Geomorphology 391 (2021) 107894

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Lowering water level of Dongting lake of the Mid-Yangtze River in response to large-scale dam construction: A 60-year analysis

Xiaohe Lai [a,*], Haiwei Chen [a], Yuebao Hou [a], Brian Finlayson [b], Maotian Li [c], Jing Chen [c]

[a] Department of Water Resources and Harbor Engineering, College of Civil Engineering, Fuzhou University, Fuzhou 350116, China
[b] School of Geography, The University of Melbourne, Victoria 3010, Australia
[c] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China

ARTICLE INFO

Article history:
Received 26 November 2020
Received in revised form 6 August 2021
Accepted 8 August 2021
Available online 11 August 2021

Keywords:
Sediment load
Water discharge
Water level
Dam construction
Dongting Lake
Middle Yangtze River

ABSTRACT

River-lake systems, crucial to both the ecological environment and societal development, have been affected by increasing anthropogenic activities in addition to climate and environmental changes. Here, annual water discharge and sediment load data (1956–2017) and rainfall data (1960–2016) from Dongting Lake in the middle catchment of the Yangtze River were analysed at four major inlets and one outlet, and their connections with lake level variations were evaluated using multiple analytical methods. The results show that minor fluctuations were found in rainfall and discharge during the study period, but the sediment load entering Dongting Lake decreased significantly from 231 mt/year (before 1969) to 123 mt/year (1970–2002) and then 17 mt/year (after 2003, post TGD). The variation in the sediment was mainly induced by increasing anthropogenic activities in the lake system. During period 1 (before 1969), human impact was weak compared to the dominant natural forces. However, anthropogenic force showed an increasing contribution to the loss of sediment load since then, as it increased from 43.0% (1970–1987, post cut-off engineering) to 64.8% (1988–2002, post Gezhou Dam) and extended to 90.2% during 2003–2017 (post TGD). Nevertheless, continuous sediment accumulation over the past decades in the lake has caused a rising water level. During period 1, high sediment input contributed to an average annual increase of 13.96 cm in the lake level, but it decreased significantly to 1.94 cm year^{-1} during 1970–2002 due to intensive anthropogenic regulations. Since 2003, the completion of the TGD intercepted abundant sediment, eventually leading to a shift from net deposition to net loss of the sediment budget in Dongting Lake, and consequently, the lake level fell. In the future, if the net sediment supply was kept below ~18 mt/year, the lake level would continue to fall, causing severe problems to the lake ecosystem, especially during drought years.

1. Introduction

Lakes are productive ecosystems that influence the local climate and ecological balance (Wetzel, 2001; Zedler and Kercher, 2005). The hydrological condition of a lake reflects its internal changes, which are vital for the lake ecosystem and human habitation (Ye et al., 2020). Lake level, for example, is directly associated with these changes and is mainly affected by climate changes and human activities (Carpenter et al., 1992; Gao et al., 2014; Yuan et al., 2015). In detail, climate changes may affect the precipitation in lake basins, adjusting the water discharges and sediment loads of lakes (Murray-Hudson et al., 2006; Guo et al., 2008), while extensive anthropogenic activities in the lake catchment, such as dam construction, irrigation, and lakeshore reclamation, would directly alter the lake's water and sediment supply (Graf, 2006; McDonald et al., 2009). Studies have shown that both climatic and anthropogenic factors have caused alterations in the water level, which are harmful to the ecosystem and societal development (Adamowski et al., 2013).

In the Yangtze catchment, >50,000 reservoirs have been constructed since the 1950s, and these reservoirs have greatly changed the hydrological conditions in the Yangtze River and brought new challenges to the river system (WCD, 2000; Dai and Liu, 2013; Yang et al., 2014). It has been reported that the annual discharge of the Yangtze River has barely changed over the past 50 years, and the seasonal discharge pattern has been redefined as flow reduction in flood seasons and flow increment in dry seasons, which is one of the major functions of large reservoirs (Chen et al., 2016; Lai et al., 2017). However, after the construction of the Three Gorges Dam (TGD), the sediment load from the Yangtze River into the sea reduced by 65%, dropping from 420 mt year^{-1} to 145 mt year^{-1} (2003–2012, averaged) (Chen et al., 2010). Recent studies have shown that anthropogenic activities have become a major contributor to the shifts in water and sediment on a decadal time scale, especially the interception of sediment by dams, which has

* Corresponding author.
E-mail address: laixiaohe@fzu.edu.cn (X. Lai).

https://doi.org/10.1016/j.geomorph.2021.107894
0169-555X/

changed the sedimentary processes of the entire Yangtze catchment (Wei et al., 2014; Zhang et al., 2014; Li et al., 2016).

As China's second largest freshwater lake, Dongting Lake has been inhabited by humans since the Early Holocene (Liu et al., 2012). It is located ca. 250 km below the TGD site and thus is sensitive to the changes in water and sediment from upstream of the Yangtze River. Previous studies have analysed the variations in water and sediment in Dongting Lake. The results show that the discharge is mainly from the four local tributaries and the sediment is mainly from the mainstream and is transported into Dongting Lake via the three inlets (Li et al., 2005). The overall decreasing trend of water and sediment in Dongting Lake is synchronous in the early stage, but the sediment has decreased significantly due to the impoundment of the Three Gorges Reservoir in 2003 (Li et al., 2011; Han et al., 2016).

In recent years, both popular press and scientific articles have reported that extensive dam construction has caused the deterioration of Dongting Lake, endangering agricultural and economic development due to a degraded water system (Lai et al., 2013; Yuan et al., 2014). Seasonal drought became normal in the Dongting Lake region, especially in the northern part of the region, after the impoundment of the Three Gorges Reservoir in 2003. The discharge supply from both the Yangtze mainstream and the local tributaries are the primary influencing factors for the change in the Dongting Lake water level (Huang et al., 2011; Zhou et al., 2017). Hu et al. (2018) concluded that the mainstream of the Yangtze River has a decisive influence on the water level of East Dongting Lake based on a SVR model. We noted that some studies have attributed the variation in the Dongting Lake level to the runoff variation effect by climate changes and human interference in past decades, especially the construction of the TGD, which has extended the seasonal low water period of Dongting Lake (Ou et al., 2012; Yuan et al., 2015; Han et al., 2016). However, many scholars (Jiang and Huang, 2004; Yin et al., 2012; Liu et al., 2019) have also found that the area and capacity of Dongting Lake has changed significantly based on underwater topographic data, remote sensing images, etc. Therefore, we believe that as a critical factor, the long-term sediment load and related sedimentation in the lake should also be taken into consideration, as presented in this study, while discussing the hydrological alteration in the Dongting Lake basin.

Dongting Lake is fed by three inlets from the Yangtze mainstream and four local tributaries, all of which drain back into the Yangtze River through a single Chenglingji (CLJ) outlet. Thus, the variations in water and sediment in the Yangtze River and local tributaries would cause ecological changes in Dongting Lake, although the mechanism is still unclear. Our work is different from previous studies that paid more attention to a single factor, such as runoff. In this study, we aim to 1) obtain the annual variations in water and sediment inflow and outflow of Dongting Lake, 2) reveal the spatiotemporal variations in the water and sediment fluxes, and 3) estimate the relative effects of climate changes and human activities on discharge and sediment in the basin. Finally, we discuss the future trend of the variations in the level of Dongting Lake. This study will shed light on the hydrological regime of lakes in the Yangtze catchment and provide new insights into the administrative supervision of lake environments.

2. Study area

Dongting Lake is located on the fluvial plain of the middle Yangtze catchment (28°30′N-30°20′N, 111°40′E-113°10′E) (Fig. 1). The three inlets from the Yangtze mainstream are Songzikou (SZK), Taipingkou (TPK), and Ouchikou (OCK), and the four local tributaries are the Xiangjiang River (XJR), the Zishui River (ZSR), the Yuanjiang River (YJR), and the Lishui River (LSR). Chenglingji (CLJ) has only one outlet connected with the Yangtze River (Fig. 1).

Dongting Lake is located in a subtropical monsoon climate zone, and most of the annual rainfall (ca. 1300 mm) is concentrated in the wet season from May to September. The annual mean temperature in the lake area is 17.0 °C. The lake coverage was over 6000 km^2 in the mid-1900s, but now it has decreased to only 2691 km^2 (Chen et al., 2001). The water level is ca. 33 m in elevation in the western part of the lake, and ca. 27 m at the CLJ station in the eastern part (DLWRABHP, 2018). The water depth is 6.4 m on average and is 23.5 m at its deepest.

