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Water Level Fluctuation under the Impact of Lake Regulation and Ecological Implication in Huayang Lakes, China

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Abstract: Water level fluctuation (WLF) in shallow lakes in the middle and lower reaches of the Yangtze River has been a concern of many researchers. This work aims to investigate the effects of climate change and regulation of floodgates and the Three Gorges Dam (TGD) on WLF and lake volume in Huayang Lakes during the past 52 years. The results revealed that precipitation is the dominant factor that leads to seasonal variation of lake levels, whereas regulation of floodgates and TGD are the key drivers of hydrology regime change in the past 20 years. Natural lake regime has higher water level when there is more precipitation and less lake volume. Floodgates and TGD regulations have changed this pattern since 2003, causing less difference in water level in spite of more precipitation and lake recession. Under the combined impacts of floodgates and TGD regulations, Huayang Lakes have experienced a prolonged outflow time since 2003 and the contribution rate caused by the floodgates and TGD regulations has increased by 19.90%. Additionally, the water level of Huayang Lakes decreased by approximately 0.3~0.5 m from September to November, but it showed no alteration from January to March in the past two decades. This indicated that floodgate regulations used for agricultural irrigation and fishery culture dominate the hydrology regime in winter and early spring. This study is beneficial for aquatic ecosystem protection in floodgate-controlled lakes under the circumstance of climate change and vigorous anthropology activities.

Keywords: water level fluctuation; Huayang Lakes; climate change; regulation of floodgates and the Three Gorges Dam

1. Introduction

Lakes are essential to ecosystems at regional scales related to water resources, utilization of water resources, and communities of plants and animals in the wetland [1]. Water level fluctuation (WLF) associated with depth regulates the structure and functioning of shallow lakes, including habitat structure, primary producers, benthic consumers, and macrophyte vegetation, etc. [2]. Climate change, which embraces variation of precipitation, evaporation and temperature, has been a key factor in the alteration of the water level in recent years. Water level in many shallow lakes in the Yangtze River Basin exhibits seasonal variation because of the East Asian monsoon [3]. However, with the development of economy and society, variation of water level in the shallow lakes of the Yangtze River Basin is remarkably influenced by intensive anthropogenic activities, including reclamation, floodgate construction and the TGD regulations, which have attracted great attention from hydrological and environmental researchers [4–6].

There has been a long-time and heated controversy over the influencing factors of water level variation and its complication in lakes. For example, water level in natural lakes (e.g., Poyang Lake and Dongting Lake) declined in the autumn over the past 20 years [3–7]. Some researchers pointed out that TGD regulation is the core factor leading to water level decline in September and October every year in natural lakes since 2003 [4–6]. Furthermore, some research revealed that TGD impoundment weakened the river forcing on the natural lake and reduced the water level of Poyang Lake in autumn under similar precipitation conditions [8]. However, other researchers hold the opposite view that the declining trend exhibited in lakes of the middle Yangtze River since the 2000s was affected less by precipitation than by TGD regulations [1]. Despite many efforts to analyze the causes of water level variation in natural lakes interrelated and interacted with the Yangtze River, most studies focused on the influence of TGD regulation, reclamation and climate change on Poyang Lake and Dongting Lake, while few of them paid close attention to floodgate-controlled shallow lakes, which take up 60% of the total lake area in the middle and lower reaches of Yangtze River area in China [3]. In addition, there are no studies attempting to distinguish the contribution of each possible factor on variation of the lake water level in Huayang Lakes.

Owing to scarce researches for floodgate-controlled lakes, it is urgent to explore how factors such as anthropogenic activities and climate change influence the WLF of such lakes. We present a sufficient investigation of water level variation, reveal the characteristics of water level and quantify the impacts of lake regulation and climate change on water level variation in Huayang Lakes during 1967–2018 using hydrometeorological data. In addition, the ecological implication of WLF in shallow lakes is further discussed.

2. Materials and Methods

2.1. Study Area Description

Huayang Lakes (29°52′–30°58′ N, 116°00′–116°33′ E), which consist of four lakes, namely the Longgan Lake, the Daguan Lake, the Huang Lake and the Po Lake, are located in the north of the middle reaches of Yangtze River (Figure 1). The total area of Huayang Lakes is about 966 km^2 when the water level of lakes is 17 m. The Huayang Lakes belong to the zone with a north subtropical monsoon humid climate, which is characterized by four distinct seasons, abundant sunshine and heat, sufficient precipitation and long frost-free period. The annual average temperature and annual precipitation at Huayang Lakes are 16.6 °C and 1307.2 mm, respectively, and the dominant wind direction is the northeast wind. There are distinctive seasonal shifts associated with a subtropical monsoonal climate in the Huayang Lakes Basin, with precipitation concentrated from May to August. Seasonal precipitation leads to seasonal hydrological characteristics at Huayang Lakes. In summer, the weather is rainy, windy and hot, thus giving rise to a high lake water level. The average water depth in Longgan Lake, Daguan Lake, Huanghu Lake and Pohu Lake in summer is 2.78 m, 3.10 m, 3.18 m and 4.13 m, and lake area is 296 km^2, 189 km^2, 122 km^2 and 200 km^2, respectively. In winter, the weather is dry and cold, thus resulting in a low lake water level. The average water depth in Longgan Lake, Daguan Lake, Huanghu Lake and Pohu Lake in winter is 1.67 m, 2.17 m, 1.92 m and 1.94 m, and lake area is 88 km^2, 96 km^2, 60 km^2 and 100 km^2, respectively. The Huayang Lakes were shaped by the diversion of the ancient Yangtze River channel and a stable hydrological situation was basically formed after the construction of the Huayang Floodgate and the Yangwan Floodgate in the 1950s. Water in the lakes flows from west to east, on the whole. Specifically, water in Longgan Lake flows into Daguan Lake through Zhudun Channel, and water in Daguan Lake and Huanghu Lake flows into Pohu Lake through Changhe Channel. There are three major inflow rivers and two outflow rivers in the basin, with two rivers named Xindicha River and Erlang River flowing into Longgan Lake, one river named Liangting River flowing into Pohu Lake and another two rivers named Yangwan River and Huayang River outflowing to the Yangtze River via the Yangwan Floodgate and the Huayang Floodgate. Accordingly, water level of Huayang Lakes responds to flood pulses of both the Yangtze River and basin-wide tributary rivers.

