Strategic Study of CAE 2022 Vol. 24 No.1
DOI 10.15302/J-SSCAE-2022.01.018

Strategies for Water Security and Aquatic Ecosystem Restoration in the Yangtze River Economic Belt

Hu Chunhong [1, 2], Zhang Shuanghu [1, 2]

1. China Institute of Water Resources and Hydropower Research, Beijing 100038, China;
2. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing 100038, China

Abstract: Working together on protection instead of excessive development is the key to the high-quality development of the Yangtze River Economic Belt. It is, thus, necessary to resolve the principal contradictions involved in the process of protection by using targeted measures. In this study, we analyzed the major issues related to water security and aquatic ecosystem protection in the Yangtze River Economic Belt, including the severe flood control situation, considerable shrinkage of suitable habitats for aquatic animals, and biodiversity reduction, as well as the dysfunctional relationship between the Yangtze River and its formerly connected lakes. Additionally, we have proposed several targeted measures and strategies to tackle these issues. Measures for improving flood control capability include accelerating the construction of safety projects in critical flood storage and detention areas and revising the *Yangtze River Basin Flood Control Planning* document. Strategies for restoring damaged aquatic ecosystems include constructing substitute habitats in the tributaries of the upper reaches of the Yangtze River, restoring the connection between the Yangtze River and some formerly connected lakes in the middle and lower reaches, and improving the ecological operation of reservoirs. Finally, strategies for regulating the river–lake relationship include improving the four water systems in the north of Dongting Lake and building floodgates at the outlet of Poyang Lake.

Keywords: Yangtze River Economic Belt; water security; aquatic ecosystem restoration; flood control safety; habitat reconstruction; river–lake relationship

1 Introduction

The Yangtze River Economic Belt extends along the main stem of the Yangtze River and its tributaries, covering 11 provinces in China (Yunnan, Sichuan, Chongqing, Guizhou, Hunan, Hubei, Jiangxi, Anhui, Jiangsu, Zhejiang, and Shanghai) and amounting to a total area of 2.052×10^6 km^2. The population and gross domestic product (GDP) of the Yangtze River Economic Belt account for more than 40% of China's total population and GDP, respectively. The region spans across the eastern, middle, and western regions of China; enjoys favorable

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Received date: November 10,2021; **revised date:** January 12,2022

Corresponding author: Hu Chunhong, Professor-level senior engineer of the Chinese Academy of Water Resources and Hydropower Research, member of the Chinese Academy of Engineering. Major research fields include theories and applications of mechanics of sediment transport, river bed evolution, and channel improvement. E-mail: huch@iwhr.com

Funding program: CAE Advisory Project "Research on Several Strategic Issues of Ecological Civilization Construction in the Yangtze River Economic Belt"(2019-ZD-08)

Chinese version: Strategic Study of CAE 2022, 24 (1): 166–175

Cited item: Hu Chunhong et al. Strategies for Water Security and Aquatic Ecosystem Restoration in the Yangtze River Economic Belt. ***Strategic Study of CAE***, https://doi.org/10.15302/J-SSCAE-2022.01.018

conditions in terms of water, soil, sunlight, and temperature; and has a strong economy. Its development based on the Golden Waterway project is the key to the overall development of China.

The Yangtze River plays a key role in the socioeconomic development of the Yangtze River Economic Belt and of China as a whole. Reducing the risk of water disasters and promoting the conservation of water have been constant themes in the management and development of the Yangtze River. Nevertheless, the emerging cumulative effects of long-term and high-intensity development, in combination with a lack of rational ecological protection measures, have contributed to a series of environmental issues hindering the management and development of the Yangtze River. Owing to this, the National Management Authority, the provincial administrations in the Yangtze River Economic Belt, and academic scholars have conducted extensive work on the protection and restoration of the Yangtze River ecosystem since 2016. *The Plan for Ecosystem Protection in the Yangtze River Economic Belt (2017)* outlined key objectives and tasks based on six aspects, including the optimal arrangement of water resources and enforcement of standards for ecological protection. *The Action Plan for the Final Battle of Protection and Restoration of the Yangtze River (2018)* further identified the main tasks needed to achieve ecosystem protection based on eight aspects, including the spatial control of the ecological environment and renovation of sewage outlets. All provinces along the river have implemented ecosystem protection and restoration measures, with a focus on comprehensively administering the aquatic environment, managing river banks and lakes, prohibiting fishing in key basins for ten years, resolving the disorders of rivers and lakes, and rectifying small hydropower stations. Through these, considerable improvements in the water quality of the Yangtze River have been achieved, further ecological deterioration has been contained, and fishery resources have been showing a trend of recovery [1–4].

