Water safety assessment and spatio-temporal changes in Dongting Lake, China on the basis of water regime during 1980–2014

Rongrong Wan, Peng Wang, Xue Dai and Zheng He

ABSTRACT

The drastic changes in water regime are of great importance for maintaining water security in lakes with violent seasonal fluctuations. Based on hydrological data of Dongting Lake, the second largest freshwater lake in China, during 1980–2014, a set of water safety assessment methods suitable for seasonal lakes was constructed. Results demonstrated the following. (1) The year 2003 was a major time point for changes in water regime in Dongting Lake between 1980 and 2014. (2) The water regime changes in different parts of Dongting Lake exhibited certain similarities in periodicity and overall change trends. Among them, South Dongting Lake presented the best water security status, followed by East Dongting Lake and West Dongting Lake. (3) Compared with 1980–2002, the complexity of the water safety level change in East Dongting Lake increased in 2003–2014, as manifested in the tendency of the distribution of water safety levels to change sharply. (4) The influence of dry years on the water safety of Dongting Lake was greater than that of rainy years. The multi-time, multi-scale and multi-target lake water safety assessment method based on water regimes provides new ideas and methods for global research on seasonal lake water safety.

Key words | Dongting Lake, lake water regime, natural lakes, seasonal water level fluctuations, water safety

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INTRODUCTION

The safety status of a lake is not only of great significance to the socio-economic sustainable development of its surrounding areas but also plays an important role in maintaining the health of the lake and wetland ecosystem (Meyer *et al.* 1999; Overton & Doody 2009; Chin *et al.* 2014) . In recent years, human activities such as agricultural irrigation, dam construction and underlying surface changes have changed the lake hydrological process, resulting in serious flood disasters, seasonal water shortages and degradation of wetland ecosystems in the lake region (Alrajoula *et al.* 2016; Yang *et al.* 2016; Silio-Calzada *et al.* 2017). These issues have attracted widespread attention on a global scale (Acreman *et al.* 2007; Dawidek & Ferencz 2016; Costi *et al.* 2018). Water level is the most direct and commonly used indicator for lake water regime (Raulings *et al.* 2010; O'Farrell *et al.* 2011; Zhang *et al.* 2017b). It results from the complex effects of various elements of the lake's water balance and indicates whether the lake's water regime threatens the security status of the surrounding area (Nienhuis 2006; Wan *et al.* 2018). For example, extremely high water levels lead to flooding, which can cause huge loss of life or property in a lake area; by contrast, extremely low water levels lead to drought, which affects water supply in the lake area (Zhang *et al.* 2015, 2017a; Goertler *et al.* 2018). In current studies, water levels are widely used in the characterization of lake water safety in terms of flood and drought prevision (Liu *et al.* 2011, 2013; Li *et al.* 2017). Current lake water safety

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assessment methods generally focus on the indication significance of high flood eigenvalues in lake flood control safety, as well as low and dry water eigenvalues in lake water supply security (Huang *et al.* 2014; Li & Zhang 2015; Liang *et al.* 2015). In-depth studies on the threshold determination of the safety level of lake flood control and water supply are limited. Moreover, some existing methods for water safety classification are based on the absolute value of the amount of water entering or exiting the lake or numerous or complicated assumptions for different hydrological stages, making their practical application in specific areas difficult.

For the river-communicating lakes (floodplain lakes) in the middle and lower reaches of the Yangtze River, where the water level fluctuations are complex during the year and seasonal rhythm is apparent, the classification and evaluation methods of the above lake safety levels are less applicable. The method of dividing the safety level by the absolute value of water level or flow rate cannot easily determine the uniform threshold in the significantly different dry–rising–flood–recession rhythm (Dai *et al.* 2015, 2018). Therefore, a new method for evaluating lake water safety is established due to the characteristics of natural river-communicating lakes, which is of great significance for understanding the changes in lake water safety status caused by alterations in water regime in recent years.

Dongting Lake is the second largest freshwater lake in China and an important river-communicating lake in the middle reach of the Yangtze River. As a typical floodplain lake, its water regime change is determined by the Yangtze River and basin waters. It has a clear seasonal rhythm of dry season–rising-season–flood season–recession-season (He *et al.* 2015; Dai *et al.* 2018). Recent studies have shown that the relationship between rivers and lakes in the middle and lower reaches of the Yangtze River has been constantly adjusted under the dual effects of nature and human activities (Lai *et al.* 2014; Wan *et al.* 2014; Yang *et al.* 2016). The Three Gorges Project and other river and lake remediation projects have important effects on the hydrological environment of Dongting Lake, thereby resulting in changes in lake water regime (Sun *et al.* 2012; Huang *et al.* 2014; Liu *et al.* 2016). Such changes have led to a sharp decline in the water security status of Dongting Lake. 'Safety disasters' include seasonal water shortages, degradation of wetland ecosystems and reduction in migratory bird habitats (Li *et al.* 2013; Guan *et al.* 2016; Jing *et al.* 2017; Zhang *et al.* 2018b). For example, the water surface area of Dongting Lake decreased by over 55% in May 2011, leading to more than 1,000 hectares of wetlands in East Dongting Lake drying up (Sun *et al.* 2012); count data show that wintering greater white-fronted goose (*Anser albifrons*) numbers in Dongting Lake have markedly declined from about 50,000 in the late 1980s and early 1990s to less than 1,000 in 2008/2009, which was caused by earlier water table recession (Zhao *et al.* 2012).

On the basis of the daily water level data of Dongting Lake from 1980 to 2014 and the Mann–Kendall test to determine and divide the relative stability study period, this study explores water safety assessment methods from the perspective of seasonal flood and drought. The specific steps are as follows. (1) The Shapiro–Wilk method was used to test the probability distribution characteristics of the water level sequence. The water safety level threshold was determined by the modified normal distribution method. (2) The water safety status of each lake area in different time periods was divided and compared on the 10-day (dekadal) scale. (3) The reasons for the difference in the water safety status of Dongting Lake in different research periods were revealed. This study is expected to provide new methods and ideas for seasonal lake water safety assessment and to improve the water safety warnings and forecasts.