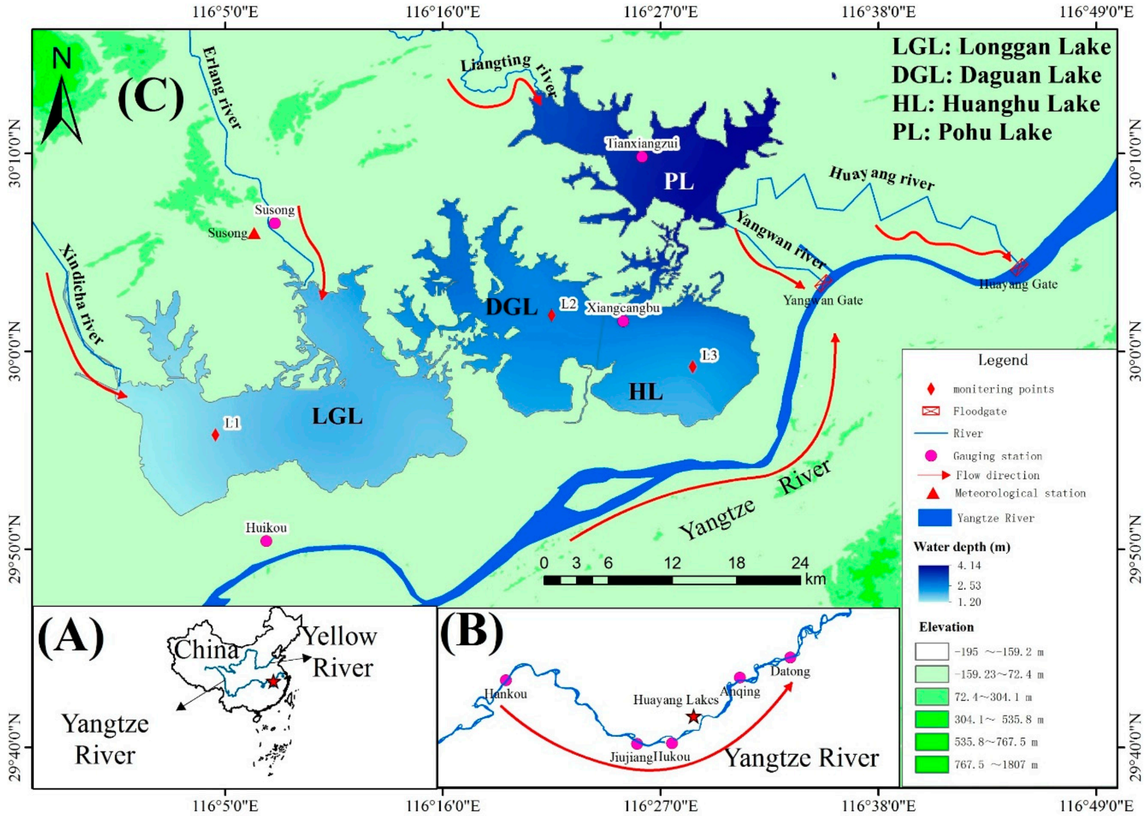

Figure 1. Map of the study region of the Huayang Lakes Basin: (**A**) Location of the Huayang Lakes Basin in relation to the Yangtze River; (**B**) Location of gauging stations in the Yangtze River; and (**C**) the Huayang Lakes Basin and hydrologic/meteorological stations used in this study.

2.2. Data Sources

The data included in this study comprises four groups. The first group includes mean daily water level and water discharge data collected from 1967 to 2018 at the following six gauging stations: Xiacangbu, Susong, the Upper Huayang Floodgate, the Lower Huayang Floodgate, the Upper Yangwan Floodgate and the Lower Yangwan Floodgate. The last three stations' data were available for 2006–2018 (Figure 1). All of these data were obtained from three websites (http://60.171.153.178:9000/shw/; http://113.57.190.228:8001/web/Report/RiverReport#; and http://aqswj.cn:9000/aqshqw/shqmh/index.html#/home) and the Water Resources Bureau of Susong County (WRBSC). The second group includes daily precipitation and monthly evaporation data obtained from the Susong Meteorological Station located in the Huayang Lakes Basin from 1967 to 2018 (Figure 1), which were collected from the WRBSC. The third group includes monthly water variable data from 2016 to 2018 in Huayang Lakes. The fourth group data were remote sense data, ranging from 1973 to 2019, which was obtained from the Remote Sensing Sharing Center of China (http://www.gscloud.cn/).

2.3. Data Analysis

In this study, the Mann–Kendall Trend Test (MK) was carried out to detect variation of the lake water level. Prior to applying this method, we first investigated the data set, among which a fraction of outlier data was deleted. Next, we made statistical analyses including calculations of the average monthly and annual water level, maximum and minimum daily value based on the daily water level data set ranging from 1967 to 2018.

The MK method used is briefly introduced below. The Mann–Kendall test [9–11] is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right), \tag{1}$$

where n is the number of data points, x_i and x_j are the data values in time series i and j ($j > i$), respectively and $\mathrm{sgn}(x_j - x_i)$ is the sign function as:

$$\mathrm{sgn}\left(x_j - x_i\right) = \begin{cases} +1, if\ x_j - x_i > 0 \\ 0, if\ x_j - x_i = 0 \\ -1, if\ x_j - x_i < 0 \end{cases}. \tag{2}$$

The variance is computed as:

$$\mathrm{Var(S)} = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18}, \tag{3}$$

where n is the number of data points, m is the number of tied groups and t_i denotes the number of ties of extent i. A tied group is a set of sample data having the same value. In cases where the sample size $n > 10$, the standard normal test statistic U_F is computed using Equation (4):

$$U_F = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var(S)}}}, if\ S > 0 \\ 0, \qquad if\ S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var(S)}}}, if\ S < 0 \end{cases}. \tag{4}$$

Positive values of U_F indicate increasing trends while negative U_F values show decreasing trends.

