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Research article

Multidimensional water level and water quality response to severe drought in Xingyun Lake

Junxu Chen [a,b,*], Jia Xu [a], Qi Yi [a], Jiabin Peng [a,c,**], Yang Lang [a], Liang Emlyn Yang [d], Jihui Zhang [a]

[a] *International Joint Research Center for Karstology, Yunnan University, Kunming, 650091, China*
[b] *Yunnan Key Laboratory of Soil Erosion Prevention and Green Development, Yunnan University, Kunming, 650504, China*
[c] *Yunnan International Joint Laboratory of China-Laos-Bangladesh-Myanmar Natural Resources Remote Sensing Monitoring, Yunnan University, Kunming, 650091, China*
[d] *Department of Geography, Ludwig Maximilian University of Munich (LMU), Munich, 80333, Germany*

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ABSTRACT

Drought stress has a significant impact on the quality and quantity of lake water. Understanding this impact is crucial for preventing water security risks and pollution recovery. However, there is a lack of systemic understanding of how drought affects water quality and quantity, and how they change in multiple dimensions. This manuscript established a synthesized methodology with the principles to judge the applicability and three steps of application to detect the change in water quality and water level under severe drought in Xingyun Lake, China. Results show that (1) The water level and water quality of Xingyun Lake have a synchronous and evident response to drought during 2009–2014. The rainfall during 2008–2015 declined by 22.9 % to normal, and the inundated area and lake water depth in 2012 decreased by 10.50 % from 2002 to 1.38 m to the average depth, respectively. The pollution index climbed above 1.21 after 2008, fluctuating around 1.42. (2) Under drought, the water quality indicators significantly changed in the terms of the overall feature, trend, eigenvalue, and morphological characteristics. The water quality indicators of Set$_{2008\text{-}2015}$ are significantly different from set$_{2000\text{-}2007}$ and not in the groups of set$_{1994\text{-}2000}$. The morphological characteristics of water quality indicators in set$_{2008\text{-}2015}$ differs significantly from that in set$_{2000\text{-}2007}$ shown by the minimum, maximum, median, quartiles, and extreme values. (3) Although NH_3–N showed no significant change, the water quality deteriorated in the physical, chemical, and biological aspects. The TP, I_{MN}, and BOD_5 changed more evidently than DO and NH_3–N. (4) Water quality grade and indicator concentration deteriorated significantly and sharply under severe drought and are threatened deeply by TP and TN. The synthesized methodology is scientifically constructed and canbe employed in the characteristics cognition of water quality and water level to severe drought in and out of this research. And the intervention time and various regulating measures for pollution degradation and water quality recovery canbe constructed based on the multi-dimensional analysis of water quality change under drought evolution.

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[*] Corresponding author. International Joint Research Center for Karstology, Yunnan University, Kunming, 650091, China.
[**] Corresponding author. Yunnan International Joint Laboratory of China-Laos-Bangladesh-Myanmar Natural Resources Remote Sensing Monitoring, Yunnan University, Kunming, 650091, China.
E-mail addresses: chenjunxu@ynu.edu.cn (J. Chen), jiabin@ynu.edu.cn (J. Peng).

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1. Introduction

Lakes, holding 87 % of earth's liquid surface freshwater and supporting a global heritage biodiversity and key ecosystem services, are critical natural resources that are sensitive to climate change [1]. A large proportion of lakes in the world are suffering from water quality deterioration [1–4]. Over the next 30–50 years most of the world's major water bodies (rivers and lakes) are predicted to show large increases in frequency of hydrological drought [1]. Under drought, the lake water quantity declines or even dries up [5], and the water quality generally deteriorates [6] in most water quality parameters [7,8], leading the water intaking contaminated [8], eutrophication [9] and decreasing richness [10] or massive fish mortality [9]. Meanwhile, the increasing water pollution and associated impacts originated from drought and human activities have also led to severe ecological-environment problems [11,12], pollution exposure and water scarity [13,14] and impaired ecosystem [15]. Hence, conducting water quality and quantity change in water bodies under drought become a serious concern worldwide [11,16,17].

Drought is a perturbation in the hydrologic regime that makes considerable negative impacts on water quantity and quality [18,19]. Drought can affect water quality determinants in multiple ways [20] and dramatically affect aquatic systems by reducing the quantity of freshwater within lakes [21]. Previous studies indicated that the drought affected water quantity in a lake as the water volume declined [8,18], lake level/inundated areas receding [6], increase in salinity [6], reduced inflow river flushing [20], water temperature increase [22], and low-flow situations [23]. During a drought, the chlorine concentrations, DO, pH, suspended solids, and algal levels often increase in lake systems [20]. Also, drought intensifies symptoms of eutrophication [24,25] and creates a higher proportion of coarse grain sizes in the sediment [26]. To detect the effects of drought on water quantity and quality, a usual way is to take the start year of drought as the demarcation point, and analyze the change of water quality and quantity from pre-drought to drought conditions based on typical water quality indicators comparison in typical years [6,27]. Another way is to identify the change point of water quality/quantity time series, and compare the change characteristics of water quantity and quality before and after the determined change point [16,28]. Various methods have been employed to assess water quality, including the water pollution index [16,29], Mann-Kendall test, Spearman's rho test, and cross-wavelet transform [16,30,31]. Other techniques, such as linear regression and Mann-Whitney U statistic [21], lake sediments [32,33], diatom analysis [34], machine-learning models [35], and hydrodynamic modeling [36], have also been used to study the effects of drought on water systems.

Assessing the changes in water quality and quantity during drought is a challenging task for researchers and administrators due to the need for balancing various indicators of water quality and identifying the main pollution threats [16,37]. Water quality is determined by the chemical, physical, biological, and radiological characteristics of water [38,39]. To assess water quality accurately, all contaminants and related water quality indicators must be listed and evaluated. However, due to limited situ monitoring data and the high cost of water quality testing, previous studies have only assessed changes in some certain indicators [6,16,36]. Moreover, the methods used to assess water quality vary depending on the intended purpose [6,16,36]. Despite the wide range of water quality indicators, the main processes and contaminants [20] that alter water quality during low-flow situations [23] can be identified. Hence, two theoretical problems are required to be uncovered here, one is what are the suitable indicators to represent water quality [40], and the other is what are the realistic features of water quality change under drought. Therefore, integrating the multi-dimensional indicators to present the water quality and multi-dimensional aspects to characterize the water quantity and quality change is required from the previous discussion.

Xingyun Lake, one of the nine typical plateau lakes of Yunnan province in China, experienced a severe drought lasted from 2009 to 2013, which broken records [16,41]. Acoodingly, the lake has become a typical research object to study changes in water quality and quantity change under drought stress. Xingyun Lake is a crucial area for study the recorded Asian monsoon anomaly [33] and plays a critical role in providing freshwater resources for adjacent areas and developing aquaculture [42]. Despite spending 0.425 billion RMB (US$ 60.8 million) on protecting the lake from pollution during 2011–2015, the water quality of Xingyun Lake deteriorated considerably [43] with severe algal blooms [42]. During the severe drought, significant water level receding and inundated areas decline were reported, and obvious accompanying water quality degrading was validated. However, a systemic depiction of water level and water quality change based on the drought occurrence time and multi-temporal change features has not been found yet.

The study aims to evaluate the multi-temporal change of water quality and water level under severe drought from the perspective of holistic change of water quality of Xingyun Lake. A comprehensive assessment indicator system constructed on the principles of indicator selection and presentation of multi-aspects of water quality is asserted, and multi-dimensions characteristics of water quality change under a severe drought are identified to deduce the holistic change characteristics of water quality and water lever under the severe drought. We test hypotheses that (1) negative water quality and quantity change to severe drought is validated; (2) change synchronization is in the change of water level, water quality, and drought; (3) water quality including chemical, physical, and biological aspects are altered from the features of trend, eigenvalue, morphological characteristics, and grade of water quality. Our study will provide a systemical methodology to reveal water level and water quality change under drought, which has broad relevance to related research and other lakes.

2. Design and methods

2.1. Synthesized methodology for characterizing water quality and lake level change under drought

The purpose of the design is to develop a comprehensive approach to analyze the changes in water quality and quantity during a drought. It also provides guidance on how to deal with drought stress, trends in water quality, and evaluating framework for integrating water quality assessments. The goal is to combine all of these aspects to evaluate the quality and level of water changes during a severe drought in Xingyun Lake.

2.1.1. *The principles to establish a synthesized methodology*

Four principles are advised to construct a synthesis methodology to characterize water quality and water quantity change under drought.

- An effective metric for synchronization of water quality, water level, and drought changes.

The response of propagation from meteorological drought to hydrological drought is clarified in the majority of research [18], which will affect the start time and duration of changes in water quantity and quality [18]. This knowledge can help establish the relationship between water quality, water level, and drought. Yearly scale water quality response requires determination of the start year of a drought, but monthly or daily scale response requires more precise time determination. Hence, to scientifically construct a synthesis framework, the initial principle is considering the effective metric for synchronization of water quality, water quantity, and drought changes.

- Reasonable presentation perspectives of change ratio on water quality under drought.