Although many aspects of the conservation and rehabilitation of the Yangtze River have been successful, several limitations persist. First, although the necessary objectives and related tasks have been determined, the specific countermeasures and strategies remain insufficient. For instance, the *Plan for Ecosystem Protection in the Yangtze River Economic Belt (2017)* clearly states the need for a balanced river–lake relationship, but no specific measures or strategies that would benefit both rivers and lakes or protect and restore the associated wetland ecosystems have been proposed. Second, past studies related to water management focus on the treatment of water, whereas the protection and restoration of aquatic ecosystems have received relatively less attention. Third, flood control of the Yangtze River has not been considered thoroughly enough. The Yangtze River basin, particularly the middle and lower reaches, has experienced the most serious flood disasters in China; such disasters can result in the loss of life and property, as well as severe ecological and environmental damage. Hence, flood control of the Yangtze River is of great significance for the protection of the surrounding ecosystems. However, recent planning and research [5,6] have not paid sufficient attention to flood control in the Yangtze River basin.

The challenges facing the ecological environment of the Yangtze River Economic Belt are complex and show strong regional linkages. This has hindered the sustainable development of the region. The sustainable development of the Yangtze River requires not only assessing the relevance of each measure and strengthening the links between them but also breakthroughs within specific targeted measures [7]. The present study focused on the analysis of issues related to water safety and the aquatic ecological environment of the Yangtze River Economic Belt and proposed specific measures and strategies to address the same. Our results provide a reference for further studies on the conservation of the Yangtze River ecosystem.

2 Need for flood control in the Yangtze River

Flood control is vital for protecting the economic and natural resources of the Yangtze River basin. The Yangtze River Economic Belt covers a large area and is subject to heavy and concentrated precipitation. Floods in the middle and lower reaches of the Yangtze River are characterized by high peaks, large volumes, and long durations, and the low flood-discharge capacities of these reaches have resulted in frequent flood disasters throughout history. The construction of new reservoirs in the upper reaches of the Yangtze River has focused on aiding the regulation of the existing Three Gorges Reservoir, and these reservoirs have reduced the burden of flood control in the middle and lower reaches of the Yangtze River to some extent. However, there are still a series of flood-control related challenges restricting the region’s development.

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2.1 Vulnerability of the middle and lower reaches of the Yangtze River to excess flood volumes

Although the Three Gorges Reservoir and its regulating reservoirs in the upper reaches of the Yangtze River have a large collective storage capacity, it is limited in comparison with the excess flood volumes in these reaches. For example, the excess flood volume of the 1870 flood far exceeded the discharge capacity of the Jingjiang River, despite the flood attenuating benefits of these reservoirs. The Three Gorges Reservoir experienced a significant reduction in its excess flood volume capacity after the 1954 flood, which impacted the middle and lower reaches of the Yangtze River. Therefore, appropriate measures are required to ensure that the water level of the main stem of the Yangtze River does not exceed the critical water level. In 1954, before the construction of the Three Gorges Reservoir, the excess flood volume in the middle and lower reaches of the Yangtze River was 4.92×10^{10} m^3. By contrast, after the construction of the Three Gorges Reservoir, the excess flood volume of the middle and lower reaches of the Yangtze River during the 1954 flood was 3.36×10^{10}–3.98×10^{10} m^3. Previous studies [8,9] have simulated that the joint flood control capacity of the current 21 regulating reservoirs in the upper reaches of the Yangtze River would have led to excess flood volumes of 3×10^{10}–3.45×10^{10} m^3 in the middle and lower reaches of the river during the 1954 flood.

2.2 Difficulties in planned and controlled flood diversion and storage owing to delays in the construction of the flood storage and water retention areas

Flood storage and water retention areas are key components of the flood control system in the middle and lower reaches of the Yangtze River. Reservoirs work to retain flood water, whereas flood storage and water retention areas divert most of the flood water volume. There are plans to construct 40 flood storage and water retention areas in the middle and lower reaches of the Yangtze River with a total capacity of 5.9×10^{10} m^3. Thus far, such construction has been limited for a number of reasons, including difficulty acquiring the required soil and land, low compensation to displaced people, reluctance of residents to relocate, and difficulty in its implementation. To date, flood-diversion sluices have been successfully constructed in four flood storage and water retention areas (namely, Jingjiang Flood Diversion Area, Weidihu Embankment, Linan Embankment, and Xiguan Embankment), while there have been delays in the completion of other key flood storage and water retention areas; this hinders the overall flood diversion effort [10]. After the construction of the Three Gorges Reservoir, the maximum measured inflow peak discharge was 7.5×10^4 m^3/s, with a short duration and low flood volume. The flood storage and water retention areas of the middle and lower reaches of the Yangtze River have not recently been activated, mainly owing to a lack of basin-wide floods, such as those that occurred in 1954 and 1998. The middle and lower reaches of the Yangtze River experienced considerable flooding in July 2020, and the measured maximum water level at the Dongting Lake the Chenglingji Station was 34.73 m, exceeding the critical water level for up to at least 40 h. The flood storage and water retention areas would have been activated with a further rise in the water level; the Poyang Lake Estuary reported a maximum water level of 22.49 m, only 0.01 m lower than the flood diversion and storage control level of the water retention basin.

