



Modified Hydrological Regime on Irrigation and Water Supply in Lake Areas: A Case Study of the Yangtze River–Dongting Lake

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Lake systems are of fundamental significance for the ecological environment and social development. Driven by climatic changes and human activities, the hydrological situation of rivers and lakes has been altered considerably, and it has directly affected the reliability of irrigation and water supply in lake areas. In the case of the Yangtze River–Dongting Lake area, the quasi-equilibrium of their hydrological states and water balance have been affected by the operation of the Three Gorges Project that has led to irrigation and water supply problems across the lake area. Ever since, the available water supply in the Dongting Lake area has decreased by 31.5% and 47.7% during the months of September and October, and the overall water level in the lake area has dropped by 0.8–2.0 m. The proportion of domestic and agricultural irrigation water demands to available water supply in the Dongting Lake area is very small, and the decline of water level is the main reason for the lack of water supply in Dongting Lake area. Although the total amount of water in the lake area is still above the water supply threshold, an obvious decreasing trend has been observed in the fulfillment of the demand for both irrigation and water supply in urban and rural regions. Additionally, the fulfillment of secured water supply and irrigation requirements has respectively dropped from 95% to 78% before the operation of the Three Gorges Project to 82% and 46% after it. Meanwhile, the total water shortage increased from 57.683 to 143.607 million cubic meters. By advancing or postponing impoundment schedules, the impact of the Three Gorges Reservoir on irrigation and water supply in the lake area during September and October can be alleviated, and the water supply capacity can be respectively increased by approximately 1.3% and 1.4%. The highlights of this study include the quantification of the impacts of the operation of large-scale water conservancy projects at the level at which the requirements on irrigation and water supply in the lake area are satisfied, and the prediction of the trends for future evolution. In addition, corresponding strategies that provide a technical reference for the comprehensive regulation and control over water resources and the security of water supply in the river basin are discussed.

Keywords: hydrological regime evolution, irrigation and water supply safety, three Gorges project, Dongting Lake, impact of impoundment plans

1 INTRODUCTION

Lakes are not only important ecosystems that influence the local climate and ecological balance but also valuable economic resources for the development of human society (Du et al., 2011; Lai et al., 2021; Zhu et al., 2021). In recent decades, the hydrological regimes of many lakes around the world have been modified because of climatic changes and human activities, which have exerted a direct impact on both the regional ecological environment and the sustainable development of the economy and society (Du et al., 2011; Feng et al., 2021; Yuan et al., 2021). Since the beginning of this century, human activities have become the leading factor in the evolution and adjustment of the hydrological situations of rivers and lakes (Yuan et al., 2015; Lai et al., 2021; Lei et al., 2021; Yuan et al., 2021). In the case of the Yangtze River Basin, considerable attention has been given to the impact of the Three Gorges Project on the hydrological regimes (Lai et al., 2016; Guo et al., 2021), sediment transport (Yang et al., 2014; Huang et al., 2019), river erosion and deposition (Dai and Liu, 2013; Tang et al., 2021), shipping (Fan et al., 2015; Xue et al., 2021), and other fields (Xu et al., 2013; Han et al., 2022). Meanwhile, studies on the river–lake relationship, featured by both the Dongting and Poyang Lakes, respectively situated in the middle and lower reaches of the Yangtze River, have become the focus in water security and water resources (Lai et al., 2014; Wang et al., 2014; Yuan et al., 2015; Feng et al., 2017; Gao et al., 2020; Lai et al., 2021).

Dongting Lake is the second largest freshwater lake in China and is interconnected with the Yangtze River. It is not only a natural reservoir of the Yangtze River but also an important wetland in the world. The lake area has a warm and humid climate with four distinct seasons and superior hydrothermal conditions. In addition, it is considered a giant and vital agricultural production base in China; agricultural irrigation activities have been affected remarkably by water levels in the lake area as the irrigation water comes from either the inner lakes or Dongting Lake (Wang et al., 2021). Owing to the particularity of its geographical location and inflow water conditions, the water levels of Dongting Lake have been dependent not only on climatic factors and other natural conditions, but also on the incoming water from the Yangtze River and the four tributaries (Xu and Milliman, 2009; Tang et al., 2010). In recent years, the river–lake relationship between the Yangtze River and Dongting Lake has experienced the effects of natural evolution and influences from human activities, such as the blocking of the Tiaoxiankou, the natural and artificial bending of the lower Jingjiang River, the closure of Gezhouba Dam, and the impoundment of the Three Gorges Reservoir. Consequently, great changes have taken place in the hydraulic relationship between rivers and lakes and the hydrological regime of lakes, and the water level has also been greatly affected (Gao et al., 2013; Wang et al., 2013; Yuan et al., 2015; Zhou et al., 2017; Li et al., 2020). Among them, the impact of the operation of the Three Gorges Reservoir is the focus of ongoing research. Many researchers have analyzed the impact of the operation of the Three Gorges on Dongting Lake from different perspectives, including the landscape pattern (Wu et al., 2017), ecosystem response (Gao et al., 2020), changes in

sediment transportation (Chen et al., 2010), water quality (Geng et al., 2021a; Geng et al., 2021b), hydrological regime (Dai et al., 2017), flood processes (Lai and Wang, 2017), and change of lake area (Wang et al., 2014). According to Zhong and Yu (2015) reported that after 50 years of operation of the Three Gorges Reservoir, flow diversion at the three channels would decrease, the cut-off time during the rainless seasons would be further prolonged, and the low-flow situation in the lake area would thus get worsened. All these changes would result in difficulties in irrigation and degraded water supply reliability, which would affect the safety of water supply and irrigation in the lake area. As a result, engineering and non-engineering measures are needed to alleviate the adverse effects of changes in the river–lake relationship (Zhong and Yu, 2015). However, the impact of the modified flow regimes induced by the Three Gorges Project on the irrigation and water supply safety, which influences the water utilization in the lake area, has not yet been quantitatively assessed.

Taking Dongting Lake on the Yangtze River as a case study, this study investigated the characteristics of the changes in water resources and water level in the lake area, before and after the operation of the Three Gorges Project. Based on the relationship between the demand and water supply with the irrigation and urban and rural uses in the lake area, the impact of the Three Gorges Project on the hydrological regimes and water safety of irrigation and water supply were analyzed quantitatively. Results from this study provided a reference to the implementation of comprehensive control of water resources and the safety guarantee of the irrigation and water supply in the Dongting Lake area.

2 RESEARCH REGION AND METHODOLOGIES

2.1 Research Region

Dongting Lake is located from 111°14'E to 113°10'E, and from 28°30'N to 30°23'N, that is, in the south reach of Jingjiang River and the north of the Hunan Province. The topography of Dongting Lake is higher in the west and lower in the east, and it can be divided into the eastern, southern, and western Dongting Lakes, thus forming a sloping water surface from the west to the east. The river network of Dongting Lake is mainly composed of four tributaries, namely, Xiang, Zishui, Yuanjiang, and Lishui rivers, together with three channels from the Jingjiang River, namely, Songzi, Taiping, and Ouchi rivers. In addition, it has several other tributaries, such as the Miluo and Xinqiang Rivers. The water in the lake flows into the Yangtze River at Chenglingji, with an average annual water inflow of approximately 254 billion cubic meters.

This study focused on the Dongting Lake area, which refers to the vast plain and lake regions located in the south reach of Jingjiang River below the tail control stations of the four tributaries (Xiang, Zishui, Yuanjiang, and Lishui rivers) with a maximum elevation of 50 m across the Hunan and Hubei provinces. The total lake area is 20,109 km², out of which the natural lakes account for approximately 2,625 km². The river networks and hydrological stations in the lake area are shown in **Figure 1**.