When discussing changes of water quality during a drought, it is important to determine the perspective or attribution of the change. Most research discusses the change ratio of certain indicators such as PH, DO, COD, BOD, TN, and TP. However, the metrics used to measure are often limited to the increase/decrease ratio, the trend of indicators, and the species amount. There is generally a lack of true change characteristics from a mathematical perspective, including indicators' trend, eigenvalue, temporal morphological characteristics, and data morphology. Additionally, it is important to explore the change in water quality grade, main contaminants,

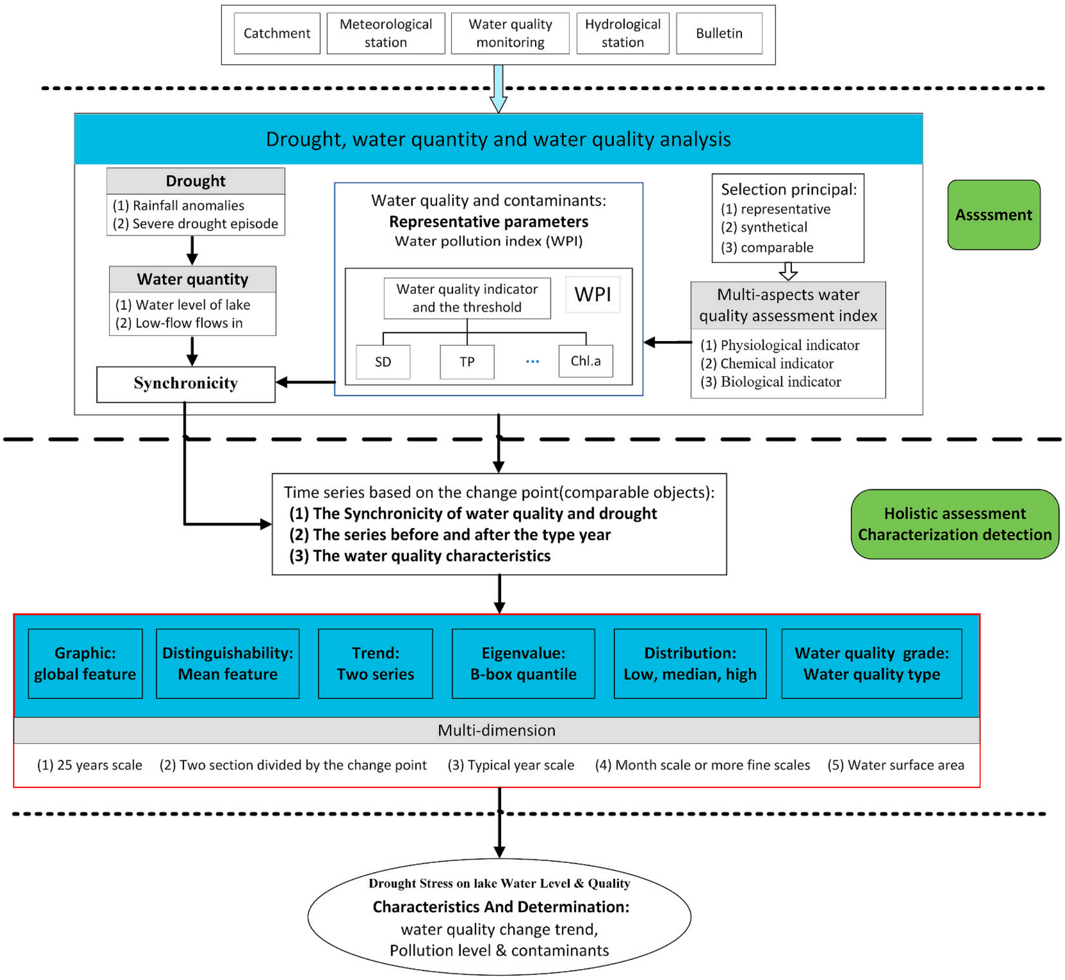

Fig. 1. The flowchart of research on water quantity and quality change under drought.

and overall change to help those using the service get systematic and consistent findings.

- Multi-temporal dimensional changes in water quality before and after a drought event.

No matter what method is used, the differentiation of water quality attributed to drought should be presented based on the water quality characteristics during different periods. These periods are referred to as pro-drought, under-drought, and post-drought. The overall yearly scale water quality differentiation is useful to show the prolonged drought effects, while monthly scale water quality differentiation is more useful to identify the consistency and synchronicity of water quality and drought process. The daily scale water quality change can provide fine details of the changes. As droughts usually last for several years till recovery from a lasting water shortage, it is important to consider the overall time series, pre-drought yearly series and drought lasting series to understand multi-temporal changes in water quality before and after a drought event. Therefore, multi-temporal dimension water quality change before and after drought is a principle advised.

- The critical indicators identified to present the objective water quality.

To assess the water quality, it is difficult to evaluate every aspect due to the limited availability of situ monitoring data and high cost of water quality tests. Therefore, it is essential to identify the critical contaminants and representative indicators from the chemical, physical, and biological aspects based on the lake management requirement.

2.1.2. Three steps of the synthesized methodology

The methodology for researching the impact of drought on water level and water quality is presented in Fig. 1.

Step 1 assess the synchronization of drought, water quantity, and water quality change

The synchronic problem is grounded in the question of what features or traits characterize water quality and quantity under drought. Here, we consider the consistent and asymptotic time change of drought, water quality, and water quantity as the basic indicator for synchronization detection. Meanwhile, the well-fitted process between the drought, water quality, and water quantity are judged. Accordingly, the rainfall, lake water level, and water pollution index are plotted, and the change stages of water quality indicators are divided by the change year, and then the synchronization is discussed. Such analysis can provide short- and long-term assessment of the possible water quality response. In this study, drought starts from the beginning of the precipitation anomaly and lasts until the drought termination. Thus, a lake is assumed to recover from drought when the precipitation and water quantity (level) naturally return to the pre-drought condition, and the water quality stays in a stationary stage or impoves.

Step 2 identify the water quality assessment indicators, critical contaminants, and water pollution index

To assess the Xingyun Lake water quality, specific indicators are limited by water quality standards and lake functions. In accordance with the Environmental Quality Standards for Surface Water of China [38], the function of the Xingyun Lake is supposed to be Type III. This type is defined as a general protection zone for centralized drink surface water sources, fishes' migration, and swimming areas. To evaluate the water quality, a total set of 109 items have been formulated, including 24 basic standards of surface water quality, 5 items of centralized surface water supplement for domestic and drinking water, and 80 specific items [16]. Considering the huge overload work and the lack of historical monitoring data, the representative indicators were chosen in this manuscript considering the four principles, multi-aspects of water quality, and determination criterion according to the "Surface Water Environmental Quality Standards of GB3838-1" [38], and the "12ed Five-Year Water Environmental Protection Plan of the Xingyun Lake Basin". The dissolved oxygen (DO) and transparency (SD) were designated as physical indicators. The total phosphorus (TP), total nitrogen (TN), biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3–N), and permanganate index (I_{MN}) were settled to represent chemical indicators. Additionally, chlorophyll-a (Chl.a) was chosen as a biological indicator (Table 1). Despite I_{Mn} being an indirect measure of biodegradable and non-biodegradable organic matter, because there is a lack of long-term monitoring data of

Table 1
Water quality indicators and criteria Unit: mg/L (SD: m).

Indicator	Grade					
	I	II	III	IV	V	VI
$BOD_5 \leq$	3	3	4	6	10	>10
TP $\leq$	0.01	0.025	0.05	0.1	0.2	>0.2
$I_{Mn} \leq$	2	4	6	10	15	>15
NH_3–N $\leq$	0.15	0.5	1.0	1.5	2.0	>2.0
TN $\leq$	0.2	0.5	1.0	1.5	2.0	>2.0
Chl.a	–	–	–	–	–	–
DO $\geq$	90 % (saturation)	6	5	3	2	<2
SD	–	–	–	–	–	–

Notes: there are no exact value limitation standards for Chl.a & SD.

CODCr and it is a natural water body quality index suggested in the “Surface Water Environmental Quality Standards of GB3838-1” [16], it has been included in this study.

Step 3 make the multidimensional assessment of water quality and water quantity change under drought

Once the objective and assessment indicators system has been identified, three main tasks are essential in the assessment of water quality and quantity response to drought stress: (i) determinate change stages, (ii) multidimensional assess the water quality and water quantity change under a drought, (iii) summarize and identify the water quality and quantity change characteristics under drought.

The core task is to synthesize and accomplish a multidimensional assessment; here, the representative aspects and characterization perspectives are as follows.

- Graphics: uses the overall feature to detect the change synchronization
- Distinguishability: identifies the mean differentiation of indicators in different stages
- Trend: assesses the series trend of the different stages with a non-parametric test
- Eigenvalue: shows the quantile difference in series with B-box
- Morphological characteristics: exhibits low, median, and high values change with Sen’s method
- Water quality grade: assesses water quality grade according to water quality standard

Furthermore, characterizing water quality change in two decades, yearly series, and typical years under drought can show the multi-time scale change characteristics of water quality.

2.2. The water pollution index

The Water Pollution Index (WPI) [44] is a comprehensive index that helps interpret the assessment results of water quality[16] under drought:

$$WPI = \frac{1}{n} \times \sum_{i=1}^{n} \frac{C_i}{C_{io}} \tag{1}$$

where C_{i} is the pollutants value of the i_{th} indicator; C_{io} is the water quality standard; n is the number of pollutants.

2.3. Methods for characterizing water quality trend

2.3.1. The non-parametric test method

The $\mathrm{M}-\mathrm{K}$ statistical test [16,45,46] has been widely used for detecting trends in water quality time series. The $\mathrm{M}-\mathrm{K}$ test statistic is determined by the ranks of the time series, each value in the sequence should be compared with the rest, then the sum of the number of values greater than the value is calculated as S [16,31]:

$$S = \sum_{k-1}^{m-1} \sum_{j=k+1}^{m} \mathrm{sgn}(x_j - x_k) \tag{2}$$

where sgn is the sign function, x_j and x_k are the values of sequence j,k. m is the length of the dataset, and j is the series number.

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} 1, & x_j - x_k > 0 \\ 0, & x_j - x_k = 0 \\ -1, & x_j - x_k < 0 \end{cases} \tag{3}$$

The variance of statistics S is defined as:

$$\mathrm{var}(S) = \frac{m*(m-1)*(2m+5)}{18} \tag{4}$$

The statistical detection value of Z is computed by:

$$Z = \begin{cases} (S-1)\Big/\sqrt{\mathrm{var}(S)}, & S > 0 \\ 0, & S = 0 \\ (S+1)\Big/\sqrt{\mathrm{var}(S)}, & S < 0 \end{cases} \tag{5}$$

Here, α is the significance level, set to 0.05 where $Z_{1-\alpha/2}$ equals 1.96. The hypothesis is rejected in a two-sided test when $|Z| \geq Z_{1-\alpha/2}$. A positive Z value indicates an increasing trend, and a negative value indicates a decreasing trend.

The trend magnitude can be determined by Sen’s slope, calculated [47,48] as follows:

$$Q_{\mathrm{med}} = \begin{cases} Q_{[(m+1)/2]} & \text{if } m \text{ is odd} \\ \dfrac{Q_{[m/2]} + Q_{[(m+2)/2]}}{2} & \text{if } m \text{ is even} \end{cases} \tag{6}$$

where Q_{med} is the median value of the slope of all data pairs (Q_m, the Q_m series are ranked from the smallest to the largest), and Q_j is the trend magnitude calculated with the ratio of the difference of *j*th and *k*th origin water quality value to the difference of number *j* and *k*:

$$Q_j = \frac{x_j - x_k}{j - k} \ \ for\ j = 1, \ldots, m \tag{7}$$

2.3.2. Two-sample Student's t-test

The two-sample Student's t-test is commonly used to detect whether or not variables have changed over time or space [49]. Here, the series of water quality before and during a severe drought are settled as the two samples for the test. Variables with a p-value <0.01 are considered to show a significant difference between the two groups. For the unpaired Student's t-test, the *t* statistic is calculated as:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{S_w \left(\frac{1}{n_1} + \frac{1}{n_2} \right)^{1/2}} \tag{8}$$

where n_1 is the sample size of group 1, n_2 is the size of group 2, $\overline{x}_1$ is the mean of group 1, $\overline{x}_2$ is the mean of group 2, and s_w is the pooled variance given by:

$$S_w = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}} \tag{9}$$

S_1 and S_1 are the standard deviations of group 1 and group 2, respectively.