2.3 Low flood control standards of the Lianjiang Embankment, Huqu Dyke, and riverbank embankments

The flood disasters of the middle and lower reaches of the Yangtze River in 2016, 2017, and 2020 highlighted the high flood risk to the lake area and tributary embankment within the region, whereas the main stem of the Yangtze River experienced a relatively low flood risk. Most polders in the two lake areas of the middle and lower reaches of the Yangtze River were only designed to withstand 1:10 and 1:20-year floods. In addition, the construction standards of the 11 embankments implemented earlier in the Dongting Lake area are low. This indicates a high risk of safety hazards in the embankment body and foundation and the need for comprehensive reinforcement to fully meet the current construction standards. The flood-prevention dykes in the lowlands cover an area of 1×10^4–5×10^4 mu (Chinese area unit, 1 mu ≈ 666.7 m^2) in the Poyang Lake area. Since most of these dykes have not been systematically reinforced, they are highly likely to collapse when water levels exceed a certain height [11]. The riverbank area, thus, plays a key role in flood storage; the deployment of riverbank embankment storage during the major flood of 2020 effectively lowered the water level during the flood peak. To date, 406 riverbank embankments have been constructed along the main stem of the middle and lower reaches of the Yangtze River, accounting for a total area of 2.5 × 10^3 km^2 and protecting a population of ~1 300 000 people. As most riverbank embankments are poorly constructed, they are more vulnerable to collapse during heavy floods, which makes them a safety hazard [12].

2.4 Increase in regional flood risk owing to frequent and extreme precipitation

In recent years, there has been an increase in the frequency of extreme rainfall events across the Yangtze River Economic Belt, which points to the growing impact of climate change and increases regional flood risks. Six extreme rainfall events occurred during the rainy season in 2016 in Wuhan, and the annual rainfall was 814.8 mm in the same year, breaking historical records [13]. In June 2017, rainfall in Hunan Province reached 397.4 mm, the highest since historical records began in 1951. In July 2021, the Zhengzhou meteorological station reported a maximum hourly precipitation of 201.9 mm, which is the highest hourly peak rainfall measurement ever recorded in mainland China.

3 Severe decrease in suitable habitat and aquatic biodiversity

The main stems and tributaries of the Yangtze River run through diverse terrains and landscapes from their sources to the river estuary. The varying climate and water sources of the Yangtze River provide diverse habitat conditions for a range of aquatic organisms, thereby contributing to aquatic biodiversity. Over 400 species (and more sub-species) of fish live in the Yangtze River basin; among them, 156 species are endemic to the basin (i.e., approximately 39% of all fish species in the Yangtze River) [14]. The distribution of endemic fish species is closely related to local habitat conditions, such as the tidal regime, landforms, connectivity of rivers and lakes, physical and chemical characteristics of water, and food web structure. Over the past decades, anthropogenic activities have resulted in serious disturbance and damage to the ecosystem of the Yangtze River basin. The habitats of endemic species are shrinking rapidly and there has been a considerable decrease in the biodiversity of endemic species. This includes the functional extinction of baiji and a considerable decrease in populations of rare fish species, such as Dabry's sturgeon and suckerfish, as well as in endemic mammals such as the black finless porpoise. The challenges faced by biodiversity and the corresponding coping strategies differ in the upper, middle, and lower reaches of the Yangtze River.

3.1 Construction of reservoirs in the upper reaches results in degradation of the ecological environment

The natural environment of the upper reaches of the Yangtze River includes canyon river habitats with alternating beaches and ponds that have varying water flow rates, thereby providing habitats for many rare and endangered endemic fish. The upper reaches host 126 species of endemic fish (e.g., Dabry's sturgeon, suckerfish, and *Hucho bleekeri*), which account for 80% of all endemic fish species in the Yangtze River. The upper reaches of the Yangtze River also contain the most concentrated water energy resources in China. Consequently, dozens of hydropower stations have been constructed on major tributaries, significantly changing the natural habitats of the rivers.