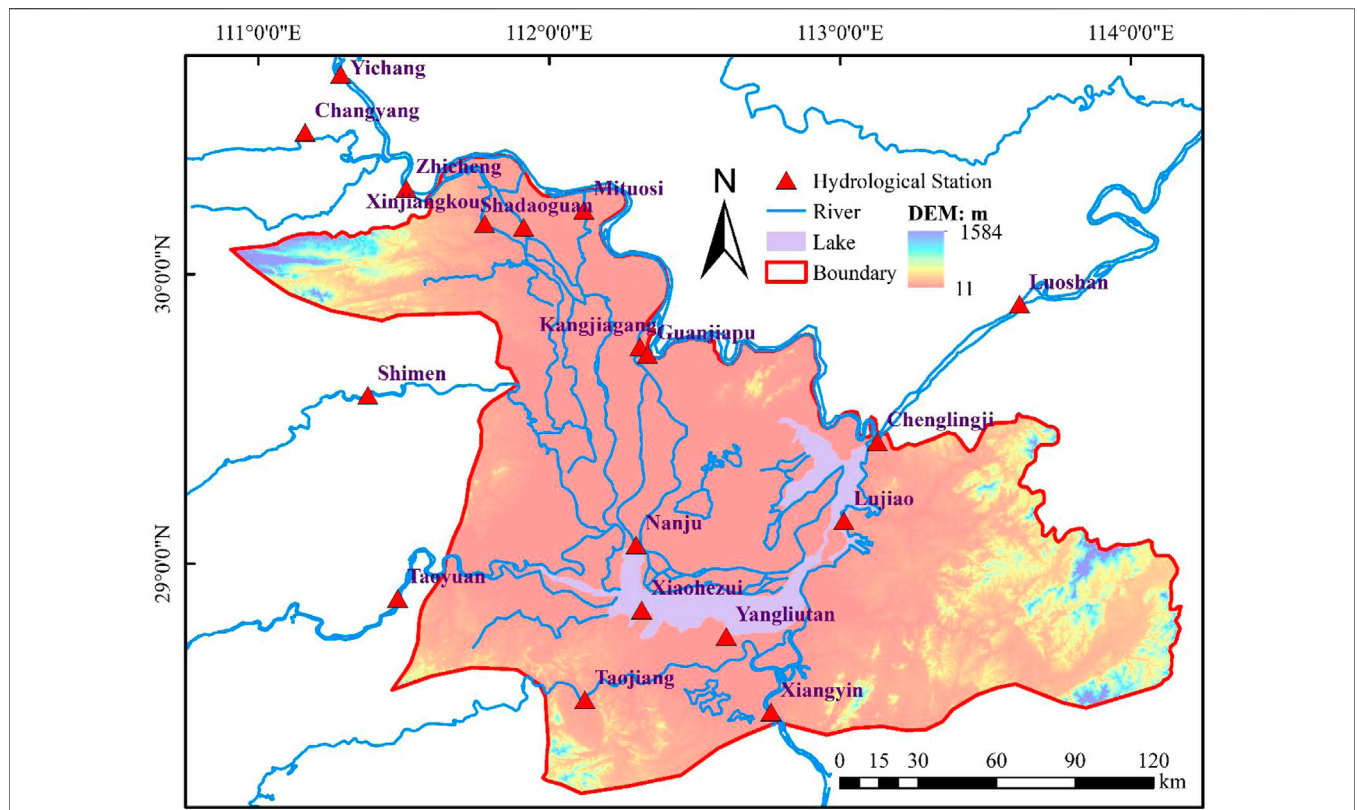


FIGURE 1 | River networks and hydrological stations in the Dongting Lake area.

TABLE 1 | Hydrological data.

Category	Rivers/Regions	Hydrological stations	Data type	Period
Representative stations of Dongting Lake	Dongting Lake	Lujiao, Xiaohezui, Yangliutan	Water level	1960–2019
	Outflow	Chenglingji	Water level and runoff	1960–2019
Inflow from the four tributaries	Xiang river	Xiangyin	Runoff	1960–2019
	Zishui river	Taojiang	Runoff	1960–2019
	Yuanshui river	Taoyuan	Runoff	1960–2019
	Lishui river	Shimen	Runoff	1960–2019
Inflow from the three channels	Songzi river	Xinjiangkou, Shadaoguan	Runoff	1960–2019
	Hudu river	Mituosi	Runoff	1960–2019
	Ouchi river	Kangjiagang, Guanjiapu	Runoff	1960–2019

2.2 Experimental Data

All the hydrological data used in the study consist of information regarding water level, as well as inflow and outflow volumes of the Dongting Lake from 1960 to 2019. These data were acquired on a daily basis from the hydrological stations managed by the Hydrology Bureau of the Changjiang River Water Resources Commission. **Table 1** lists the type of hydrological data of some representative stations. The Lujiao, Xiaohezui, Yangliutan and Chenglingji stations were used to measure the water levels in Dongting Lake area, and Chenglingji was also used for obtaining outflow observations. Data for the inflow volume were collected from the Xiangyin, Taojiang, Taoyuan, and Shimen stations that represent the four tributaries—Xiang,

Zishui, Yuanjiang, and Lishui rivers, respectively. Discharge data for the three channels were collected from the Xinjiangkou and Shadaoguan stations of the Songzi River, Mituosi station of the Hudu River, and Kangjiagang and Guanjiapu stations of the Ouchi River.

The water intake data used in the study include the data of water plants and polders in the lake area. There is one water plant and 26 polders in the lake area, each with several distributed water intake outlets. According to the location of irrigation water intake in the Dongting Lake area, irrigated farmland can be divided into four subregions: western, southern, south of eastern, and north of eastern Dongting Lake. The data of water plants and polders are summarized in **Table 2**.

TABLE 2 | Water intake data.

Category	Subregion/Location	Elevation of water intake (m)	Other info
Water plants	Yuanjiang city	27.66	One water plant whose water supply capacity is 12 million cubic meters
Polder	Western Dongting Lake	27.5–29.6	Four polders
	Southern Dongting Lake	26.5–30.0	Ten polders
	South of eastern Dongting Lake	19.5–27.3	Seven polders
	North of eastern Dongting Lake	21.0–25.5	Five polders

TABLE 3 | Establishment of three impoundment plans for the Three Gorges Reservoir.

Plan	Start time:water level	Control time:water level	Full storage time
1	8.20:146.5 m	8.31:150 m; 9.30:165 m	10.31
2	8.10:146.5 m	8.20:150 m; 8.31:155 m; 9.30:167 m	10.31
3	8.20:146.5 m	8.31:150 m; 9.30:163 m; 10.31:170 m	11.30

2.3 Methodologies

In this study, the moment at which the Three Gorges Reservoir came into operation was utilized to divide the observation period into two phases: the phase before its operation (1960–2002) and that after its operation (2003–2019). Changes in water volume and the balance of supply and demand for water resources were then analyzed. Variations in the water level, as well as the impact on both irrigation and water supply for urban and rural uses were then scrutinized based on the irrigation and water supply safety index of the lake area. Finally, different impoundment plans of the Three Gorges Reservoir in terms of the safety of water supply were compared.

2.3.1 Analysis of Water Volume Changes and Water Resources Supply and Demand Balance

When analyzing the changes in volume, variation in the water storage capacity of the Dongting Lake in different periods can be calculated from the following water balance equation,

$$V_s = V_{in} - V_{out} \tag{1}$$

where V_{in} and V_{out} are the inflow and outflow runoff volumes of the Dongting Lake, respectively. Given that the Dongting Lake flows into the Yangtze River at Chenglingji, the runoff volume at Chenglingji station was therefore regarded as the outflow volume V_{out} . The total inflow volume is calculated from the three channels of Jingjiang River and the four tributaries as follows,

$$\begin{aligned} V_{in} &= V_{TC} + V_{FT} \\ V_{FT} &= V_{XY} + V_{TJ} + V_{TY} + V_{SM} \\ V_{TC} &= V_{XJK} + V_{SDG} + V_{MTS} + V_{KJG} + V_{GJP} \end{aligned} \tag{2}$$

where V_{FT} and V_{TC} are the inflow volumes from the four tributaries and the three channels into the lake, respectively. V_{XY} , V_{TJ} , V_{TY} , and V_{SM} denote the volumes from the Xiangyin station of Xiang River, Taojiang station of Zishui River, Taoyuan station of Yuanshui River, and Shimen station of Lishui River, respectively. V_{XJK} , V_{SDG} , V_{MTS} , V_{KJG} , and V_{GJP} represent the volumes of Xinjiangkou and Shadaoguan stations of Songzi River,

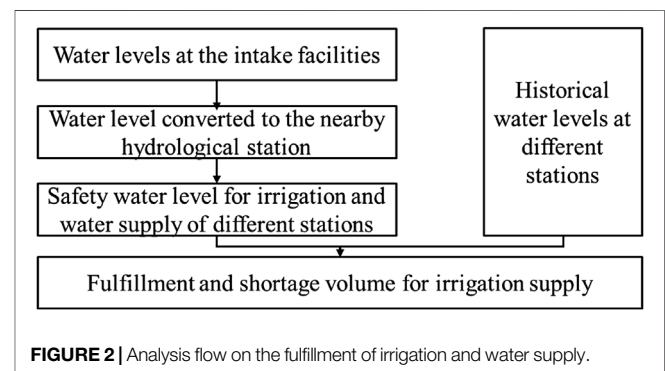


FIGURE 2 | Analysis flow on the fulfillment of irrigation and water supply.

Mituosi station of Hudu River, and Kangjiagang and Guanjiapu stations of Ouchi River, respectively. The variation in the water storage capacity described here represents the difference between the inflows from the three channels and four tributaries and the outflows from Chenglingji and not the real variation in water storage capability.

In the analysis of the balance of supply and demand for water resources, the volumes of Dongting Lake in different months were calculated according to the volume curve of the natural Dongting Lake and the water level of Dongting Lake, and regarded as the available water supply volumes. The monthly water demand was determined based on results from research and surveys. Consequently, the available water supply and water demand in the Dongting Lake area were compared and analyzed.