2.3.3. Sen's illustration

The direct graphical trend method proposed by Şen [50] is employed to compare the water quality change before and during a drought. The water quality time series is divided into two equal halves from the first date to the end date and sorted in ascending order. The first sub-series (X_i) is settled as the X-axis, and the other sub-series (X_j) is settled as the Y-axis. Accordingly, there is no trend when

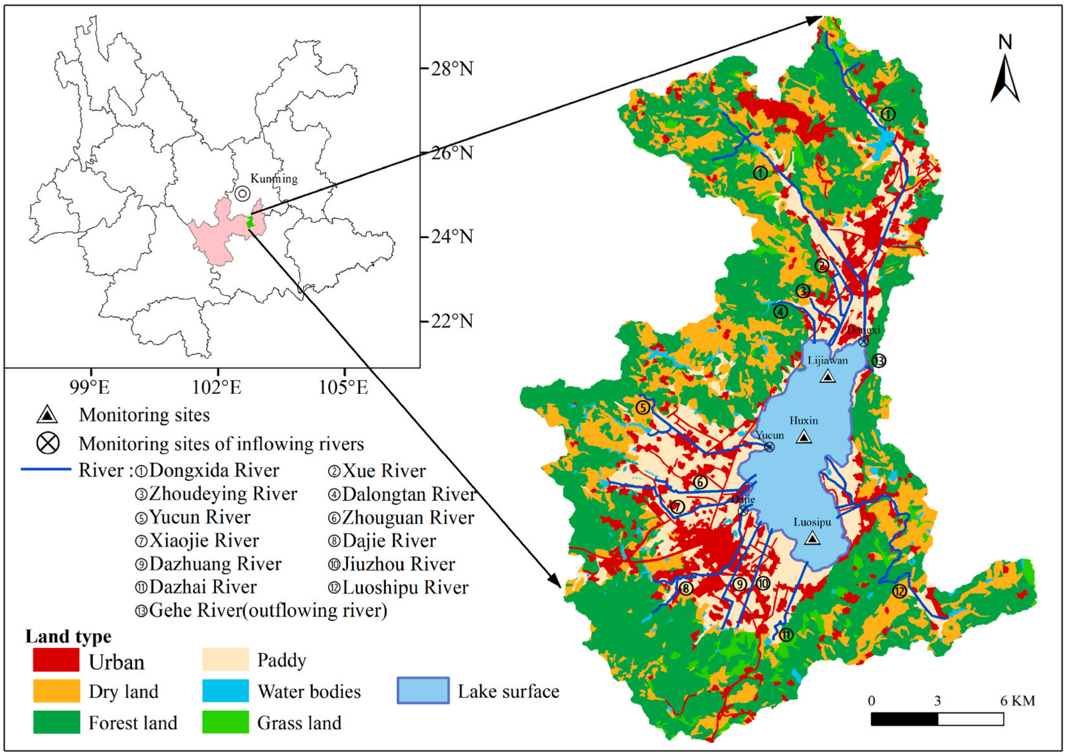

Fig. 2. The geographical information of the Xingyun Lake Basin.

the data is distributed on the 1:1 (45°) straight line. The second half is lower than the first half when data are in the below triangular area of the 1:1 straight line. If data is distributed above the 1:1 straight line, it shows an increasing trend. The low, median, and high values of parameters can be evaluated graphically [50,51].

3. Study area and materials

3.1. Xingyun Lake

Xingyun Lake (24°17′20″-24°23′03″N, 102°45′20″-102°48′20″E) is a typical semi-closed shallow-water lake in a plateau fault depression. This basin is above 1740 m sea level and surrounded by mountains with steep topography in the east and flat in the west [33], covering an area of 389 km^2 and a lake surface area of 34.7 km^2. The water capacity is 183.3 million m^3 at 1722 m water level elevation. The rivers flowing into Xingyun Lake are mainly 12 seasonal low-flow rivers, including Dajie, Dongxi, Yucun, Luosipu rivers, etc. (Fig. 2). The outflow river is Gehe, which is a narrow channel connecting the Xingyun Lake and Fuxian Lake. The rivers' runoff and lake surface precipitation are the primary recharge sources, accounting for 55.4 % and 26.8 % of the inflowing water, respectively. The groundwater recharge takes part of 18 %. Xingyun Lake belongs to the north subtropical humid plateau monsoon climate with a mild climate, 12–16 °C mean annual temperature, and approximately 883.3 mm mean annual precipitation. Xingyun Lake plays a crucial role in providing freshwater for domestic water supply, industrial production, developing aquaculture, and ecological system maintenance in Yuxi prefectural district. In this basin, the population was 2.63 × 10^5, and the GDP was 9.1 × 10^8 China yuan in 2017. The dryland, forest land, and paddy fields occupy 80.6 % of the basin area. Since 1996, the water quality of Xingyun Lake gradually deteriorated from grade I ~ II to V and underwent a sharp deterioration after 2008.

3.2. Materials

The water quality indicators of Xingyun Lake, including DO, SD, TP, TN, BOD$_5$, NH$_3$–N, I$_{MN}$, and Chl.a, were determined in section 2.1. Yearly data from 1994 to 2015 of Xingyun Lake were collected from the environmental monitoring station and the Water Environmental Protection Plan of the Xingyun Lake basin. To validate the Lake's water quality indicators data, we selected three sampling monitoring sites: namely Lijiawan, Huxin, and Luosipu, representing respectively the northern part, central, and southern parts of the lake, and obtained the average values of these sites during 2009–2020. Additionally, the precipitation, water level, climate data, and social-economy data were collected from the government departments. The lake basin, water level line, and water surface data were obtained from the remote sensing images with a resolution of 30 m × 30 m (2001 image from Landsat 4–5 TM, 2012 image from Landsat 7, 2014–2020 images from Landsat 8). These images were acquired from the International Scientific Data Service

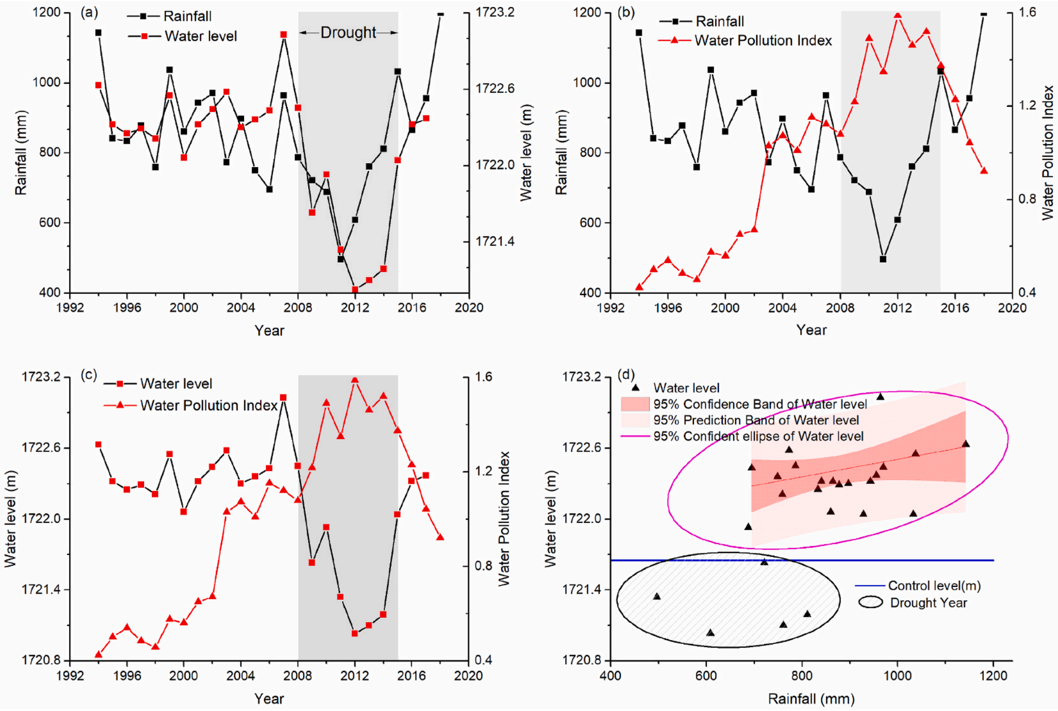

Fig. 3. The synchronization of water quality, water level and severe drought change. The grey bar in the figures presents the drought period during 2009–2015.

Platform of the Chinese Academy of Sciences (http://www.cnic.cn/zcfw/sjfw/gjkxsjjx/). The routine monitoring data of river flow are available in the Dajie, Dongxi, and Yucun river,and the river water quality was tested during fieldwork in 2016 and 2019. The inflows TN, TP, and COD quantity data were from the government departments and lake protection planning.

