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Detecting changes in water level caused by climate, land cover and dam construction in interconnected river—lake systems

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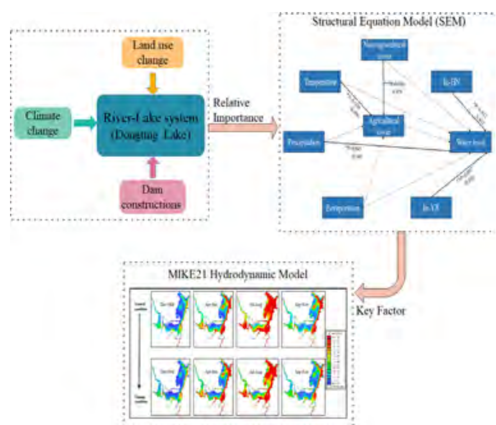
HIGHLIGHTS

- The interaction of river-lake systems plays a key role in lake hydrological changes.
- At different stages of water level changes, the relative importance of driving factors is changing.
- The three inlets inflow of Yangtze River is the key factor for the sudden change of the water level in 2003.
- The MIKE21 hydrodynamic model is used to analyze the spatiotemporal variation of water level driven by key factors.

GRAPHICAL ABSTRACT



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ABSTRACT

There is a growing recognition of the broader environmental significance of exploring the relative importance of climate change and anthropogenic impacts on hydrologic fluctuations in river-lake systems. In the case of Dongting Lake, the typical river-lake system, we collected the water level from 1990 to 2019, spanning before and after the operation of the Three Gorges Dam (TGD) in 2003. This study was conducted to detect water level fluctuations in Dongting Lake and to quantify the relative influence of climate, land cover and dam construction on water levels. We defined the impact of the dam construction as the three inlets inflow of Yangtze River (In-YR), and four waters inflow of Hunan (In-HN). The Mann-Kendall (M-K) test revealed the trends and change points of water level fluctuations. Structural Equation Model (SEM) was used to detect the direct and indirect effects of these factors on water level and quantify their relative importance. The MIKE21 hydrodynamic model reflected the spatial-temporal variability of water levels under the action of key driver. The results showed that the water level appeared a downward trend during 1990–2019 and the change point appeared in 2003; During 1990–2002, the significant factors were: precipitation (V = 0.469, $P = 0.013$), evaporation (V = −0.424, $P = 0.029$), non-agricultural cover (V = −0.334, $P = 0.025$), and agricultural cover (V = 0.235, $P = 0.033$); During 2003–2019, the significant factors were: In-YR (V = 0.436, $P = 0.007$), In-HN (V = 0.431, $P = 0.012$), and precipitation (V = 0.349, $P = 0.045$); The In-YR was the key factor affecting the changes of the water level during 1990–2019; Under the influence of In-YR, the most obvious fluctuation of water level was in the flood adjustment

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period (Jun-Aug) and the impoundment period (Sep-Nov) when the average declined by about 0.50 and 0.67 m, respectively. Our findings provide a new insight into how to better maintain the stability of river-water system water resources under the influence of multiple factors.

1. Introduction

Many natural lakes are usually hydrologically linked with rivers, forming various types of river-lake system (Daneshvar et al., 2010). The interactions of the river-lake system are often intricate and dynamic, closely related to changes in hydrological process and ecological patterns within lakes (Liang et al., 2021a; Zhang et al., 2020). For most river-lake systems, the exchange of water is the key to flood prevention and mitigation, maintenance of water resources, and amphibious ecosystem (Xia and Pahl-Wostl, 2012). Water level, an important indicator for maintaining the biodiversity of river-lake ecosystems, has a considerable impact on the topography of the basin in time and space (Liang et al., 2014). In recent decades, climate and high-intensity human modification of rivers have severely disrupted lake systems, and subsequently changed the hydrological interactions of the river-lake system (Aryal and Zhu, 2020). This raises an important question of global concern: How will these already occurring and other ongoing environmental changes affect the water resources of river-lake system? Research on this issue will be a reference for management and forecasting of water resources.