Time series x_i and x_j are made in reverse order and calculated according to the formulas mentioned above, and meet the following requirement at the same time:

$$U_B = -U_F. \tag{5}$$

Testing trends is done at the specific α significance level. When $|U_F| > U_{1-\alpha/2}$, the null hypothesis is rejected and a significant trend exists in the time series. $U_{1-\alpha/2}$ is obtained from the standard normal distribution table. In this study, the significance level α = 0.05 was used. At the 5% significance level, the null hypothesis of no trend is rejected if $|U_F| > 1.96$. The Mann–Kendall statistical test has been frequently used to quantify the significance of trends in hydro-meteorological time series.

In addition, the water-balance model was chosen to calculate the rate of changes in lake volume, water supply and water consumption, which can be expressed as:

$$\Delta V = I_1 + I_2 + P * A_1 - E * A_1 - Q \pm \varepsilon, \tag{6}$$

where I_1 is annual streamflow of rivers entering the lake, I_2 is annual runoff into the lakes, which was generated by precipitation from the land surface, $\boldsymbol{P}$ is annual precipitation directly on the lake, A_1 is the initial lake area, $\boldsymbol{E}$ is annual evaporation from the lake surface, $\boldsymbol{Q}$ represents the outflow from the lakes and ε is the supply or seepage of the ground water. In this study, it was assumed that groundwater flow and seepage were not major factors contributing to lake volume, and they were ignored.

3. Results

3.1. Annual Variation of Water Level

Generally, lake water levels in Huayang Lakes tended to decrease slightly in the years from 1967 to 2018 (Figure 2). The inter-annual variation and abrupt changes of water level during the period of 1967–2018 were calculated by the MK test (Figure 2). The change could be seen from the curve of statistic U_F. As showed in Figure 2, a fluctuant decreasing trend appeared during the period of 1970–1988. Water level between 1989 and 1997 showed a trend of fluctuation. Besides, it showed a significantly decreasing trend during the period of 1998–2016.

The point where U_F and U_B curves intersected was identified as the turning point, indicating that the time series had a sudden change at that time. During the period of 1967–2018, there were 10 turning points, namely 1968, 1970, 1988, 1990, 1994, 1995, 1997, 1998, 2014, 2016. Given the variation period, turning points and the realistic situation of Huayang Lakes, we divided the time series (1965–2018) into three distinguishable periods, namely 1970–1988, 1989–1997, and 1998–2016.

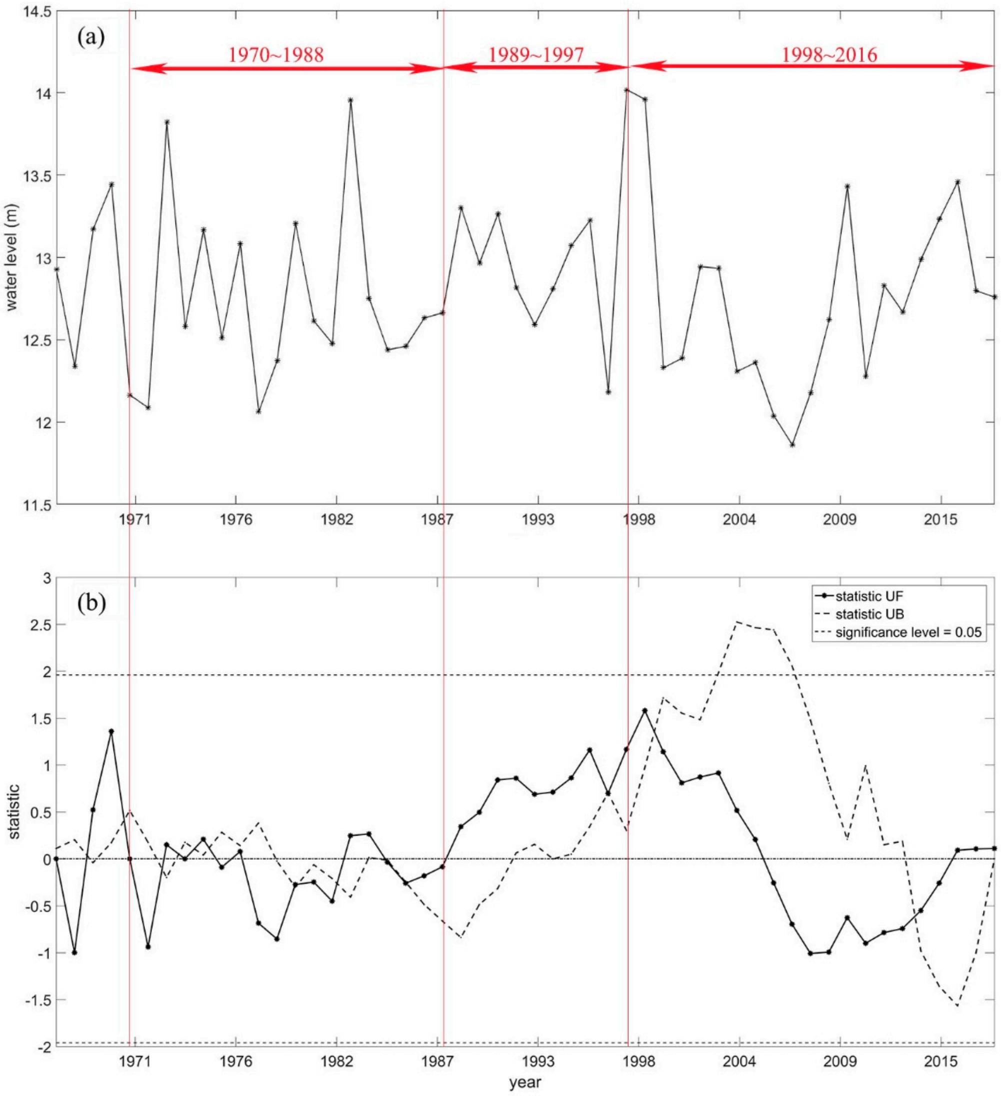

Figure 2. (**a**) Variation of annual water level series. The values are calculated using daily water level from 1967 to 2018; and (**b**) Mann–Kendall Trend Test (MK) of annual water level in Huayang Lakes.

