Quantitative assessment of water level regime alterations during 1959–2016 caused by Three Gorges Reservoir in the Dongting Lake, China

Hongxiang Wang, Yongwei Zhu, Hufei Zha and Wenxian Guo

ABSTRACT

Water level is considered as the key factor affecting the structure and function of lake ecosystems. The Mann-Kendall technique and range of variability approach (RVA) were used to quantitatively evaluate the hydrologic alteration due to Three Gorges Reservoir (TGR) in Dongting Lake. Results indicate the following. (1) The average annual water levels at Chenglingji station showed increasing trends ($p < 0.05$), while that at Nanzui station showed a decreasing trend ($p < 0.05$). The turning year occurred in 2003, which reflects the significant effects of the TGR on the water level regime. (2) The highly altered parameters were 1-, 3-, and 7-day minimum water levels both at Chenglingji and Yangliutan, and in October both at Nanzui and Yangliutan, with the degree of hydrologic alteration being larger than 80%. However, 1-, 3-, 7-, and 30-day maximum water levels at three stations had relatively small alteration, with the degree of hydrologic alteration being smaller than 41%. (3) The hydrologic alteration degrees at Chenglingji, Nanzui and Yangliutan station were all moderate, with changes of 50, 46 and 49%, respectively. (4) Water level regimes at Dongting Lake were mainly jointly affected by reservoir operation, land utilization change and river channelization. These changes in water level regimes have a negative impact on aquatic and terrestrial ecosystems. This study provides a scientific reference for the protection of lake ecosystems under hydrologic alteration.

Key words | Dongting Lake, hydrologic alteration degree, Three Gorges Reservoir, water level

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HIGHLIGHTS

- Statistically characterize the trend and variability of water level regimes in Dongting Lake from 1959 to 2016.
- Quantitively evaluate the water level regime alterations caused by the TGR by comparing the pre- and post-reservoir periods with RVA.
- Water level regimes at Dongting Lake were mainly jointly affected by reservoir operation, land utilization change and river channelization.

INTRODUCTION

Lakes, providing numerous goods and services, are important for the development of human life, including water supply for industrial and agricultural purposes, and maintenance of the ecological environment (Beeton 2002; Brönmark & Hansson 2002; Wantzen *et al.* 2008). At the same time, water level fluctuations are the most primary factors affecting the structure and function of lake ecosystem (Williamson *et al.* 2009). However, most of lakes around the world have been severely

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impacted by human activities, especially dams and reservoirs (Coe & Foley 2001; Schindler 2001; Hampton *et al.* 2008; Ariztegui *et al.* 2010). Dams and reservoirs can provide important sources of renewable energy, irrigation water and flood and drought control, and can help to improve the safety of water, but they also have a remarkable impact on the ecological integrity of the aquatic system and the productivity of the downstream lake and wetland systems (Arthington *et al.* 2010; Poff & Zimmerman 2010; Grill *et al.* 2015). The water level variation induced by the reservoir may also impact the lake habitat, which potentially influences the health of aquatic organisms (Hu *et al.* 2007; Zolezzi *et al.* 2009; Zhang *et al.* 2015a, 2015b). Therefore, the quantitative assessment of water level variations due to the impoundment and operation of reservoirs is beneficial to protect the lake ecosystem.

To evaluate the hydrologic alterations induced by dams and reservoirs, numerous researchers have developed and applied multiple methods to analyze the relationships between hydrological variations and ecological diversity (Yang *et al.* 2008; Zhang *et al.* 2015a, 2015b). Many indicators have been put forward to analyze the changes in the lake water level regime (Olden & Poff 2003). These indicators offered the basis for assessing the hydrologic alteration induced by reservoirs to guide lake ecosystem management. The software of indicators of hydrologic alteration (IHA), which was proposed by the Nature Conservancy, is one of the most common methods for evaluating the hydrologic regime alteration induced by human activities in the stream and lake system. Based on the natural flow regime theory, the natural flow regime contains five critical components, namely, magnitude, frequency, timing, duration and rate of change. The IHA contains 33 hydrologic parameters that characterize five critical components (Richter *et al.* 1996). The range of variability approach (RVA) proposed by Richter *et al.* (1997) was applied to evaluate the hydrologic regime alteration of rivers and lakes (Richter *et al.* 1997). The RVA method has been successfully applied to evaluate hydrologic regime alteration in numerous rivers around the world (Richter *et al.* 1998; Shiau & Wu 2004; Chen 2012; Yang *et al.* 2012; Jiang *et al.* 2014). However, most of previous researchers focused on the hydrologic alterations of the rivers, and few studies about water level alterations were reported. Therefore, the estimation of water level regimes alteration in the lakes can help to understand the impact of water level alteration on lacustrine organisms.

Dongting Lake is the second biggest freshwater lake in China. For nearly 60 years, the relationship between the Dongting Lake and Yangtze River has experienced the natural evolution and the influence of human activities, especially Three Gorges Reservoir (TGR) impoundment. The activities have caused the hydrological regimes of Dongting Lake. Scholars have carried out extensive studies on the distinguishing features and causes of water level change in Dongting Lake (Shi *et al.* 2012), the impact of TGR on water level change (Huang *et al.* 2011; Lai *et al.* 2014), and the response of wetland ecosystem to water level fluctuation (Guan *et al.* 2016). However, they seldom discussed the water level alterations, including the five critical components of the water level regime. In addition, more detailed estimation is requisite on the alteration of water level regimes because of TGR construction.

Therefore, the objectives of this study are: (1) to statistically characterize the trend and variability of water level regimes in Dongting Lake from 1959 to 2016; and (2) to quantitively evaluate the water level regime alterations caused by the TGR by comparing the pre- and post-reservoir periods with RVA. The investigation and estimation of TGR impacts on water level regimes could be beneficial for ecological restoration in Dongting Lake.