(1) The river changes from a flowing water environment with natural variations to a stagnant environment near the lakes. There was a gradual change in the water level after the construction of the reservoir, resulting in a significant decrease in the river flow rate and an increase in the depth and transparency of the river. The habitats of some fish genera (e.g., *Schizothorax*, *Triplophysa*) have almost completely disappeared [15]. The four cascade hydropower stations (Wudongde, Baihetan, Xiluodu, and Xiangjiaba) in the lower reaches of the Jinsha River have a reservoir length equal to 93.6% of the total length of the developed river reach. There was also a decrease in the flow of the 600 km river section of the Three Gorges Reservoir. (2) There was a decrease in the temporal and spatial variability of the tidal regime of the river owing to the influence of the reservoir, which affected fish spawning. The average annual water level fluctuations (daily flow fluctuation amplitude > 1000 m^3/s) at the Yichang station from1980–1989, 1990–1999, 2000–2009, and 2010–2019 were 103, 92, 87, and 70, respectively. (3) Fish are ectotherms that require specific temperatures for spawning. There was an obvious hysteresis in the temperature rise and drop of the downstream flow after completion of the cascade hydropower projects, resulting in a delay in the fish breeding period. After completion of the Three Gorges Reservoir, the suitable spring-season spawning water temperature (18 °C) for the four important fish species was delayed by one month, and the suitable water temperature (18 °C) for the spawning of the Chinese sturgeon in autumn was delayed by nearly 20 days (Fig. 1). (4) Dams create physical barriers along rivers, which hinder fish migration. Chinese sturgeons are typical migratory fish, and adult sturgeons enter the Yangtze River to

DOI 10.15302/J-SSCAE-2022.01.018

spawn. The spawning grounds of Chinese sturgeons have historically extended up the Yangtze River by as much as 800 km, mainly within the lower reaches of the Jinsha River and the upper reaches of the Yangtze River. The upstream reproduction and migration channels of the Chinese sturgeon were physically blocked after the closure of the Gezhouba Water Conservancy Project in 1981. Although the Chinese sturgeon formed a new spawning ground below the dam, its range was less than 10 km. Therefore, presumably, there has been a gradual decrease in the natural breeding population of Chinese sturgeons, although their natural reproduction has not been monitored since 2017 [16].

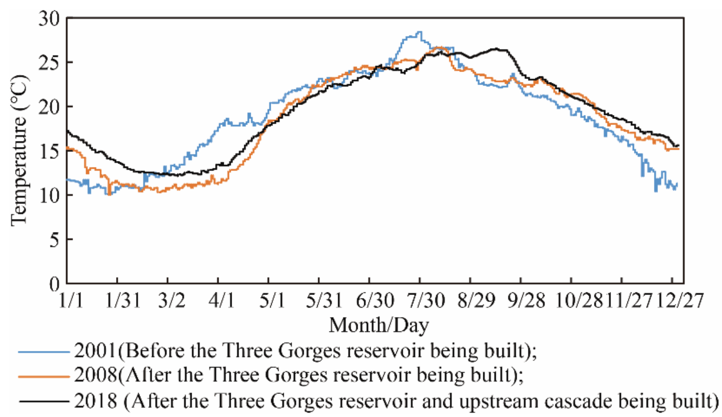

Fig. 1. Measured water temperatures under different working conditions at the Yichang station on the Yangtze River.

3.2 Weakened connectivity of rivers in the middle reaches

The middle reaches of the Yangtze River flow through floodplains formed under the East Asian monsoon climate, which is characterized by abundant naturally connected rivers and lakes, forming a unique river–lake integrated ecosystem. The rapid river flow in this ecosystem provides sites with suitable hydrological conditions for fish spawning. Water flow is slower in river-connected lakes, providing suitable habitats for zooplankton, benthic animals, and aquatic plants. Fish fry also have access to abundant food sources in connected rivers and lakes. This static–dynamic composite ecological environment provides rich endemic biodiversity in the middle and lower reaches of the Yangtze River. In particular, the middle reaches of the Yangtze River provide habitats and reproduction sites for rare aquatic wildlife, such as the black finless porpoise, and economically important fish species.

The middle reaches of the Yangtze River used to contain approximately 100 river-connected lakes. However, since the 1950s, the reclamation of land from lakes and dam construction have resulted in reduced connections between the lakes and rivers. Currently, only Dongting and Poyang lakes are naturally connected to the Yangtze River. The water exchange between rivers and lakes plays a fundamental role in the exchange of organic and inorganic materials. Periodic fluctuations in the water levels of rivers and lakes are of great significance to aquatic environments. The development of the Yangtze River has resulted in barriers to migratory fish channels, thereby reducing the number of areas available for breeding and feeding and resulting in drastic reductions in fish diversity and abundance. The development of the Yangtze River has resulted in a reduction in the number of recorded fish species from 230 to 74.