Human activities are closely related to water exchange in river-lake system, such as dam construction, agricultural transformation, and land reconstruction (Wang et al., 2013; Zhao et al., 2015). The impoundment of the dam will produce a hydrological state that is different from the original hydrological pattern before the water storage, and will cause huge changes in water and sediment on time and frequency, further affect the water level (Syvitski et al., 2009). The dam not only affects the flood discharge of the reservoir, but also changes the water and sand exchange in the river-lake system, triggering a series of social, ecological, and river-lake water resources issues. Land use, the direct manifestation of human activities, which alters the hydrological cycle through root evaporation, vegetation retention, and land permeability (Gerrits et al., 2010; Gu et al., 2013; Liang et al., 2021b; Walsh et al., 2005), is a core element in the field of water resources balance (Berit and Göran, 2019). With the development of the social economy, increase in construction area accompanied with decrease in vegetation coverage caused by rapid urbanization and agricultural transformation, have significantly altered the hydrological cycle of the catchments (Remondi et al., 2016). There has a strong consistency between the water storage capacity of the root zone after the vegetation cover changes and the changes in the hydrological system (Nijzink et al., 2016). In recent years, land coverage has changed due to the implementation of land policies (Xie et al., 2020), and the capacity of flood regulation and storage has been reduced accordingly (Mao et al., 2019).

Since global warming, climate fluctuations have become more frequent (Chen et al., 2018), mainly manifested by rising temperatures and fluctuate precipitation, which may directly alter the hydrological cycle of the basin (Kundu et al., 2017; Tan et al., 2018). The latest reports indicated that the middle and lower reaches of the Yangtze River entered the rainy season 5 days earlier than normal in June 2020, and the cycle length was far longer than normal (China Weather Network 2020). Climate variability exacerbates the water cycle and changes the temporal and spatial characteristics of precipitation (Azam et al., 2020). To some extent, these processes influence vegetation cover changes, which indirectly lead to changes in watershed hydrology (Tan et al., 2020). The uncertainty of climate and its effect on lake hydrology have always been a hot topic of recent researches (Ludwig et al., 2014).

Recently, the hydrological response to climate variability and anthropogenic activity has been well revealed (Giles-Hansen et al., 2019; Li et al., 2016; Wang et al., 2020). Nevertheless, the hydrological changes in different regions are affected by various degrees of climate and human factors (Kuentz et al., 2016). Relationships among water level changes in river-lake systems and climate factors, land use, and dam construction are still unclear. Therefore, more attribution analysis methods are being mined for research in this field, including Probability Distribution Model (Yao et al., 2020), S-HYPE model (Berit and Göran, 2019), Budyko framework (Yuan et al., 2016), Least Squares Regression Model (Ledford et al., 2020), etc. The application of these methods does solve many potential problems, but it is impossible to visually distinguish the direct or indirect effects of these factors. Structural Equation Model (SEM) is a new hydrological attribution research model. With the help of path model tools, it clarifies the relationships among climate, human factors, and water level. The established causal hypothesis equations helps to quantify the relative importance of various driving factors, including direct and indirect impacts (Jia et al., 2020). SEM has been increasingly used in attribution researches because of the advantages of greater flexibility, simple operation, and easy-to-understand results compared with other models.

Dongting lake, the typical river-lake system, is hydrologically joined to the Yangtze River, forming a system with complex hydrological characteristics (Yuan et al., 2015). In the Yangtze River basin, considerable progress has been made in implementing schemes based on the joint dispatch of cascading reservoir groups, especially the Three Gorges Dam (TGD), which is one of the largest dams in the world (Feng et al., 2013; Ma et al., 2012; Zhang et al., 2017). Moreover, large and small dams have been built on the four tributaries of Hunan province that are connected to Dongting Lake. Although these dams have the function of flood control and power generation, the large-scale artificial reconstruction inevitably triggered a series of hydrological and hydraulic changes between the river and lake (Ma et al., 2012; Shen et al., 2018; Zhang et al., 2017). The special impact of the dam on hydrology has attracted wide attention from many scholars around the world (Li et al., 2020b; Yang et al., 2016). However, research on the relative importance of driving factors to the Dongting Lake water level has been ignored to some extent. Therefore, the connection between Dongting Lake water level change and dam construction, land cover, and climate change are still unclear.