STUDY AREA AND DATA

Dongting Lake is the second largest freshwater lake in China with an area of 2,625 km^2. It is located in the middle of the Yangtze River, which is divided into three sub-lakes (east, south, and west) (Figure 1). Chenglingji, Yangliutan and Nanzui station are the hydrological stations in the Dongting Lake. There are three diversions (Songzi River, Hudu River, and Ouchi River) and four other major rivers (Xingjiang river, Zishui river, Yuanjiang river and Lishui river) in the Dongting Lake basin. All the water drains back into the Yangtze River from the Chenglingji station (Huang *et al.* 2011; Guan *et al.* 2016). The annual mean precipitation of the Dongting Lake is about 1,200–1,400 mm. Because of its distinct geographical position, climate conditions and dry–wet cycles, Dongting Lake hosts a significant ecosystem, which includes approximately 1,300 plant species and a wide variety of fish, birds and other mammals. Especially, it provides a vital

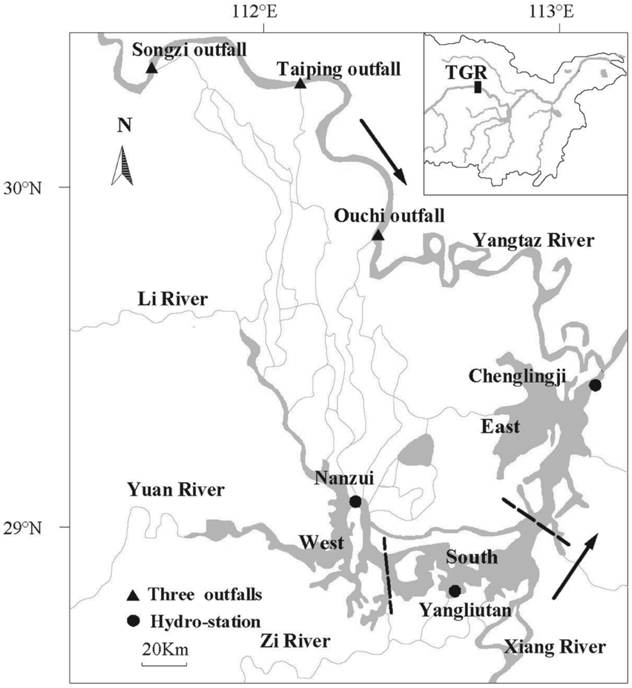

Figure 1 | Map of Dongting Lake and the location of the TGR.

winter wetland habitat for valuable migratory birds. TGR, upstream of Dongting Lake, has been given extensive attention since it began to store water in 2003. In 2010, the full impoundment raised the water level to 175 m, which is the historic highest water level. The project has strong flood control, power generation, shipping and other comprehensive utilization benefits. However, it also brings the negative impacts on the river and lake ecosystems downstream of the Yangtze River.

The daily water level data from 1959 to 2016 at the Chenglingji, Nanzui, and Yangliutan stations were collected from the Institute of Water Conservancy and Hydroelectric Science of China. The streamflow regimes of the Yangtze River have been impacted remarkably by the TGR operation starting in 2003. As a result, the year 2003 was used to divide two periods at the Chenglingji, Nanzui and Yangliutan hydrological stations, the pre-impact period (1959–2002) and the post-impact period (2003–2016).

METHODS

Non-parametric Mann-Kendall (M-K) test

The M-K test has been identified as a scientific and practical technique to examine the trend, significant and inflection points of hydrological data in previous studies due to its robustness for non-parametric normally distributed time series (Burn & Elnur 2002; Kahya & Kalaycı 2004; Zhang *et al.* 2006; Mei *et al.* 2015).

M-K test of trend

The test statistic S is given by the following:

$$S = \sum_{i=1}^{n-1} \sum_{j=n-1}^{n} \operatorname{sign}(x_i - x_j) \tag{1}$$

$$\operatorname{sign}(x_j - x_i) = \begin{cases} 1 & \text{if} \quad x_j > x_i \\ 0 & \text{if} \quad x_j = x_i \\ -1 & \text{if} \quad x_j < x_i \end{cases} \tag{2}$$

where x_i and x_j are observed value, and n is the length of data. S is a normal distribution and its mean value is 0. The standard normal variate Z is computed by using the following equation.

$$\operatorname{var}(S) = [n(n-1)(2n+5) - \textstyle\sum_t t(t-1)(2t+5)]/18 \tag{3}$$

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}}, & S < 0 \end{cases} \tag{4}$$

where t is the extent of any given tie and $\sum_t$ denotes the sum over all ties.

If $|Z| < Z_{\alpha/2}$ at a α level of significance, the result should be accepted. A positive value of Z indicates upward trend, and vice versa.

The ability of M-K test to detect trends can be influenced by autocorrelation in the data. Given this, the 'trend-free pre-whitening' (TRPW) technique was applied before the M-K test to avoid this issue in this paper. More details of calculation procedures about the TRPW technique can be obtained from Yue *et al.* (2002) and Shahid *et al.* (2020).

M-K test of inflection points

Under the assumption of random independence of time series, the defined statistics are as follows:

$$d_k = \sum_{i=1}^{k} n_i, \quad 2 \leq k \leq n \tag{5}$$

$$E(d_k) = \frac{k(k-1)}{4}, \; 2 \leq k \leq n \tag{6}$$

$$\mathrm{Var}(d_k) = \frac{k(k-1)(2k+5)}{72}, \; 2 \leq k \leq n \tag{7}$$

$$UF(d_k) = \frac{d_k - E(d_k)}{\sqrt{\mathrm{Var}(d_k)}}, \; 2 \leq k \leq n \tag{8}$$

$$UB(d_k) = -UF(d_k) \tag{9}$$

where $E(\mathrm{d}_k)$ is the mean of d_k. $\mathrm{Var}(\mathrm{d}_k)$ is the variance of d_k.