3.3 Overexploitation of the riverbank line of the lower reaches of the Yangtze River

The riverbank line is an important component of the river–lake ecosystem. Analysis of remote-sensed images [17] indicates that the main stem of the Yangtze River (downstream of Yibin City) has a riverbank line extending for 7909 km. Approximately 36% of the riverbank line of the main stem of the Yangtze River was developed by 2017. However, the extent of the development of the riverbank line varies among the upper, middle, and lower reaches of the Yangtze River, with the highest development located in the downstream area. For example, the extent of riverbank line development is ~50% in Shanghai City and ~60% in Jiangsu Province (>80% in the cities of Changzhou and Suzhou, and ~0% in Wuxi City). The natural beach area of the riverbank has the highest ecological value; its proportion in the main stem of the Yangtze River is less than 20%, and the resources in Jiangsu Province located in the lower reach have almost been exploited. Overexploitation of the natural riverbank line and complete utilization of river beaches have greatly reduced wetland areas, resulting in considerable decreases in biodiversity, habitat density, and biomass, as well as increased vulnerability within the river–lake ecosystem.

4 Abnormal relationships between the Yangtze River and the Dongting and Poyang lakes

The Dongting and Poyang lakes are the only remaining river-connected lakes in the middle and lower reaches of the Yangtze River, respectively (Fig. 2). The main stem of the Yangtze River passes through four estuaries on the south bank of the Jingjiang River (the Songzi, Taiping, Ouchi, and Tiaoxian estuaries), and the diverted flow and sediments then reach Dongting Lake. The barrier on the Yangtze River results in a clear backing up of the outflow from the Dongting and Poyang lakes, which then raises the water level of the main stem of the Yangtze River. The development of the Yangtze River has weakened its relationship with the Dongting and Poyang lakes. The evolution of the river–lake relationship is dependent on the flow and sediment processes of the upper reaches of the Yangtze River, changes in the erosion and deposition of the main stem of the Yangtze River, flow and sediment processes of the two lakes, and siltation and reclamation of lakes. The evolution of the river–lake relationship affects the safety of river embankment, path of the main stem of the Yangtze River, lake wetland ecosystem, and development of water resources [18]. Modification of the river–lake relationship presents a serious and complex challenge for the management of the Yangtze River [19].

Fig. 2. Schematic diagram of the Yangtze River and the two lakes.

4.1 Historical and future evolution of the river–lake relationship

Natural evolution and anthropogenic activities have contributed to the continual evolution of the river–lake relationship. For example, the Yangtze River flooding in 1860 and 1870 damaged the cities of Ouchi and Songzi, respectively. This disaster prompted the diversion of four inlets of the Jingnan River into the lake [18,20]. The river–lake relationship has remained relatively stable since such intense anthropogenic activities, including the cutting off of the Jingjiang River and lake area reclamation in the 1970s and the 1980s (which continued until the Three Gorges Reservoir was completed in 2003). Erosion deposition remained balanced in the main stem of the Yangtze River; although there was a slight decrease in the bypass flow of the Yangtze River into Dongting Lake, there was no noticeable change in the hydrological regime of the two lakes.

Since the completion of the Three Gorges Reservoir in 2003, several regulating reservoirs have been constructed in the upper reaches of the Yangtze River. This has significantly changed the flow and sediment processes of the main stem of the middle and lower reaches of the Yangtze River, resulting in sudden changes in the river–lake relationship. On one hand, the upper reaches of the Yangtze River have experienced a sharp decline in incoming sediment (by 70%). The Three Gorges Reservoir also retains ~76% of all incoming sediment. Consequently, the outflow water is almost clear, indicating a very low sediment concentration. In addition, the

DOI 10.15302/J-SSCAE-2022.01.018

riverbanks of the main stem in the middle and lower reaches of the Yangtze River have been scoured by unsaturated flow [21], and there has been a significant reduction in the low-flow water level. On the other hand, the Three Gorges Reservoir and the regulating reservoirs in the upper reaches retain water in September and October, resulting in a sharp reduction in river flow and a reduction in the effect of flow backing up into the lakes and accelerating the decline in lake water. The Three Gorges Reservoir retained a water height of 175 m during the flood recession of 2008. From late August to late October of 2008–2020, the average water level of the Chenglingji Station in Dongting Lake decreased by 4.7 m, which demonstrates an increase of 1.23 m compared with the level in the same months during 1981–2002. In late October, the average water level at Chenglingji Station decreased by 2.13 m. From late August to late October, 2008–2020, the average water level of the Xingzi Station in Poyang Lake decreased by 4.49 m, an increase of 1.69 m compared with the level in the same months between 1981 and 2002. In late October, the average water level of the Xingzi Station decreased by 2.68 m. Figs. 3 and 4 illustrate the water levels of the two lakes before and after the operation of the Three Gorges Reservoir. The decreasing amplitude of the water-level change in September and October resulted in the two lakes entering the dry season earlier (Dongting Lake entered the dry season after the flood recession on average on October 19 between 2008 and 2018, which is 27 days earlier than that between 1981 and 2002; Poyang Lake entered the dry season after the flood recession on average on November 3, 39 days earlier than that between 1981 and 2002). Frequent droughts with exposed lakebeds have also been recorded in the Dongting and Poyang lakes, revealing a drastic change in the river–lake relationship, as well as the early arrival and further extension of the dry season.