DATA AND METHODS

Overview of the study area

Dongting Lake lies north of Hunan Province, China, and south of Yangtze River Jingjiang River section. It is the second largest freshwater lake, next to Poyang Lake, with an area of 2,625 km^2 (1995) (Jiang & Dou 2000). Dongting Lake is connected with the Xiangjiang, Zishui, Yuanjiang and Lishui Rivers in the south and the Yangtze River in the north, embracing the floods of the Yangtze River through 'four entrances', namely, Songzi, Taiping, Ouchi and Tiaoxian (plugged in 1958). The water enters the Yangtze River through Chenglinji in the east, which serves as the most important lake for regulation and storage in the Yangtze River. In recent years, Dongting Lake has been divided into East, South and West due to sediment siltation and reclamation; all these parts significantly differ in hydrological conditions (Jiang & Dou 2000; Yin *et al.* 2007) (Figure 1). East Dongting Lake occupies the largest area of 1,363 km^2, accounting for 51.9% of the total lake area. South Dongting Lake is second with an area of 917 km^2, accounting for 35.0% of the total lake area. West Dongting Lake has the smallest area of about 345 km^2, accounting for 13.1% of the total lake area. The average water depth of Dongting Lake is 6.39 m, the deepest point is 23.5 m (Jiang & Dou 2000). The average levels (1980–2014) of West, South and East Dongting Lakes are 25.3, 27.7 and 29.8 m, respectively (Table 1). Dongting Lake is the most important lake for storage and regulation in the middle and lower reaches of the Yangtze River, and it is irreplaceable in terms of flood control and ecological security in the middle reaches of the Yangtze River.

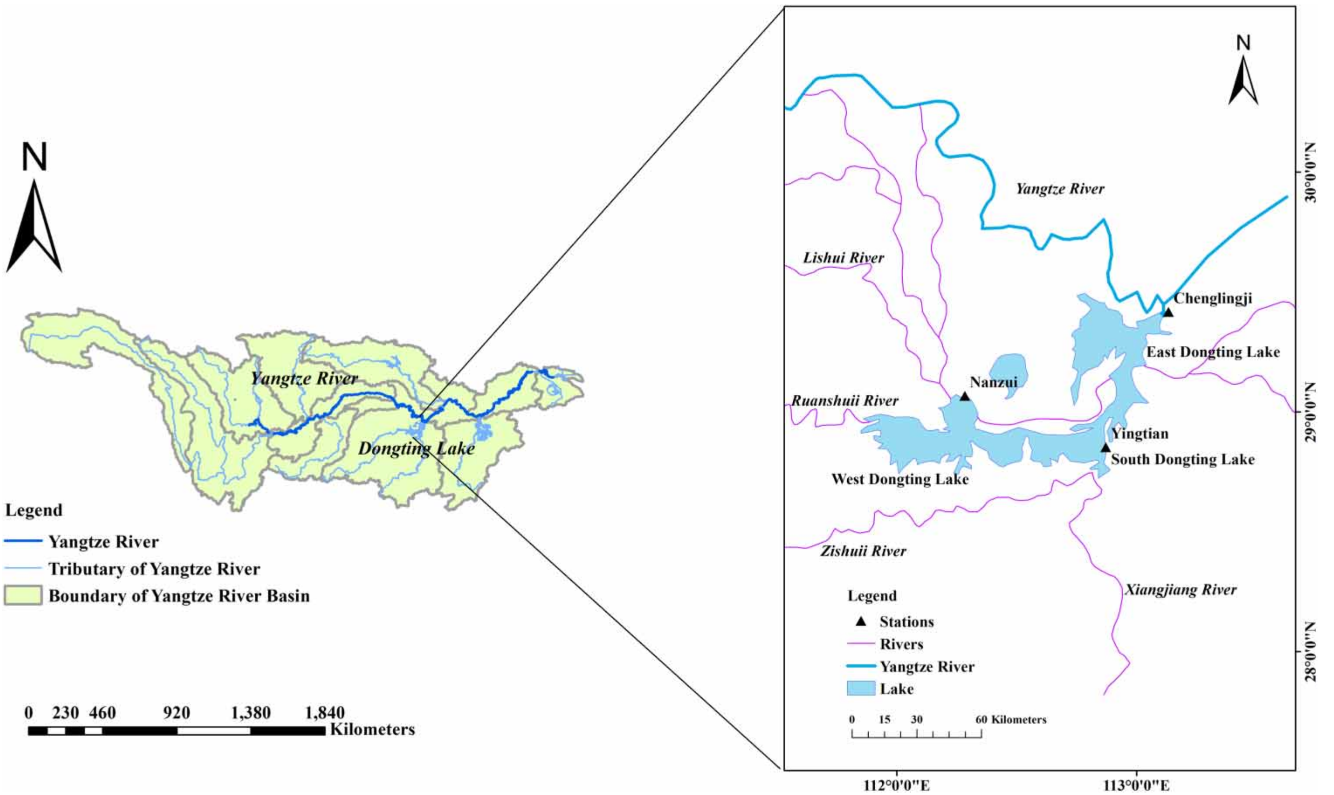

Figure 1 | Water system structure and hydrological station locations of Dongting Lake.