3. Material and methods

3.1. Data sources

In this study, we collected annual discharge (1956–2017) and annual sediment load (1956–2017) at the inflows and outflow of Dongting Lake (CWRC, 2000–2018) and lake water level data (1960–2016) from publications of the Changjiang Water Resources Commission (CWRC, 2001–2018). For a better comparison with previous studies, we use the data from Chenglingji to represent the water level of Dongting Lake. The annual rainfall data (1960–2017), including 7 gauges in the Dongting Lake Basin, were obtained from the National Meteorological Information Center of the China Meteorological Administration (CMA) (http://data.cma.cn/).

3.2. Methods

In this study, Mann-Kendall (Chen et al., 2014; Li et al., 2016) and empirical mode decomposition tests (Huang and Wu, 2008; Massei and Fournier, 2012; Sang et al., 2012) are used to detect the critical annual changes in water discharge and sediment load of the 8 gauging stations (3 inlets, 4 local rivers, and 1 outlet). The empirical orthogonal function method (Dommenget and Latif, 2002; Dai et al., 2010) is used to find possible modes of changes in water discharge and sediment load and the associated climate factors, which are rainfall variations in this study. Then, the double mass curve method (Searcy and Hardison, 1960; Dettinger et al., 1999; Wei et al., 2020) is used to estimate the relative effects of climate changes and human activities on discharge and sediment. All of the above tests were processed using MATLAB software (version 2015b).

3.2.1. Mann-Kendall

The Mann-Kendall test is widely used to analyse rainfall, discharge, temperature, and water quality for temporal trends (Hamed and Rao, 1998; Chen et al., 2014; Li et al., 2016). This is a nonparametric test that can be used regardless of the underlying distribution of the data; thus, the MK test can be used to analyse hydrological and meteorological data that are not normally distributed.

In a Mann-Kendall test, if the sample number "n" is >10, then the standard normal system variable is calculated by the equation below:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V_{ar}(S)}} & S>0 \\ 0 & S=0 \\ \frac{S+1}{\sqrt{V_{ar}(S)}} & S<0 \end{cases}$$

where the test statistic S is calculated by the following equation:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{Sgn}(x_j - x_i)$$

$$\mathrm{Sgn}(x_j - x_i) = \begin{cases} +1 & (x_j - x_i)>0 \\ 0 & (x_j - x_i)=0 \\ -1 & (x_j - x_i)<0 \end{cases}$$

$$E(S) = 0$$

$$V_{ar}(S) = \frac{n(n-1)(2n+5)}{18}$$

The Z statistic shows an increasing trend if it is >0, and vice versa. If the absolute value of Z is no <1.28, 1.64, or 2.32, it means the statistic Z has passed the significance tests at the confidence level of 90%, 95%, and 99%, respectively.

When using the MK test to detect an abrupt change in a time series, an order column UF_k is created as follows:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{V_{ar}(S_k)}} \quad k = 1, 2 \cdots, n$$

where

$$S_k = \sum_{i=1}^{k} r_i \; r_i = \begin{cases} 1 & x_i > x_j \\ 0 & \text{else} \end{cases} \quad j = 1, 2 \cdots, n$$

$$E(S_k) = \frac{k(k+1)}{4}$$

$$V_{ar}(S_k) = \frac{k(k-1)(2k+5)}{72}$$

A UF_k column belongs to the standardized normal distribution, with a significance level α. If $|UF_k| > UF_{(1-\frac{\alpha}{2})}$, then a significant trend variation is indicated for the column. An increasing trend is indicated by a UF_k value >0, and vice versa. If the time series is set in a backward sequence, then another column UB_k is created. Only if the two curves of UF_k and UB_k have an intersection located in the zone of critical values would the intersection indicate the timing of the abrupt change.

3.2.2. Empirical mode decomposition

EMD can decompose complicated data into a residual component and a small number of intrinsic mode functions (IMFs). The EMD method has been widely applied in hydrological research (Rao and Hsu, 2008; Lee and Ouarda, 2010; Sang et al., 2012). In this study, discharge and sediment load are decomposed to obtain a series of IMFs and a residual, which is described below:

$$X(t) = \sum_{i=1}^{n} C_i + r(t)$$

where $X(t)$ is the raw data to be decomposed, C_i is the IMFs, and $r(t)$ is the residual component, which reflects the trend of the raw data (Huang and Wu, 2008; Massei and Fournier, 2012). In this study, the trends of discharge and sediment load are used.

3.2.3. Empirical orthogonal function

The EOF test can be used to decompose a series of variables that change with time into a spatial function that does not change with time and a temporal function that changes with only time. The spatial function contains the spatial distribution features of the data, and the temporal function is the linear combination of the spatial variables, which are called the main component.

The temporal and spatial dependence of the data can be separated for corresponding functions of time (eigenweighting) and space (eigenvectors). Eigenvectors are a special set of vectors associated with a linear system of equations (i.e., a matrix equation) that are sometimes also known as characteristic vectors, proper vectors, or latent vectors (Marcus and Minc, 1992). Therefore, EOF has been applied to indicate potential physical modes in recent years (Dommenget and Latif, 2002; Lane, 2004).

In an EOF analysis, there are several modes that are believed to affect the analysed data, but only the first and second modes are accepted as the main contributors (contribution level > 98%) that affect water discharge and sediment load. Other modes with extremely low contributions are considered noise (Emery and Thomson, 2001; Dai et al., 2010).

3.2.4. The double mass curve method

The double mass curve method is a common method to check the consistency of and variation in the relationship between two parameters. It is the relation line drawn in the rectangular coordinate system between the continuous accumulation value of one variable and the continuous accumulation value of another variable in the same period. It can be used to check the consistency of hydrological and meteorological elements, interpolate or correct missing values in the data, and analyse the trend change and intensity of hydrological and meteorological elements (Searcy and Hardison, 1960; Dettinger et al., 1999; Wei et al., 2020).

In this study, the double mass curve method employs a linear regression analysis of the first mode's time series. Then, the regression equation is used to simulate the first mode's eigenweighting of discharge and sediment in the modified period. Since the climate factor, precipitation, is the same for both the original and predicted eigenweighting of discharge/sediment, which eliminates the influence of climate changes, the difference between the original and predicted eigenweighting of discharge/sediment is the variation induced by human activities.

4. Results

4.1. Variations in annual water discharge and sediment load

According to the MK test, the absolute Z values of the four rivers are <1.28, indicating that the variation in annual discharges is not statistically significant. The Z values of the three inlets and the outlet CLJ are −6.092, −7.781, −7.842 and −3.098. These absolute values are much >2.32, indicating significant decreasing trends over the past 50 years (Table 1). The annual discharges of inlets SZK and TPK decreased significantly in the 1980s (confidence level 95%), and the discharge of OCK decreased in the 1970s, but there were no abrupt changing points at the inlets (Fig. 2). The annual discharge of CLJ started to decrease in the 1980s, and it became statistically significant after 2003 (Fig. 2).

The EMD test calculates the residual values of the original data that reflect the trend of the data. As seen in Fig. 2, the EMD test shows similar features as the MK test: no significant changes are found in the annual discharges of the four rivers, but a continuous decrease occurs at the three inlets and CLJ; in particular, periods of rapid decrease are found at OCK around 1970 (Fig. 2).

The MK test shows absolute values of Z much >2.32 at the four rivers, three inlets, and at the CLJ outlet, reflecting a significant decreasing trend of annual sediment load of the inflows and outflow at Dongting Lake (Table 1). An abrupt decrease in sediment load occurred at XJR and LSR in the 1990s, and the decreasing trend became significant in the 2000s (Fig. 3). Additionally, the sediment load decreased at ZSR and YJR in the 1980s, yet no abrupt change point was detected (Fig. 3). The sediment load decreased significantly at OCK and CLJ in the 1970s, TPK in the 1980s, and SZK in the 1990s.

The EMD test shows a generally decreasing trend in sediment load at the four rivers, the three inlets, and the CLJ outlet, among which the YJR, OCK and CLJ decreased as early as the 1970s, much earlier than at the other sites (Fig. 3).

4.2. Modes of discharge and sediment loads

The first mode of the annual discharge shows positive values at all the gauging stations, especially the CLJ station, which exhibits the highest eigenvector value (Fig. 4A). The eigenweighting of the first mode shows minor fluctuations in the time sequence. The first mode of the annual sediment loads also shows positive values at these gauging stations, and SZK and OCK have higher eigenvector values than CLJ (Fig. 4B). On the time sequence, the first mode of sediment load shows an obvious decreasing trend over time. The first modes of both the discharge and sediment load show periodic variations and indicate extreme changes in some particular years, such as the record-breaking flood in 1998 and the drought in 2011.