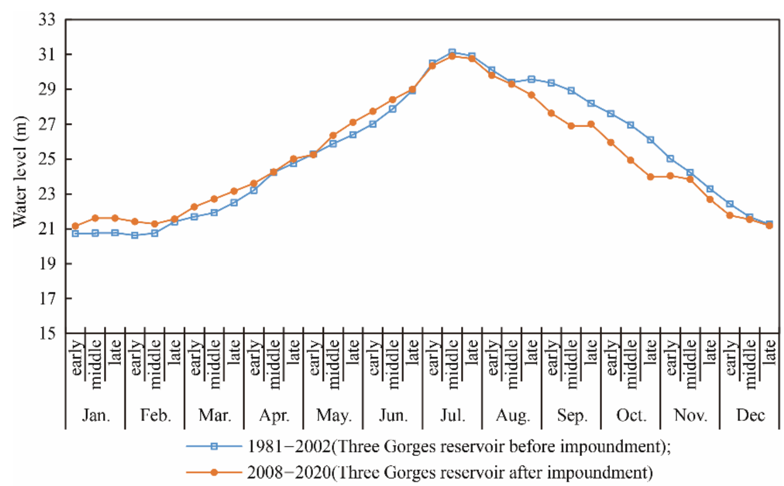

Fig. 3. Water levels of the Dongting Lake Chenglingji Station during different periods.

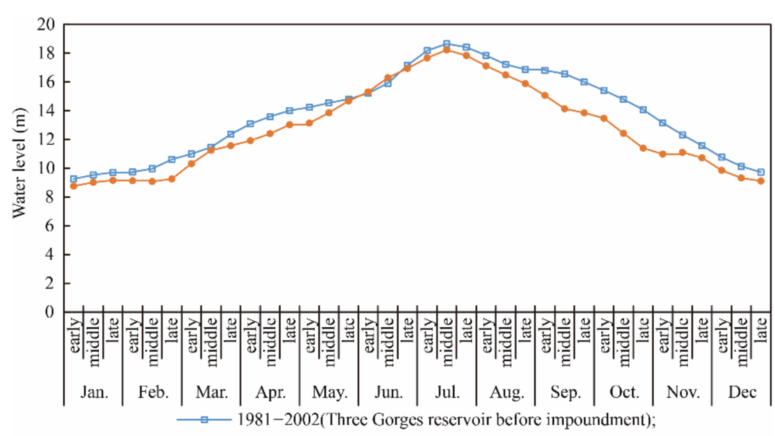

Fig. 4. Water levels of the Poyang Lake Xingzi Station during different periods.

The tributary rivers entering the Jingjiang River on the south bank and Dongting Lake on the north bank have a bypass flow that is closely related to the evolution of the river–lake relationship. The drastic change in the river–lake relationship resulted in a sharp reduction of the water flow from the tributaries of the Yangtze River into Dongting Lake and an extended cut-off period of the three diversion entrances in Southern Jingzhou City. In the current river–lake relationship, the west branch of the Ouchi River only experiences overflow during the flood period (July and August), whereas the cut-off was more dominant during the other periods, with an average annual cut-off of approximately 280 days. The eastern branch of the Ouchi River and western branch of the Songzi River entered the cut-off period during mid and late October, with an average annual cut-off duration of ~180 d. The cut-off of Hudu River began in mid-November, with an average annual cut-off duration of ~130 d.

The construction of key water regulation projects such as the Wudongde, Baihetan, Shuangjiangkou, and Lianghekou reservoirs is currently in progress in the upper reaches of the Yangtze River. The completion of these reservoirs, coupled with the existing regulation reservoirs, will increase flood control capacity. It is estimated that the main stem of the middle and lower reaches of the Yangtze River will continue to scour over the next hundred years, thereby further reducing flow in September and October and continuing to change the river–lake relationship. Additionally, there will be an acceleration in the decline of the water levels of the two lakes in September and October, resulting in an earlier dry season. The decrease in bypass flow from the Yangtze River to Dongting Lake and a longer cut-off time will last longer and become irreversible.

4.2 Effects of change in the river–lake relationship on the two lakes

The interaction between the two lakes and the Yangtze River shapes the seasonal hydrological patterns of the two lakes. The shallow topography of the lake basins contributes to their unique and rich wetland landscapes. The role of lakes in maintaining the ecosystem and biodiversity of the Yangtze River has been recognized globally. The two lakes experience a gradually decreasing water level in September and October, allowing the gradual establishment of grass on the lake bank and maintaining a balance between areas of deeper water, shallow water, mud flats, and lake bank and providing suitable ecological environments for different wintering birds. The rates at which water levels of the lakes decrease in September and October have accelerated since the operation of the Three Gorges Reservoir, with the water surface rapidly shrinking and grass growing earlier. Consequently, some grass areas are already established, mudflats are solidified, and the lake water area has shrunk too much by the time large numbers of wintering birds arrive, thereby seriously affecting their food sources and habitat [22]. The two lakes also provide an important habitat for black finless porpoises, and the decrease in water levels in September and October limits their activity, thereby forcing them to move into deeper lake waterways and exposing them to danger from boats. These two lakes are also important sources of domestic and agricultural water. Low lake water levels in September and October contribute to increased seasonality in agriculture.