Table 1 | Characteristics of the three areas of Dongting Lake

Lake area	Location	Area (km^2)	Elevation (m)	Annual average water level (m)
East Dongting Lake	28°59′–29°38′N 112°43′ –113°	1,363	23–30	25.3
South Dongting Lake	28°38′–29° 112°18′–112°51′	917	25–32.5	27.7
West Dongting Lake	28°–29°08′ 111°48′–112°	345	27–30	29.8

Data

This study applied the daily water level data of the representative hydrological stations of East, South and West Dongting Lakes from 1980 to 2014 (data source: *Hydronomic Data of the Yangtze River Basin*, in which East Dongting Lake is represented by the hydrological station of Chenglingji station, West Dongting is represented by the hydrological station of Nanju station and South Dongting is represented by the hydrological station of Yingtian station). As the original water level data are based on the data measured by the frozen base of the respective hydrological station, the original data of each hydrological station were first preprocessed in this paper. The water level data of each station were converted into the water level data based on the Wusong reference surface. In addition, the paper applied the annual average rainfall data of 26 meteorological stations in the Dongting Lake watershed and its surrounding areas from 1980 to 2014 (http://data.cma.cn/) to analyse the effect of rainfall on the water safety status of Dongting Lake in different hydrological stages.

Design of water level safety rating method

The water safety rating for this study was based on two settings related to the normal distribution. (1) In medical statistics, the measurement results range of most people is the health interval, and the measurement results below or above this health interval are unhealthy. (2) In probability statistics, an event with a probability less than 0.01 is a small probability event, which is commonly referred to as an impossible event. Random variable X (Figure 2) that conforms to a Gaussian distribution is a small probability event beyond the range of the feature interval $[u-2\sigma, u+2\sigma]$. Given that the long-term water level sequence is generally of the Gaussian distribution, the water safety level rating can be converted into the delimitation and measurement of the extreme water level such as whether the water level is too high or too low in accordance with the setting based on normal distribution theory. On the basis of our previous research results (Wan *et al.* 2018), the dekadal (a period of 10 days) scale is ideal for lake water safety assessment. This study evaluated the water level safety of Dongting Lake.

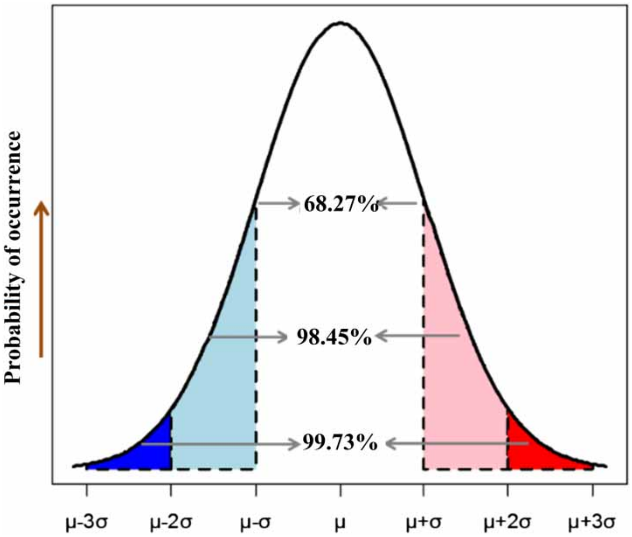

Figure 2 | Probability distribution of random events occurring in Gaussian distribution.

The specific water security level was divided through the following method. First, we checked whether the sequence of the water level in the dekadal scale conformed to the Gaussian distribution through Shapiro–Wilk. If the water level sequence in the dekadal scale conformed to the positive distribution, then the division thresholds for each level of water safety were determined by the average value of each water levels u and the standard deviation σ, as $X_1(u-2\sigma)$, $X_2(u-\sigma)$, $X_3(u+\sigma)$, $X_4(u+2\sigma)$.

In addition, the actual disaster prevention capacity and water demand of the lake area should be considered because the water safety level is related to the historical distribution trend of the water level sequence. Therefore, in accordance with the preliminary division of the water safety level based on normal distribution theory, the above threshold values were also corrected by using the actual warning water level (w) and guaranteed water level (g) of each lake area (the guaranteed and warning water levels of the representative hydrological station in the lake area are shown in Table 2). The interval threshold of the water safety level in Dongting Lake was corrected by w and g. If the warning water level was $w < X_3$, then X_3 was corrected to w. If the water level was $g < X_4$, then X_4 Modified tog should be used. Finally, the corrected normal distribution of water security levels in each lake area threshold values are $X_1, X_2,$

Table 2 | Warning and guaranteed water levels of each representative hydrological station in the three lake areas

Lake area	Hydrological station	Warning water level (*w*) (m)[a]	Guaranteed water level (*g*) (m)[a]
East Dongting Lake	Chenglingji	32.54	34.40
South Dongting Lake	Yingtian	34.00	35.05
West Dongting Lake	Nanzui	34.00	36.05

[a]*Note:* Wusong Elevation.

X_3 and X_4, and the final water safety level can be determined using Formula 1:

$$L = \begin{cases} Poor, X_i < X_1 \text{ or } X_i > X_4 \\ Good, X_1 \leq X_i < X_2 X_3 \leq X_i < X_4 \\ Fair, X_2 \leq X_i < X_3 \end{cases} \quad (1)$$

where L represents the evaluated security levels of Poor (no security), Fair (secondary security) and Good (safe); X_i is the average water level at a certain time that must be evaluated.

In a series of special days when the average water level sequence did not correspond to the positive distribution, the normal distribution threshold value determined by the mean and standard deviation, $u-2\sigma$, $u-\sigma$, $u+\sigma$, $u+2\sigma$, was insufficient to reflect the distribution characteristics of the data. Feature values X_1, X_2, X_3 and X_4 were determined by the quantile at 0.023, 0.1587, 0.8413 and 0.9772, respectively, of the sequence in the accumulated f frequency in this paper. The modified method of the threshold value was the same as the days corresponding to the normal distribution.