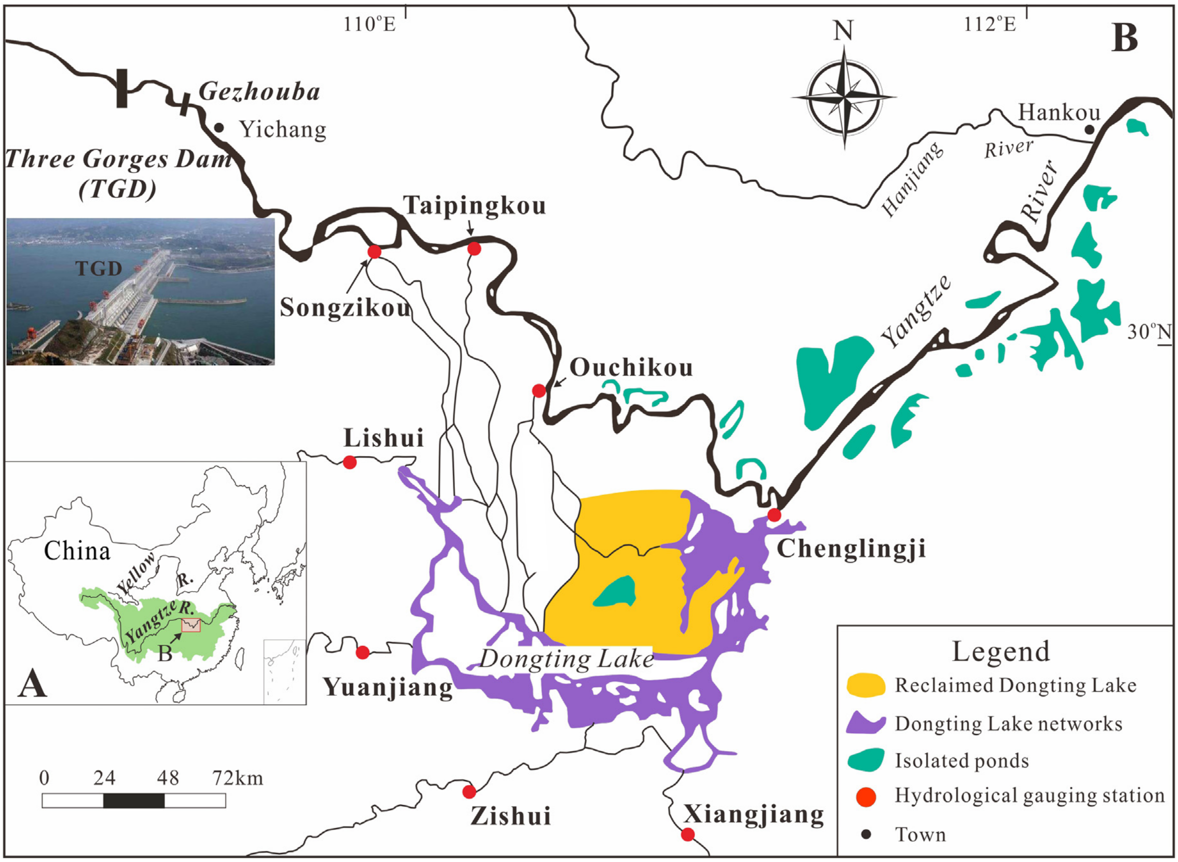

Fig. 1. Location of the Dongting lake basin and the middle Yangtze River. Also illustrated are the gauge stations recording the inflow and outflow of the lake.

The contribution levels of the first mode of annual discharge and sediment load exceed 90%, indicating an overwhelmingly controlling factor. The second mode contributes little, with either positive or negative spatial eigenvector values (Fig. 4), reflecting multiple factors of influence. Thus, the present study focuses on the analysis of the first mode, and the second mode is not discussed.

4.3. Impacts of climate changes and human activities

In a chronological sequence, it appears that rainfall, discharge, and sediment load fluctuate periodically, with some extremely high or low values, such as during the flood in 1998 and the drought in 2011 (Fig. 5). Overall, rainfall and discharge always maintain the same trend, but sediment load has three distinct periods over 1956–2017. During period 1 (before 1969), the high eigenweighting value correlated well with the rainfall. During period 2 (1970–2003), the fluctuating and reducing values of eigenweighting showed different patterns with the natural forces. During period 3 (2003–2017, post TGD), the value of eigenweighting (sediment) showed a significant bias with the rainfall.

The double mass curve method was used to estimate the relative effects of climate changes and human activities on discharge and sediment in the basin (Fig. 6). The correlation coefficients of all fitted regression equations were above 0.99, which indicates that the equation analogue effects were very good (Fig. 6A, C). The correlation between cumulative annual precipitation and discharge exhibits a linear trend from 1960 to 2018 (Fig. 6A). The time series for the sediment load can be divided into three phases (a linear phase, decreasing phase, and decreasing phase) with turning points in 1970 and 2003 (Fig. 6C). Notably, one small turning phase occurred in 1988 at the completion of the Gezhou Dam. Fig. 6B and D presents original data and predicted data for discharge and sediment load. The predicted value (red) represents the impact of climate changes, while the origin value (blue) represents the joint influence of human activity and climate changes. The original annual values of the discharge are slightly lower than the predicted data throughout the period (Fig. 6B). Regarding sediment load (Fig. 6D), the original values are generally lower than the predicted values in the 1970–1990s, while since 2003, the original values began to be significantly lower than the condition without human activities.

5. Discussion

The above dataset-based observations and statistical analyses help comprehend the interrelation between lake hydrology and human interference in the context of the impact of dam construction on Dongting Lake level fluctuations over time.

5.1. Patterns of discharge and sediment load in Dongting Lake since the 1950s

The water and sediment budget of a lake system is usually associated with intensive anthropogenic forces in addition to natural processes. For Dongting Lake in the present study, the water supply from the four tributaries changed little (~5%) (Fig. 2), but the sediment loads declined greatly (~70%) after 2000 (Fig. 3). Dam construction in the upstream basins of the local tributaries could be the main reason for such a reduction in sediment load, which trapped a large amount of sediment behind the dam (Tan, 2013). Additionally, tree-planting projects in the Dongting Lake area since the 1980s could have prevented soil erosion and reduced the loss of surface soil (Yuan et al., 2014).

For the Yangtze mainstream, both our collected data and previous publications show that the annual discharge of the Yangtze mainstream

Table 1
Z values of discharge and sediment load at 8-gauge stations.

Z	XJ	ZS	YJ	LS	SZK	TPK	OCK	CLJ
Discharge	1.215	0.875	0.826	−0.589	−6.092	−7.781	−7.842	−3.098
Sediment	−4.070	−4.908	−6.323	−4.677	−6.991	−8.145	−8.893	−8.899

remained stable since the 1950s (Yuan et al., 2012; Chen et al., 2016), yet the annual sediment load showed a significant decline (Chen et al., 2010). Meanwhile, the water and sediment supply from the Yangtze mainstream to Dongting Lake showed visible declines over the past few decades (Fig. 3). There are several possible reasons for this. First, severe siltation occurred at the three inlets in the earlier year, resulting in the rising threshold elevation at the lake entrance and reducing the water and sediment into the lake (Li et al., 2011; Tan, 2013). Second, as coarse sediment was kept in the TGD, it enabled the less turbid water to erode the Yangtze River bed immediately below the dam site, making the riverbed lower than the entrance of the three inlets (Lai et al., 2017). Then, it makes it difficult for the water and sediment from the Yangtze River to enter Dongting Lake (Hong et al., 2007; Li et al., 2011). Third, a channel cut-off occurred in the 1970s between the OCK and CLJ (Fig. 1), resulting in less sediment load from the mainstream being transported into Dongting Lake via the three inlets (Li et al., 2011; Tan, 2013).

The water supply from the four tributaries was stable, which constituted nearly 70% of the lake's water. Although the water supply from the Yangtze River decreased markedly during 1956–2017, the annual discharge at the CLJ outlet only a showed marginal decrease (Fig. 2). However, the sediment load at the CJL outlet has decreased significantly since the 1970s due to decreased sediment supplies from both the Yangtze mainstream and the local tributaries. Overall, intensive anthropogenic forces, especially dam construction, have been the main contributor to the loss of sediment supply for Dongting Lake.