Supposed $\mathrm{UF}_1 = 0$, all $\mathrm{UF}(\mathrm{d}_k)$ set up a curve UF. When $\mathrm{UB}(\mathrm{d}_k)$ and $\mathrm{UF}(\mathrm{d}_k)$ of a time series intersect and are located between the confidence lines, the time corresponding to the intersection is considered to be the start time of the mutation. A confidence of 95% is usually used when testing the series.

RVA and degree of hydrologic alteration

The original IHA uses 33 parameters to assess the hydrologic alteration, which are divided into five groups addressing the magnitude, timing, frequency, duration and rate of change. In the hydrological analysis of lakes, 'number of zero-water level day' and 'base flow index' are not considered. The parameters were exhibited in Table 1 and the degree of hydrologic alteration can be easily calculated by IHA software.

RVA is applied to quantitative estimation the degree of hydrologic alteration by analysing daily water level in the pre- and post-impact periods. The RVA targets range for each hydrologic parameter is usually based upon selected percentile levels or a simple multiple of the parameter standard deviations for the natural or pre-impact hydrological regime. In the RVA analysis, the RVA targets are computed based on the full range of pre-impact data and the 25th and 75th percentile incidences of each parameter. The degree of hydrological alteration, D_i, is calculated to quantify the deviation of the post-reservoir hydrological regime from the pre-reservoir regime, and, defined as follows:

$$D_i = \left| \frac{N_{oi} - N_e}{N_e} \right| \times 100\% \tag{10}$$

where D_i denotes the degree of the hydrological alteration for the i th parameter, N_{oi} denotes the observed number, and N_e is the expected number. To assess the degree of hydrological alternation, three classes were divided by Richter *et al.* (1998). D_o ranging between 0% and 33% denotes a low degree, 33–67% denotes moderate degree, and 67–100% denotes a high degree. In addition, an overall index, D_o, is defined as follows:

$$D_O = \left(\frac{1}{31} \sum_{i=1}^{31} D_i^2 \right)^{0.5} \tag{11}$$

The methodological steps

The summarized schematic diagram of the methodological steps is presented in Figure 2.

RESULTS

Characteristics of the annual water levels

Trend analysis of the annual water levels

Figure 3 gives the average annual water level at the Chenglingji, Yangliutan and Nanzui stations for 1959–2016. Figure 3 shows that during this period, generally speaking, there are an upward trend at the Chenglingji and Yangliutan stations, and a downward trend at the Nanzui station.

In Table 2, the mean M-K values of annual water level at the Chenglingji station was 2.39, which greater than 1.96, there was an obvious upward trend at the Chenglingji station ($p < 0.05$). The mean M-K values of annual water level at the Yangliutan station was 0.48 which less than 1.96, there was not an obvious upward trend at the Chenglingji station ($p < 0.05$). The mean M-K values of annual

Table 1 | IHA groups and parameters

General group	Water level parameters used in the IHA	Explains
Group 1: Magnitude of monthly water condition	Medians value for each calendar month	A measure of availability or suitability of habitat.
Group 2: Magnitude and duration of annual extreme conditions	Annual minimum 1-day medians Annual maximum 1-day medians Annual minimum 3-day medians Annual maximum 3-day medians Annual minimum 7-day medians Annual maximum 7-day medians Annual minimum 30-day medians Annual maximum 30-day medians Annual minimum 90-day medians Annual maximum 90-day medians	The medians magnitudes of high and low water extremes of various durations provide measures of environmental stress and disturbance during the year; such extremes may be necessary precursors or triggers for the reproduction of certain species.
Group 3: Timing of annual extreme water condition	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum	Can determine whether certain life-cycle requirements are met.
Group 4: Frequency and duration of high and low pulses	Number of high pulses each year Number of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year	High pulses: the daily flows are above the 75th percentile of the pre-dam period. Low pulses: the daily flows are below the 25th percentile of the pre-dam period.
Group 5: Rate and frequency of water condition changes	Rise rate Fall rate Number of hydrologic	The rate of change in water condition may be tied to the stranding of certain organisms along the water edge.

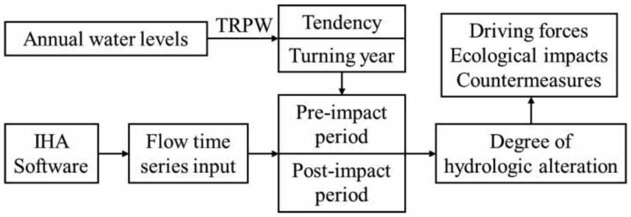

Figure 2 | The schematic diagram of steps involved in methodology.

water level at the Nanzui station was –2.76, with absolute value greater than 1.96, there was an obvious downward trend at the Nanzui station ($p < 0.05$).

Turning years in the annual water level

The annual water level, as revealed by the M-K method, showed an abrupt upward change on 2003. To verify the abrupt change, a cumulative departure curve and moving t-test were used to analyze the turning years. Through comprehensive analysis, it was determined that the annual water level at the Chenglingji, Nanzui and Yangliutan stations turned in 2003. Therefore, the TGR had an apparent effect on the water level variations in Dongting Lake.

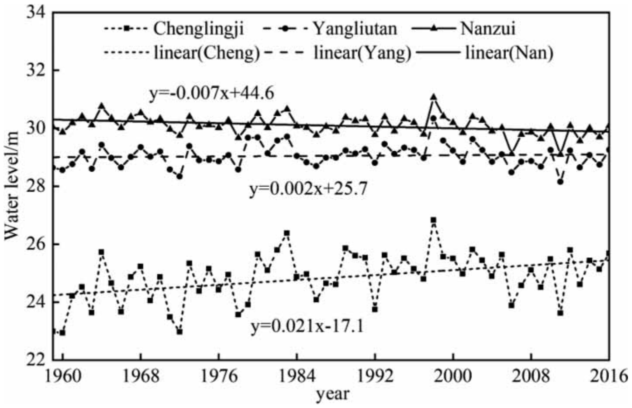

Figure 3 | Trend of the water levels in the Dongting Lake.