RESULTS AND ANALYSIS

Annual scale evolution characteristics of water levels

Figure 3 shows the mutation results of the annual average water level of the three hydrologic stations in Dongting Lake through the Mann–Kendall method. Figure 3(a) shows that the water level of East Dongting Lake fluctuated in the 1980s. In the 1990s, the water level remained steady. After 2000, the water level showed a significant downward trend. The three mutation points were 1985, 1988 and 2003. The water level demonstrated a significant downward trend especially after 2003. Figure 3(b) shows that the water level change of South Dongting Lake since 1980 was similar to that of East Dongting Lake, which was also divided into three periods. The mutation periods were 1985, 1987 and 2003. Figure 3(c) shows that the water level change of West Dongting Lake was significantly different from that of the former two lakes in that it had only one apparent mutation period since 1980. The water level of the three regions in Dongting Lake exhibited a significant downward trend after 2003. Combined with the important influences of the Three Gorges Reservoir in the middle reaches of the Yangtze River in 2003 on the downstream rivers and river-communicating lakes, as well as the concept of the hydrological year, the water regime change of Dongting Lake was divided into two periods of relatively stable hydrology: 1980–2002 and 2003–2014.

Water level safety rating results

Water level safety rating results of three regions in Dongting Lake

Figure 4(a) shows several peaks in the trend line of the number of safety levels in East Dongting Lake at 1991, 1995 and 2005, indicating that the numbers of safety levels of East Dongting Lake in the three periods of 1989–2001, 1993–1995 and 2003–2005 were the highest. The valleys of the dekadal security level were 1988 and 2011. Therefore, the number of dekadal security levels in East Dongting Lake in the two periods of 1986–1988 and 2009–2011 was the lowest. Regarding the trend of security level, two 'cycles' were observed in the changes in water safety status in East Dongting Lake, namely, 1988–1999 and 1999–2011. In each period, the number of dekadal security levels rose first and then declined. East Dongting Lake showed unsafe dekadal levels for 22 years, accounting for 62.9% of all years. The number of high-frequency unsafe dekadal levels increased significantly since 1998, and the years with high frequencies were 1998, 1999, 2002, 2006 and 2011. Thus, the frequency of extreme water regime in East Dongting Lake has increased since 2000.

Compared with East Dongting Lake, two peaks of water levels in South Dongting Lake at the safety level occurred at

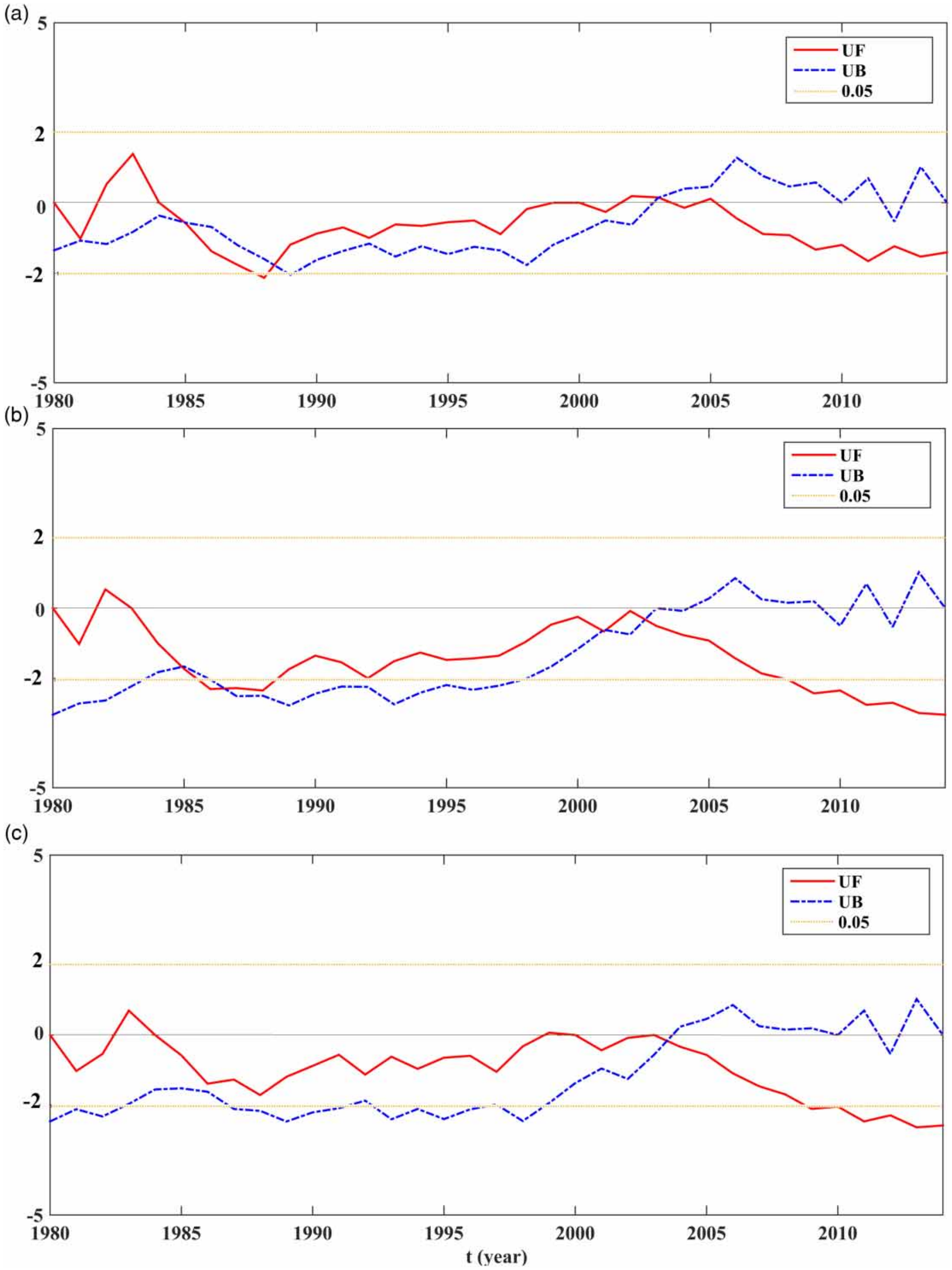

Figure 3 | M-K test of the annual average water level in the three lakes of Dongting Lake: (a) East Dongting Lake, (b) South Dongting Lake and (c) West Dongting Lake.