2.3.2 Analysis of the Satisfaction of Irrigation and Water Supply

The flow diagram used to analyze irrigation and water supply satisfaction is shown in **Figure 2**. First, based on data collection and onsite investigations, water level data at representative intake facilities for both urban and rural water supply and agricultural irrigation around Hunan Province and Hubei Province were acquired. Subsequently, the intake water level

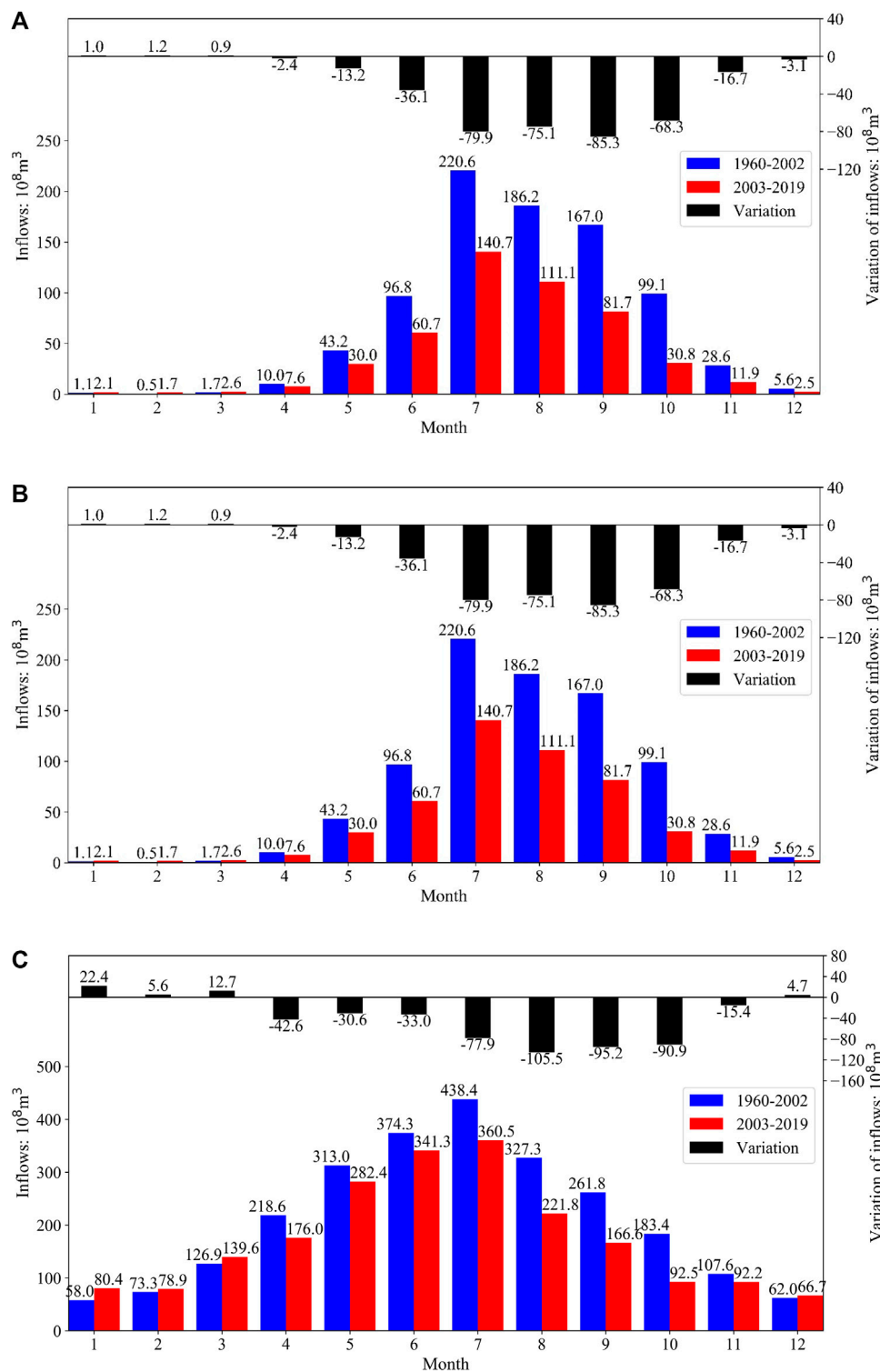


FIGURE 3 | Inflow volumes and variations of Dongting Lake at different time periods (A) Inflow from three channels; (B) Inflow from four tributaries; (C) Total inflow.doc.

was converted to the water level of nearby hydrological stations to examine the security of water supply of each station. Finally, the fulfillment and shortage volume of irrigation and water

supply were calculated by comparing the safety water level and recorded water levels during the period of 1960–2002 and 2003–2019.

TABLE 4 | Inflow and outflow of Dongting Lake and the corresponding water storage change.

Period	Three channels		Four tributaries		Total inflow		Outflow		Water storage change	
	September–October	Yearly	September–October	Yearly	September–October	Yearly	September–October	Yearly	September–October	Yearly
	1960–2002	266.0	860.2	179.1	1684.4	445.2	2544.7	540.4	2848.0	-95.3
2003–2019	112.5	483.3	146.6	1615.5	259.1	2098.8	339.6	2427.9	-80.5	-329.1
Difference	-153.6	-376.9	-32.5	-69.0	-186.1	-445.9	-200.9	-421.0	14.8	-25.8
Change (%)	-57.7	-43.8	-18.2	-4.1	-41.8	-17.5	-37.2	-14.7	-15.5	8.5

The method used to convert the intake water level to the water level at the hydrological station is as follows. According to the water surface slope of the lake area for a low-water flow <85% in each subregion, combined with the distance between the water intake and the adjacent control section, the conversion was achieved using the following equation,

$$H_r = H_0 + L * S \tag{3}$$

where H_0 is the lowest water intake elevation, S is the water surface slope for a low-water flow in the area <85%, L is the distance between the water intake and the representative station, which is negative in the upstream of the station and positive in the downstream of station, and H_r is the lowest intake water level near the control representative station, that is, when the water level of the station reaches the elevation of H_r , water can be drawn.

After the conversion of all the requirements based on the lowest intake of water level to those of the adjacent control representative station, we took the outer envelope of the required lowest intake water level for each station (that is, the maximum value) as the safety water level for irrigation and urban and rural water supplies of the station. Considering the different objects and properties of water supply, a set of water level safety indices for urban and rural water supply and agricultural irrigation were proposed.

After the determination of the safety water level of different hydrological stations, the water level satisfaction period of urban and rural water supplies and agricultural irrigation were calculated based on the recorded water levels for the pre- and post-operation of the Three Gorges Reservoirs. The fulfillment of water levels as well as the water shortage (cases in which the water level does not meet the requirements) were also calculated.

2.3.3 Impact of Different Impoundment Plans on the Three Gorges Reservoir

According to the instructions on the impoundment of the Three Gorges Reservoir specified in the approval on the “Cascade Regulation of the Three Gorges (normal operation period)-Gezhouba Dam Water Control Project (revised in 2019)” by the Ministry of Water Resources, different water storage plans were prepared to emulate the change process of water level at the Chenglingji station from August to November, and their impacts on water supply security were analyzed. The control times and corresponding water levels of the three impoundment plans are shown in Table 3.

3 ANALYSIS ON VOLUME CHANGES AND WATER SUPPLY AND DEMAND IN THE DONGTING LAKE AREA

3.1 Volume Changes in the Dongting Lake Area

3.1.1 Inflow Runoff Volume of the Dongting Lake

3.1.1.1 Inflow Runoff Volume of the Three Channels of Jingjiang River

For the three channels of the Jingjiang River, the inflow runoff volumes and the variations during different periods are shown in

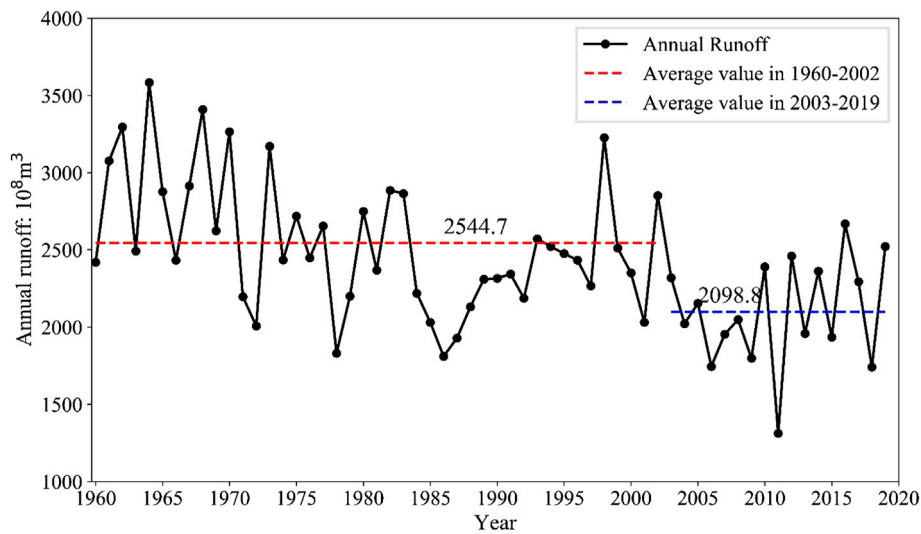


FIGURE 4 | Variations of annual inflow of Dongting Lake.

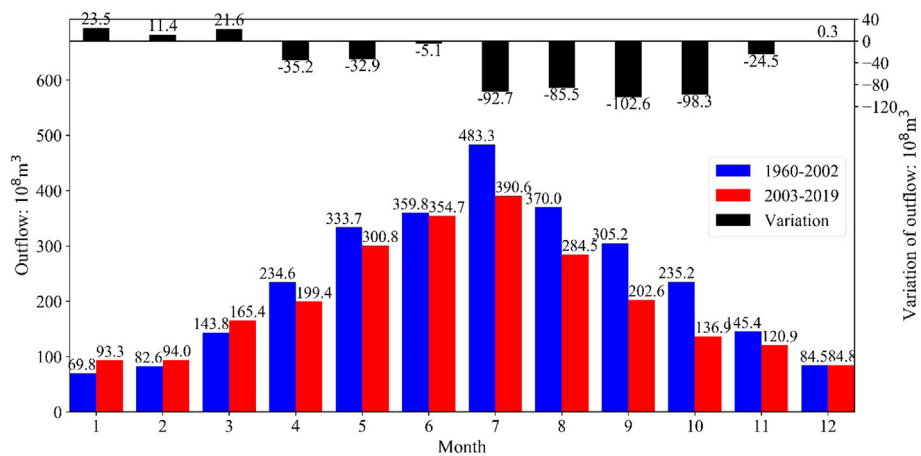


FIGURE 5 | Outflow volumes and variations of Dongting Lake at different time periods.