3.2. Seasonal Variation of Water Level

For the monthly average water level, the statistical parameters of the maximum, median values, and minimum in the box-whisker plots showed significant seasonal variations (Figure 3), and average water level ranged from 11.79 m to 14.08 m. There are four stages for lake level fluctuation: Stage 1 is the low lake water level period from January to March, revealing that the average level in these months for the 52 years studied is less than 12 m; Stage 2 is the ascending period, during which the average monthly level rises from 11.99 m in April to 13.02 m in June; Stage 3 is the high-level period, maintaining the lake water level as high as around 14 m between July and August; Stage 4 is the descending period when the lake water level goes down to approximately 12 m. In general, the magnitude of the increase was more remarkable than that of the decrease. Additionally, obvious seasonal fluctuations in different years were observed during the study period (Figure 3). Dry years were roughly 1985–1988 and 2000–2008. The lake water level during the high lake water level period since 2000s kept low, 0.7 m less than the average level during the study period of 52 years. During the low water level period, lake water level was also low, 0.07 m less than the controlling lake water level of 11.8 m in the past 52 years. Wet years were 1973, 1983, 1989–1999, 2010 and 2016. The high lake water levels lasted for a long time during these years, mainly emerging from June to October. The highest level 17.09 m was observed on July, 2016 and the lowest one 11.18 m was observed on August, 2004.

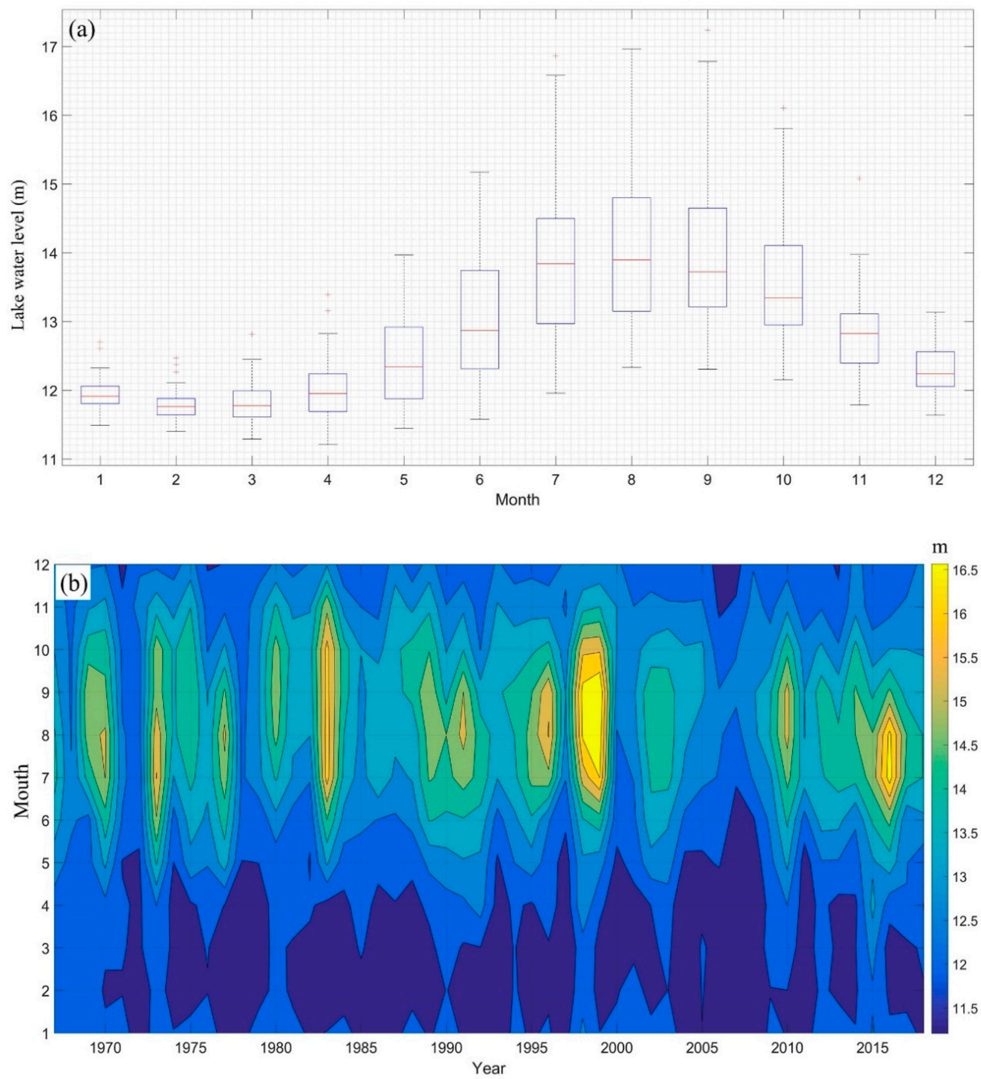

Figure 3. (**a**) Box-whisker plots of monthly water level from 1967 to 2018 in Huayang Lakes; and (**b**) Seasonal water level variation from 1967 to 2018 in Huayang Lakes.

Besides, the tendencies of lake water levels during different water periods was easily seen. Water level in July representing the flood season showed slight increase trend and that in October representing the normal season showed the opposite tendency. However, water level in February and April representing the dry season revealed nonsignificant variation.