1986 and 1991, as shown in Figure 4(b). In the two periods of 1984–1986 and 1989–1991, the water safety status of South Dongting Lake was significant. Only one valley point was observed in 1999, when the number of dekads for South Dongting Lake at the security levels in 1997–1999 was the lowest in nearly 30 years. The two 'cycles' of the dekadal safety level of South Dongting Lake were 1983–1999 and 1999–2014. The period of rising and falling was longer than that of East Dongting Lake. East Dongting Lake showed unsafe dekadal levels for 17 years in total, accounting for 48.6% of all years. Compared with years before 1997, the number of dekads for unsafe water levels

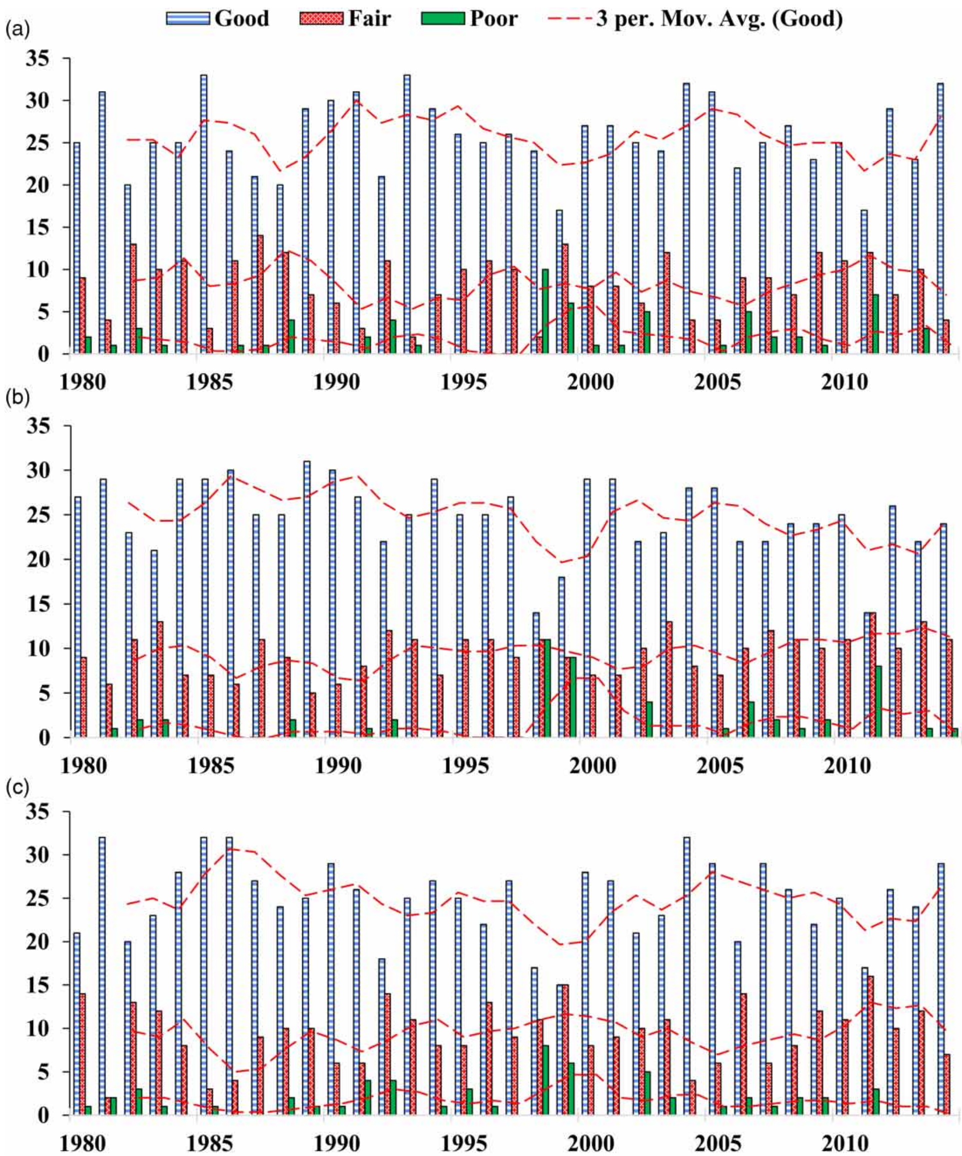

Figure 4 | The water safety rating of Dongting Lake from 1980 to 2014: (a) East Dongting Lake, (b) South Dongting Lake and (c) West Dongting.

of South Dongting Lake was relatively high after 2003. The three-year moving average value reached two dekads.

Figure 4(c) shows that the overall trend of the number of water safety dekads in West Dongting Lake was similar to that in East and West Lakes, which implied two major change 'cycles' for the number of dekads at the safety level, namely, 1982–1999 and 1999–2014. The peaks of the two periods were in 1986 and 2005, indicating that the overall water level was optimal during 1984–1986 and 2003–2005. On the basis of the number of dekads changes of unsafe water levels in West Dongting Lake, the overall level was relatively high compared with that of East and South Dongting Lakes. Thus, the dekadal unsafe levels occurred frequently in a total of 23 years, accounting for 65.7% of all years. The change trends showed that the numbers of unsafe levels in West Dongting Lake were relatively high since 1991, and the average number of annual unsafe level was two dekads.

The water regime changes in the three Dongting Lakes were similar in terms of periodicity and overall change trends. The water safety situation of Southwest Dongting Lake was the worst among the three lakes, followed by East Dongting Lake; South Dongting Lake had the best water safety situation. The number of dekadal water safety levels in the three lakes in the past 20 years generally declined, whereas that of unsafe levels was high. This finding indicated that the water safety status of Dongting Lake has recently faced serious threats.