Figure 3A and **Table 4**. The average annual inflow runoffs to Dongting Lake from 1960 to 2002 and from 2003 to 2019 were $860.2 \times 10^8 \text{ m}^3$ and $483.3 \times 10^8 \text{ m}^3$, respectively. The decrease was $376.9 \times 10^8 \text{ m}^3$ (43.8%). In terms of runoff distribution across the year, the inflow runoff was only found to be increased from January to March, but it decreased in other months (especially in September and October), and the loss reached $153.6 \times 10^8 \text{ m}^3$ and accounted for 57.7%.

3.1.1.2 Inflow Runoff Volume of the Four Tributaries

For the four tributaries, the inflow runoff volumes and the variations in different periods are shown in **Figure 3B** and **Table 4**. The average annual inflow runoffs to Dongting Lake from 1960 to 2002 and from 2003 to 2019 were $1,684.4 \times 10^8 \text{ m}^3$ and $1,615.5 \times 10^8 \text{ m}^3$, respectively. The decrease was $69.0 \times 10^8 \text{ m}^3$ (4.1%). In terms of runoff distribution during the

year, the months of April, August, and October were associated with larger decreases, which were equal to $40.3 \times 10^8 \text{ m}^3$ (19.3%), $30.3 \times 10^8 \text{ m}^3$ (21.5%), and $22.7 \times 10^8 \text{ m}^3$ (26.9%), respectively.

3.1.1.3 Total Inflow Runoff Volume

The total inflow runoff volume and the variations of the three channels and the four tributaries in different periods of time are shown in **Figure 3C** and **Table 4**, and the total inflow runoff volumes in different years are shown in **Figure 4**. The average annual inflow runoffs of the Dongting Lake from 1960 to 2002 and from 2003 to 2019 were $2,544.7 \times 10^8 \text{ m}^3$ and $2,098.8 \times 10^8 \text{ m}^3$, respectively, which correspond to a decrease of $445.9 \times 10^8 \text{ m}^3$ (17.5%). Specifically, the runoffs from September to October decreased by $186.1 \times 10^8 \text{ m}^3$ (or equivalently by 41.8%). In terms of inflow runoff distribution, the inflow

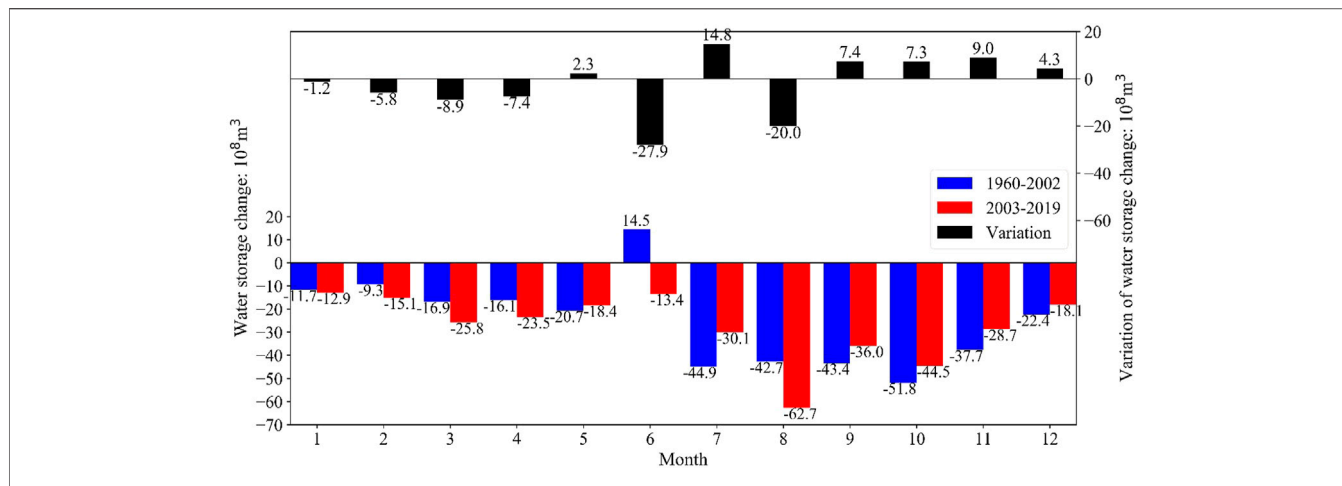


FIGURE 6 | Water storage changes of the Dongting Lake and variations at different periods of time.

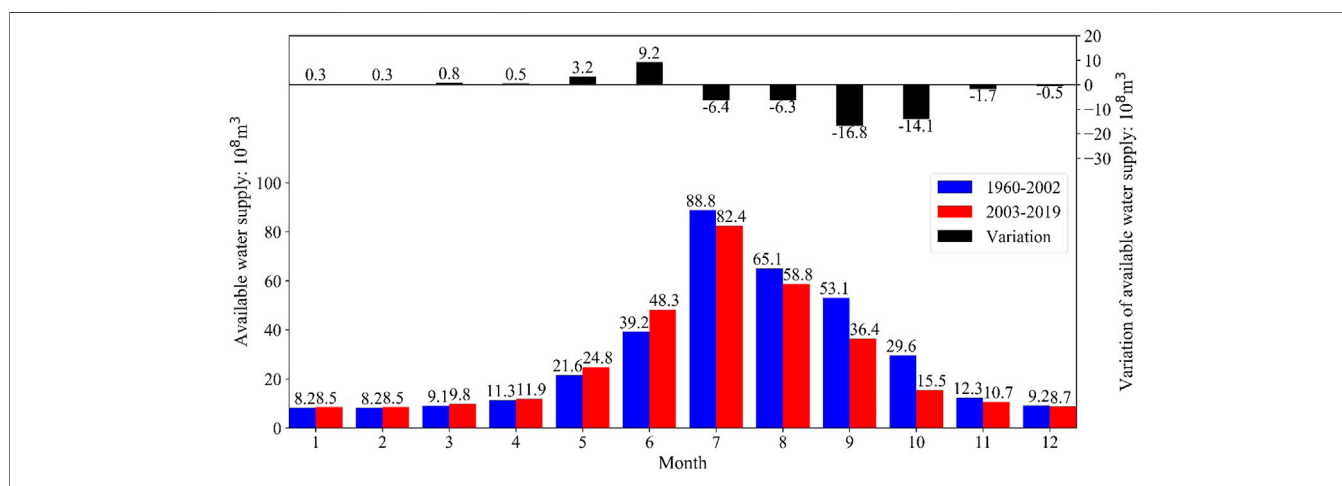


FIGURE 7 | Multiyear average available water supply and monthly variations before and after the operation of the Three Gorges Reservoir.

runoff from December to March of the following year increased by 7.6%–38.5% (the absolute volume values were in the range of $4.7 \times 10^8 \text{ m}^3$ – $22.3 \times 10^8 \text{ m}^3$), while from April to November, the inflow runoff decreased by 8.8%–49.6% (the absolute volume values were in the range of $15.4 \times 10^8 \text{ m}^3$ – $105.5 \times 10^8 \text{ m}^3$). Based on comparisons of the inflow runoff data against time, the decrease in volume mainly took place from September to October. The reason can be attributed to the significant decrease of inflow runoff from the three channels of Jingjiang River after the operation of the Three Gorges Project, which accounts for about 82.5% and 84.5% of the total reduction in inflow from September to October and during the whole year, respectively.

3.1.2 Outflow Volume of the Dongting Lake

The outflow volumes and the variations are shown in Figure 5 and Table 4. From 1960 to 2002, and from 2003 to 2019, the average annual outflow runoffs were $2848.0 \times 10^8 \text{ m}^3$ and 2427.9

$\times 10^8 \text{ m}^3$, respectively. Their difference was $420.1 \times 10^8 \text{ m}^3$ (or equivalently, 14.7%). Specifically, the most notable decrease was also observed during the months of September and October, which was $200.9 \times 10^8 \text{ m}^3$, with a decrease rate of 37.2%. In terms of the outflow runoff distribution across the year, from December to March of the following year, the runoff volume increased by 0.4%–33.7% (the absolute volume values were $0.3 \times 10^8 \text{ m}^3$ – $23.5 \times 10^8 \text{ m}^3$), while from April to November, the outflow runoff decreased by 1.4%–41.8% (the absolute volume values were $5.2 \times 10^8 \text{ m}^3$ – $102.5 \times 10^8 \text{ m}^3$).