The four rivers entering the south bank of the Jiangjiang River flow through the plain areas north of Dongting Lake and act as the main water sources of the area. Interruption of the flow of these four rivers has contributed to increasing seasonal water deficits in the Jingjiang River, affecting four cities and 12 counties in the Hunan and Hubei provinces with a cultivated land area of 5.54×10^6 mu and a population of 4.2 million. Moreover, the ecological base flow of each branch of the four rivers in the southern Jingjiang River cannot be guaranteed. The hydrodynamic conditions of each branch have deteriorated, with most branches becoming “dead water” during the dry period and the self-purification capacity of water bodies decreasing, resulting in worsened water quality in some sections and algal blooms in other reaches [23].

5 Countermeasures

5.1 Accelerating the construction of key flood storage and water retention areas and revising the *Plan for Flood Control of the Yangtze River Basin*

Regulating reservoirs numbering 21 (with a total capacity of 1×10^{11} m^3) have been constructed in the upper reaches of the Yangtze River since 1998, with their capacity expected to reach 1.4×10^{11} m^3 by 2025. The regulating reservoirs reduce the flood control pressure in the middle and lower reaches of the Yangtze River flood

DOI 10.15302/J-SSCAE-2022.01.018

to a certain extent, thereby creating conditions for the adjustment and improvement of the flood control system. The rapid development of the Yangtze River Economic Belt has increased the necessity for flood control.

5.1.1 Accelerating the safety and standards construction of key flood storage and water retention areas

Flood storage and water retention areas play a key role in flood control in the middle and lower reaches of the Yangtze River. However, low compensation for displaced people and the resulting delays in land acquisition have resulted in serious delays in the construction of flood storage and water retention areas. In addition, most of the key flood storage and water retention areas do not meet the necessary requirements. Regulatory departments at the national level must coordinate and place more emphasis on accelerating the construction of key flood storage and water retention areas while maintaining good standards. This is particularly important for areas experiencing high-frequency and large-capacity floods, such as Qianlianghu, Gongshuangcha, Datonghudong, and Kangshan, within the Poyang Lake area.

5.1.2 Revision of the plan for flood control of the Yangtze River Basin

The plan for flood control of the Yangtze River Basin (2008) aimed to address the challenges in flood control that emerged during the heavy floods in 1998. The plan provides guidance for flood disaster reduction and the construction of flood controls in the Yangtze River Basin. The construction of the Three Gorges Reservoir and regulating reservoirs in the upper reaches of the Yangtze River has fundamentally changed the flood control of the Yangtze River. These changes include long-term and extensive scouring of the main stems of the middle and lower reaches of the Yangtze River, thereby affecting the river channel and embankment safety, causing a decline in excess flood volumes of the middle and lower reaches, and increasing the probability of the activation of flood storage and water retention areas. There is a strong need to readjust the layout of flood storage and water retention areas and optimize the water level based on flood control requirements. Recent flood disasters in the middle and lower reaches of the Yangtze River have shown that the Lianjiang embankment and the Huqu dyke play minor roles in flood control. This suggests that there should be comprehensive consideration of new flow and sediment conditions in the middle and lower reaches of the Yangtze River and that the flood control water levels of key areas should be readjusted (such as for Jingjiang River and Dongting Lake). Therefore, it is important to revise and adjust the *Plan for Flood Control of the Yangtze River Basin* to provide accurate guidance for flood control in the middle and lower reaches of the Yangtze River in the future [24].

5.1.3 Flood rearrangement and an increase in the discharge capacity of the Three Gorges Reservoir to no less than 5×10^4 m^3/s

The maximum discharge of the Three Gorges Reservoir has been no less than 4.9×10^4 m^3/s since it began to operate in 2003, with the discharge exceeding 4×10^4 m^3/s on average only 4.5 days per year. There was a significant decrease in medium and small flood processes downstream of the dam, with the probability of flood outflow being almost zero. The rapid growth of weeds and trees along the riverbank has resulted in a decrease in the flood discharge capacity of the lower reaches of the river. Consequently, the designed flood discharge capacity of the Jingjiang River dike is yet to be tested. This suggests that the flood discharging of the Three Gorges Reservoir with a discharge flow no lower than 5×10^4 m^3/s should be implemented every few years to prevent river shrinkage. In addition, the safe discharge of the river should be assessed and potential embankment failure risks should be identified to adequately respond to future floods [25].

