survey revealed high-density areas of porpoises in Poyang Lake, and there were similarities and dissimilarities among the data of wet season and dry season (Figure 4).
The number and locations of finless porpoises observed in the dry season are significantly greater than in the flood season. The main reason for this is likely because it is more difficult to find the finless porpoise during the flood season due to the large water surface of Poyang Lake. In the dry season, the unique river-like water surface allows investigators on ships to observe the finless porpoise more clearly. In addition, since the habitat of the finless porpoise shrinks as the water surface decreases during the dry season, a large part of Poyang Lake cannot be reached by boat during the dry season. Thus, the study of the hydrological conditions in the areas populated by the finless porpoise is of great significance to the protection of this species during the dry season, and it should be a key future research direction to provide scientific guidance for the patrol of the finless porpoise in Poyang Lake.

DISCUSSION AND REMARKS

There is a well-known local saying about Poyang Lake, which says ‘When the water level is high, we see an expansive lake; when the water level is low, we see isolated rivers’. However, this regular seasonal variation is destabilizing. In the current year (2019), Poyang Lake has again experienced an advanced dry season and an extremely low water level. This paper has thus reviewed many recent papers concerned with the constant water decline in Poyang Lake. Whereas numerous previous studies usually focused on a specific hydrological feature such as water levels at certain gauging stations or inundation areas, we present here a systematic summary of the important results: After entering 2000, the occurrence of extremely low lake levels (below 10 m) has increased to 25%, while occurrences of extremely high levels (over 22 m) have ceased. The average decline of the lake water level is 0.66 m, and the annual mean inundation area is declining by 30 km²/yr, the minimum lake area varied from 702.8 km² (2009) to 1,259.7 km² (1997) (Feng et al. 2020a; Li et al. 2016a; Ye et al. 2018).

A thorough temporal analysis of how to quantify the continuous water decline in Poyang Lake was carried out by Huang et al. (2018), in which a total of 47 hydrological indicators were considered including monthly mean water levels, monthly maximum water levels, monthly minimum water levels, and the rate and frequency of water level changes. These indicators were analyzed to accurately determine the time period when the most dramatic alteration happens through the year. Nevertheless, there still exists a gap in understanding the spatial differentiation within Poyang Lake. Taking the year 2019 as an example, when the low-water period of Poyang Lake was advanced and the minimum water level was continuously refreshed, extreme water decline was also seen in the main tributaries.

Another factor that may have a significant effect on the hydrological and ecological processes of Poyang Lake is the dynamics of seasonal lakes in floodplain regions. Floodplain lakes occupy a relatively small part of Poyang Lake’s water volume, yet they contain a large part of the surface water area during low water periods (Tan et al. 2020). The study by Li et al. (2019) showed that the temporal influences of the seasonal lakes on water levels, lake outflows, and inundation were greater during dry seasons, and the impact of
seasonal lakes on the magnitudes of hydrological responses during the dry season is much stronger than during the flood season. Water balance analyses carried out by Li et al. (2020b) highlighted that the catchment rivers and the associated groundwater system are important parts of Poyang Lake. These findings suggested that the study area should be enlarged to the basin scale, starting from changes in the overall hydrological conditions, and then distinguish the changes in different areas. It is particularly important to take hydrological hysteresis into consideration, which is created by the combined dynamics of the Yangtze River, its associated lakes, and its floodplains. This approach should prove to be more successful in discovering the driving forces with greater accuracy.

Most previous studies mainly discussed specific driving forces, such as climate change, operation of the TGD, sand mining, etc (Table 1). It is true that both the operation of the Three Gorges Dam and large-scale sand mining occurred after 2000, and these events are strongly correlated with the continuous water level decline in Poyang Lake. In addition to extreme weather conditions, the continuous decline of the water level in Poyang Lake is likely related to the combined effect of the changes in the interaction between the lake and the Yangtze River due to the operation of the TGD and the topography variation caused by extensive sand mining. The operation of the TGD may have amplified the weakened blocking effect and the enhanced emptying effect, which can lead to a reduction of the water storage capacity of Poyang Lake. This review concludes that river bed erosion along the middle-lower Yangtze River and reservoir impoundment of TGD operation have both increased the outflow of Poyang Lake to the Yangtze River, which are the primary driving forcing for lake recession. Climate change, especially variations of precipitation, and sand mining activities (some of which is performed illegally) have also exacerbated the problem of water decline in Poyang Lake. Reasonable regulation of sand mining in Poyang Lake should be a top priority of current management, and the effects of sand mining should be a primary focus of future research. The budget and balance of water and sediment in Poyang Lake under the dual impacts of such a large amount of sand mining and the establishment of dams on the five major inlet tributaries are likely to vary more in the future, and these factors should be monitored and analyzed carefully.