5.2. The mechanism of the variations in water discharge and sediment load

The EOF analysis of discharge and sediment load for Dongting Lake showed the contribution from the first mode to be over 90% (Fig. 4), which may represent the process of flow concentration. Therefore, it could reflect the water and sediment entering Dongting Lake via the tributaries and the three inlets and then outflowing at CLJ. Additionally,

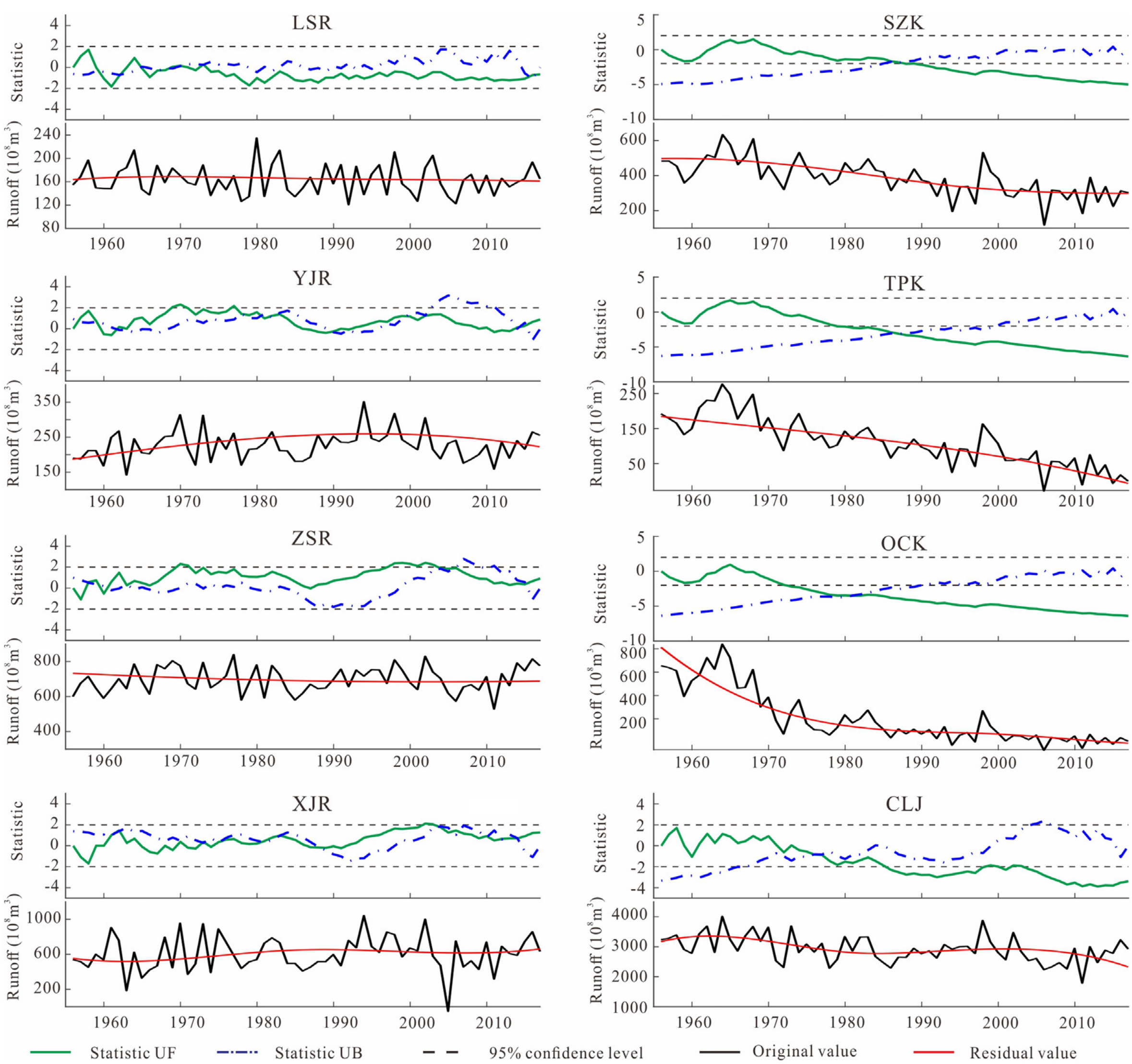

Fig. 2. Mann-Kendall and EMD analyses showing the variation trend of discharge at the 8-gauge stations around the Dongting Lake over the past 50 years.

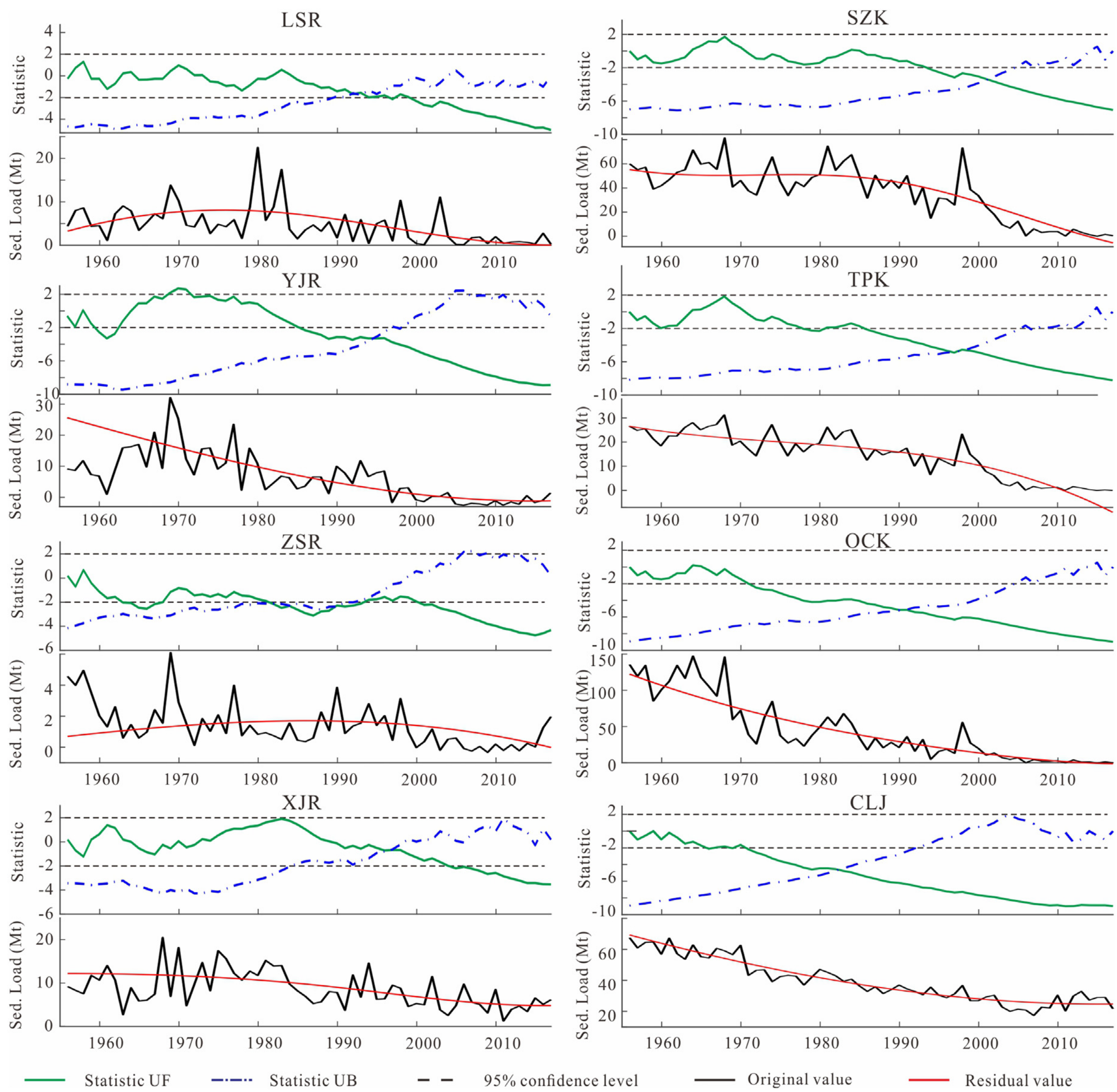

Fig. 3. Mann-Kendall and EMD analyses showing the variation trend of sediment load at the 8-gauge stations around the Dongting Lake over the past 50 years.

the highest eigenvalue of discharge occurred at CLJ, implying that most water that entered Dongting Lake flowed out via CLJ (Fig. 4A). However, the eigenvalues of sediment load at inlets SZK and OCK are higher than CLJ (Fig. 4B), indicating more sediment coming into the lake than going out, suggesting annual net deposition in the lake over the past 50 years.