Seasonal variation characteristics of water safety level in the three lakes during two periods

In the two hydrological periods of 1980–2002 and 2003–2014, the percentage of dekadal water safety levels in the three parts of Dongting Lake varied with the hydrological rhythm of dry, rising, flood and recession (Figure 5). When the water safety level was high during 1980–2002, East, South and West Dongting Lakes presented the highest percentage in the rising period and the lowest in the dry season. When the water safety level was low, the unsafe levels' percentage of South Dongting Lake during the flood season was significantly higher than that of the other three seasons. The unsafe levels in the recession period of East, South and West Dongting Lakes were of the lowest percentage. During 2003–2014, East Dongting Lake showed the highest percentage of dekad numbers when the water safety level was high in the flood season, whereas that of South Dongting Lake was high in the dry and flood season. West Dongting Lake had the highest number in the dry season, and a decreasing trend was observed in the four periods. The percentage of dekadal water safety was the lowest in the recession period for East, South and West Dongting Lakes. When the water safety level was unsafe, the percentage of East, South and West Dongting Lakes was relatively high in the rising and recession periods. Therefore, the water safety status of Dongting Lake was relatively poor during these two periods.

In accordance with the seasonal variation characteristics of the water regime in Dongting Lake, the water condition proportions of the corresponding seasons of the 1980–2002 and 2003–2014 hydrological years are shown in Figure 5. The ratio of dekadal safety levels in each season between 1980 and 2002 did not decrease or increase significantly compared with that of 2003–2014, and the overall proportion was between 60% and 70%. However, the proportion in 2003–2014 clearly fluctuated with seasonal changes. The percentage of the safety level in dry season in South Dongting Lake was 15% lower than that in the recession season, and the difference of the highest and lowest seasons in other lakes was also nearly 10%; thus, the water regime was not stable. After 2003, the dekadal unsafe level of the three lake areas was relatively high in

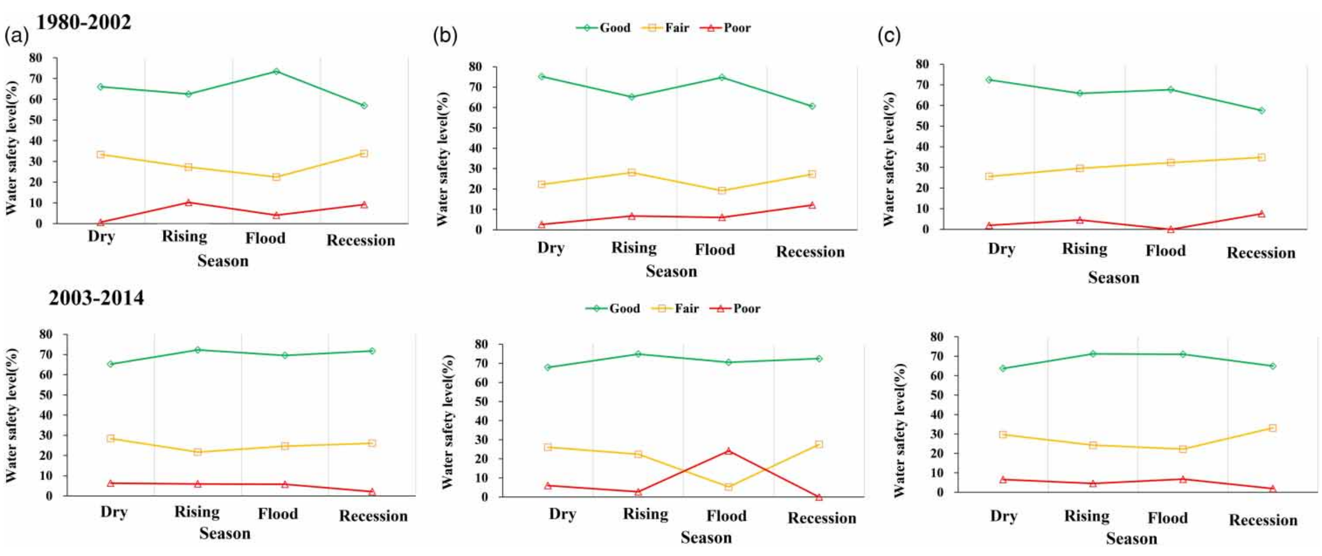

Figure 5 | Water regime status in dekadal scale during two periods (1980–2002 and 2003–2014) in three lake areas (a) East Dongting Lake, (b) South Dongting Lake and (c) West Dongting Lake areas. WSL represents water safety level.

the water-rising and water-falling season, whereas that in the flood and dry seasons was low, which was not available until 2003. An apparent bump was the flood season in South Dongting Lake, during which the unsafe level accounted for about 30%. After 2003, the dekadal safe level in East Dongting Lake decreased by nearly 10% in the recession season, whereas that in South and West Dongting Lakes greatly improved in the dry season; this result indicated an improvement in the water condition in the dry season. Compared with 1980–2002, the percentage of the safe and unsafe levels in 2003–2014 showed considerable fluctuations with the hydrological rhythm of the dry, rising, flood and recession status.

DISCUSSION

Response of water regimes to human factors

The results of the t-value test (confidence level $\alpha = 0.1$) corresponding to the average water level of the three lake areas in two time periods (Figure 6) showed that this change was revealed in time and space. The water level changes in the three lake areas were reflected in the rising and recession seasons. In the rising seasons, four and two dekads changed in South and West Dongting Lakes, respectively. In the recession season, four dekads significantly changed in East and South Dongting Lakes. Simultaneously, three dekads changed in West Dongting Lake due to nature and human activities. The interaction between rivers and lakes changed with the operation of large-scale water conservancy projects such as