The impact of these changes on hydrological process and natural reserve areas should be taken into consideration to obtain an accurate understanding of prohibited sand mining areas in order to develop better management procedures. However, most of the previous studies have not focused on the entire watershed area, which should be given more consideration in future efforts. Some studies have pointed out that changes in land cover, especially changes in vegetation cover, will greatly affect the average annual runoff and minimum runoff in the watershed (Cecílio et al. 2019). Under the dual interference of rapid economic development and ecological protection measures such as afforestation, measuring the impact of significant changes in the land use of the basin on the hydrological processes is a critical research direction for the future. The question of whether there are other driving forces leading to the emergence of this problem, such as land use and land cover change, should be another future research direction concerning Poyang Lake ecohydrology. A detailed investigation of the coupled impact of causative factors responsible for the extended dry conditions will be more practical than an isolated inquiry of driving forces.

This article chose four elements of ecohydrology (water quality, landscape, migratory birds, and Yangtze finless porpoise) as representative examples to analyze the impacts of the water decline in Poyang Lake. One clear conclusion is that decreasing water level in Poyang Lake has led to the deterioration of the water quality. The advance of Poyang Lake’s dry season and the frequent occurrence of extremely low water levels will increase the area of exposed wetlands and may provide more habitat for migratory birds. The habitat and foraging of migratory birds in Poyang Lake is a complicated process, as the gradually exposed wetlands provide rich food resources for birds, while the rapid and large-scale exposed wetlands may accelerate wetland desiccation and change plant community structure, which may affect the foraging habits of migratory birds (Jiang et al. 2015; Zhi et al. 2019). Moreover, the increased area of exposed wetlands may enlarge the range of human activities, further reducing the habitat of migratory birds. The current research on Yangtze finless porpoise protection focuses on the effectiveness of ex-situ conservation (Zheng et al. 2005; Wang 2009), and how changes in hydrodynamic conditions caused by water decline will affect the distribution and survival of...
finless porpoises in Poyang Lake, this is another issue that should be examined closer in future studies. Fortunately, Poyang Lake is about to enter a long fishing moratorium period (10 years), so that the fish biomass and biodiversity of Poyang Lake are likely to show an increasing trend (Wang et al. 2019a). Though many open research questions remain, it is clear that the impact of water decline on Poyang Lake will affect many secondary systems. Evaluating the ecosystem services of Poyang Lake, and investigating its variation under a decreasing trend of water level can assess the effectiveness of lake ecosystem management. Future studies can address whether the various types of nature reserves on Poyang Lake need to have their locations and ranges adjusted to achieve better protection.

A recent proposal by the government of Jiangxi Province has received much debate, which is to build a hydraulic project on the Poyang Lake to solve the drought problem. On one hand, this project seems to be a direct and effective way to control the water level in the lake. Some scholars have suggested that establishing a dam will be an effective solution to reduce the Yangtze river effect and can bring significant economic benefits. On the other hand, some experts have claimed the dam may trigger a fundamental and possibly detrimental change in the wetland ecosystem (Lai et al. 2015; Wang et al. 2015; Wu et al. 2019b). In view of this quandary, specific future research questions may be suggested, such as: Will the construction of a dam solve the influence of water decline in Poyang Lake or it will be enhanced? Will the ten-year fishing moratorium period benefit the hydrobiology condition? To what degree will the hydrological conditions caused by the construction of the dam affect the habitat of birds and finless porpoises?

Overall, the recent water decline has become an undeniably serious problem of the ecohdrology of Poyang Lake. The changes in the interaction between the river and the lake caused by the operation of the TGD and increasing sand mining operations are the most probable internal and external reasons for the water level decline in Poyang Lake observed since 2000. It will be practical for future studies to focus on the impacts of the decreasing water level to better understand the different responses of the environmental factors of Poyang Lake to the water decline. These efforts will serve to better protect and ensure the continued health of the wetland ecosystem.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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