In this research, we used SEM to identify the relative importance of climate, land cover, and dam construction on the water level of Dongting Lake, and to determine the key factors among them. Then, with the aid of the MIKE21 hydrodynamic model, only the impact of key factors on the spatiotemporal dynamic characteristics of the water level is revealed under the condition of excluding other disturbances. This will provide a theoretical basis and deeper insights for the understanding of Dongting Lake hydrological changes. The purposes of this research were: (1) to incarnate the changing trend and change points of the water level of Dongting Lake from 1990 to 2019; (2) to identify the relative importance of climate, land cover changes, and dam construction on water level in conjunction with the key factor extraction; and (3) to explore the spatiotemporal dynamic characteristics of the water level of Dongting Lake under the influence of key factors.

2. Materials and methods

2.1. Study region and data sources

We carried out this research in the Dongting Lake basin, which is located in the middle-lower reaches of the Yangtze River, the northern

Hunan Province. Dongting Lake exchanges water with the Yangtze River via the entrance of three intlets and the Chenglingji (Fig. 1b), forming a complex rive-lake system. In the north, it receives water from three inlets of the Yangtze River (Songzi, Taiping and Ouchi River); in the south and west, it receives water from four waters of Hunan(Xiang, Zi, Yuan and Li River). Finally, the water is discharged directly from Chenglingji, the only outlet of Dongting lake, and then returns to the Yangtze River.

The Dongting Lake basin has a subtropical climate. The average temperature is around 16.5–17.2 °C, and the annual precipitation is about 1289.8–1556.2 mm. It usually has a wet period from July to September and a drier period from November to next February. The Dongting Lake Economic Zone, including 15 counties (covering 20,227.13 km^2) in Anxiang, Yiyang, and Yueyang City in Hunan Province, is the major ploughland in China and an important base for commercial grain, cotton, and oil (Fig. 1a). The main vegetation cover type in the Dongting Lake area is dominated by the crops.

The daily climate data (1990–2019), composed of precipitation, temperature and evaporation, were collected at China Meteorological Data Center (http://data.cma.cn). Three typical meteorological stations of Dongting Lake were selected: Yueyang, Changde, and Yuanjiang Weather Station, representing the three sub-basins of Dongting Lake, and use their average value as the climate of the entire lake area. The annual trend of climate data and its seasonal changes are shown in Fig. 2. The land-use data of Dongting lake area (with spatial resolution of 1 km) of the 1990s, 2000s, 2010s and 2015s were acquired from the Resource and Environmental Science and Data Center, the Chinese Academy of Sciences (http://www.resdc.cn). According the actual situation of land use in Dongting Lake, it is reclassified into three categories, namely agricultural cover, non-agricultural cover, and water body (Fig. 3). Hydrological data series (1990s–2019) of the annual water has been collected from the Hunan Hydrology and Water Resources Survey Center (https://www.hnsw.com.cn), including daily and monthly flow and water level data. The inlet hydrological data was acquired from typical hydrological stations in the three outlets of the Yangtze River and four tributaries in Hunan, the outlet data were obtained from Chenglingji hydrological station. For the missing data, we used Regression Imputation to supplement the time series (Li et al., 2019).

2.2. Statistical methods

A change point means that it changes or transforms suddenly and rapidly. In hydrological time series analysis, the establishment of change points is extremely important. To explore whether there were obvious trends and change points in water level during 1990–2019, the time series of daily water level observation at Chenglingji station were compiled for Mann-Kendall (Mann, 1945) test analysis. The M-K test is a non-parametric statistical test, which is widely used to evaluate the time series trends of various element variables (Wang et al., 2020). In this study, determining whether there was a sudden change in the water level time series plays a vital role in the subsequent stages of the Dongting Lake hydrological analysis. The M-K test analysis was implemented in the R software version 3.5.2.