Table 2 | M-K trend test of average annual water level in the Dongting Lake

Station	**Chenglingji**	**Nanzui**	**Yangliutan**
Statistic	2.39	−2.76	0.48
Confidence level	1.96	1.96	1.96
Trend	Significant	Significant	Non-significant

Changes of the hydrologic indicators

Based on the time of TGR impoundment, the water levels from 1959 to 2016 were divided into the pre-impact period (1959–2002) and the post-impact period (2003–2016), which represented the water level under natural conditions and alternated conditions, respectively. According to the two periods, water level was evaluated to analyze the hydrologic regime characteristics by RVA (Table 3).

Magnitude of monthly water level

Figures 4 and 5 summarize the magnitude of the median monthly water conditions before and after the TGR impoundment, as obtained by IHA. The magnitude of the monthly median water level was more than the pre-reservoir values from January to March, especially in March. However, from July, October, and November, the monthly median water level decreased after 2003, particularly in November at the Chenglingji station. Yangliutan station had the largest decrease in July. Nanzui station had the largest decrease in October. The Chenglingji, Yangliutan and Nanzui stations all experienced moderate changes, with hydrologic alterations of 51, 43, and 49%, respectively. These changes were directly related to the operation mode of the TGR, which had a regulating effect on Dongting Lake. According to the rules regulating the TGR, the rising water level was caused by the water release in the dry seasons, and the decline was caused by impoundment of the TGR in the wet seasons.

Magnitude and duration of annual extreme water level

Significant distinctions were discovered in the median minimum water level between the pre-impact and post-impact periods. In contrast, most of the medians of the 1-, 3-, 7-, 30-, and 90-day maximum water levels decreased (Table 3). Most of the annual minimum water levels showed high or moderate levels of alteration, particularly at the Chenglingji and Yangliutan stations. For example, the annual 3-day minimum water levels at the Chenglingji and Yangliutan stations were apparently greater than those during the pre-impact period (Figures 6 and 7), with high alterations of 80 and 100%, whereas most of the annual maximum water level experienced low levels of alteration. The median extreme water level at the Chenglingji, Nanzui and Yangliutan stations presented moderate alterations.

Analysis of the timing of annual extreme water level

The median of the 1-day minimum at the Chenglingji and Nanzui stations were earlier than those in the pre-impact period, whereas the median of the 1-day maximum were later than those in the pre-impact period. Chenglingji station was categorized as having moderate alternation, Nanzui station was categorized as having low alteration, and Yangliutan station was categorized as having low and moderate alteration (Table 3). Although the median of the 1-day minimum still mainly occured during December to March, the median of the 1-day minimum at the Chenglingji, Nanzui and Yangliutan stations was from early February, late January to early January, and portion of the rest of the year, even extending into December at Chenglingji station. There was no strong effect in the timing of the maximum water level by the TGR, in which the median of the 1-day maximum was 30 days later than that from the pre-impact period. Therefore, the median of the 1-day minimum has been strongly affected since the TGR impoundment.

Table 3 | The IHA parameters in pre-TGR and post-TGR periods

	Chenglingji			**Nanzui**			**Yangliutan**		
IHA parameters	**Med-pre**	**Med-post**	**D*i* %**	**Med-pre**	**Med-post**	**D*i* %**	**Med-pre**	**Med-post**	**D*i* %**
January	20.05	20.94	– 80	28.29	28.43	96	27.72	27.75	29
February	19.69	20.97	– 80	28.42	28.39	– 41	27.88	27.78	– 2
March	20.91	22.50	– 2	28.85	29.00	– 21	28.34	28.31	– 8
April	23.60	24.04	38	29.66	29.49	38	28.84	28.78	– 21
May	26.02	26.75	– 41	30.66	30.45	– 2	29.33	29.52	– 2
June	27.55	28.22	38	31.47	31.10	– 2	29.90	29.99	48
July	30.45	29.43	– 61	32.44	31.87	– 41	31.40	30.54	– 41
August	28.79	29.47	– 61	31.60	31.4	– 21	29.95	30.23	– 21
September	28.30	28.64	– 41	31.18	30.88	– 2	29.37	29.50	– 2
October	26.68	25.38	– 41	30.47	29.17	– 100	28.69	28.02	– 80
November	24.13	23.32	– 2	29.62	28.81	– 61	28.32	27.83	– 100
December	21.10	21.38	18	28.57	28.39	– 21	27.83	27.62	– 2
1-day minimum	18.95	20.34	– 80	28.03	27.97	– 21	27.28	27.27	99
3-day minimum	18.99	20.36	– 80	28.05	27.98	– 2	27.28	27.28	100
7-day minimum	19.08	20.44	– 80	28.06	28.03	18	27.30	27.31	100
30-day minimum	19.29	20.79	– 80	28.19	28.24	77	27.48	27.46	57
90-day minimum	19.96	21.6	– 80	28.56	28.48	38	27.89	27.70	– 21
1-day maximum	32.25	31.81	18	34.21	34.31	– 41	33.38	32.86	– 21
3-day maximum	32.21	31.77	18	34.14	34.18	– 41	33.33	32.77	– 21
7-day maximum	32.03	31.59	18	33.92	33.71	– 41	33.17	32.62	– 2
30-day maximum	31.00	30.91	– 2	32.98	32.81	– 21	31.96	31.54	– 41
90-day maximum	29.59	29.61	18	32.16	31.84	– 21	30.78	30.57	– 2
Date of minimum	35.00	0.50	– 65	28.50	20.00	– 2	7.50	6.50	– 2
Date of maximum	199.50	207.00	– 48	195.50	201.50	11	192.50	202.50	– 61
Low pulse count	2.00	2.00	– 33	2.00	4.50	– 50	3.00	5.50	– 61
Low pulse duration	56.00	19.00	– 16	39.25	10.00	– 58	13.00	10.25	48
High pulse count	2.00	2.00	– 15	5.00	4.00	– 35	4.00	3.50	– 6
High pulse duration	38.00	55.25	– 82	9.00	10.50	– 55	13.00	24.50	– 21
Rise rate	0.14	0.12	– 40	0.08	0.06	– 67	0.07	0.08	– 37
Fall rate	– 0.11	– 0.11	10	– 0.06	– 0.06	– 21	– 0.06	– 0.06	9
Number of reversals	43.00	51.00	– 41	59.00	73.50	– 83	78.00	90.50	– 63