4. Results

4.1. The synchronization of water quality, water level change and drought

4.1.1. The water level change under drought stress

In southwest China, a severe drought occurred after 2008, lasting for six years until it returned to normal status in 2014[19]. During this time, there were specific seasonal droughts, such as in autumn 2009 to spring 2010 and summer 2011 [41], where the rainfall deficit exceeded 80–90 % [52,53]. The amount of rainfall declined from 963.8 mm in 2007 to 786.3 mm in 2008 (Fig. 3(a)), to 496.8 mm in 2011, and then gradually recovered to the average levels by 2014. As a result of the drought, the inundated area and the lake depth in 2012 decreased by 12.88 % compared to 2002 and 1.38 m to the average depth (7 m) before the drought, respectively (Fig. 4), and the lake's water storage was reduced by 21.6 % approximately. During 2009–2013, there was an average 17 % decrease in water

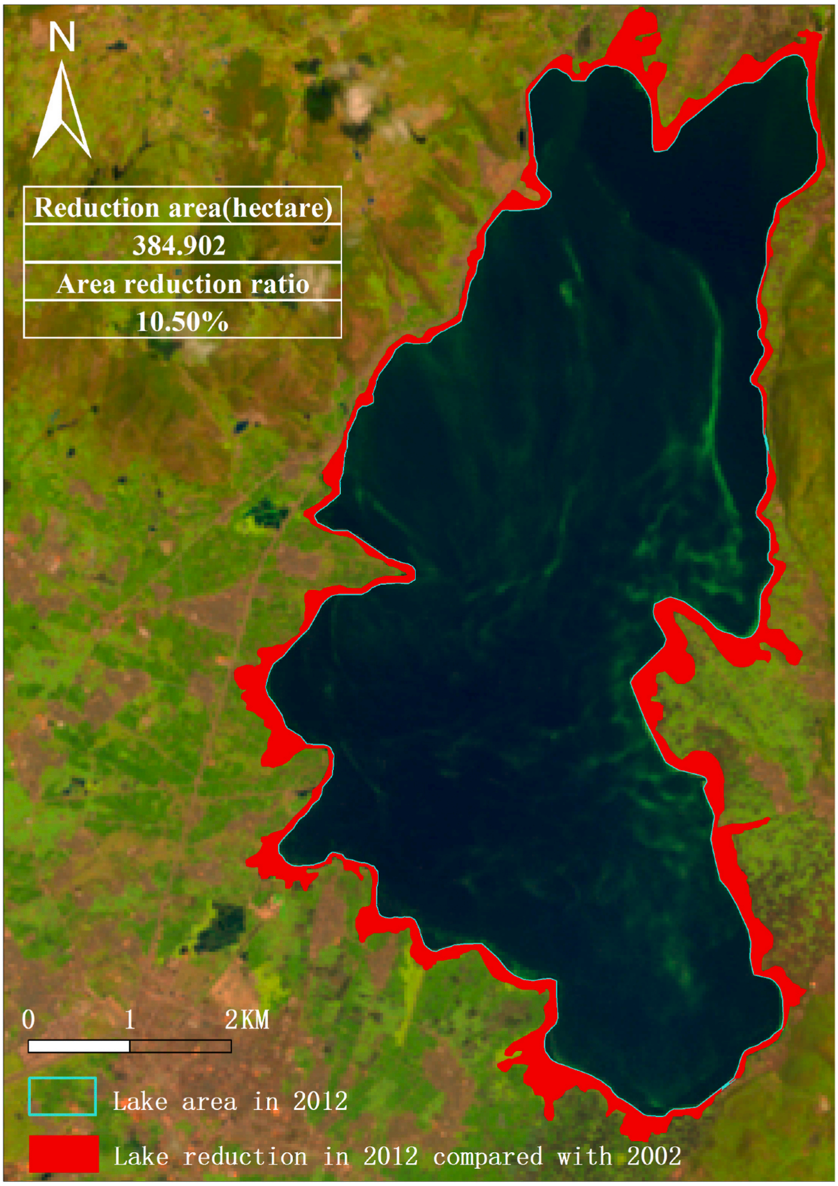

Fig. 4. The inundated area change between 2002 and 2012.

storage compared to 2000–2008. From the rainfall change, the drought persisted from 2009 and recovered to normal status by 2014. However, from the water lever change, the drought persisted until 2015 when the water level returned to normal. Therefore, at the yearly scale, the drought propagation from metrological drought to hydrological drought is synchronized at the beginning and one year delayed at the end (Fig. 3(a)).

During this severe drought period, it is evident that the water level presents a high level of consistency and synchronization with the rainfall change in the overall trend, as illustrated in Fig. 3(a). From 1994 to 2002, the water level synchronously rose with the increase in rainfall, and vice versa. From 2003 to 2007, the water level fluctuated slightly with changes in rainfall. After that, the water level changes synchronously with the rainfall again, albeit with some uneven magnitude (Fig. 3(a), (d)). The average rainfall during the three stages was recorded as 918.2 mm, 815.5 mm, and 696.1 mm, respectively. As shown in section 3.1, during the period of 1994–2003, the agricultural water utilization in nearby areas was guaranteed by Xingyun Lake, and the third waterworks of Jiang-chuan County pumped water from this lake. However, around 2003, the third waterworks shut down, and the agriculture water pumps were restricted. Despite the rainfall declining by 100–150 mm to the normal during 2005–2006, the water level recovered steadily after 2003 and fluctuated with the rainfall. During the severe drought that struck after 2008, the water level and the rainfall decreased sharply synchronously. The water level in 2009, 2011, 2012, 2013, and 2014 was recorded as being under the legal water level of Xingyun Lake. Meanwhile, the rainfall in 2009 was −22.9 % to the normal, and in 2011, it was recorded heavily as −43.8 % (Fig. 3(d)–. 4).

4.1.2. *The water pollution index change under severe drought*

Four change stages are shown by the water pollution index line (Fig. 3(b)–(d)). Prior to 2000, the water pollution index was predominantly around 0.5, below the threshold of 0.6. During 2000–2008, the water pollution index rose from 0.55 to 0.65 at 2001, increased sharply from 2002 to 2003, and then stablized around 0.9 (with a maximum of 1.15 and a minimum of 0.65). During this period, the pollution index undergone a noticeable increase. Without considerable investment, rectification measures, and protection projects, the water quality index could have continued to increase. However, from 2006 to 2010, aiming to make the water quality reach or exceed type IV standards, the government implemented various measures to protect and recover the water quality of Xingyun Lake. Ideally, major pollutant emissions would be reduced by no less than 40 %, the lake's pollution load would be reduced by 30 %, and the pollution index would drop sharply. The steady-state and fluctuating magnitude during 2003–2008 desmontrate that these measures were effective (Fig. 3(c)). Unfortunately, after 2008, severe drought occurred, and efforts to implement such intense measures were counteracted (Fig. 3(c)). After 2008, the water pollution index exceeded the threshold of 1.20 and fluctuates around 1.42. The water quality deteriorated sharply, and entered another stage where rainfall, water level, and pollution index changed roughly in sync (Fig. 3(b)–(c)). It is evident that the combination of the water pollution index and water level during 2008–2015 is different from before (Fig. 3(c)–(d)). After 2015, with rainfall and water quantity recovering from the severe drought (Fig. 3(a)–(d)), the pollution index decreases sharply and synchronously to values near those observed during 2003–2008.

4.1.3. *The synchronization of drought, water level and water pollution index*

Considering the rainfall, water level, and the pollution index, the difference is clear that a. with the water level declining after 2008, the pollution index shows an increase and presents wholly high and discrete values; b. during 2000–2008, the pollution index presents roughly discrete and nonstationary values; c. before 2000, a low-value change and less fluctuation is presented by water pollution

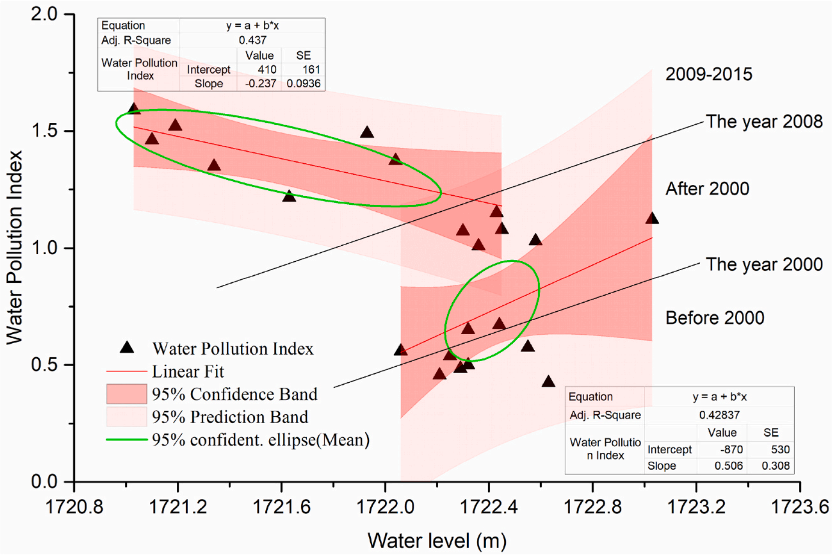

Fig. 5. The water quality change along with the Lake water level gradient.

index. The rainfall, water level, and water pollution index have consistent and synchronic changes in the predominant change period. According to the drought process, water quality, and water level change, the pro-drought, drought persistence, and post-drought period are determined as the periods of 2000–2008, 2009–2015, and after 2015. The years 2000, 2008 and 2015 are settled as change points to help the analysis of drought stress on the change of water level and water quality (Fig. 5).

4.2. Yearly characteristics of water quality parameters change before and during the drought

Drought perturbs the natural climatic and hydrologic regime and affects water quality determinants [20,54]. In Xingyun Lake, TP, TN, I_{Mn}, BOD_5, and Chl.a are similar in increase trend as that the pollution in the later period gets higher over time (Fig. 6). The DO levels showed a slight increase between 1994 and 2007 but fluctuated significantly during 2008–2015. The NH_3–N presents a significant decrease trend. TP, I_{MN}, and BOD_5 change apparently with large amplitude before and during the severe drought, while DO and NH_3–N shows less of a change.

The indicator graphics in Fig. 6 show non-stationary changes and different amplitudes. BOD_5 levels shows a significant upward trend and maintained high values after 2008. The slopes of the fitted equation showed a distinct difference of 0.208 and 0.082. TP increases sharply after 2008 from 0.125 to 0.522 mg/L; the slopes of TP during 1994–2007 and 2008–2015 show a near-equal change trend. There is no large slope and value shifts in the I_{MN} series. For the NH_3–N, the gentle change trend during 1994–2007 is sharply disrupted after 2008. The TN has a significant upward trend from 1994 to 2015 and maintains high values after 2008 with an approximate flat change. The Chl.a increases from 1994, reaches a high-value interval during 2003–2008 and remains higher values after that. In 2013, it reached a peak value of 109.45, which is 11 times the lowest value in 1995. DO experiences a sharp change at 2008 when it goes from its lowest at 2007 to its crest at 2011. SD demonstrates that the physical situation of water quality decreases consecutively after 1994, experiences an upward impulse during 2004–2008, and then shifts to a downward change.