The fluctuation in the chronological sequence of rainfall, discharge, and sediment load (Fig. 5) indicates that both the first modes of discharge and sediment load could be related to rainfall. Furthermore, correlation analysis revealed that the relationship among rainfall, water discharge, and sediment load shows relatively good correlations (Table 2). The correlation of discharge-rainfall is 0.67 ($p > 0.99$), indicating that rainfall is the main reason for the variations in discharge in the Dongting Lake area, which is also supported by earlier studies (Chen et al., 2014; Wei et al., 2014; Li et al., 2016). Similarly, a good correlation between discharge and sediment suggests that the sediment load fluctuated with water discharge under conditions dominated by natural processes (Table 2).

Three periods over 1956–2017 on the chronological sequence of the first mode of sediment load (Fig. 5) relate to three distinctive dynamics. During Period 1 (before 1969), the good relationship between the sediment and rainfall suggests a persistent natural dominant period when the impact of man-made engineering projects was low, so rainfall and water discharge were the main factors in the sediment load. Then, both natural and enhanced anthropogenic forces modulated the water and sediment supply in the Dongting Lake area during Period 2 (1970–2003). In this period, many artificial projects were performed, including channel cut-off between OCK and CLJ leading to geomorphological adjustment in the Yangtze mainstream and intensive construction of reservoirs that stored additional sediment. Thus, the impact of rainfall and water discharge on the sediment load was weakened due to increased anthropogenic impact. Finally, as the completion of TGD construction intercepted most of the sediment in the mainstream of the Yangtze River and caused the loss in sediment load to become severe, the natural forces became less influential in sediment and water transportation after 2003 (Period 3).

These three periods are also clearly evident in Fig. 6. As shown in Fig. 6B and D, the anthropogenic forces started to show their impact in period 2 and were enhanced in period 3, as reflected by the increasing difference between the red (without human impact) and blue curves (with human impact). The quantification of the contributions of anthropogenic impacts on water discharge and sediment load variations indicated that human activities caused an additional decrease in the water

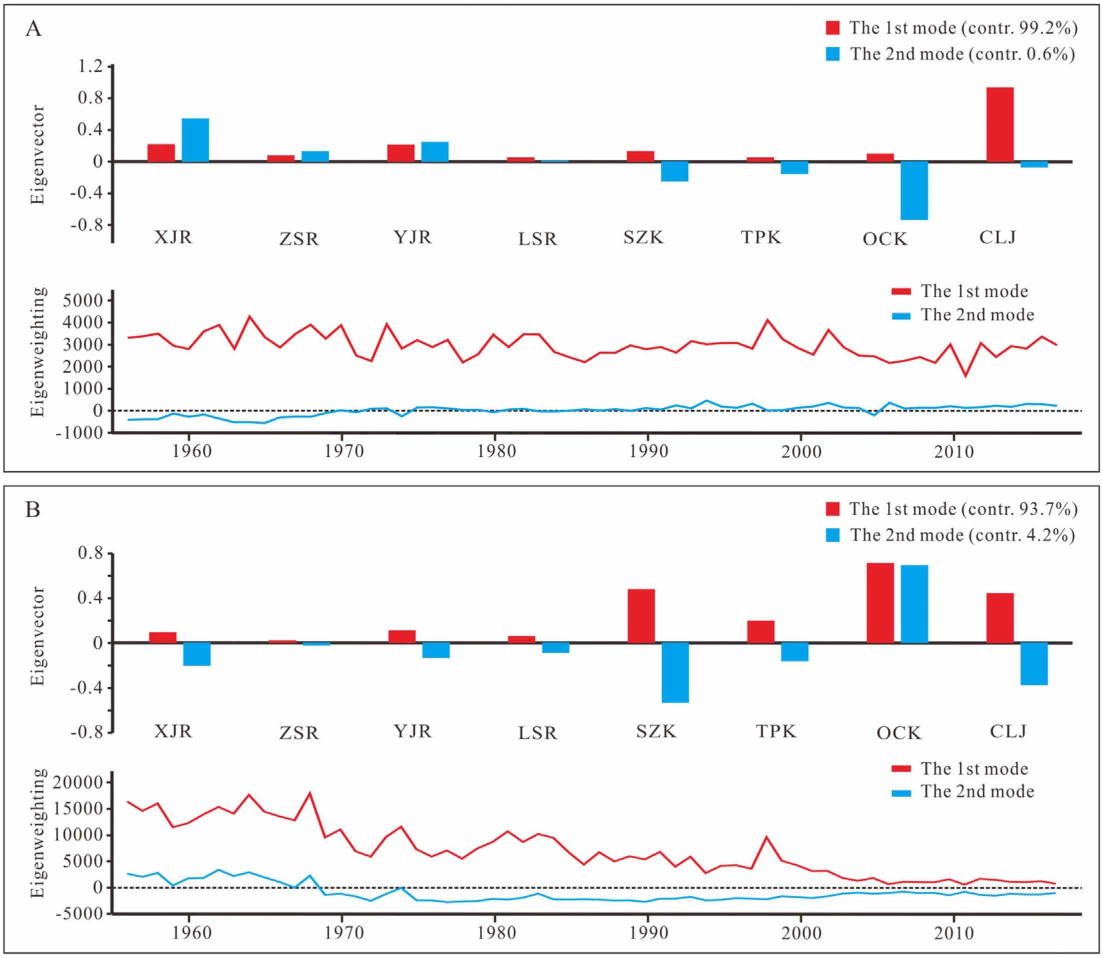

Fig. 4. **A**) EOF analysis of discharge at 8-gauge stations; and **B**) EOF analysis of sediment load at 8-gauge stations.

supply for Dongting Lake by 13.1% during period 2 and extended to 23.8% in period 3 after construction of the TGD (Fig. 6B). The sediment load showed greater reduction due to human activities, as it decreased by 43.0% as a result of cut-off engineering at Jingjiang at approximately 1970, a further 64.8% after the completion of Gezhou Dam in 1988, and 90.2% with the addition of TGD in periods 3 (Fig. 6D). Compared with

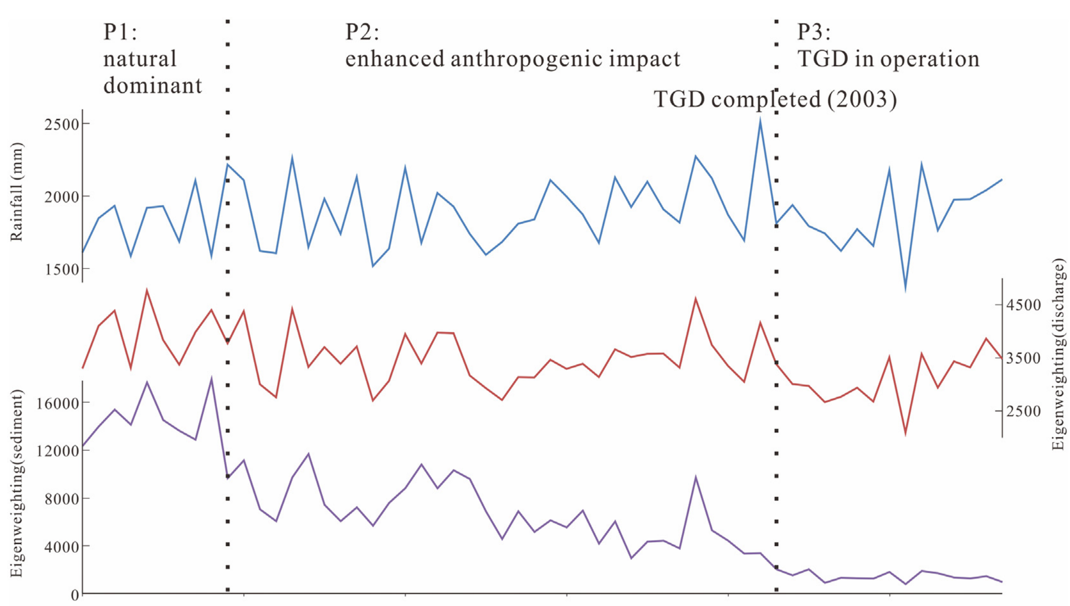

Fig. 5. the trends of rainfall, the first mode's eigenweighting of water discharge and sediment load over 3 periods. P1, P2 and P3 represent Period 1, Period 2 and Period 3 respectively.