Frequency and duration of high and low pulses of water level

The low pulses count has increased but the duration of low pulses has decreased, and the high pulses count has decreased but the duration of high pulses has increased in the post-impact period at Chenglingji station, Yangliutan station and Nanzui station. Frequency and duration of high and low pulses of water level were altered at Nanzui station, which displayed moderate alteration, whereas the low pulse duration decreased dramatically from nearly 39 days per event to less than 10 days per event at Nanzui station (Figure 8). The high pulse duration increased dramatically from nearly 38 days per event to 55 days per

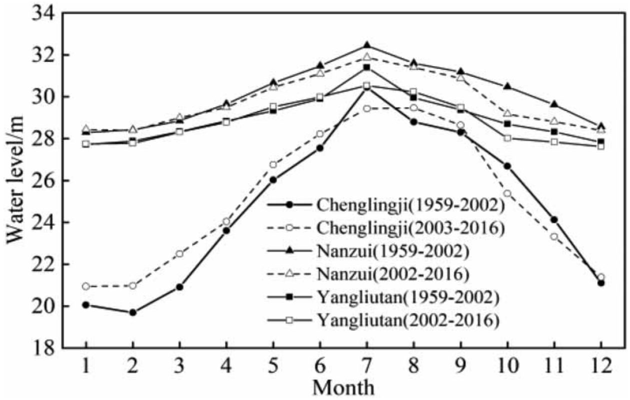

Figure 4 | Monthly water level alteration magnitude.

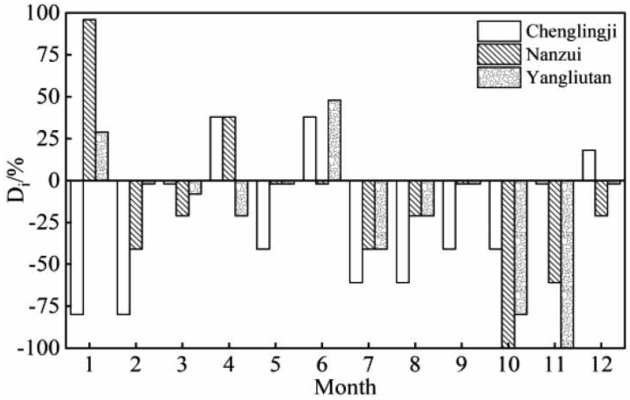

Figure 5 | Monthly water level difference value.

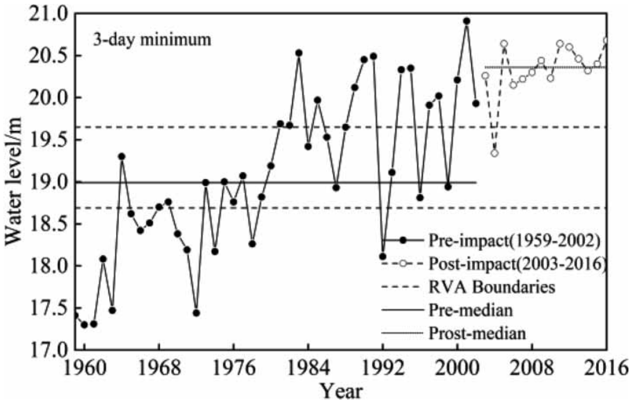

Figure 6 | The annual 3-day minimum water level at Chenglingji station.

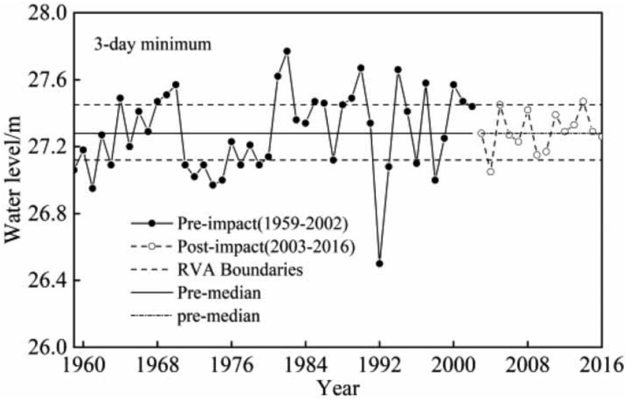

Figure 7 | The annual 3-day minimum water level at Yangliutan station.

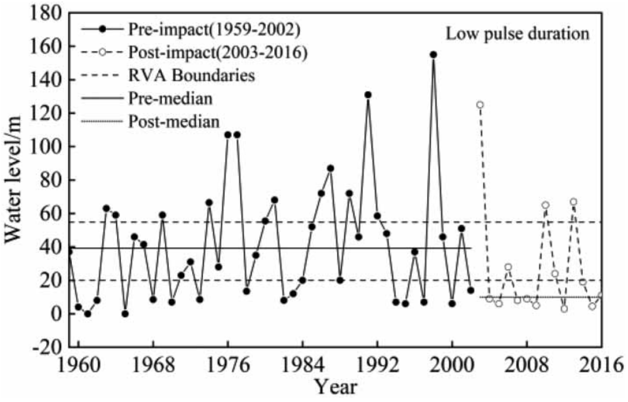

Figure 8 | Low pulse duration at Nanzui station.