3.1.3 Water Balance in the Dongting Lake Area

From the inflow runoff data of the three channels of Jingjiang River and the four tributaries as well as the outflow runoff data organized in the previous sections, water storage change, and the variations of Dongting Lake in different periods of time are presented in Figure 6 and Table 4. For the two observation periods, 1960–2002 and 2003–2019, the average annual water

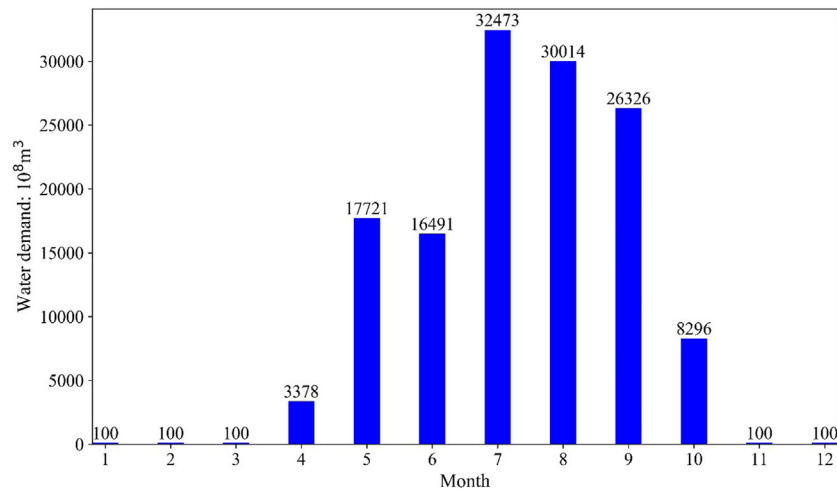


FIGURE 8 | Monthly demand for domestic and irrigation water in the Dongting Lake area.

storage changes were $303.3 \times 10^8 \text{ m}^3$ and $-329.1 \times 10^8 \text{ m}^3$, respectively. The decrease in volume was $25.8 \times 10^8 \text{ m}^3$, out of which the largest loss was $14.8 \times 10^8 \text{ m}^3$ during the months of September and October. In terms of the distribution across the year, the decreased volume for January to April, June, and August ranged between $1.2 \times 10^8 \text{ m}^3$ and $27.9 \times 10^8 \text{ m}^3$, while for the rest of the year, that is, for May, July, and September to December, the water storage increased. Increases were in the range of $2.3 \times 10^8 \text{ m}^3$ – $14.8 \times 10^8 \text{ m}^3$.

3.2 Analysis of Water Supply and Demand in the Dongting Lake Area

3.2.1 Available Water Supply in the Lake Area

The change processes of the Dongting Lake of the multiyear average available water volume among different months before and after the operation of the Three Gorges Project are demonstrated in **Figure 7**. From 1960 to 2002, and from 2003 to 2019, the available water supply among different months in the Dongting Lake area were in the range of $8.2 \times 10^8 \text{ m}^3$ – $88.8 \times 10^8 \text{ m}^3$ and $8.5 \times 10^8 \text{ m}^3$ – $82.4 \times 10^8 \text{ m}^3$, respectively. For the months from January to June, the numbers changed from $8.2 \times 10^8 \text{ m}^3$ – $39.2 \times 10^8 \text{ m}^3$ to $8.5 \times 10^8 \text{ m}^3$ – $48.3 \times 10^8 \text{ m}^3$ in the two observations phases, which implied increases of $0.3 \times 10^8 \text{ m}^3$ – $9.2 \times 10^8 \text{ m}^3$ in volume (equivalently the percentage change was in the range of 3.3%–23.4%). For the second half of the year, from July to December, the average supply as a function of month changed from $9.2 \times 10^8 \text{ m}^3$ – $88.8 \times 10^8 \text{ m}^3$ to $8.7 \times 10^8 \text{ m}^3$ – $82.4 \times 10^8 \text{ m}^3$ in the two observations phases, respectively, which implied decreases of $0.5 \times 10^8 \text{ m}^3$ – $16.8 \times 10^8 \text{ m}^3$ in volume (equivalently the percentage change was in the range of 5.3%–47.7%). Specifically, the largest losses were found for the months of September and October, the water level decreased from $53.1 \times 10^8 \text{ m}^3$ and $29.6 \times 10^8 \text{ m}^3$ to $36.4 \times 10^8 \text{ m}^3$ and $15.5 \times 10^8 \text{ m}^3$, respectively (or equivalently by 31.5% and 47.7%, respectively).

3.2.2 Water Demand in the Dongting Lake Area

Water demand in the Dongting Lake area is classified into domestic and agricultural irrigation water demands. Based on onsite investigations in conjunction with the verification results of water intake facilities in the Yangtze River Basin in 2019, the single water plant that drew off water from the Dongting Lake had an annual water intake capacity of 12 million cubic meters, which was distributed evenly across the 12 months. The water demand for agricultural irrigation purposes was mainly during the months from May to October, as well as during the spring irrigation (that is, from April to May). According to the present situation of irrigation in the lake area and the quota method, the monthly requirement on water for irrigational purposes can be determined. Combining domestic water demand and irrigation water demand, the total demand in the Dongting Lake area was 1.35 billion cubic meters. Accordingly, the monthly water demand process is shown in **Figure 8**. It can be indicated that the requirements on water for domestic uses and irrigations in the Dongting Lake area mainly concentrated from April to October, and the monthly demand ranged from $3,378 \times 10^4 \text{ m}^3$ to $32,473 \times 10^4 \text{ m}^3$. During this period, the month with the highest demands above $2.5 \times 10^8 \text{ m}^3$ were July (ranked first at $32,473 \times 10^4 \text{ m}^3$), followed by August ($30,014 \times 10^4 \text{ m}^3$), and September ($26,326 \times 10^4 \text{ m}^3$).

3.2.3 Analysis of Supply and Demand Balance of Water Resources in the Dongting Lake Area

When the total water demand and the available water volume of the lake area were compared (**Figures 7, 8**), the proportion of domestic and irrigation water demand of the Dongting Lake against the water volume was quite small. This implied that the water supply could meet the demand, and no water shortage should exist with respect to volume of available water. However, when projecting the trend of changes in water volume in the lake area, a decreasing tendency was prevalent from July to December. Specifically, during the months with high demand