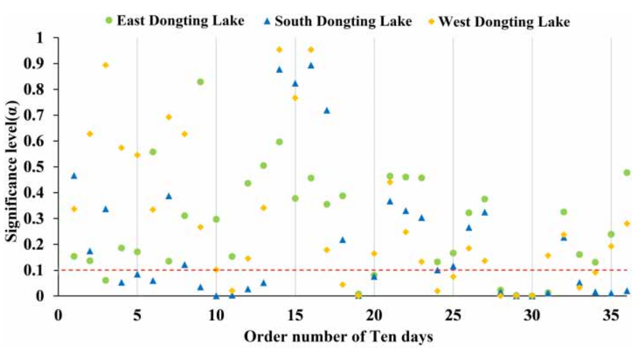

Figure 6 | T-test results of average dekadal water level during two periods (1980–2002 and 2003–2014) in three lake areas.

regulation of the Tiaoxian mouth, cutting of the Jingjiang River system, interception of the Gezhouba Dam and the Three Gorges Project, which influenced the middle and lower reaches of the Yangtze River and Dongting Lake to varying degrees (Yang et al. 2007, 2009; Wan et al. 2014). Actual subflows of the three diversions were small, such that the annual runoff was reduced by about 7%, and the three-diversion discharge ability decreased 2.39% (Li et al. 2016). The Three Gorges Project officially began in 2003. It drains water in front of the raft, leading to the rising water level of the Yangtze River in advance, but the rising water level of Dongting Lake advances through three diversions. The water level after flooding leads to rapid decline in the water level in the main stream of the Yangtze River, which leads to increased hydraulic gradient of the lake outlet, increased discharge flow of Dongting Lake and decreased lake water level. The diversion of the Yangtze River leads to water supply reduction and decreased water level in the lake area. Lai et al. (2014) used the Coupled 1D and 2D Hydrodynamic Analysis Model for the middle Yangtze River basin (CHAM-Yangtze) (Lai et al. 2013) to model the effect of the Three Gorges Dam (TGD) on the water level of Dongting Lake. The modelling results showed that the water storage of the Three Gorges Dam exerted a major effect on the water level of Dongting Lake. After TGD, the water level at Chenglingji (East Dongting Lake) fell by an average of 1.32 m. The increase or decrease of incoming water from the upper reaches of the Yangtze River will enable the water level of Dongting Lake to rise or fall in advance, so it will have a certain effect on the water level in the rising and recession seasons in a short time. Such changes in water level caused by this effect are reflected in the changes in the water safety levels; this result was consistent with the conclusion that the number of dekads of non-safety levels in the three lake areas after TGD in the recession season was relatively high from the perspective of the dekadal scale. Meanwhile, in the flood season, the water level of the Yangtze River at the diversion of Chenglingji can be reduced such that flooding of Dongting Lake can be easily transferred due to the weakened river water (He et al. 2015; Dai et al. 2018). By increasing discharge flow and the interception of flood peak, the number of non-safety levels of Dongting Lake in the flood season was reduced. These results showed that the water regime of the three lake areas in the flood and rising seasons improved.

Response of water regimes to natural factors

The water condition evaluation results revealed that the changes in water regime in the three lake areas demonstrated significant spatial heterogeneity. Dongting Lake is a typical seasonal floodplain lake with great seasonal water level fluctuations. Since the beginning of the recession season, the bottom of the lake is gradually exposed. Dongting Lake is gradually divided from a large whole lake into a series of scattered small lakes, which lead to poor connectivity among East, South and West Dongting Lakes. Therefore, changes in water regime have led to apparent differences. In the recession season, East Dongting Lake and the eastern part of South Dongting Lake are connected by a floodway, and water flow is continuous. The rapid decline in the water level of the main stream of the Yangtze River can quickly spread to the southern lake area, and changes in the water regime remain consistent. This phenomenon is reflected in the consistency of water regime changes in the two lake areas during the flood and recession seasons. For example, the water levels of the two lake areas clearly change in the flood and recession seasons in October and early November (Figure 6). In the dry season, the hydraulic connectivity of most of South and West Dongting Lakes is poor due to considerable development of shoals, such that the water volume of East Dongting Lake cannot be adjusted in the dry season. The consistency of this change in East and South Dongting Lakes during the dry season does not exist. The water supply mechanism of Dongting Lake also presents a certain effect on changes in water regime in the three lake areas. East Dongting Lake is directly supplied by the Yangtze River; West Dongting Lake is directly supplied by the Yuanjing and Lishui Rivers; and South Dongting Lake is supplied by the Zishui and Xiangjiang Rivers. The percentage of safety levels for South Dongting Lake in the dry season increased to nearly 10% after 2003. Given the spatial pattern of water level changes, the water closer to the Yangtze River and the close relationship with water power were severely affected by the Yangtze River. The influence of the TGD on the water level of Dongting Lake was 'high in the north, low in the south, strong in the east and weak in the west', which indicated that East Dongting Lake was influenced at the most significant level, followed by South Dongting Lake and West Dongting Lake in the recession season (Lai et al. 2013). The water safety levels of Dongting Lake in the east and west during the two seasons before and after 2003 changed significantly.

The effect of climate change on the hydrological environment is concentrated on changes in precipitation and temperature in the hydrological environment. The change in precipitation leads to changes in river runoff. Dongting Lake is a typical river-communicating lake. The change in lake water level is affected by the incoming water from the Yangtze River in the north and the Xiangjiang, Zishui, Yuanjiang and Lishui Rivers in the south. The change in rainfall leads to changes in the basin exchange volume, which causes the water volume running into Dongting Lake to change, which is directly represented in the changes in the lake water area and water level. Annual rainfall data were selected from 26 meteorological stations in the Dongting Lake Basin from 1980 to 2014. The average annual rainfall (mm) anomaly percentage for 35 years in Dongting Lake and the anomaly percentage of the total non-safety dekadal level in the three lake areas from 1980 to 2014 were calculated and subjected to linear regression ($P < 0.05$); R^2 reached 0.53. A certain correlation was noted between the change in water safety level and the change in rainfall. The result is shown in Figure 7. When the average annual rainfall was less than the average rainfall in 30 years, the percentage of non-safety levels of Dongting Lake increased and decreased compared with the historical average levels, but the increase was significantly greater than the decrease. When the annual rainfall was greater than its 30-year average rainfall, except for one year, the number of dekads of non-safety levels of Dongting Lake in other years was less than or equal to the historical average. The effect of dry years on the water safety of Dongting Lake could be greater than that in the wet years. Changes in the hydrological environment due to climate change can be achieved through precipitation (Abdulla et al. 2009; Zhang et al. 2010, 2018a). Moreover, the hydrological cycle mechanism and the change in hydrological environment caused by the intensification of human activities in recent years affects the water security of Dongting Lake. The mechanism of action in this aspect is worth further exploration.