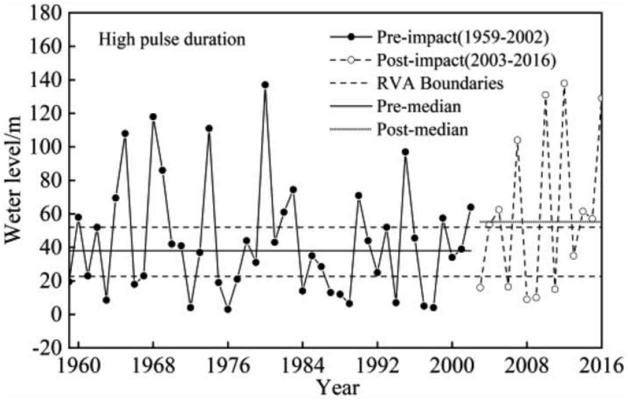

Figure 9 | High pulse duration at Chenglingji station.

event at Chenglingji station; almost all of them were outside the RVA target range with alterations of 82% (Figure 9). In summary, the construction of the TGR reduced the count and duration of low pulses, which could prevent drought. The decrease in the high pulse count and duration could effectively reduce the flood peak, whereas the low water level increased.

The rate and frequency of variations in water level

Both the rate of increase and number of the reversals were strongly affected at Nanzui station, particularly the number of reversals for which no values were within the RVA target; the degree of alteration reached 83% (Figure 10). Both the rate of increase and the number of reversals were moderately affected at Yangliutan station and Yangliutan station, where the rate of decrease was categorized as low. In summary, the rate and frequency of the changes in water levels at Nanzui station were the most significant. It was shown that the TGR had the greatest influence on the water level at Nanzui station during the process of the peak and frequency modulation.

Evaluation of hydrologic alteration

Comparison of hydrologic alteration before and after impoundment

The 31 hydrologic alteration absolute values at the Chenglingji, Nanzui and Yangliutan stations in the Dongting Lake were analyzed (Figure 11). From Figure 11, it can be observed that the degrees of alteration in October reached 100% at Nanzui station (Figure 11(b)); the changes in the November, 3-day minimum and 7-day minimum reached 100% at Yangliutan station (Figure 11(c)).

The proportion of the degrees of hydrological alteration at each hydrological station was plotted (Figure 12). From Figure 12, the proportions of high levels of alterations in the IHA indicators were the highest at Chenglingji station and accounted for 26% of the changes, and the proportion of high alterations in the IHA indicators at the Nanzui and Yangliutan stations followed, reaching 13 and 16%, respectively. The proportion of moderate alterations in the IHA indicators at Nanzui station was 42%, at Yangliutan station was 29%, and at Chenglingji station was 35%. The highest proportion of low alteration in the IHA indicators at Nanzui and Yangliutan stations reached 55%, followed by Chenglingji with 39%. The results indicated that the hydrologic regime at Chenglingji, Nanzui and Yangliutan were dominated by low alteration. However, the degree of IHA at Chenglingji station was altered more than that at Nanzui and Yangliutan stations. This may be because Chenglingji station is the only entrance to Dongting Lake.

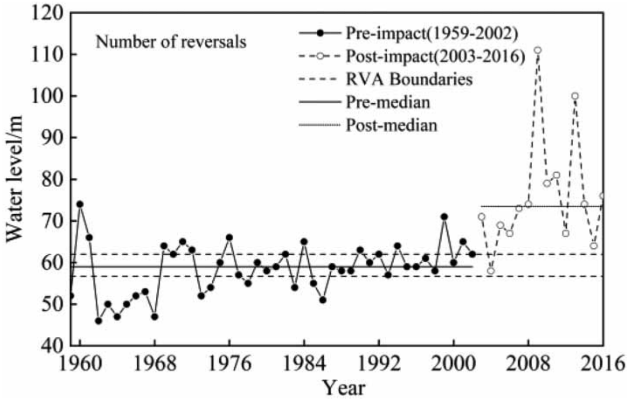

Figure 10 | Change of number of reversals at Nanzui station.

Integrated evaluation of the hydrologic alteration

Table 4 lists the integrated hydrologic alteration indicators, D_o. We can find that the overall hydrological comprehensive analysis shows that 50, 46 and 49% of the change at the Chenglingji, Nanzui and Yangliutan stations were at the moderate degree of alteration. The degree of alteration at the Chenglingji station was more obvious. The reason was preliminarily speculated to be that Chenglingji station is near the main channel of the Yangtze River and is affected by flood regulation and storage of the upstream TGR.

DISCUSSION

Human activities such as reservoir operation, land utilization change and river channelization will affect the hydrological regimes in the lake. In addition, the water level alteration in Dongting Lake may also be attributed to the river-lake system change and long-term lake evolution (Yuan *et al.* 2015; Wang *et al.* 2017). In the past 60 years, the Yangtze River has experienced a series of projects, such as Tiaoxuan outfall closure, Jingjiang cutting bend and the Gezhou Dam. Frequent human activities have led to many adjustments in the relationship between rivers and lakes. It was not until the 1990s that this relationship gradually stabilized. In 2003, the TGR began to impound, and the dam trapped a large amount of flow and sediment