3.3. Duration of Extreme Water Level

We selected a water level (WL) below 11.5 m or 12 m as the extreme low water level, and meanwhile chose a WL above 14 m and 15 m as the extreme high water level. Total days of WL < 11.5 m, WL < 12 m, WL ≥ 14 m, WL ≥ 15 m were 451 days, 5563 days, 2781 days and 1065 days, respectively (Figure 4), accounting for 2.37%, 29.29%, 14.64% and 5.61%, separately. Days of less than 12 m frequently appeared in the 2000s, averaging 28 days more than the 107 days of the 52-year average value. There were only two years in the 2000s during which lake water levels surpassed 14 m, 15.8 fewer days than the 99.3 days of the 52-year average value. Meanwhile, the duration of extreme high water levels (≥14 m or ≥15 m) within the year gradually shrank. Days of WL ≥ 14 m declined from 179 days in 1983 to 151 days in 1999 and 118 days in 2016, and those of ≥15 m were reduced from 143 days to 122 days and 83 days, respectively. It indicated that the water level variation in Huayang Lakes exhibited different behaviors pre- and post-TGD regulation, especially in summer and autumn. Time during extreme high water level decreased in recent decades.

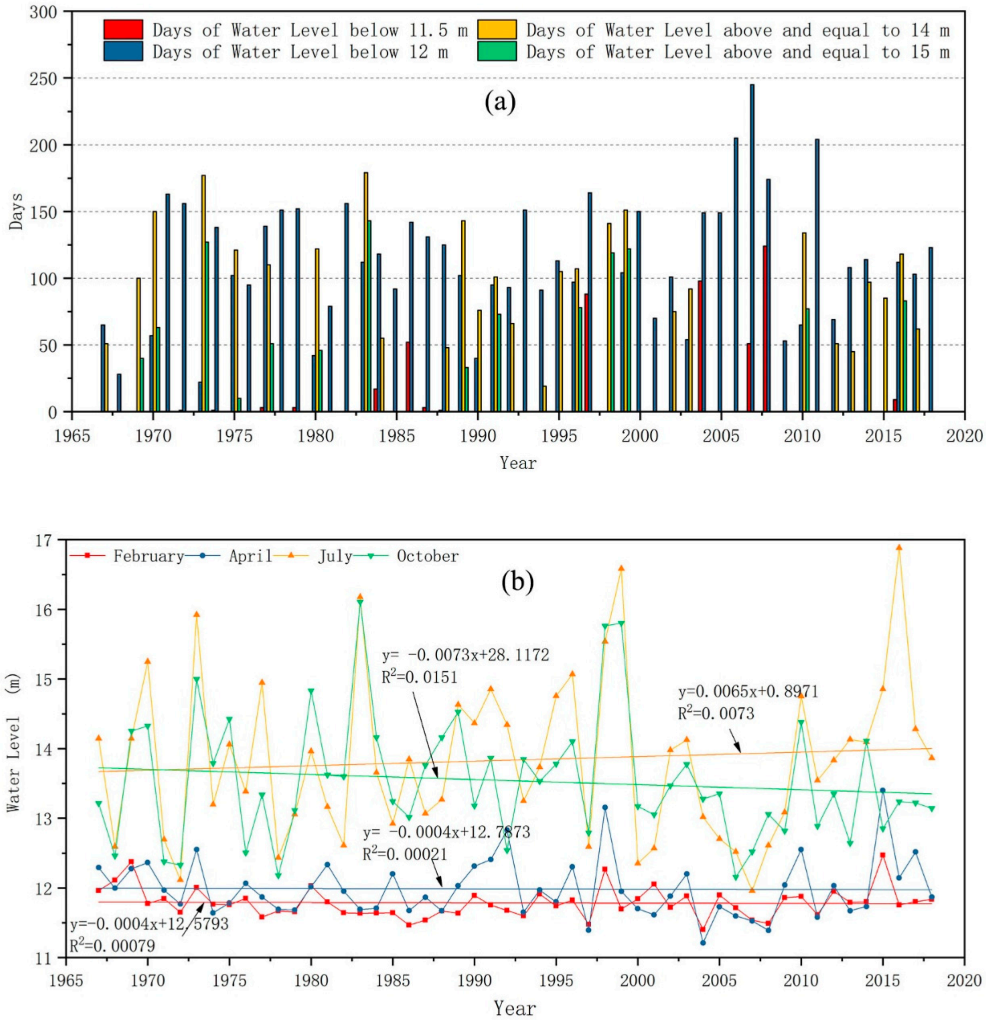

Figure 4. (**a**) Days of extreme low water level (<11.5 m or <12 m) and extreme high water level (≥14 m or ≥15 m) from 1967 to 2018; and (**b**) Long term variations of water level in February, April, July and October in Huayang Lakes.

3.4. Relationship between Precipitation and Water Level

Precipitation plays a significant role in water level fluctuation. A previous study indicated that the summer monsoon strongly influences the middle and lower reaches of the Yangtze River, thus leading to abundant precipitation and making the area humid [12]. A contour image of monthly precipitation during 1967–2018 shows heavy precipitation was concentrated between April and September with June as the peak value (Figure 5), which is similar with the phenomenon in the Yellow River [13] and Dongting Lake located at the middle of the Yangtze River [4]. Ye et al. [14] also reported that a large amount of surface flow was produced by heavy precipitation during wet season, which caused the rise of water level in Poyang Lake (located opposite the Huayang Lakes) adjacent to the Yangtze River. Monthly precipitation peaks in 1995, 1998, 1999 and 2016 were much higher than any other years, during which flood disaster in the Yangtze River Basin occurred [4,14]. Moreover, dry years lasted for about 10 years in the early 2000s, which was possibly caused by the Three Gorges Dam Project and global climate change [14].