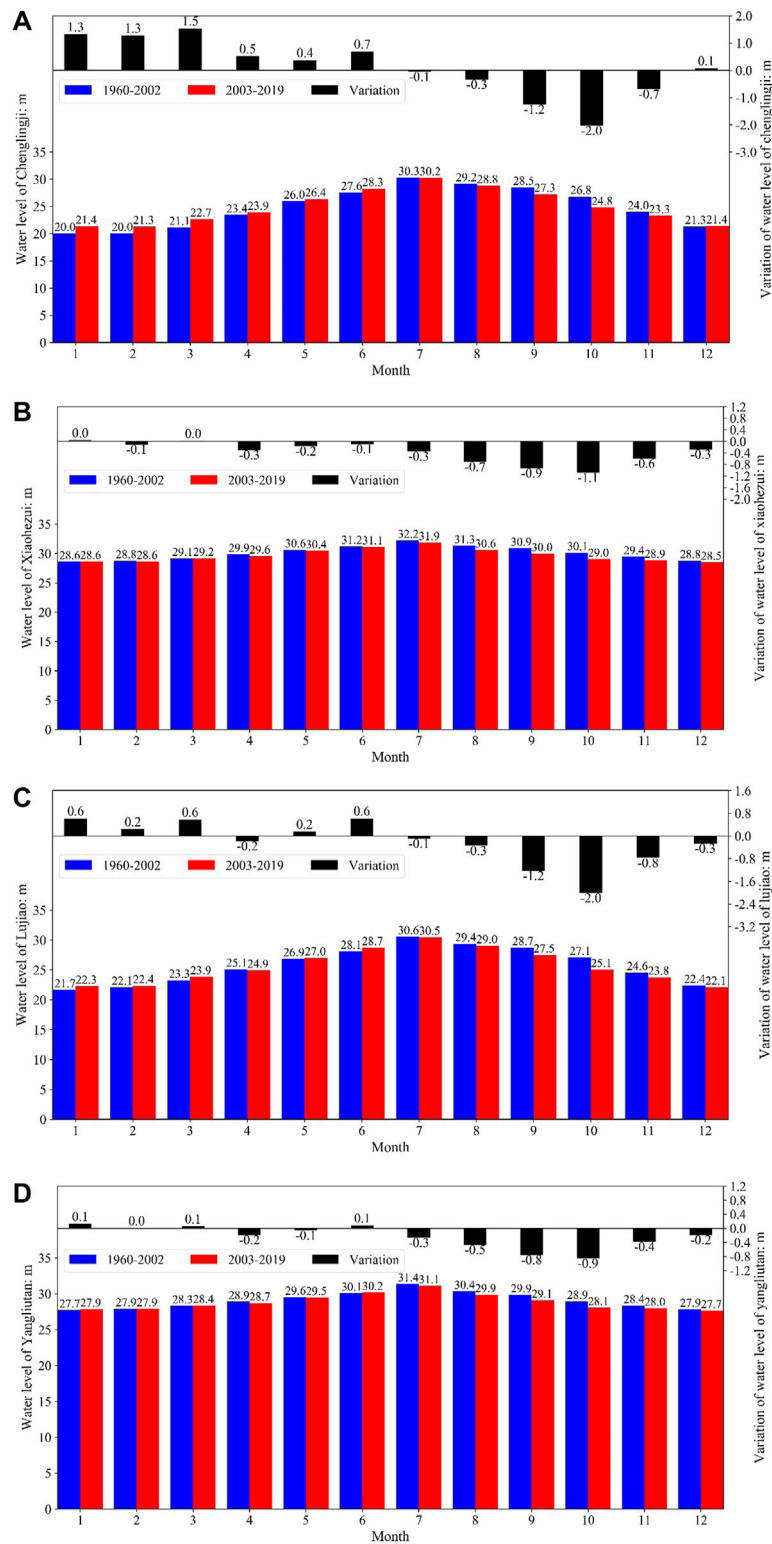
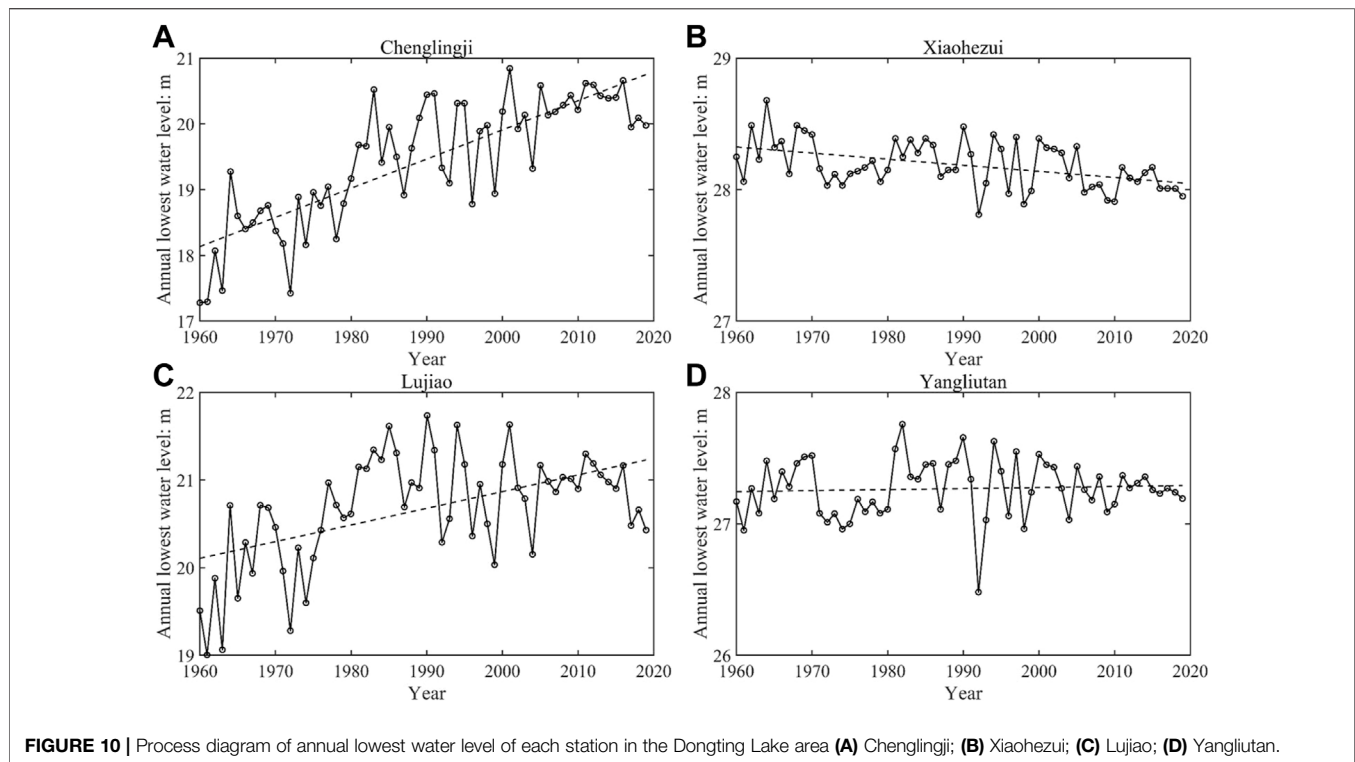


FIGURE 9 | Variations of water levels at different time periods at the (A) Yangtze River at Chenglingji, (B) Xiaohezui, (C) Lujiao, and (D) Yangliutan stations. The dotted lines in each figure is the fitted trend line.



(from July to October), the water volume in the Dongting Lake area exhibited a loss of $6.3 \times 10^8 \text{ m}^3$ – $16.8 \times 10^8 \text{ m}^3$, which should be considered as a potential threat for future utilization of the water resources in the lake area.

4 CHANGES IN WATER LEVEL AND SAFETY ASSESSMENT OF IRRIGATION AND WATER SUPPLY IN THE DONGTING LAKE AREA

4.1 Changes of Water Level in the Dongting Lake Area

4.1.1 Variations in the Average Water Level by Month in the Lake Area

Variations of average water level with month at Chenglingji, Xiaohezui, Lujiao, and Yangliutan stations over the two observation phases, from 1960 to 2002 and from 2003 to 2019, are displayed in **Figure 9**. With regard to Chenglingji station, the average water level by month over the two observation phases ranged in 20.0–30.3 m and 21.3–30.2 m, respectively. These variations were between -2.0 and 1.5 m. The most prominent water level decrease was observed during the months from July to November. The largest drop of 2 m was documented in October. By contrast, from December to June of the following year, the water level increased, and the largest boost was observed in March (1.5 m). With regard to the Xiaohezui station, the average monthly water levels during the two observation phases were in the ranges of 28.6–32.2 m and 28.6–31.9 m, respectively; the

respective variations were between -1.1 and 0.0 m. With the exceptions of January and March, the water level exhibited a decreasing trend in the other 10 months. The largest loss of 1.1 m was documented in October. With regard to the Lujiao station, the average monthly water level over the two observation phases ranged from 21.7 to 30.6 m and 22.3–30.5 m, respectively; the respective variations were between -2.0 and 0.6 m. In the months of April, as well as from July to December, the water level decreased by values which ranged between 0.1 and 2.0 m. The maximum decrease was in October (2.0 m). By contrast, the water level increased in the other months by 0.2 and 0.6 m. With regard to the Yangliutan station, the average monthly water level during the two observation phases ranged from 27.7 to 31.4 m and 27.7–31.1 m, respectively; the respective variations were between -0.9 and 0.1 m. In the months of April, May, as well as from July to December, the water level values decreased between 0.1 and 0.9 m. Water levels were replenished again and reached their highest levels by October (0.9 m). Overall, October was the month with the most significant changes in water level at each of the hydrological stations. Decreases ranged from 0.9 to 2.0 m, while September was the month with the second largest fall in the water level, and ranged from 0.8 to 1.2 m. From the perspective of geological distribution, the closer the station is to the main stream of the Yangtze River, the greater the decrease in water, which is attributed to the operation of the Three Gorges Reservoir. To sum up, given the operation of the Three Gorges Reservoir, the safety of the water supply for irrigation from the Dongting Lake area was mainly concentrated in the months of September and October, which is the period of water storage in the reservoir.