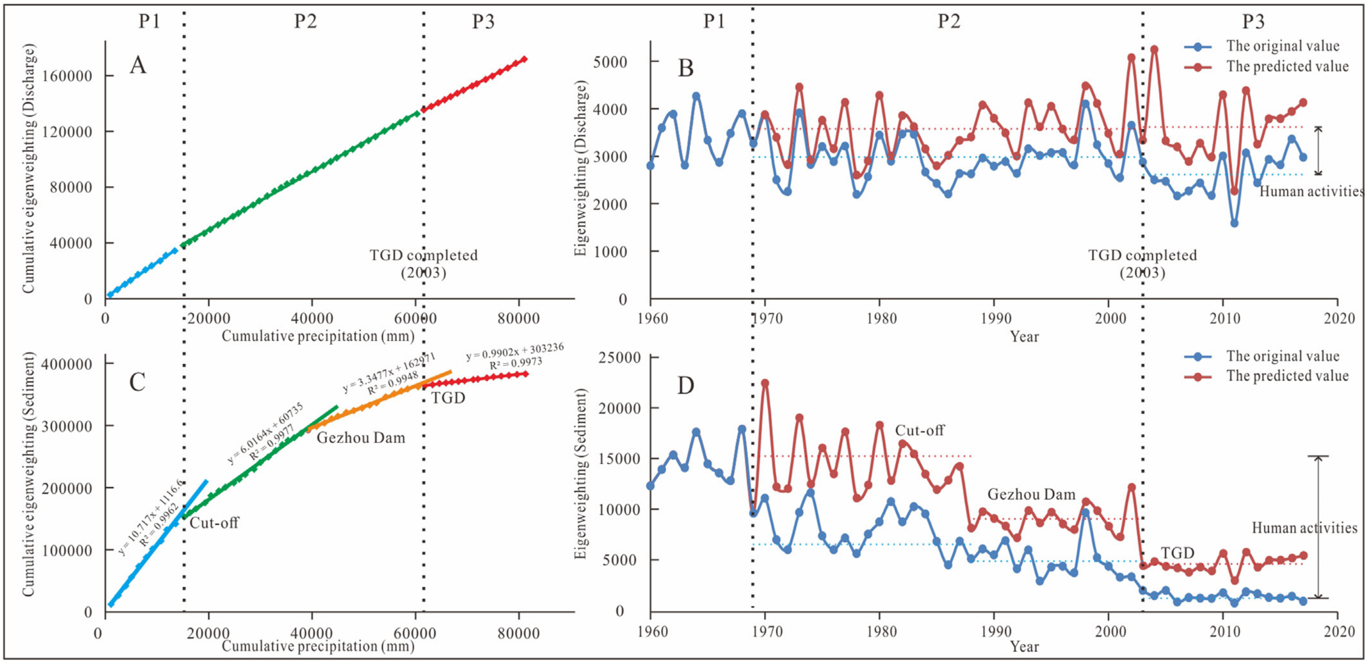

Fig. 6. A) Cumulative rainfall compared to the first mode's eigenweighting of water discharge; **B)** Quantitative estimates of the responses of water discharge to human activities**; C)** Cumulative rainfall compared to the first mode's eigenweighting of sediment load; and **D)** Quantitative estimates of the responses of sediment load to human activities. P1, P2 and P3 represent Period 1, Period 2 and Period 3 respectively.

the predicted value without the engineering project, the contribution rates of engineering to sediment reduction in their respective phases are 45.0% (cut-off), 44.8% (Gezhou Dam), and 70.0% (TGD).

5.3. The variations of lake level

Previous studies ascribed the change in the Dongting Lake water level over recent decades mainly to rainfall, discharge and evaporation (Ou et al., 2012; Yuan et al., 2015; Han et al., 2016). In this study, we re-evaluated the controlling hydrological factors that affected the water level variation by adding a new factor, i.e., sediment load and sedimentation of the lake.

As shown by the CLJ gauge station, the water level of Dongting Lake increased during 1956–2003 and decreased slightly during 2003–2017 (Fig. 7B). In general, changes in rainfall, water storage and sediment accumulation are the chief contributors to the fluctuations in lake levels. As revealed by a previous study, rainfall has been relatively stable since the 1950s (Fig. 5) (Chen et al., 2016), and rainfall is not a significant factor affecting the fluctuation of the Dongting Lake level. Therefore, we calculate the difference in the Dongting Lake water storage (DWS), as the DWS may roughly equal the annual inflow from the Yangtze River + the annual inflow from local tributaries – evaporation − the annual outflow at the CLJ outlet. Evaporation data for the past 50 years (1961–2014) are from Han et al. (2016). The results show that Dongting Lake suffered a net loss of ~61.8 billion m^3 of water during 1956–2003 (data from annual reports of CWRC, 2000–2018). Thus, the decreased water storage in the lake would not have caused the

Table 2
correlations among rainfall, the first mode's eigenweighting of water discharge and sediment load.

	Rainfall	Discharge	Sediment
Rainfall	1		
Discharge	0.67*	1	
Sediment	−0.04	0.60*	1

water level to rise. Thus, the sediment accumulation in Dongting Lake must be a key factor affecting the lake level. The sediment accumulation increased before 2003 but remained static afterwards (Fig. 7A). This good relationship with the water level of Dongting Lake indicates that sediment accumulation could be a significant contributor to the change in water level. Thus, we hypothesized that continuous sediment accumulation in the lake would have caused the lakebed to rise and further lift the water level, even when the water storage was reduced.

There were three distinctive periods of sediment accumulation affected by varied human interference (Figs. 5, 6 and 7A). During Period 1 (before 1969), minor human activity in the lake catchment caused little modification to the sediment supply to the lake. Thus, as mentioned above, the annual net input of sediment led to a continuous increasing accumulation of sediment deposition in Dongting Lake during 1961–1969. According to the data published by CWRC (2000–2018), the average net sediment deposition in Dongting Lake was 168 mt year^{-1}, and the water level rose by 13.96 cm per year, yielding a water level/sediment (W/S) ratio of 0.083 cm/mt. During Period 2 (1970–2002), several major incidents might have affected the sediment budget. First, the channel cut-off between OCK and CLJ due to artificial regulation resulted in less sediment available in the Yangtze mainstream (Figs. 5, 6). The Gezhou Dam being built and becoming functional in 1981 combined with many reservoirs being built in the catchment resulted in a substantial reduction in sediment supply to Dongting Lake. As a result, the net sediment deposition in Dongting Lake declined to 87 mt year^{-1} during 1970–2002, and the water level rose by 1.94 cm per year. The W/S ratio declined to 0.022 cm/mt, indicating a rising lakebed due to sediment accumulation in the lake over the years. In addition, according to previous research (Liu et al., 2019), the water storage volume decreased by 1380 million m^3 (1952–2003) due to siltation at 32 m elevation in East Dongting Lake (Supplement A). The lake area has been shrinking since the 1950s, which has resulted in a net loss in water storage (Jiang and Huang, 2004; Yin et al., 2012; Liu et al., 2019). Thus, it is reasonable to claim that the progressive accumulation of sediment would have lifted the elevation of the lakebed and eventually increased the Dongting Lake level during 1956–2002.

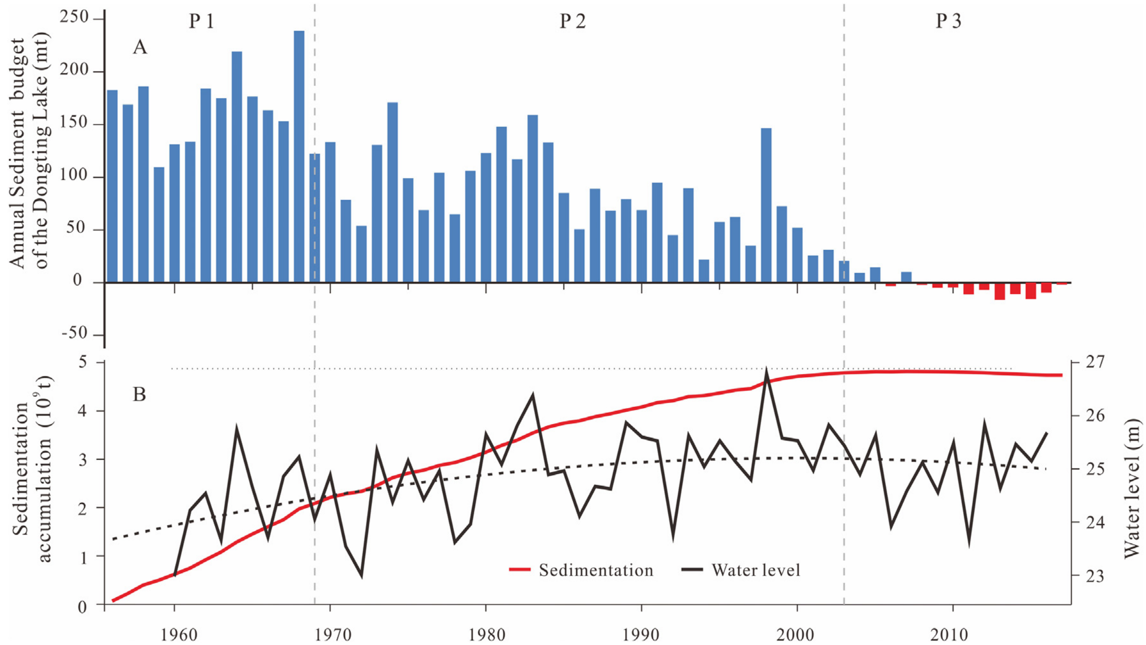

Fig. 7. A) annual sediment deposit in the Dongting Lake over the past 50 years, which showed a significant decline in P3; and **B)** total accumulation of sediment in the Dongting Lake and the variation of lake level, the dashed black line represents tendency of the water level. P1, P2 and P3 represent Period 1, Period 2 and Period 3 respectively.