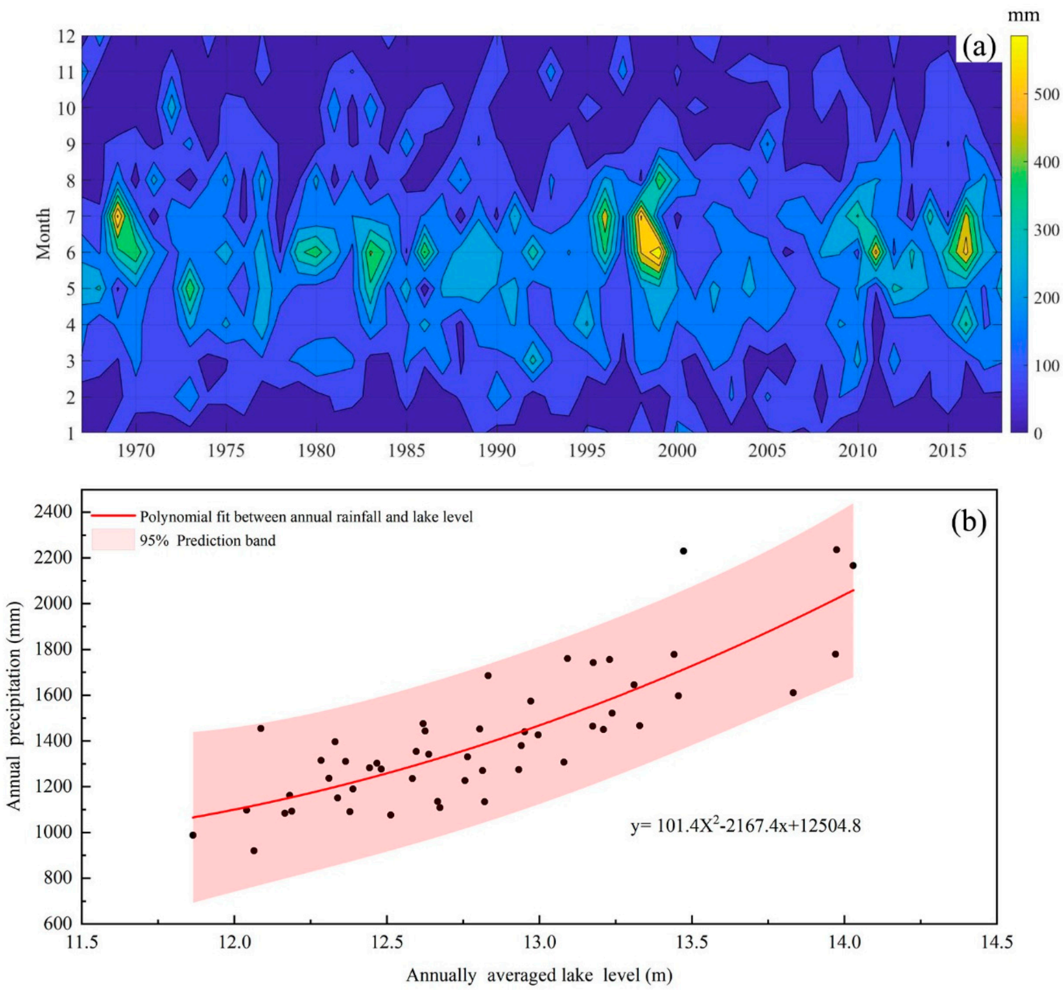

Figure 5. (**a**) Seasonal precipitation variation from 1967 to 2018 in Huayang Lakes Basin; and (**b**) Relationship between precipitation and water level of the Huayang Lakes.

Monthly precipitation rose before June and declined after June, but Figure 3 shows that the peak of monthly average water level in Huayang Lakes happened in August, which was the same as Poyang Lake, but a little bit different from Dongting Lake [14]. The time of peak water level in Huayang Lakes was later than Dongting Lake because it is located downstream of the Yangtze River. Correlation between water level and precipitation was positive, indicating that the water level rose with the precipitation rise within a 95% prediction band. It can be explained why the peak of monthly average water level happened in August. It was observed that the lowest annual average water level was lower than 12 m and the highest was higher than 14 m, which meant the fluctuation of the annual average water level was larger than 2 m. Results showed that the maximum inter-annual water level fluctuation reached 6 m in the year 2016. This lake has been located along the Yangtze River for thousands of years, therefore groundwater conductivity may be reduced resulting from accumulated clay and silt on the lake bottom [15]. It is obvious that high water level fluctuation in Huayang Lakes was caused by monthly precipitation distribution in the lake basin and the water level of the Yangtze River connecting with lakes through floodgates directly [14,16,17].

4. Discussion

4.1. Combined Effects of Floodgates and the Three Gorges Dam Regulation on Water Level Fluctuation

WLF in lakes is very sensitive to floodgate operation. Floodgates in the Huayang Lakes open to discharge lake water into the Yangtze River when the water level below the gates, representing Yangtze River level, is lower than that above the gates, representing lake water level. In addition, the Three Gorges Dam, the largest hydropower station, affects many natural lakes located in the middle and lower reaches of the Yangtze River [4,5,18,19]. TGD operation has held water from September to November every year since 2003, and has released water during dry seasons. Water level of the Yangtze River has decreased earlier after TGD regulation, and the low water level has lasted for a longer time since September every year [20]. Floodgate-controlled lakes such as Huayang Lakes have also suffered from hydrological variation under the combined effects of floodgates and TGD regulation. The average water level of Huayang Lakes has decreased from September to November since TGD regulation and the difference of average water level is 0.3 to 0.5 m (Figure 6). However, it has little influence on January to March. Variation of outflow time from lakes controlled by floodgates is the essential mechanism of water level fluctuation. We used the first order difference of lake water level to analyze the impacts of TGD and floodgate operation on water level without considering evaporation (Figure 6). When the water level dropped, the first difference of water level was negative, meaning that the lakes drained water into the Yangtze River. The total time of draining lasted longer after the TGD operation. It was found that cumulative distribution with the negative value of the first difference of water level post-TGD regulation was larger than pre-TGD. In other words, about 10 more days have been added when water from Huayang Lakes outflows to the Yangtze River under the impact of TGD regulation. That explains why the duration time of the high water level above 15 m was shorter in 2016 than in 1998 with similar precipitation.