4.3. The water quality change trend and distinguishability before and after 2008

4.3.1. The water quality change trend before and after 2008

Based on the M − K test and Sen's slope, the trends and change amplitudes of BOD_5, TP, and I_{Mn} were evaluated. Table 2 shows that BOD_5 experienced a significant increase during 1994–2015, while the increase from 2008 to 2015 was not significant, as the Z score

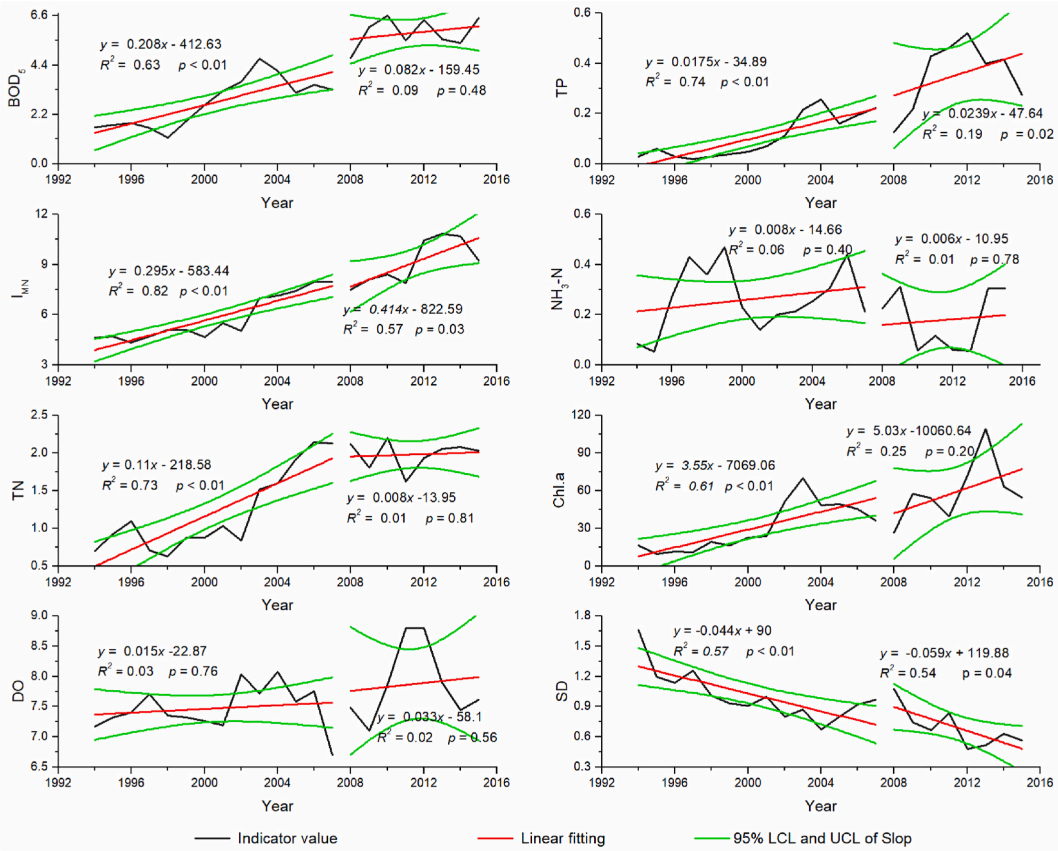

Fig. 6. The water quality indicators change before and after the 2008 year Unit: mg/L (SD: m).

decreased from 4.74 to 1.15. There was a noticeable upward shift between the 1994–2007 and 2008–2015 sets, which is supported by Fig. 6. The amplitudes of the three series differed, with the largest in the 1994–2015 set and the smallest in the 1994–2007 set. TP increased significantly during 1994–2015 with a Z score greater than 2.56 ($\alpha < 0.01$). The significant increase trend during 1994–2007 was consistent with the trend during 1994–2015. However, the upward trend was not significant after 2008 ($Z = 0.94$ ($\alpha > 0.05$)). The change magnitude during 2008–2015 was greater than that during1994–2007, which was in turn greater than that during 1994–2015. For I_{Mn}, the Z scores during 1994–2015, 1994–2007, and 2008–2015 were 5.30, 3.72, and 1.98, respectively, indicating a significant upward trend. The magnitude of the 2008–2015 set was 0.36, larger than that of during 1994–2007, which was equivalent to the 1994–2015 set.

NH_3–N changed negatively during 1994–2015, 1994–2007, and 2008–2015, as their Z values are −0.48, 0.88, and −0.10, respectively. The change magnitude of the 1994–2007 set was 0.01, reaching ten times of that in 2008–2015 set. TN increased significantly during 1994–2015 with a Z score of 3.81 butdecreased in the 2008–2015 set. It changed with a large magnitude during 1994–2007 and then shifted sharply from 2008 to 2015. Chl.a increased significantly during 1994–2015 and 1994–2007, but there was no significant trend after 2008. For DO, there were no significant trends in the 1994–2007 set and 2008–2015 set. but there was a slight upward trend in the entire set. DO had an upward trend in the entire series, which maybe relate to the water quality deterioration, increasing pollution, and algae bloom during 2011–2012. The differences in trend and magnitude among the three series demonstrate a sharp upward shift between the 1994–2007 set and the 2008–2015 set, which can be proven in Fig. 6. As shown by the Z values of the three SD series, there was a significant downward trend. A sharp upward shift was observed in SD at the tail of the 1994–2007 set and the start of the 2008–2015 set, indicating that the water quality trend was different before and after 2008. BOD_5, TP, I_{Mn}, TN, and Chl.a showed an increasing trend during 2008–2015, as demonstrated by the Z values and slopes. Moreover, SD showed a decreasing trend, while there was no significant trend for NH_3–N and DO.

4.3.2. The water quality after 2008 differs with that of the original sets and sub-sets

The indicators' series from 1994 to 2015 had been divided into different sets based on specific time intervals, namely 1994–2000, 2000–2007, 2008–2015, and 1994–2007. These sets have been labelled as $Set_{2008\text{-}2015}$, $Set_{2000\text{-}2007}$, $Set_{1994\text{-}2007}$, and $Set_{1994\text{-}2000}$, respectively. Each indicator sets were examined to judge whether there are differences of population means in them by employing two-sample Student's t-test. Results show that BOD_5, TP, I_{Mn}, TN, and SD have a significant population mean difference between $Set_{2008\text{-}2015}$ and $Set_{2000\text{-}2007}$ (Table 3), but there are no significant difference in the population mean between the two groups in NH_3–N, Chl.a, and DO. The mean difference between $Set_{2008\text{-}2015}$ and $Set_{1994\text{-}2000}$ of each indicator is also assessed (Table 3). At the 0.01 significant level, a significant mean difference is demonstrated separately in BOD_5, TP, I_{Mn}, NH_3–N, TN, Chl.a, and SD. However, there is no mean difference shown in NH_3–N and DO. As the set may be one part of the forefront set, it is necessary to test whether there is a significant population mean difference between $Set_{2008\text{-}2015}$, and $Set_{1994\text{-}2007}$. Similar test results to $Set_{2008\text{-}2015}$ and $Set_{2000\text{-}2007}$ had been obtained. After testing the differences between $Set_{2008\text{-}2015}$ and $Set_{2000\text{-}2007}$, $Set_{2008\text{-}2015}$ and $Set_{1994\text{-}2000}$, $Set_{2008\text{-}2015}$ and $Set_{1994\text{-}2007}$, highly consistent test conclusions can be drawn: after 2008, the water quality is significantly different in the mean level in BOD_5, TP, I_{Mn}, TN, SD, and no difference in mean level in DO and NH_3–N.

4.4. The morphological characteristics differences of water quality indicators before and after 2008

4.4.1. Low-median-high values change of water quality indicators under drought

Trends of the water quality indicators had been illustrated and compared with Sen's illustration in Fig. 7. A consistent conclusion that the water quality decrease is shown in BOD_5, TP, I_{Mn}, TN, and SD illustration that these indicators data are in the upper triangular area of the 1:1 straight line ($x_i = x_j$ and 5 % confidence bound). NH_3–N has no significant trend as its data hovers around the equilibrium line. For Chl.a and DO, the trend is clear but not significant as the values during 2008–2015 are approximate to those during

Table 2
Water quality change trend in different period.

Indicator	M-K								
	1994–2015			1994–2007			2008–2015		
	Z	Slope	Trend	Z	Slope	Trend	Z	Slope	Trend
BOD_5	4.74	0.25	Upward[a]	2.85	0.19	Upward[a]	1.15	0.21	–[d]
TP	4.71	0.02	Upward[a]	3.45	0.02	Upward[a]	0.94	0.03	–[d]
I_{Mn}	5.30	0.29	Upward[a]	3.72	0.28	Upward[a]	1.98	0.36	Upward[b]
NH_3–N	−0.48	−0.002	–[d]	0.88	0.01	–[d]	−0.10	−0.001	–[d]
TN	3.81	0.08	Upward[a]	3.01	0.11	Upward[a]	−0.52	−0.01	–[d]
Chl.a	4.12	2.73	Upward[a]	2.96	3.19	Upward[a]	1.56	4.17	Upward[c]
DO	1.81	0.02	Upward[c]	0.93	0.03	–[d]	1.04	0.10	–[d]
SD	−4.26	−0.03	Downward[a]	−2.90	−0.04	Downward[a]	−1.98	−0.07	Downward[b]

Note.

[a] For $p < 0.01$.

[b] For $p < 0.05$.

[c] Upward but not pass the significance test.

[d] No upward or downward trend.

Table 3

Water quality difference between Set2008-2015 and other sets.

Indicator	*t*-test											
	$Set_{2008\text{-}2015}$ - $Set_{2000\text{-}2007}$				$Set_{2008\text{-}2015}$ - $Set_{1994\text{-}2000}$				$Set_{2008\text{-}2015}$ - $Set_{1994\text{-}2007}$			
	Dif.	t	p	Sig.	Dif.	t	p	Sig.	Dif.	t	P	Sig.
BOD_5	2.30	7.05	5.8E-6	Different[a]	4.05	14.06	6.77E-9	Different[a]	3.11	8.29	7.11E-8	Different[a]
TP	0.20	3.57	0.004	Different[a]	0.32	6.61	2.74E-4	Different[a]	0.25	4.7	7.93E-4	Different[a]
I_{Mn}	2.54	3.82	0.002	Different[a]	4.38	9.02	2.47E-5	Different[a]	3.32	5.54	2.02E-5	Different[a]
NH_3–N	−0.07	−1.33	0.207	Not[c]	−0.09	−1.24	0.242	Not[c]	−0.08	−1.52	0.149	Not[c]
TN	0.47	2.34	0.044	Different[b]	1.15	12.62	1.2E-8	Different[a]	0.77	4.82	1.45E-4	Different[a]
Chl.a	16.11	1.57	0.142	Not[c]	44.24	5.00	0.001	Different[a]	28.69	2.86	0.014	Different[b]
DO	0.34	1.22	0.244	Not[c]	0.52	2.25	0.054	Not[c]	0.41	1.68	0.124	Not[c]
SD	−0.18	−2.24	0.047	Different[b]	−0.47	−3.91	0.002	Different[a]	−0.32	−3.34	0.004	Different[a]

Note: Dif. means the difference, Sig. means the significant level.