5.2 Strengthening reservoir ecological regulation to restore or reconstruct the ecological environment

Maintaining the growth and reproduction of flagship species in the Yangtze River, such as the finless porpoise, requires the maintenance of specific hydrological processes. Although the release of artificially bred individuals can reduce the risk of extinction of some aquatic animals to a certain extent, efforts to maintain the ecology they require remain insufficient. Hence, further efforts are required to restore and reconstruct the natural habitats of the Yangtze River Basin [26].

5.2.1 Strengthening ecological regulation of large- and medium-sized reservoirs in the Yangtze River Basin through basin management agencies

Ecological regulation that aims to promote spawning and reproduction of four major Chinese carp species has been implemented in the Three Gorges Reservoir for ten consecutive years, and these efforts have yielded notable results. For example, fish species in the upper reaches now account for 70–80% of the total endemic fish species in the Yangtze River Basin. However, the upper reaches of the Yangtze River contain concentrated cascade reservoirs. The regulation of reservoir ecologies should be gradually introduced to each major river basin cascade of the upper reaches of the Yangtze River, and the ecological and hydrological processes needed for fish spawning and reproduction should be fostered. This ecological regulation should be incorporated into the scope of operational responsibility of basin management agencies. Further studies on the implementation of joint ecological regulation of the Three Gorges Reservoir and regulating reservoirs in the upper reaches of the Yangtze River should be conducted in the short term. Additionally, different approaches to counteracting the hysteresis effect of the Three Gorges Reservoir should be developed, and the natural reproduction of Chinese sturgeons should be promoted.

5.2.2 Rehabilitating habitats and increasing the connectivity between river and lakes

The ecological protection and restoration of ecological elements, including the connectivity of rivers, natural hydrology, and water temperature, must be conducted in accordance with nature. Although restoration of the upper reaches of the Yangtze River habitat is unlikely to be undertaken in cascade reservoir areas, it can be initiated in tributaries connected to the main stem. It is suggested that tributaries rich in endemic fish species in the upper reaches of the Yangtze River should be prioritized for restoration. Buildings that block tributary river channels should be demolished to increase the natural connectivity of rivers and restore endemic fish habitats. The establishment of the Chishui River Aquatic Ecosystem Conservation Demonstration Area should be prioritized. Important tributaries, such as the Qingyi, Anning, and Shuiluo rivers, should be prioritized for restoration and habitat reconstruction. Lakes of higher and lower ecological and development importance should be selected for restoration of the river–lake connectivity to restore migration channels and promote interactions between rivers and lakes.

5.3 Implementing integrated and rational river–lake management

Major ecological restoration projects should be based on ecosystem integrity. The regulation of water storage in the upper reaches of the Yangtze River by the Three Gorges Reservoir is the main driver of the evolution of the current river–lake relationship. The construction and application of regulatory reservoirs in the upper reaches of the Yangtze River over the next century will likely worsen water and sediment supply to the two lakes. The application of appropriate engineering measures can effectively regulate the river–lake relationship to allow the recovery of the natural hydrological rhythms of the lakes.

5.3.1 Implement rational regulation of the hydrological patterns of the Poyang Lake

Controversy exists over the construction of the sluice at the Poyang Lake estuary, with one opinion being that the extended high water level of the lake will result in the loss of natural hydrological rhythm and affect the gradual emergence of wetland vegetation. A long-term study determined that the construction and regulation of a sluice in the Poyang Lake estuary can effectively counteract the change in the river–lake relationship and will not influence the ecological environment. Overall, construction is a better option than maintaining the status quo, and early construction is always better than late construction. The sluice constructed at the Poyang Lake Estuary should remain open to allow a complete connection between the river and lake from April to August, whereas the sluice should maintain a slow decline in lake water levels from September to November. To some extent, these operations can recover the average natural annual hydrological rhythm of the Yangtze River. The minimum level of the lakes can be increased slightly from December to March. These measures can contribute to establishing a wetland ecological environment layout that provides a suitable habitat for overwintering birds, increase the habitat of aquatic wildlife, and strengthen the ecological function of lakes.

DOI 10.15302/J-SSCAE-2022.01.018

5.3.2 Execute comprehensive improvement of the water system in north Dongting Lake to increase the amount of water diverted into the lake during the dry season

The comprehensive improvement of the northern water system of Dongting Lake is more urgent than the construction of a sluice at the lake estuary, as the former can provide more significant benefits. The comprehensive improvement of the northern water system should focus on the dredging of the three rivers in southern Jingjiang to improve river–lake connectivity and restore the ability of the Yangtze River to divert water into Dongting Lake in the dry season. Relevant measures can significantly improve the water supply security and the water quality of rivers and lakes in the northern part of Dongting Lake. In addition, interactions between fish in the Yangtze River and Dongting Lake could, thus, be increased.

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