Lake water safety was evaluated from the perspective of lake flood control and water resources, and indicators of

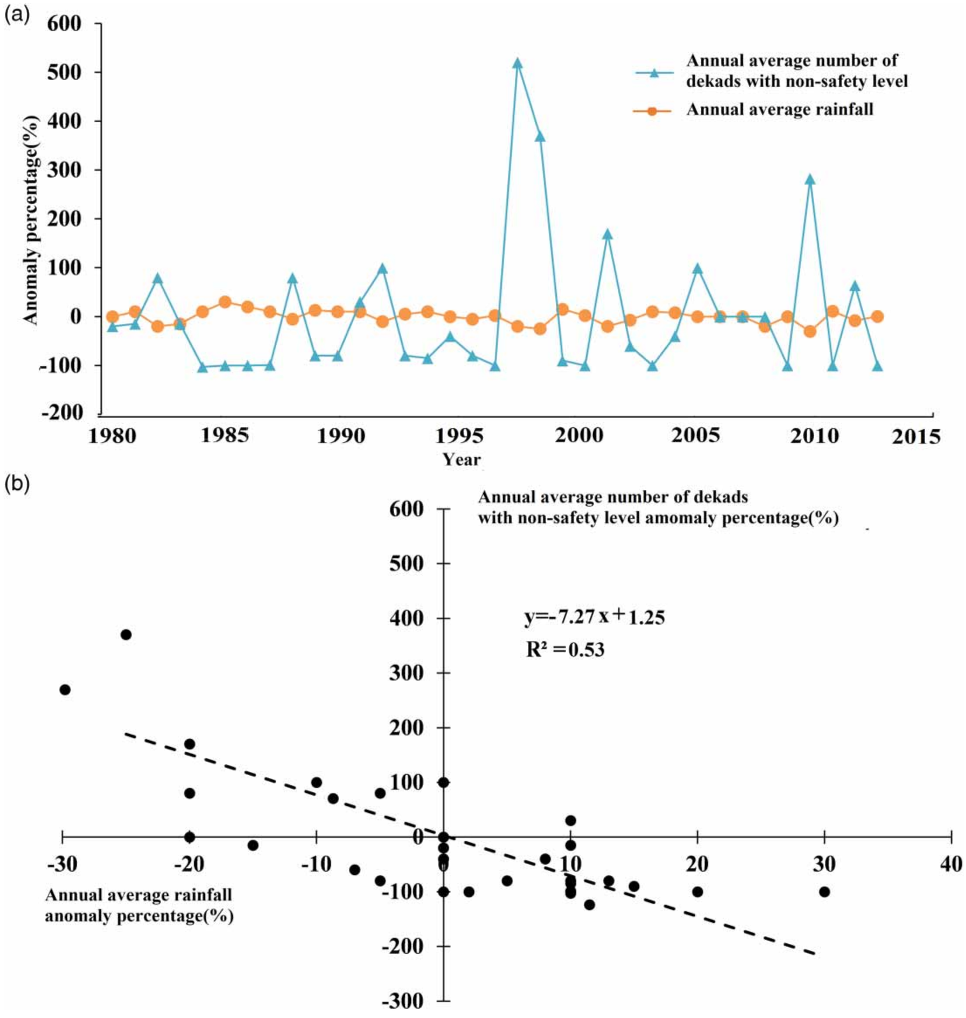

Figure 7 | Relationship between the annual average rainfall anomaly percentage and the annual average number of dekads anomaly percentage of the non-safety level of Dongting Lake.

water environment and water ecology were neither considered nor included in the evaluation system. Research on water environment and water ecology and incorporating results into the indicator system are urgent problems to be solved in lake water safety assessment.

CONCLUSIONS

A set of water safety assessment methods for lakes based on water regimes for seasonal fluctuations in water levels was constructed in this paper. Using the lake water level as the water safety assessment factor and based on normal distribution theory, the frequency analysis method was used to preliminarily determine the boundary water level of the water safety status level in a specific period. The water level value of the lake flood control and water supply was used to correct the safe water level threshold. Moreover, the water safety status of lakes in the lake area was evaluated. The following conclusions were drawn from the study. (1) Events in 2003 were crucial in hydrological regime changes of Dongting Lake during 1980–2014. Water levels in Dongting Lake apparently declined after 2003. (2) The water regime changes in the three lake regions exhibited certain similarities in periodicity and overall change trends. The water security status of West

Dongting Lake in the three lake regions was the worst at the overall level, followed by East and South Dongting Lakes. (3) Compared with the complexity of the water security status of Dongting Lake in 1980–2002, that in 2003–2014 increased and the fluctuation of water regime intensified. (4) The change in water safety level of Dongting Lake was correlated with rainfall changes. The extreme dry years induced a greater effect on the water security status of Dongting Lake than the wet water year.

The multi-time scale and multi-objective water safety evaluation system proposed in this paper is featured by easy expansion of social development and technological progress and easy and comprehensive application for multiple objectives. Moreover, it is characterized by its prominent predictability and concern about the water safety status of the lake region's production and life for the water safety assessment of the lake area, where the climate change in the monsoon region is severe during the year compared with other common water safety assessment systems. This assessment method will have wider application prospects after superimposing the lake water environment and water ecological security threshold. The multi-time, multi-scale and multi-target lake water safety assessment method based on water regimes constructed in this paper will provide new ideas and methods for similar lake water safety research in the world.

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