[a] Indicates trend statistically significant at the 95 % confidence level.

[b] Indicates trend statistically significant at the 90% confidence level.

[c] No significant difference.

2000–2007. This trend judgment is in accordance with the results of the M − K test in section 4.3.

The non-stationary water quality change has been explored with the trends and characteristics change of indicators (Table 4, Fig. 6). Here, the non-stationary water quality change is indirect assessed with the mean, standard deviation and scatter plots over time. During the period of $Set_{2008\text{-}2015}$ to $Set_{2000\text{-}2007}$, more than 30 % of the mean value has changed for BOD_5, TP, I_{Mn}, TN, and Chl.a. The mean deviation of TP reached 125 %. The mean values of NH_3–N and SD have changed negatively to −28.00 % and −20.69 %,

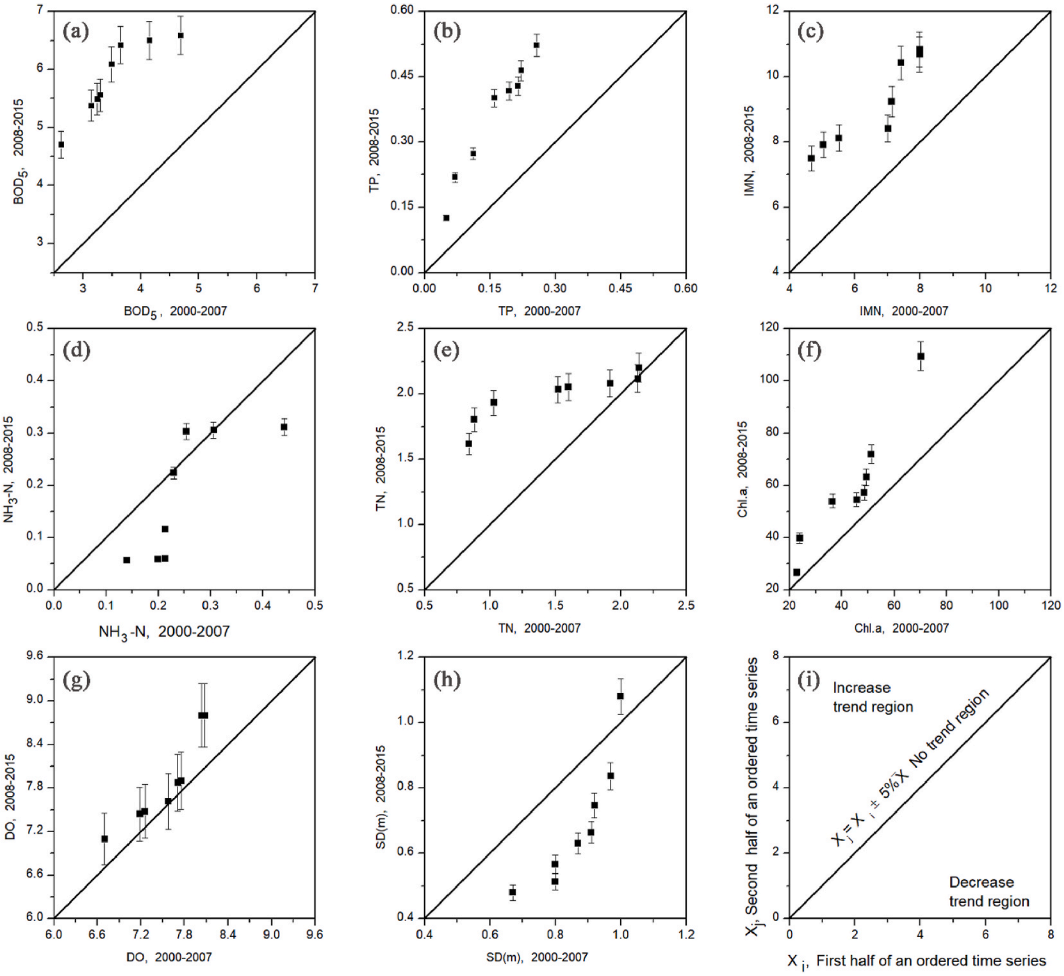

Fig. 7. The change difference between $Set_{2000\text{-}2007}$ and $Set_{2008\text{-}2015}$ demonstrated by Sen's illustration. Indicators unit: mg/L (SD: m).

respectively. DO has recorded the lowest mean change of 4.51 %. As shown by the standard deviation between Set$_{2000\text{-}2007}$ and Set$_{2008\text{-}2015}$, TP, SD, NH$_3$–N, Chl.a, and DO have spread out over a broader range of values during 2008–2015. During 2000–2007, the data points of TN spread out over a broader range. For BOD$_5$ and I$_{Mn}$, there was no significant difference in the degree of dispersion between the two sets.

The water quality change trend is consistent with the M − K test in section 4.3 (Fig. 7 and Table 4). The low, median, and high values of all the indicators can be provided by Sen's illustration (Table 4). BOD$_5$, TP, I$_{Mn}$, and DO have increasing trends for high values, while NH$_3$–N, TN, Chl.a, and SD show no significant trends. For low values, SD has a decreasing trend, and DO has no trend; the others all have an increasing trend. For the median values, BOD$_5$, TP, I$_{Mn}$, and TN have increasing trend, while SD has decreasing trend. The rest indicators have no trend.

4.4.2. Morphological characteristics and quantile characteristics of water quality indicators

The morphological characteristics, such as the minimum, maximum, median, quartiles (25th and 75th percentiles), extreme, mean (red triangle), and outliers are stated in boxplots (Fig. 8). For BOD$_5$, Set$_{2008\text{-}2015}$ distributes more tightly than Set$_{2000\text{-}2007}$, except for the 25th-75th data (Fig. 8 (a)). In Set$_{2000\text{-}2007}$, more points fall below the mean value, making the median a more credible representation of the set. In Set$_{2008\text{-}2015}$, the mean is approximate to the median, and both can represent the set. TP has more dispersed and non-stationary points in Set$_{2008\text{-}2015}$. The mean or median is an alternative to represent Set$_{2000\text{-}2007}$, as more than half of the points are above the mean. The mean value of Set$_{2008\text{-}2015}$ is affected by the low values, and it is not suitable to represent this section data (Fig. 8 (b)). For I$_{Mn}$, the morphological characteristics span is similar in the two sections, and no outlier is far away from the boxes. The front 50 % of Set$_{2000\text{-}2007}$ is close to the lower 50 % of Set$_{2008\text{-}2015}$, indicating a gentle transition between the two sections (Fig. 8 (c)). NH$_3$–N fluctuates significantly in Set$_{2008\text{-}2015}$, with the mean value close to the median. In Set$_{2000\text{-}2007}$, NH$_3$–N values gather below the mean value and are more stationary than in Set$_{2008\text{-}2015}$ (Fig. 8 (d)). TN spans from a shallow value to a high concentration in Set$_{2000\text{-}2007}$ and almost covers all the values of Set$_{2008\text{-}2015}$. It is clustered in a high-value level and shows stationary after 2008(Fig. 8 (e)). For Chl.a, the extreme value is located at a low level in Set$_{2008\text{-}2015}$ and states a high level in Set$_{2000\text{-}2007}$. More points in Set$_{2000\text{-}2007}$ are partial to the high value, making the mean value lower than the median (Fig. 8 (f)). DO does not show intense dispersion in its two sections. Opposite to Set$_{2008\text{-}2015}$, more points are distributed around the median line, and the others distribute near the 75 percentile (Fig. 8 (g)). SD shows a minimum value to the climax in Set$_{2008\text{-}2015}$, which almost covers all the values of Set$_{2000\text{-}2007}$. Still 75 % of Set$_{2008\text{-}2015}$ values are lower than Set$_{2000\text{-}2007}$'s 25 percentile value (Fig. 8 (h)). In summary, the difference between the indicators' two sections is universal with a variant extent and dispersion.

4.5. Change of water quality grade under drought

Regarding water quality, for BOD$_5$, the target concentration of water quality under type III, IV, and V for BOD$_5$ is < 4 mg/L, <6 mg/L, and <10 mg/L, respectively. For Xingyun Lake, 4 mg/L is the threshold concentration. However, BOD$_5$ exceeds the limitation in the majority of years shown in Fig. 9(a). After 2008, water quality is worse than grade IV, even worse than grade V in some years. According to TP, no year shows water quality in grade III. The water quality stated by TP is grade V from 2002 to 2009, then it worsens further than grade V (Fig. 9(b)). The water quality reflected by I$_{Mn}$ experienced a consistently deteriorates after 2000. In 2002, I$_{Mn}$ exceeded the limitation concentration of grade III, then it remained in grade IV for ten years and degraded to grade V during 2012–2014 (Fig. 9(c)). NH$_3$–N stays in grade II (Fig. 9(d)), indicating good quality in this indicator. From the aspect of TN, it exceeds the TN concentration limitation of type IV quickly and never returns to grade III since 2003 (Fig. 9(e)). It lingers around grade V after 2008. Similar to NH$_3$–N, DO is always in grade II (Fig. 9(f)).

Using the indicator in the worst grade as the water quality grade determination indicator, the water quality of Xingyun Lake in each year from 2000 to 2007 is determined as grade IV, IV, V, VI, VI, V, VI, and VI. The water quality has been worse than grade III since 1999. After 2008, the water quality degrades to grade VI completely. The TP and TN are the main contaminants as they have a fast concentration increase in the past 25 years. Under severe drought, the water quality grade changes and is deeply threatened by TP and TN. TP, I$_{MN,}$ and BOD$_5$ with 1.5–6 times ultra-standard of grade III show that the lake faces a continuing threat from the TP, TN, and Oxidizable pollutants.