In order to analyze the contribution of climate change and floodgate operation to WLF in Huayang Lakes, we established the water-balance model. According to the results (Table 1), precipitation on the lake surface, runoff generated by precipitation from the land surface, and runoff from the rivers during 2003–2018 were 0.15×10^8 m^3, 1.43×10^8 m^3, 0.37×10^8 m^3 more than during 1967–2002, respectively, whereas evaporation on the lake surface was 0.33×10^8 m^3 less than during 1967–2002. In addition, runoff generated by precipitation from the land surface was the most since 1967, which took up 68.95% during 1967–2002 and 69.12% during 2003–2018. Evaporation on the lake surface accounted for a small proportion in the total consumption, which was 21.04% during 1967–2002 and 19.58% during 2003–2018. In terms of water discharge, outflow during 2003–2018 was 2.88×10^8 m^3 annually higher than during 1967–2002 (increased by 8.22%), suggesting that days per year of discharging water from lakes in recent years lasted for longer than before. Although there was more precipitation and less evaporation during 2003–2018 than during 1967–2002, annual water volume of the lake during 2003–2018 was reduced by more outflow through floodgate regulation. It was indicated that the floodgate regulation played a vital role in the second period. In order to understand the contribution of floodgate regulation to WLF, we set two scenarios for the second period (Table 1). In scenario 1, which represents the current situation, the annual average water level was 12.67 m (during 2003–2018). In scenario 2, it was assumed that outflow during 2003–2018 was equal to that during 1967–2002, which was 35.04×10^8 m^3, but other values of water supply and water consumption were not changed. In this case, the annual average water level was 13.13 m (during 2003–2018). In comparison, the water level difference was 0.46 m and variation rate was 19.91%, contributed by outflow of floodgate regulation. More frequent floodgate outflow operations during 2003–2018 were means to cope with stronger precipitation and lake shrinkage.

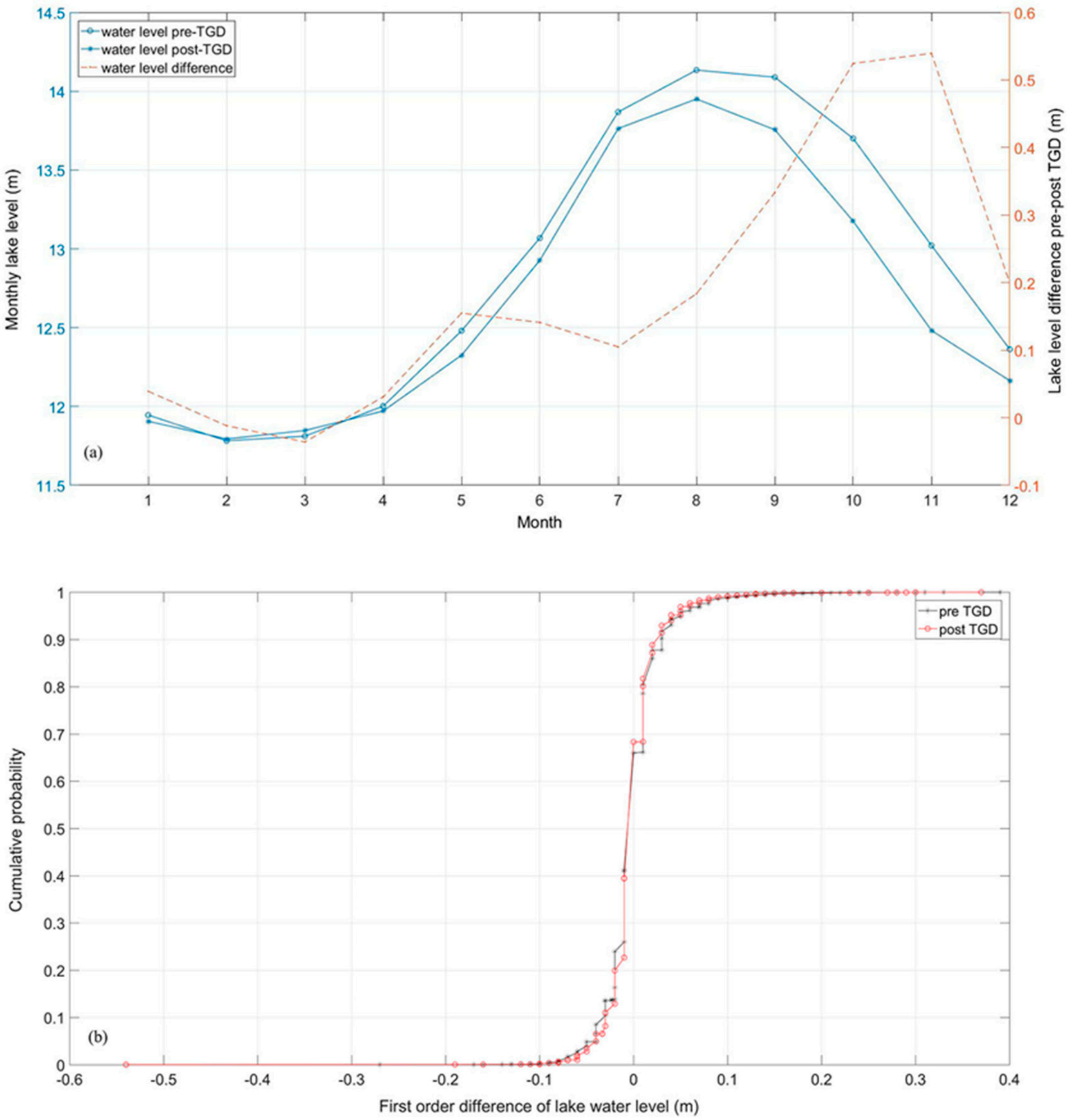

Figure 6. (**a**) Impacts of Three Gorges Dam (TGD) regulation on monthly water level in Huayang Lakes; and (**b**) cumulative probability of first order difference of water level in Huayang Lakes.

Table 1. Comparison of water supply and consumption in Huayang Lakes during the study periods.