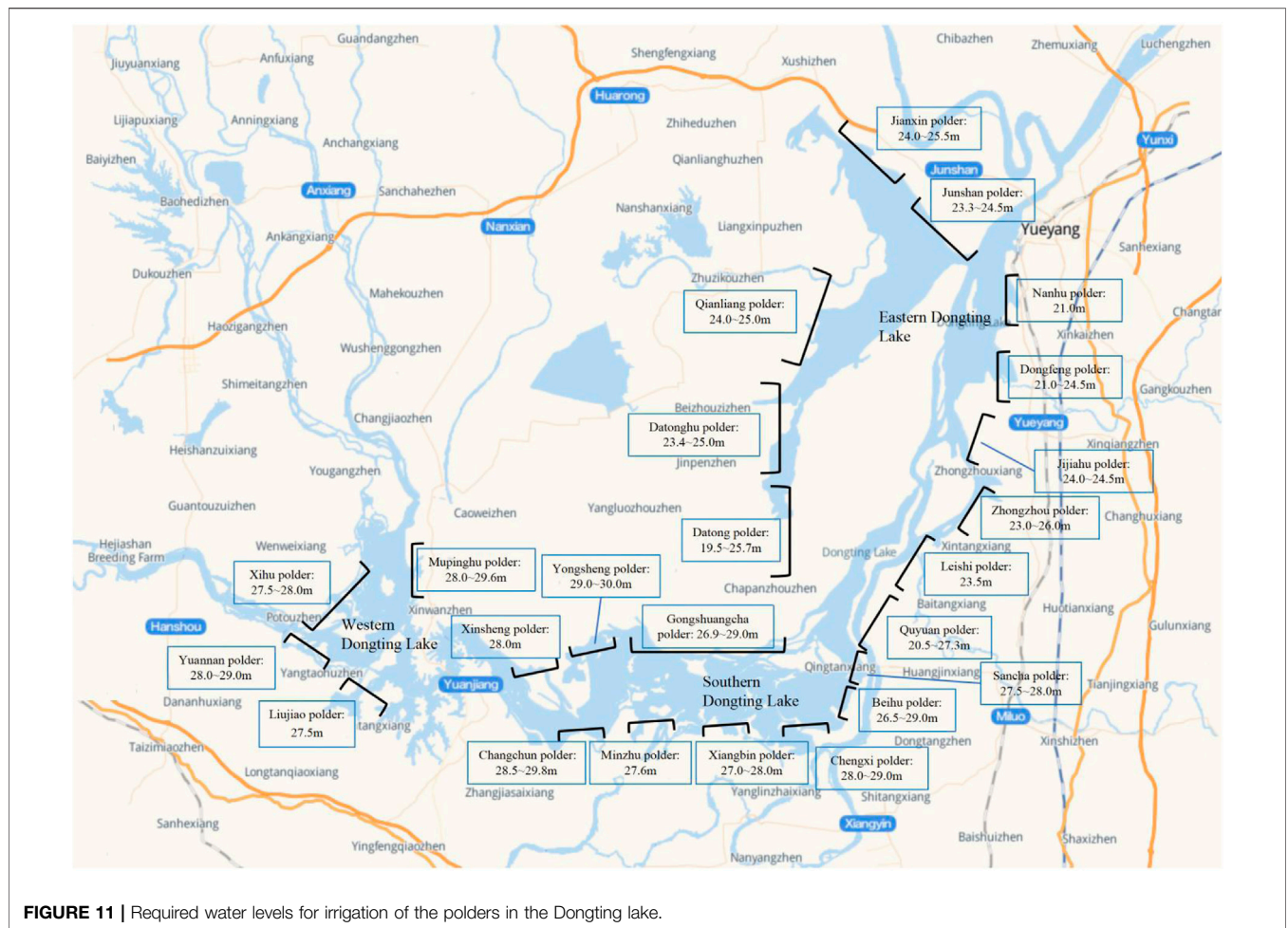


TABLE 5 | Required water levels for irrigation in the Dongting Lake area.

Lake area subregion	Western Dongting Lake	Southern Dongting Lake	South of eastern Dongting Lake	North of eastern Dongting Lake
Representative station	Xiaohuzui	Yangliutan	Lujiao	Chenglingji
Required water level for irrigation (m)	29.0	28.5	25.0	24.5

4.1.2 Changes in the Lowest Water Level in the Lake Area

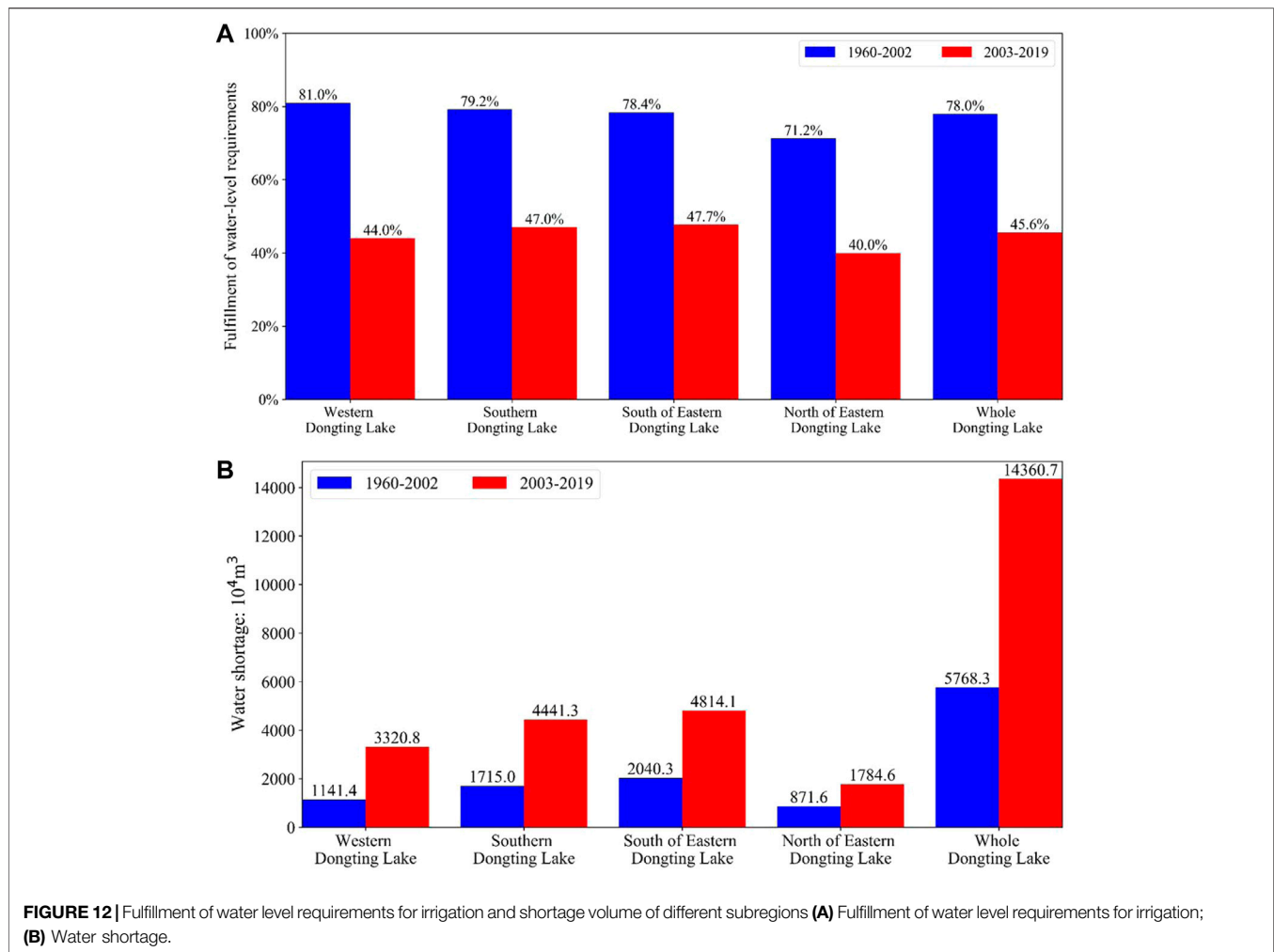
The lowest annual water levels at the Chenglingji, Xiaohuzui, Lujiao, and Yangliutan stations from 1960 to 2019 are shown in Figure 10. In the cases of the Chenglingji and Lujiao stations, the lowest annual water levels exhibited a mild upward trend, while Xiaohuzui station exhibited an opposite trend, and Yangliutan station remained relatively stable. The main reason for the boost in the lowest water level is that the Three Gorges Reservoir strengthens the water supply to the middle and lower reaches of the Yangtze River during the dry season, which has benefited both the Chenglingji and Lujiao stations. However, as the operation of the reservoir group in the upper reach is being continuously used, the low-flow channels in the middle and lower reaches of the Yangtze River have been further scoured. Thus, the

siltation along the inflow channel of Dongting Lake has become more obvious than before, and it has resulted in a decrease in the inflow volume during the dry period. Furthermore, the inflow volume from the main stream of the Yangtze River has also decreased. As a result, the lowest water level at the Xiaohuzui station has exhibited a mild downward trend.

4.2 Safety Indices of Irrigation and Water Supply for Urban and Rural Uses in the Lake Area

4.2.1 Water Supply Safety Index for Urban and Rural Uses

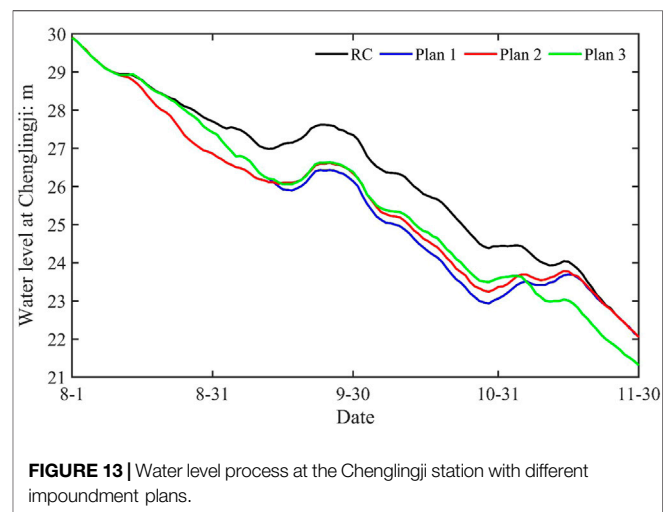
There is one water plant that draws water from the Dongting Lake, whose annual intake is 12 million cubic meters and the



elevation is at 27.66 m. With the nearby Yangliutan station selected as the representative station, the safety index of water level after conversion is 27.66 m.

4.2.2 Water Level Safety Index for Agricultural Irrigations

A total of 26 polders drawing water from the lake basin are distributed along the Dongting Lake (Figure 11). Water intake facilities and agricultural water conservancy facilities, such as internal pumping stations and irrigation canals, have mostly been completed before the operation of the Three Gorges Reservoir. Some of the polders have been built or rebuilt in recent years, and certain emergency measures have been implemented for drought resistance. Based on the elevation of irrigation sluice slab of each polder, the lowest elevation value for each polder in the western, southern, southeastern, and northeastern Dongting Lake subregions were selected as the control water levels to realize self-flow and water diversion in that polder. Meanwhile, the maximum value of the control value out of all the polders in each subregion was considered as the control value of the lowest water level for self-flow irrigation for



each subregion. After conversion, the required water levels for irrigation at the representative stations in each subregion are listed in Table 5.

TABLE 6 | Variation of average water level by month at Chenglingji station with different impoundment plans.