Table 4

The trend and characteristics of water quality change in the Set$_{2000\text{-}2007}$ and Set$_{2008\text{-}2015}$ "Mean" Unit: mg/L (SD: m).

Indicator	Value								
	Mean			Standard Deviation		Trend, ↑↓			
	2000–2007	2008–2015	Change Ratio	2000–2007	2008–2015	Low	Median	High	Whole
BOD$_5$	3.54	5.84	64.97 %	0.64	0.67	Yes(↑)	Yes(↑)	Yes(↑)	Yes(↑)
TP	0.16	0.36	125.00 %	0.08	0.14	Yes(↑)	Yes(↑)	Yes(↑)	Yes(↑)
I$_{Mn}$	6.59	9.13	38.54 %	1.32	1.34	Yes(↑)	Yes(↑)	Yes(↑)	Yes(↑)
NH$_3$–N	0.25	0.18	−28.00 %	0.09	0.12	Yes(↓)	No	No	No
TN	1.52	1.98	30.26 %	0.54	0.19	Yes(↑)	Yes(↑)	No	Yes(↑)
Chl.a	43.54	59.65	37.00 %	15.60	24.45	Yes(↑)	No	No	No
DO	7.54	7.88	4.51 %	0.47	0.62	No	No	Yes(↑)	No
SD	0.87	0.69	−20.69 %	0.11	0.20	Yes(↓)	Yes(↓)	No	Yes(↓)

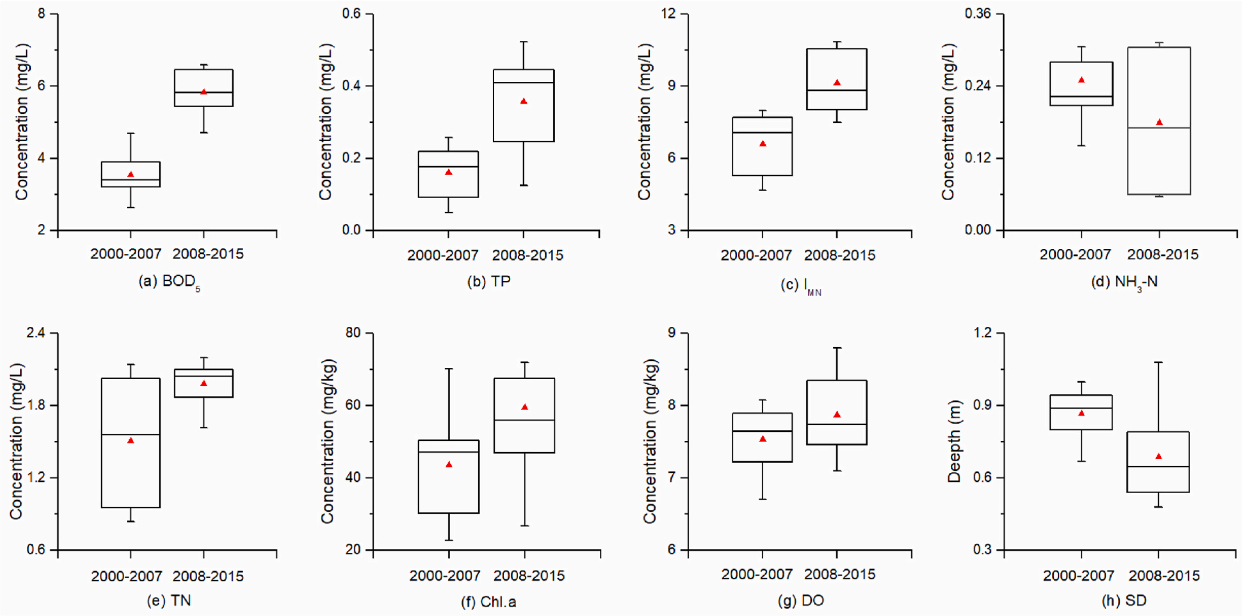

Fig. 8. The Box distribution difference of water quality indicators between $\text{Set}_{2000\text{-}2007}$ and $\text{Set}_{2008\text{-}2015}$.

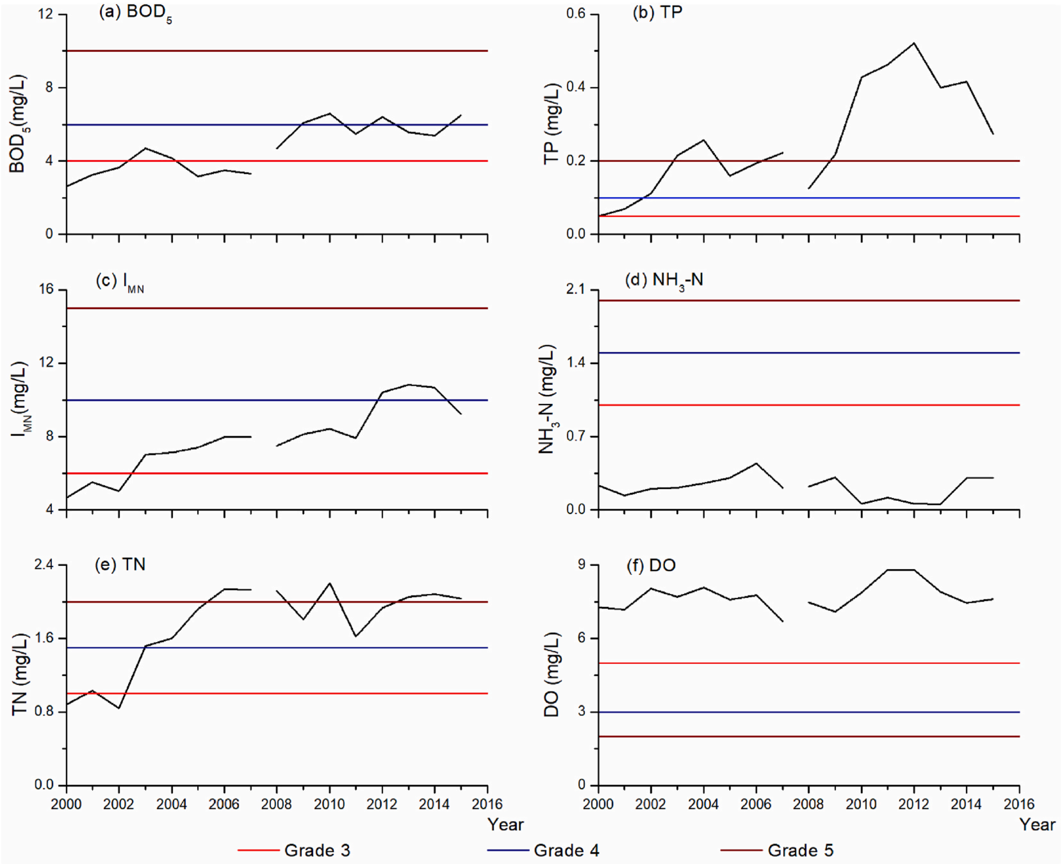

Fig. 9. The water quality grade change during 2000–2015.

5. Discussion

5.1. The synchronization of water quality and water level change under drought stress is well assessed by the constructed synthesized methodology

A synthesized methodology to detect and characterize water quantity and water quality under severe drought is provided and employed. The study finds that the water level change is consistent and synchronous with rainfall change. During severe drought, the water level and the rainfall synchronously decrease sharply. The water level after 2008, except in 2010, goes under the legal level whereas the rainfall of these years is 22.9 %–43.8 % less than normal.

The rainfall, water level, and water pollution index have three synchronous stages i.e. before 2000, stage 2000–2007, and stage 2008–2015. With the water level change after 2008, the pollution index shows an increased change and presents wholly high and discrete values. During 2000–2007, the pollution index presents roughly discrete and nonstationary values. Before 2000, the pollution index presents stationary and low-value change. Under severe drought, the concentration of TP, TN, I_{Mn}, BOD_5, Chl.a, and DO always increase with time, while the NH_3–N and SD states significantly decrease. Except for NH_3–N, the water quality of Xingyun Lake deteriorates in the primary indicators. The trend and the indicators change amplitude in three sections, namely $set_{1994\text{-}2015}$, $set_{1994\text{-}2007}$, and $set_{2008\text{-}2015}$, show non-stationary property tested by using the M − K test and Sen's slope. BOD_5, TP, and TN show a significant increase trend during 1994–2007 and shift to a no-trend change during 2008–2015. SD, Chl.a and I_{Mn} change with a significant trend during 1994–2007 and then keep the previous change in a not significant way. DO and NH_3–N change with no significant trend in the $set_{1994\text{-}2007}$ and $set_{2008\text{-}2015}$ but with sharp altitude in the mean value between the sections. After testing the differences between $Set_{2008\text{-}2015}$ and $Set_{2000\text{-}2007}$, between $Set_{2008\text{-}2015}$ and $Set_{1994\text{-}2000}$, and between $Set_{2008\text{-}2015}$ and $Set_{1994\text{-}2007}$ with two-sample Student's t-test, a highly consistent test conclusion can be drawn that after the year 2008, the water quality is different in the mean level in the representative chemical and physical indicators as BOD_5, TP, I_{Mn}, TN, SD, except for NH_3–N.