		Total Water Supplies (A = A1 + A2 + A3)/$10^8 m^3$				Total Water Consumption (B = B1 + B2)/$10^8 m^3$			V (C)/$10^8 m^3$
Years	**Indicators**	**Precipitation on the Surface of Lakes (A1)**	**Runoff Generated by Precipitation from the Land Surface (A2)**	**Runoff from the Rivers (A3)**	**Total Water Supplies (A)**	**Evaporation on the Surface of Lakes (B1)**	**Outflow (B2)**	**Total water Consumption (B)**	**Variation of Lakes Water (C)**
1967–2002	Annual average value/10^8 $m^3 \cdot a^{-1}$	9.45	33.42	5.60	48.47	10.20	35.04	45.24	3.23
	Percent of total supplies or consumption	19.50%	68.95%	11.55%	100.00%	22.55%	77.45%	100%	6.66%
2003–2018 (Scenario 1)	Annual average/10^8 $m^3 \cdot a^{-1}$	9.60	34.85	5.97	50.42	9.87	37.92	47.79	2.63
	Percent of total supplies or consumption	19.04%	69.12%	11.84%	100.00%	20.65%	79.35%	100%	5.22%
Comparison between 1967–2002 and 2003–2018	Annual average/10^8 $m^3 \cdot a^{-1}$	0.15	1.43	0.37	1.95	−0.33	2.88	2.55	0.60
2003–2018 (Scenario 2)	Annual average/10^8 $m^3 \cdot a^{-1}$	9.60	34.85	5.97	50.42	9.87	35.04	44.91	5.51
	Percent of total supplies or consumption	19.04%	69.12%	11.84%	100.00%	20.65%	79.35%	100%	10.93%

Lake utilizations such as lakeside zone reclamation led to a higher water level in July during the study period. Huayang Lakes wetland shrank by 200 km^2, which contributed to 41% of the total area of lakes in the 1950s (unpublished data). This result coincided with results of other research that found Poyang Lake area decreased by approximately 32% from 1973 to 2011 [21] and Dongting Lake area declined by around 31% from 2000 to 2009 [17]. Under the impact of reclamation, the water level in July showed a rising trend in the past 50 years, especially since the 2000s. There were linear relationships between the high water level of Huayang Lakes and the reclamation area when various water levels in the four seasons were considered individually. Meanwhile, influenced by the floodgates and the lake geometry, lake flow was low and abundant sediment was deposited in the lakes, and the result indicated that the sedimentation rate over 50 years was about 0.3 cm/year [22]. According to this result, the capacity of Huayang Lakes was reduced by 1.8 million cubic meters per year, which accumulated to 7% of total volume in the past 50 years.

4.2. Implications for Ecological Management in Shallow Lakes

Climate change in the future and lake recession may lead to frequently occurring extreme water levels in the river floodplain lakes like Huayang Lakes. The practice of water level regulation is expected to reduce adverse effects on economic development. We found that water level regulation improved flood/drought management over the past two decades under the combined impacts of floodgates and TGD operation, despite dramatic recessions in Huayang Lakes (Figure 6). Compared with natural regimes of WLF, higher water level for fishery culture in dry seasons and lower water level in wet seasons promote economic development in Huayang Lakes Basin. Meanwhile, there has been a phenomenon of eutrophication in Huayang Lakes, which was in turbid state in the past two decades. Lake water level regulation may not be favorable for lake restoration to a clear state [23]. Therefore, water level regulations need to perform multifunctionally, to not only fulfill flood prevention and human use, but also to exert less pressure on ecosystem health, especially on the growth of aquatic plants. In Huayang Lakes, we lack enough knowledge to implement restoration of macrophytic lakes, which have an important effect on the maintenance of the clear-water state.

WLF is vital to the growth of submerged macrophyte species. The magnitude, duration, and timing of extreme water levels are key factors for emergent macrophyte growth [15]. At the same time, water level drawdown followed by rewetting can switch macrophytes from a nutrient sink to a source [24]. Submerged macrophytes have declined drastically, induced by cultured Chinese Mitten Crab in recent decades in Huayang Lakes. It is essential to ecological restoration, which aims to improve submerged macrophyte species and area in lakes. Our detailed mapping of WLF change regime indicates that floodgate regulation can control the lake water level effectively. Thus, we recommend that more attention is paid to spring with low water level and summer with high water level. Extreme high water level can inhibit light penetration, which macrophytes need. Many macrophytes in shallow lakes disappeared in the Yangtze River Basin in the flood of 1998, induced by high water level [25]. Some researchers claimed that low water level is essential to macrophyte growth during seed germination stage [26]. Hence, WLF has severe effects on the species and amount of submerged macrophytes, and it might be worthwhile to restore macrophytes through lake water level regulation in shallow lakes. The regulations can help to keep lakes in the clear state, but can lead to high costs for water resource exploiting.

As discussed above, WLF in shallow lakes can obviously affect both water variables and aquatic ecosystems. In Huayang Lakes, collaboration has developed in recent years between hydrologic and environmental agencies to design better regulation schemes and improve lake ecosystem services for humans. Relationships between WLF and ecological system changes are still to be explained in the future.

5. Conclusions

The goal of this work was to estimate the impacts of climate change and floodgates and TGD regulations on water level fluctuation and their ecological implications in floodgate-controlled shallow Huayang Lakes. Our work showed that precipitation was the dominant factor that led to seasonal variation of lake levels, meanwhile, floodgates and TGD regulations were the essential causes that resulted in the higher level during the flood season and the stable level during the dry season in recent decades. During the dry season, lake levels were kept at around 11.8 m to restore water for fish culture and irrigation, and thus there was no obvious variation during this period. By contrast, during the flood season, owing to reclamation of the lakes, the volume of Huayang Lakes shrank sharply and lake levels rose to more than 14 m. Influenced by the regulation of floodgates and TGD, the annual average outflow has increased by 8.22% since 2003, and the contribution rate of floodgates has increased by 19.90%. Besides, lake levels exhibit marked difference from May to December, which is roughly 0.55 m of maximum difference between pre-TGD and post-TGD, respectively. WLF could affect water variable alterations and ultimately influence aquatic ecosystems. Accordingly, for floodgate-controlled shallow lakes, more systematic research about the relationship of WLF and the ecosystem should be conducted in the future.

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