Month	Average water level (m)			
	Reduction calculation (RC)	Plan 1- RC	Plan 2- RC	Plan 3- RC
August	28.71	-0.05	-0.32	-0.05
September	27.37	-0.96	-0.99	-0.85
October	25.70	-1.43	-1.18	-1.01
November	23.60	-0.41	-0.34	-0.91

4.3 Evaluation on Water Supply Safety for Irrigation and Urban and Rural Uses

4.3.1 Evaluation on Water Supply Safety for Urban and Rural Uses

The safety water level of urban and rural water supply in Dongting Lake area at the Yangliutan station is 27.66 m. From historical statistical water level data at the Yangliutan station, the fulfillment of safety water supply before the operation of the Three Gorges Reservoir (from 1960 to 2002) was more than 95%, while after the operation, it dropped to 82%, with an average annual water shortage of $32 \times 10^4 \text{ m}^3$.

4.3.2 Evaluation on Water Supply Safety for Irrigation

Based on the long-term measurement of water level at Xiaohuzui, Yangliutan, Lujiao, and Chenglingji stations, which are the representative stations of each subregion in the lake area, the fulfillment of intake water level for irrigation and water shortage were analyzed, as shown in **Figure 12**. From 1960 to 2002, the fulfillment of the water level requirement for irrigation of the polders in Dongting Lake area was relatively high (average level of 78%). The long-term average annual water shortage was $5768.3 \times 10^4 \text{ m}^3$. For the western, southern, southeastern, and northeastern Dongting Lake area subregions, the fulfillment of the irrigation water level requirements were 81.0%, 79.2%, 78.4%, and 71.3%, respectively. Compared with other subregions, the lowest level of fulfillment was found in the north part of the eastern subregion of the Dongting Lake area, followed by the south part of the same subregion. A decline of the fulfillment to the required water level for irrigation was observed from the west to the east throughout the lake area. From 2003 to 2019, the fulfillment of required water level for irrigation of polders in Dongting Lake decreased (with an average level of 45.6%). For the four defined subregions, the fulfillment decreased to 44.0%, 47.0%, 47.7%, and 40.0%, respectively. The north part of eastern Dongting Lake showed the lowest fulfillment value. Additionally, the average annual water shortage in the long term increased to $1.43 \times 10^8 \text{ m}^3$, thus accounting for 10.69% of the average water demand from 2003 to 2019 (the absolute volume was $13.38 \times 10^8 \text{ m}^3$). The main cause behind the decrease in the water level intended for irrigation and the aggravation of water shortage is attributed to the fact that the water level in the lake area decreased considerably during the water storage period (September and October) after the operation of the Three Gorges Reservoir. This made it difficult to meet the water supply demand for irrigation in the region. From the perspective of geological distribution, the northeastern Dongting Lake area has encountered the biggest threat in water supply owing to its proximity to the mainstream of the Yangtze River.

4.4 Impact of Different Impoundment Plans on Water Level and Water Supply Safety

The multiyear monthly average water level process and the corresponding reduction calculations at the Chenglingji station from August to November with different impoundment plans are shown in **Figure 13**. Compared with the water level from reduction calculations, the decrease in the water levels from different plans with respect to the involved months are listed in **Table 6**. In the case of plan 1, as the water storage in August was relatively small during the flood season of the Yangtze River, the water level at the Chenglingji station was affected to a lower extent (reduced by 0.05 m). In September and October, water storage reached its top capacity. Specifically, with plan 1, the storage in October was larger than that with the other two plans. Hence, the water levels in September and October were affected considerably, and a drop of 1.43 m in October was the largest among the three plans. In the case of plan 2, the impoundment in August was advanced, and the water storage was thus larger than that of the other two plans. As a result, the water level dropped 0.32 m in August, which was the largest among the three plans. Although water storage in September was less than that with plan 1, the decrease in the water level in September in the case of plan 2 (0.99 m) was still larger than that of plan 1 (0.96 m) owing to the low-water level in August. In the case of plan 3, water storage levels in August, September, and October were larger than their corresponding volumes with the other two plans; thus, the water level drop was found to be the smallest. However, as the impoundment was still ongoing in November, a considerable water level decrease was observed. The largest decrease among the three plans was 0.91 m.

From the water level process (**Figure 13**), for plan 1, the water level was affected in late August, and decreased rapidly from the middle (mid) of September to end-October. For plan 2, the water level was affected as early as the middle of August, and the impact on the water level before mid-September was the greatest among the three plans, while the water level reduction rate from mid-September to end-October was relatively small. For plan 3, the impact on the water level was the least before end-October, and the impact on the water level in November was considerable. In summary, the later the stage the impoundment is performed, the less prominent the early impact will be, while the opposite applies for later impacts. On the contrary, the earlier the impoundment is performed, the earlier the influence on the water level will be exhibited, but the magnitude of the influence will be reduced.

Compared with the current water storage schedule (plan 1), the other two plans are able to adjust the water supply capacity in the lake area *via* advanced or delayed impoundment schedules.

Compared with plan 1, plan 2 reduced the water level in the lake area in August, the month during which the water level in the lake area was relatively high; accordingly, this had a minor impact on the water intake. The average water level in the lake area from September to October increased by 0.11 m, and thus, benefited from this plan. This could raise the irrigation and water supply capacity of the Dongting Lake by 1.3%, and would mainly affect the north part of the eastern Dongting Lake area. Conversely, the postponed impoundment in plan 3 prolonged the influence time of the water level decreases, and resulted in a larger drop in water levels in November. However, given that the demand for irrigation water in the lake area was smaller after October, a decreased water level has a minor impact on irrigation. On the contrary, while the water level increased by 0.27 m from September to October, the water supply for irrigation could experience boosts of 7 MCB in volume and 1.4% in the water supply capacity. Therefore, to alleviate the impact from impoundment of the Three Gorges Reservoir on the utilization of water resources in Dongting Lake area, it is necessary to store as much water as possible in the season when larger volumes of inflow are expected from the main stream of the Yangtze River, and minimize the water storage while increasing the discharge during the irrigation period from September to October in the lake area.

5 CONCLUSION

The farmland polders in the Dongting Lake area in the middle reaches of the Yangtze River draw water from the lake area. Since the operation of the Three Gorges Project, the hydrological situation of the Dongting Lake area has been modified, and it had a direct impact on the irrigation and water supply of the lake area. We used Dongting Lake as a case study to investigate the changes of water volume and level before and after the operation of the Three Gorges Project, as well as their effects on irrigation and urban and rural water supply in the lake area. The main conclusions are as follows:

- (1) Before and after the operation of the Three Gorges Project, the inflow runoff volume, outflow runoff volume, and water storage changes of the Dongting Lake experienced notable changes, especially from September to October. Compared with 1960–2002, the inflow runoff volume of the Dongting Lake during 2003–2019 decreased by $445.9 \times 10^8 \text{ m}^3$ and accounted for 17.5%. From September to October, the decrease was the most noticeable (volume: $186.1 \times 10^8 \text{ m}^3$, or equivalently: 41.8%). Between the two observation phases, the outflow runoff volume decreased from $2848.0 \times 10^8 \text{ m}^3$ to $2427.9 \times 10^8 \text{ m}^3$, and the average annual water storage change in the lake area decreased from $-303.3 \times 10^8 \text{ m}^3$ to $-329.1 \times 10^8 \text{ m}^3$.
- (2) After the operation of the Three Gorges Project, the amount of water in the Dongting Lake area decreased from July to December (peaked in September and October) from $53.1 \times 10^8 \text{ m}^3$ and $29.6 \times 10^8 \text{ m}^3$ to $36.4 \times 10^8 \text{ m}^3$ and $15.5 \times 10^8 \text{ m}^3$ (with equivalent decreased proportions of 31.5% and 41.7%, respectively). Even though the available water was reduced, the demand for domestic water and irrigation water could still be met. However, this downward trend should be considered a potential threat to the utilization of water resources in the future.
- (3) After the operation of the Three Gorges Project, the average water level at different stations in the Dongting Lake area decreased in the second half of the year with values in the ranges of 0.9–2.0 m in October and 0.8–1.2 m in September (top-ranked months). Affected by the decrease of the water level in the lake area, the fulfillment rate of the safety water level of supply after the operation of the Three Gorges Reservoir decreased from 95% to 82% with an average annual water shortage of $32 \times 10^4 \text{ m}^3$. Additionally, the fulfillment of irrigation water level requirements decreased from 78% to 46%, and the total water shortage increased from $5768.3 \times 10^4 \text{ m}^3$ to $14,360.7 \times 10^4 \text{ m}^3$.
- (4) By advancing or postponing the impoundment of the Three Gorges Reservoir, the water level decrease in the lake area from September to October can be reduced, its impact on irrigation and water supply in the lake area from September to October can be alleviated, and the water supply capacity can be respectively increased by approximately 1.3% and 1.4%.

This study can be utilized in the water resources management to guarantee the safety of irrigation and water supply for the Dongting Lake area. However, some factors must be investigated in future works. 1) The impact of the solutions of early or postponed impoundment of the Three Gorges Project on other fields, such as hydropower and flood defying, should be assessed. 2) Several studies has been suggesting the use of both engineering and non-engineering based solutions to overcome the negative impacts of large water projects. The effects of these solutions must be further analyzed. 3) Only the impact of the Three Gorges Project was discussed in this study, the impact of other human activities on climate change should be researched in the future works.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Full text written by JF; YL put forward the research ideas; DW and SX contributed to data processing and graph rendering.

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