From the abovementioned analysis, severe drought changes the water quality trend, morphological characteristics, distinguishability, grade, and characteristics. We have evidence to support the results by exploiting the change in the yearly inflow of TN, TP, and COD into Xingyun Lake during 1994–2014 (Fig. 10). The primary pollution sources decreased during 2008–2014 from a significant increase during 1994–2008, the decrease in inflows of TN, TP, and COD after 2008 may improve water quality. TN flowing into Xingyun Lake increased steadily from 1994 to 2008, which played a significant role in the increase of TN concentration in this period. NO_3-, NO_2-, and organic amine increased from 1994 to 2015 (Fig. 6), especially during 2008–2015. Their increase balances the negative change of NH_3–N. The inflows of TP and TN had a slight decrease during 2008–2014 compared to that during 2002–2008 (Fig. 10(a)–(b)). The inflow of COD underwent an increase from 1994 to 2002, a decrease or no increase from 2002 to 2008, and a

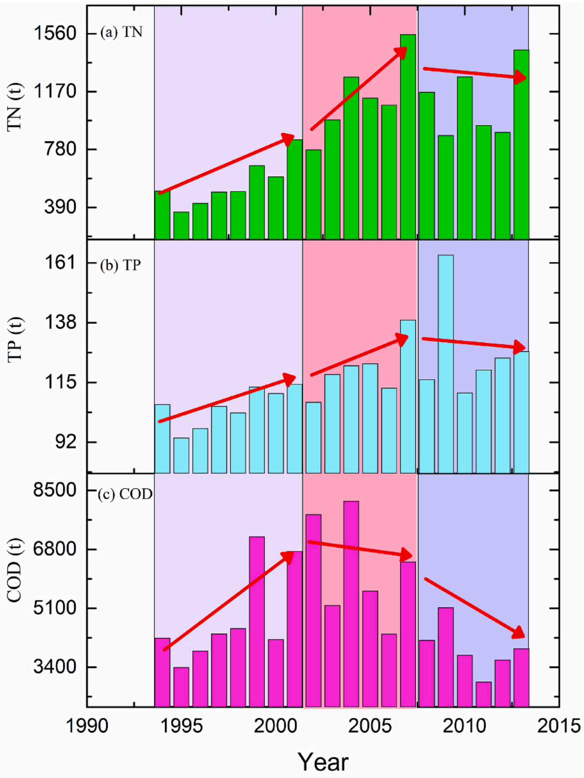

Fig. 10. The change of the yearly inflow of TN, TP and COD (t) into Xingyun Lake during 1994–2014.

sharp decrease after 2008. Moreover, no evidence shows a lasting massive sediment disturbance occurs. Therefore, the inflows of TN, TP, and COD could not have deteriorated the water quality from 2008 to 2015 as shown in Fig. 6. If severe drought had not occurred, the water quality would have improved well during 2008–2015. For DO, during 1994–2007 the pollution enhancement and slight increase in water storage may cause the higher DO. During the drought, the sharp water level decline, the pollution increase, and the sharp increase of Chl.a may have cause compound effects on the fluctuation of DO.

5.2. *The distinguishability, morphological characteristics, and grade of water quality change under drought*

The trend and morphological characteristics of water quality indicators are altered under severe drought in Xingyun Lake. The BOD_5, TP, I_{Mn}, TN, and SD during 2008–2015 were found to be far above the equal equilibrium line, while NH_3–N remained relatively stable. The trends for Chl.a and DO were not clear, as their values in the same period were similar to those from 2000 to 2007. This trend judgment is in accordance with the result of the $M-K$ test. The mean values change more than by 30 % from $Set_{2008\text{-}2015}$ to $set_{2000\text{-}2007}$ for BOD_5, TP, I_{Mn}, TN, and Chl.a. On the other hand, NH_3–N and DO experienced a decrease in mean values, with changes of -28 % and -20.69 %, respectively. DO had the lowest change at 4.51 %. The range of values for TP, SD, NH_3–N, Chl.a, and DO was wider in $Set_{2008\text{-}2015}$, while TN exhibited more dispersed data points. No difference in the degree of dispersion was observed for BOD_5 and I_{Mn} between the two sections.

The difference between $set_{2008\text{-}2015}$ and $set_{2000\text{-}2007}$ was universal across all indicators, with varying extents and dispersion. The morphological characteristics of the minimum, maximum, median, quartiles, extreme, mean, and outliers differed in the two sections due to the severe drought. BOD_5, TP, TN, I_{Mn}, Chl.a, and DO showed an upward trend, while SD exhibited a decreasing trend with higher extreme value in $Set_{2008\text{-}2015,}$ and NH_3–N decreased in mean value but had more fluctuations and dispersion. The water quality grade was worse than grade V throughout the period of severe drought, with the BOD_5, TP, and I_{Mn} exceeding the limitation of grade III in most years. After 2008, the water quality was no better than grade IV. The NH_3–N and DO remained within the limitation of grade III. Moreover, TP and TN were found to be the main contaminants and were increasing rapidly.

5.3. *Understanding the drought stress on water quality and quantity is helpful for pollution improvement and contaminant control*

During a severe drought, natural water bodies such as lakes often experience negative effects on their water level and water quality due to a lack of rainfall [6,28]. The water storage and water level in lakes, such as Lake Urmia [28], Salton Sea [5], and Lake Poyang [55], decrease when there is a rainfall deficit. Meanwhile, the deficit of water quantity inducing water quality deterioration in most water quality parameters [7,8] are reported in many lakes, including Lake Poyang [55], saline lakes of southeast Australia [6], and Castanhão reservoir [9]. Affected by the severe drought, the water surface area of Xingyun Lake falls sharply (Fig. 4) and affects the effectiveness of its protection measure. During 2000–2015, a 1.59 km^2 first-class protection zone and over 3.33 km^2 lakeside buffer zone were established. Furthermore, measures such as pollution source treatment, industrial structure adjustment, low-polluted water treatment, and ecological restoration were implemented. These measures wer effective during 2003–2008 (Fig. 3(c)). However, even with these measurement in place, water quality declined sharply during the severe drought occurred during 2009–2015 (Fig. 3(b)–(c)). The effects were weakened under the drought due to the diminishing in the ability of water purified by the buffer zone function and the reduction of lake water storage with decreasing lake surface compared to normal years, especially on the north bank, and the east and west banks of the south side (Fig. 4). The sharply decreased water quantity broken the water quality stationary stage (Fig. 3(c)). Therefore, scientifically identifing the water fluctuation and trying to guarantee water storage is a substantial way to help lake restoration from pollution [8,55]. Ecological restoration technology is also an effective means of removing organic and inorganic pollutants, including COD and nitrogen from lakes. This can be done through plant and microbial growth and nutrient cycling [56]. Biofilm repair technology [57], and artificial wetland technology [58] have been widely used in managing lakeshore zone pollution and mitigating surface source pollution in lakes. Based on the above-mentioned water quality and water level change under severe drought, it is essential to conduct scientific research on the hydrological process, various water treatment measures, and the transformation of major pollutants. This will help us accurately understand and prevent the water environment of Xingyun Lake.

5.4. *Uncertainty and limitations*

When utilizing this synthesized methodology in other regions or lake systems, it is important to carefully choose representative indicators according to the environmental quality standard. The analysis results are also limited by the quantity of time series for the indicators. We recommend that yearly indicators containing pre-drought, in-drought and post-drought data be provided, at a minimum. Additionally, the process of rainfall, water level, and water quality should be outlined by the change time, period, and time intervals. The significant yearly period of drought and abnormal water levels can assist in providing short- and long-term assessment of the possible implications for water quality, exploring long-term impacts of recurring droughts on water quality and ecosystem health, and improving the water governance strategy. However, the drought process requires multi-year, monthly, daily, and even more fine time intervals (such as hourly or minutely) research to establish cause-and-effect relationships in water quality [16] and to detect the recovery time of water quality from drought. The complex topography of low latitude plateau [59] makes the water resources and drought effects complex, which in turn makes the water quality change dependent on the hydrological process. Additionally, the water quality varies in spatial heterogeneity [13] and has diffirent effects on aquatic environments with different temporal and spatial scales [39]. Adopting a science-based approach and taking targeted measures must be done at different temporal and spatial scales based on the cause-and-effect relationships between water quality and hydrology.

6. Conclusions

The severe drought stress on water level and Water Quality in Xingyun Lake is assessed and characterized with a synthesized methodology. The results are as follows.

1. (1) The water level and water quality of Xingyun Lake have an evident and synchronous response to the severe drought, as shown by the strongly consistent and asymptotically time change point and well-fitted process. The lake's water level was below the legal water level during 2009–2014, except for 2010, when the average rainfall of these years was approximately −22.9 % under the normal period. Compared with 2002, the water surface area decreased by 10.50 %. After 2008, the pollution index climbed above 1.21 and fluctuated around 1.42. Synchronous stages, i.e. before 2000, stage 2000–2007, and stage 2008–2015, are shown in the rainfall, water level, and water pollution index.
2. (2) Severe drought induces water quality differentiation from multidimensional aspects of overall features, distinguishability, and trend. The water quality is getting worse in the physical, chemical, and biological aspects, especially in TP, I_{MN}, and BOD_5 under severe drought. The TP, I_{MN}, and BOD_5 have the apparent change amplitude, whereas the DO and NH_3–N have less change amplitude. From $set_{1994\text{-}2007}$ to $set_{2008\text{-}2015}$, the trends and change amplitude of water quality indicators tested by the M − K test and Sen's slope show a sharp shift to steady change, no one during 2008–2015 keep its significant trend (at the 95 % confidence level) and slope during 1994–2007. Results of the two-sample Student's t-test show that the $Set_{2008\text{-}2015}$ water quality is significantly different from $set_{2000\text{-}2007}$ ($p < 0.05$) in TP, I_{MN}, BOD_5, TN, and SD. Moreover, the $Set_{2008\text{-}2015}$ water quality is not in the groups of $set_{1994\text{-}2000}$ in TP, I_{MN}, BOD_5, TN, Chl.a, and SD at the 90 % confidence level.
3. (3) Severe drought induces the water quality differentiation in morphological characteristics and eigenvalue of indicators' time series. From the eigenvalue, the morphological characteristics of all indicators are not constant in the pro-drought and drought persist period in Xingyun Lake. The water quality decreases in BOD_5, TP, I_{Mn}, TN, and SD are far above the equal equilibrium line during 2008–2015. For Chl.a and DO, the trend is not clear as the values during 2008–2015 are approximate to those during 2000–2007. BOD_5, TP, and I_{Mn} have increasing trends for low, median, and high values; SD shows a decreasing trend in low and median values, whereas TN has an increasing trend. DO has an increasing trend in high values, while NH_3–N and Chl.a have an increase in low values. Moreover, the morphological characteristics of water quality indicators in $set_{2008\text{-}2015}$ and $set_{2000\text{-}2007}$ change significantly. The characteristics of the water quality indicators minimum, maximum, median, quartiles, extreme, mean, and outlier values differ under drought.
4. (4) The water quality grade and the indicator concentration under severe drought are threatened deeply by TP and TN. The water quality decreases significantly and sharply from most indicators after 2008. TP changes significantly as it reaches 6 times the ultra-standard of grade III. The concentration of TP, TN, I_{Mn}, BOD_5, Chl.a, and DO always gets higher with time, and the NH_3–N states a significant decrease trend.

CRediT authorship contribution statement

Junxu Chen: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Jia Xu:** Visualization, Validation, Formal analysis, Data curation. **Qi Yi:** Validation, Software, Investigation. **Jiabin Peng:** Writing – review & editing, Validation, Conceptualization. **Yang Lang:** Software, Investigation. **Liang Emlyn Yang:** Validation, Software, Formal analysis. **Jihui Zhang:** Validation, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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