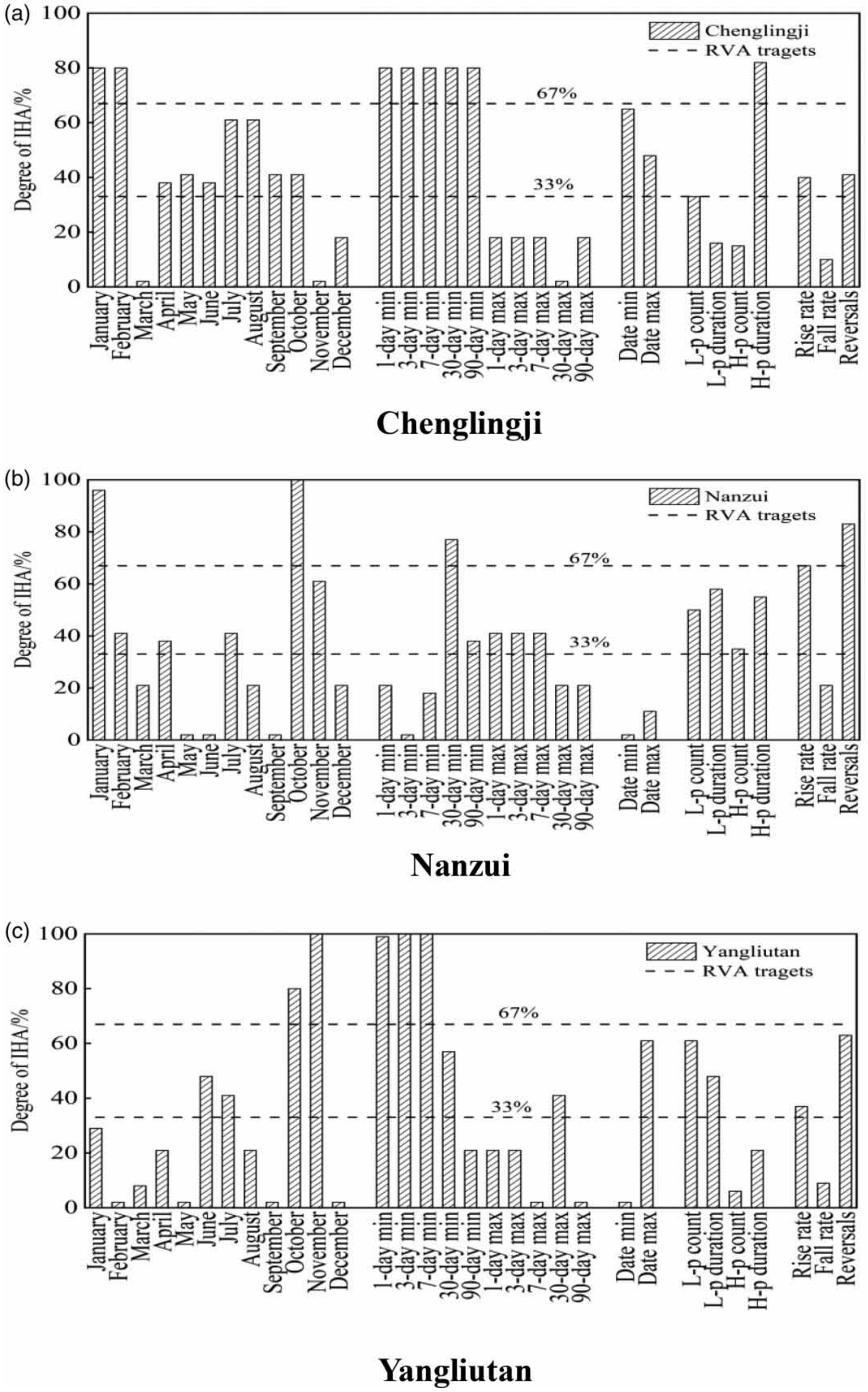

Figure 11 | The hydrologic alteration absolute values at the Chenglingji (a), Nanzui (b) and Yangliutan (c) stations in the Dongting Lake.

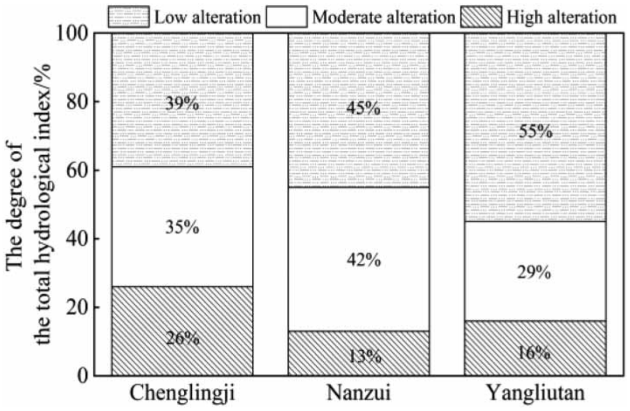

Figure 12 | The proportion of the degrees of hydrological alteration at the hydrological station.

from the upstream. Thus, the hydrological regimes of Dongting Lake connected by the Yangtze River changed dramatically (Yang *et al.* 2016). After the impoundment of the TGR, the diversion flow of the three outfalls of the Yangtze River (the Songzi outfall, Hudu outfall and Ouchi outfall) was reduced in Dongting Lake. The water level decline speed was accelerated between September and October (Zhang *et al.* 2015a, 2015b; Zhu *et al.* 2016). Figure 13 shows that the flow from the three rivers had a declining trend from 1956 to 2016.

In addition to the direct streamflow changes induced by the TGR's operation, the water level declined in the main channel immediately downstream by river bed scouring due to sediment trapping and the releasing of clear water by the TGR, increasing the water level difference between Dongting Lake and the main channel, which is the underlying cause of the water level change of Dongting Lake. The findings are similar to Huang *et al.* (2011) and Lai *et al.* (2014), indicating the impoundment of the TGR is the main cause of the water level change of Dongting Lake from 2003. Additionally, the four major rivers (Xingjiang river, Zishui river, Yuanjiang river and Lishui river) play a significant role in the water level change of Dongting Lake from September to November (Cheng *et al.* 2017). What is more,

Table 4 | Integrated hydrological alteration indicators unit: %

	IHA subgroups					
Stations	**Group 1**	**Group 2**	**Group 3**	**Group 4**	**Group 5**	D_o
Chenglingji	49(M)	58(M)	57(M)	46(M)	34(M)	50(M)
Nanzui	49(M)	37(M)	8(L)	50(M)	63(M)	46(M)
Yangliutan	43(M)	60(M)	43(M)	40(M)	43(M)	49(M)