Since the TGD became functional (Period 3), the Yangtze channel below the dam was severely eroded by the less turbid water due to massive sediment entrapment in the TGD (Lai et al., 2017), causing a significant reduction in the sediment supply to Dongting Lake. Thus, the sediment budget of Dongting Lake further decreased and even became negative in the past few years (8 mt year^{-1} from 2008 to 2017, Fig. 7A). The actual topographic water storage volume increased by 480 million m^3 (2003−2011) (Supplement A) at 32 m elevation in East Dongting Lake due to sediment loss (Liu et al., 2019). Under such circumstances, the lake level showed a slight downward trend since 2003.

A combined factor including rainfall and negative sediment accumulation as well as anthropogenic modulations could affect the water level. For instance, due to the flood control effect of the TGD, the water level of the Yangtze mainstream at the CLJ station became lower than that of Dongting Lake, allowing water and sediment in the lake to flow out (Hong et al., 2007). In addition, in extremely dry years such as 2006 and 2011, when the annual water discharges at CLJ were only 70% and 50% of the average value before TGD, Dongting Lake exhibited two record-breaking low water levels (Fig. 7B), reflecting the possible consequence of rainfall shortages. Thus, it is easy to predict that the water level of Dongting Lake will hit another low if another year of severe drought comes. In the future, if the government plans to build more dams in the Yangtze River upstream of the TGD, it might further reduce the sediment mass supplied to Dongting Lake (Yang et al., 2014).

This phenomenon also occurred in Poyang Lake, and the sediment balance in Poyang Lake changed from sedimentation to a sediment deficit after construction of the TGD (Wu et al., 2007; de Leeuw et al., 2009; Nakayama and Shankman, 2012). Moreover, an increase in the river-lake water level gradient induced by the TGD altered the lake balance by inducing greater discharge into the Yangtze River, which is most likely the cause of the current lake shrinkage (Mei et al., 2015). At present, seasonal drought is a frequent problem in Poyang Lake, which has caused a problems for agricultural irrigation, water quality, and the ecological environment. These principles should be universal, so will these problems in Poyang Lake also appear in the future of Dongting Lake?

This study indicates that not only discharge and rainfall but also lakebed aggradation caused by sedimentation are responsible for the change in water level. Furthermore, if the sediment entering Dongting Lake further decreases (<18 mt/year, the current amount of sediment at Chenglingji), then the water level might continue to decline, causing water shortages and related critical issues to the ecosystem. Perhaps a water gate or other project is needed to help keep the water in Dongting Lake, similar to what is planned for Poyang Lake (Wang et al., 2013).

6. Conclusions

The present study analysed the variations in the annual rainfall combined with water discharge and sediment load inflow and outflow of Dongting Lake over the period of 1956–2017. The conclusions of the study are as follows.

1. A significant decrease was observed in sediment load inflow to Dongting Lake, caused by extensive channel regulation and dam construction, including the Gezhou Dam and the Three Gorges Dam.
2. The significant correlation (0.67) between sediment and discharge, together with poor correlation between sediment and rainfall (−0.04), shows that the sediment load was more related to discharge and anthropogenic factors than to rainfall.
3. Compared to the nature-dominated period 1, human activities became the major force in modulating the water discharge and sediment load of Dongting Lake since the 1970s. The water discharge decreased by 23.8%, and the loss in sediment became much more significant, as it already declined by 90.2% (post-TGD).
4. The increase in the Dongting Lake level was due to intensive sediment accumulation in the lake during 1960–2003. After 2003, the annual sediment budget in Dongting Lake became negative, causing the lake level to decline.
5. With less sediment supplied to Dongting Lake, the water level will further decline, especially in drought years.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2021.107894.

Declaration of competing interest

There is no conflict of interest.

Acknowledgement

Special thanks are extended to Dr. Yan Liu and Prof. Qianli Sun for their constructive comments during the preparation and revision of the manuscript. This research was funded by the National Science Foundation of China (Grant No. 2016YFE0133700) and the Fundamental Research Funds for the Central Universities.