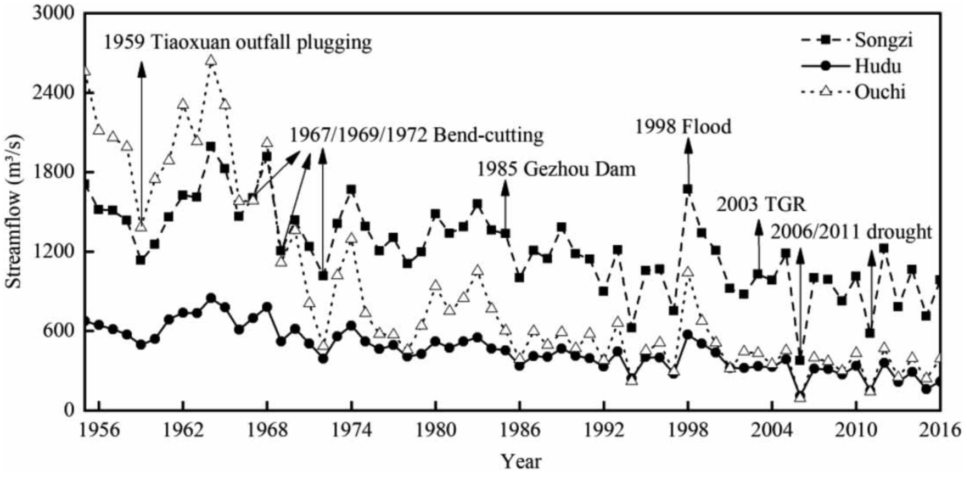

Figure 13 | Temporal variations in the streamflow of the Hudu River, Ouchi River and Songzi River from 1956 to 2016.

rainfall plays an important role in the water level change of Dongting Lake from May to July, and this has also been confirmed by Shi *et al.* (2012). However, the effects of rainfall and the TGR on water level change are not distinguished in this paper. This should be taken into account in future studies.

The TGR operation will not only change the hydrological regimes of Dongting Lake but also change the water quality, geomorphology and aquatic biological community of the lake; these changes will affect the health of the lake ecosystem and even produce a series of extensive, profound and long-term ecological effects. First, the change in water level will affect the vegetation coverage and species composition of wetlands and eventually lead to community succession (Yao *et al.* 2014). The TGR reduced the fluctuation range of the water level in Dongting Lake from 2003. This reduction was mainly conducive to the growth and biomass increase of the reeds at lower elevations, while the reeds at higher elevations were gradually replaced by shelterbelts. The decrease in the lake water inflow leads to a decrease in the water level of Dongting Lake, and the outcrop time of the beach is extended, which intensifies the forward succession of wetland vegetation toward the lake center (Hu *et al.* 2015; Wu *et al.* 2017). The variation in the hydrological regime provides favorable conditions for the growth and expansion of invasive alien species, especially the invasion of poplars (Hou *et al.* 2011). The change in the vegetation community structure also promotes a corresponding change in the bird community structure, especially the wetland birds that occupy a wide water area or aquatic grass area as habitats and foraging grounds; their living space gradually disappears because of the poplars invasion, leading to a decrease in the wetland birds (Deng *et al.* 2008). Additionally, the changes in the wetland vegetation community structure and distribution pattern will also affect the food sources of water birds and seriously damage their habitat (Yang *et al.* 2016). In addition, the number of floating fish eggs and larvae in the Yangtze River decreased sharply after the impoundment of the TGR, and the number of fish larvae entering Dongting Lake significantly decreased; these changes had a great impact on the fish population structure and fishery resources in Dongting Lake. The prolonged dry season can cause the number of parent fishes in the river to reduce or increase the parent fish breeding. The shortening of the fish growth period and the extension of the autumn fishing season will affect fish growth and lead to a reduction in fish production. According to the statistical yearbook of the Dongting Lake, from 1997 to 2009, the total catch output of wild fish in the Lake decreased from 52,692.4 t to 21,932.7 t, with an average annual decrease of about 2,366.1 t. After the impoundment of the TGR (2003–2009), the populations of Four Famous had an average decrease of about 218 t per year (Li *et al.* 2012).

In order to resolve the current problems, some countermeasures should be considered to mitigate the impact of water level changes in Dongting Lake. The TGR should increase the flow and sediment and restrain the excessive erosion of the middle and lower reaches of the Yangtze River, so as to reduce the water level difference between Dongting Lake and the main channel of the Yangtze River and reduce the water level variation of Dongting Lake (Hu 2016). Moreover, the inflow into Dongting lake was restored to 100 billion m^3/a through deep excavation of Songzi outfall and regulation of Songzi River, so as to improve the water level of Dongting Lake (Zhou & Zhang 2018). Besides, more fresh water should be introduced through the four major rivers (Xingjiang River, Zishui River, Yuanjiang River and Lishui River) to improve the water environment of Dongting Lake.

CONCLUSIONS

Based on a newly updated water level dataset, the variations of water level characters in Dongting Lake caused by the TGR were evaluated with the RVA method. The major findings can be summarized as follows:

(1) The annual water level showed an increasing trend from 1959 to 2016 at the Chenglingji and Yangliutan stations. The Chenglingji station had an obvious upward trend with a degree of confidence of 95%, and the Nanzui station had a decreasing trend with a degree of confidence of 95%, while the upward trends of the Yangliutan station were not significant.

(2) Compared with hydrologic characters in the pre-impact period, those during the post-impact period demonstrated changes. The main changes included decline in the wet seasons and increase in the dry seasons. The rate of variation and extreme water level were affected

by TGR, while the timing of the maximum water level and high/low pulses (except at Chenglingji station) were less affected.

(3) The degree of hydrologic alteration at the Chenglingji and Yangliutan hydrological stations was dominated by moderate and high alterations, but Nanzui station was dominated by moderate and low alterations. The overall degrees of hydrologic alterations at Chenglingji and Yangliutan were 50 and 46%, respectively, whereas at Nanzui station, the alteration was 49%.

(4) The TGR has greatly changed the river–lake relationship along the Yangtze River and Dongting Lake. The flow regime alteration has changed the characteristics of wetland vegetation distribution, birds and water space for fish breeding; this change has resulted in a decline in the production of fishes and the number of migratory birds, eventually damaging the ecological system. It is imperative to adjust the operation scheme of the TGR to increase the flow into the lake during the dry season to maintain the dynamic balance of the Dongting Lake ecosystem.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

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

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