References

Adamowski, J., Adamowski, K., Prokoph, A., 2013. Quantifying the spatial-temporal variability of annual streamflow and meteorological changes in eastern Ontario and southwestern Quebec using wavelet analysis and GIS. J. Hydrol. 499, 27–40.
Carpenter, S.R., Fisher, S.G., Grimm, N.B., Kitchell, J.F., 1992. Global change and freshwater ecosystems. Annu. Rev. Ecol. Syst. 23, 119–139.
Chen, J., Wu, X., Finlayson, B.L., Webber, M., Wei, T., Li, M., Chen, Z., 2014. Variability and trend in the hydrology of the Yangtze River, China: annual precipitation and runoff. J. Hydrol. 513, 403–412.
Chen, J., Finlayson, B.L., Wei, T., Sun, Q., Webber, M., Li, M., Chen, Z., 2016. Changes in monthly flows in the Yangtze River, China–with special reference to the three Gorges Dam. J. Hydrol. 536, 293–301.
Chen, Z., Li, J., Shen, H., Zhanghua, W., 2001. Yangtze River of China: historical analysis of discharge variability and sediment flux. Geomorphology 41, 77–91.
Chen, Z., Wang, Z., Finlayson, B., Chen, J., Yin, D., 2010. Implications of flow control by the three Gorges Dam on sediment and channel dynamics of the middle Yangtze (Changjiang) river, China. Geology 38, 1043–1046.
CWRC-Changjiang Water Resources Commission, 2000-2018. Changjiang Sediment Bulletin available at: http://www.cjw.gov.cn/zwzc/bmgb/ (in Chinese).
CWRC-Changjiang Water Resources Commission, 2001-2018. The Yangtze River water management system available at http://yu-zhu.vicp.net/ (in Chinese).
Dai, Z., Liu, J.T., 2013. Impacts of large dams on downstream fluvial sedimentation: an example of the three Gorges Dam (TGD) on the Changjiang (Yangtze River). J. Hydrol. 480, 10–18.
Dai, Z.J., Liu, J., Lei, Y.P., Zhang, X.L., 2010. Patterns of sediment transport pathways on a headland bay beach-Nanwan beach, South China: a case study. J. Coast. Res. 26 (6), 1096–1103.
Dettinger, M.D., Cayan, D.R., McCabe, G.J., Marengo, J.A., 1999. Multiscale hydrologic variability associated with El Niño –Southern Oscillation. In: Diaz, H.F., Markgraf, V. (Eds.), El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts. Cambridge University Press, Cambridge, pp. 113–146.
DLWRABHP-Dongting Lake Water Resources Administration Bureau of Hunan Province, 2018. Historical database of water resources of Hunan Province. http://www.hnsw.com.cn/hnwr/index.asp.
Dommenget, D., Latif, M., 2002. A cautionary note on the interpretation of EOFs. J. Clim. 15, 216–225.
Emery, W.J., Thomson, R.E., 2001. Time-series analysis methods. Data Analysis Methods in Physical Oceanography 371–567.
Gao, J.H., Jia, J., Kettner, A.J., Xing, F., Wang, Y.P., Xu, X.N., Yang, Y., Zou, X.Q., Gao, S., Qi, S., 2014. Changes in water and sediment exchange between the Changjiang River and Poyang Lake under natural and anthropogenic conditions, China. Sci. Total Environ. 481, 542–553.
Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79, 336–360.
Guo, H., Hu, Q., Jiang, T., 2008. Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China. J. Hydrol. 355, 106–122.
Hamed, K.H., Rao, A.R., 1998. A modified Mann-Kendall trend test for autocorrelated data. J. Hydrol. 204, 182–196.
Han, Q., Zhang, S., Huang, G., Zhang, R., 2016. Analysis of long-term water level variation in Dongting Lake, China. Water 8, 306.
Hong, L., Dong, L., Li, W., 2007. Impact of Three Gorges Reservoir on water level, sediment and water quality of Dongting Lake. China Water Resources 6, 13–14 (in Chinese).
Hu, T., Mao, J., Pan, S., Dai, L., Zhang, P., Xu, D.H., 2018. Water level management of lakes connected to regulated rivers: an integrated modeling and analytical methodology. J. Hydrol. 562, 796–808.
Huang, N., Wu, Z., 2008. A review on Hilbert-Huang transform: Method and its applications to geophysical studies. Rev. Geophys. 46.
Huang, Q., Sun, Z., Jiang, J.H., 2011. Impacts of the operation of the Three Gorges Reservoir on the lake water level of Lake Dongting. Journal of Lake Sciences 23 (3), 424–428 (in Chinese).
Jiang, J., Huang, Q., 2004. Analysis of the lake basin change and the rushing-silting features in the past decades of Dongting Lake. Journal of Lake Sciences 16 (3), 209–214 (in Chinese).
Lai, X., Jiang, J., Huang, Q., 2013. Effects of the normal operation of the Three Gorges Reservoir on wetland inundation in Dongting Lake, China: a modelling study. Hydrol. Sci. J. 58, 1467–1477.
Lai, X., Yin, D., Finlayson, B., Wei, T., Li, M., Yuan, W., Yang, S., Dai, Z., Gao, S., Chen, Z., 2017. Will river erosion below the Three Gorges Dam stop in the middle Yangtze? J. Hydrol. 554, 24–31.
Lane, A., 2004. Bathymetric evolution of the Mersey Estuary, UK, 1906–1997: causes and effects. Estuar. Coast. Shelf Sci. 59, 249–263.
Lee, T., Ouarda, T., 2010. Long-term prediction of precipitation and hydrologic extremes with nonstationary oscillation processes. J. Geophys. Res. Atmos. 115.
de Leeuw, J., Shankman, D., Wu, G., de Boer, W.F., Burnham, J., He, Q., Yesou, H., 2009. Strategic assessment of the magnitude and impacts of sand mining in Poyang Lake, China. Reg. Environ. Chang. 10, 95–102.
Li, J., Wang, K., Qin, J., Xiao, H., Chao, L., 2005. The evolution of annual runoff and sediment in the Dongting Lake and their driving forces. Acta Geograph. Sin. 60 (3), 503–510 (in Chinese).
Li, N., Wang, L., Zeng, C., Wang, D., Liu, D., Wu, X., 2016. Variations of runoff and sediment load in the middle and lower reaches of the Yangtze River, China (1950-2013). PLoS One 11, e0160154.
Li, Z., Xie, Y., Xu, D., 2011. Runoff-sediment variation and its effect on the Dongting Lake. Journal of China Hydrology 31, 46–55 (in Chinese).
Liu, T., Chen, Z., Sun, Q., Finlayson, B., 2012. Migration of Neolithic settlements in the Dongting Lake area of the middle Yangtze River basin, China: lake-level and monsoon climate responses. The Holocene 22, 649–657.
Liu, X., Yi, F., Luan, Z., Wang, D., 2019. Processes of East Dongting Lake in recent period. J. Sediment. Res. 44 (4), 25–32 (in Chinese).
Marcus, M., Minc, H., 1992. A Survey of Matrix Theory and Matrix Inequalities. Courier Corporation.
Massei, N., Fournier, M., 2012. Assessing the expression of large-scale climatic fluctuations in the hydrological variability of daily Seine river flow (France) between 1950 and 2008 using Hilbert–Huang transform. J. Hydrol. 448, 119–128.
McDonald, K., Bosshard, P., Brewer, N., 2009. Exporting dams: China's hydropower industry goes global. J. Environ. Manag. 90, S294–S302.
Mei, X., Dai, Z., Du, J., Chen, J., 2015. Linkage between three gorges dam impacts and the dramatic recessions in china's largest freshwater lake, Poyang Lake. Sci. Rep. 5, 18197.
Murray-Hudson, M., Wolski, P., Ringrose, S., 2006. Scenarios of the impact of local and upstream changes in climate and water use on hydro-ecology in the Okavango Delta, Botswana. J. Hydrol. 331, 73–84.
Nakayama, T., Shankman, D., 2012. Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. Glob. Planet. Chang. 100 (2013), 38–50.
Ou, C., Li, J., Zhang, Z., Li, X., Yu, G., Liao, X., 2012. Effects of the dispatch modes of the Three Gorges Reservoir on the water regimes in the Dongting Lake area in typical years. J. Geogr. Sci. 22, 594–608.
Rao, A.R., Hsu, E.-C., 2008. Hilbert-Huang transform analysis of hydrological and environmental time series. Springer Science & Business Media.
Sang, Y.-F., Wang, Z., Liu, C., 2012. Period identification in hydrologic time series using empirical mode decomposition and maximum entropy spectral analysis. J. Hydrol. 424, 154–164.
Searcy, J.K., Hardison, C.H., 1960. Double mass curves. US Geological Survey Water-Supply Paper 1541-B. USA, US Government Printing Office, Washington DC.
Tan, H., 2013. The Succession and Reason Analysis of Hydrological Environment in the Dongting Lake in Recent 50 Years. Doctoral Thesis of Hunan Agricultural University.
Wang, Y., Jia, Y., Guan, L., Lu, C., Lei, G., Wen, L., Liu, G., 2013. Optimising hydrological conditions to sustain wintering waterbird populations in Poyang Lake National Natural Reserve: implications for dam operations. Freshw. Biol. 58, 2366–2379.
WCD (World Commission on Dams), 2000. Dams and Development: A New Framework for Decision-Making. The Report of the World Commission on Dams. Earthscan, London.
Wei, W., Chang, Y., Dai, Z., 2014. Streamflow changes of the Changjiang (Yangtze) River in the recent 60 years: impacts of the East Asian summer monsoon, ENSO, and human activities. Quat. Int. 336, 98–107.
Wei, X., Cai, S., Ni, P., Zhang, W.K., 2020. Impacts of climate change and human activities on the water discharge and sediment load of the Pearl River, southern China. Sci. Rep. 10 (1).
Wetzel, R.G., 2001. Limnology: Lake and River Ecosystems. Gulf Professional Publishing.
Wu, G., de Leeuw, J., Skidmore, A.K., Prins, H.H.T., Liu, Y., 2007. Concurrent monitoring of vessels and water turbidity enhances the strength of evidence in remotely sensed dredging impact assessment. Water Res. 41, 3271–3280.
Yang, S.L., Milliman, J.D., Xu, K.H., Deng, B., Zhang, X., Luo, X., 2014. Downstream sedimentary and geomorphic impacts of the three Gorges Dam on the Yangtze River. Earth Sci. Rev. 138, 469–486.
Ye, S., Cheng, M., Zeng, G., Tan, X., Zhang, Y., 2020. Insights into catalytic removal and separation of attached metals from natural-aged microplastics by magnetic biochar activating oxidation process. Water Res. 179, 115876.
Yin, H., Yang, B., Jiang, Z., Zeng, F., Peng, P., Li, J., 2012. Mutual effects between morphological characteristics and variations of flow-sediment process of Dongting Lake during 1951~2009. Geogr. Res. 31 (3), 471–483 (in Chinese).
Yuan, W., Yin, D., Finlayson, B., Chen, Z., 2012. Assessing the potential for change in the middle Yangtze River channel following impoundment of the Three Gorges Dam. Geomorphology 147, 27–34.
Yuan, Y., Zeng, G., Liang, J., Li, X., Li, Z., Zhang, C., Huang, L., Lai, X., Lu, L., Wu, H., 2014. Effects of landscape structure, habitat and human disturbance on birds: a case study in East Dongting Lake wetland. Ecol. Eng. 67, 67–75.
Yuan, Y., Zeng, G., Liang, J., Huang, L., Hua, S., Li, F., Zhu, Y., Wu, H., Liu, J., He, X., 2015. Variation of water level in Dongting Lake over a 50-year period: Implications for the impacts of anthropogenic and climatic factors. J. Hydrol. 525, 450–456.
Zedler, J.B., Kercher, S., 2005. Wetland resources: status, trends, ecosystem services, and restorability. Annu. Rev. Environ. Resour. 30, 39–74.
Zhang, Q., Ye, X., Werner, A., Li, Y., Yao, J., Li, X., Xu, C., 2014. An investigation of enhanced recessions in Poyang Lake: comparison of Yangtze River and local catchment impacts. J. Hydrol. 517, 425–434.
Zhou, L., Li, J., Tang, X., Zhou, Y., Li, X., 2017. Dynamics of water level of Lake Dongting during the past 60 years and the associated driving factors. J. Glaciol. Geocryol. 39 (3), 660–671 (in Chinese).