2.3. Structure equation model

Structural equation model is a kind of statistical data analysis formed by a comprehensive use of multiple analysis methods (Soliman et al., 2016). Which can be used to solve multiple compound correlations between independent variables and dependent variables (Kreiling et al.,

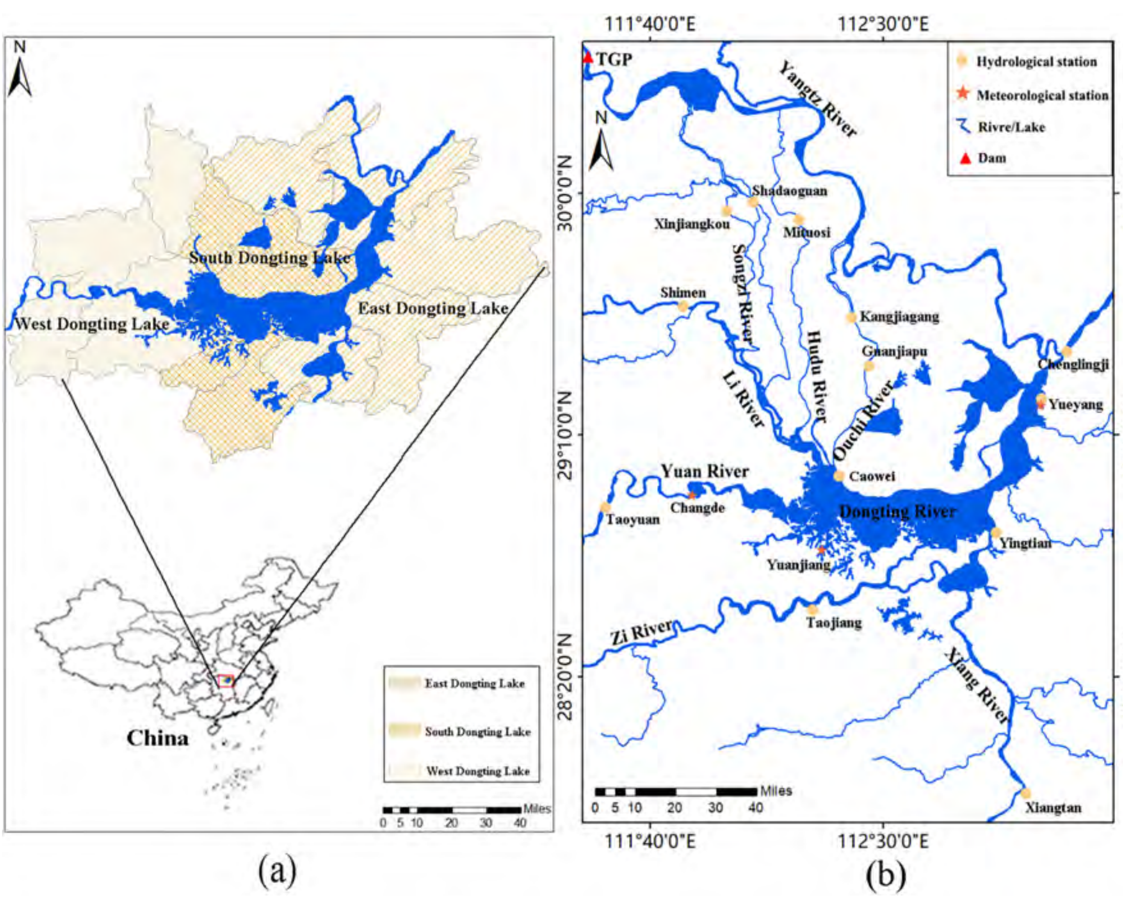

Fig. 1. The diagram map of Dongting Lake area, China. (a) means the land use study area in the Dongting Lake region; and the (b) is the specific structure of Dongting lake.

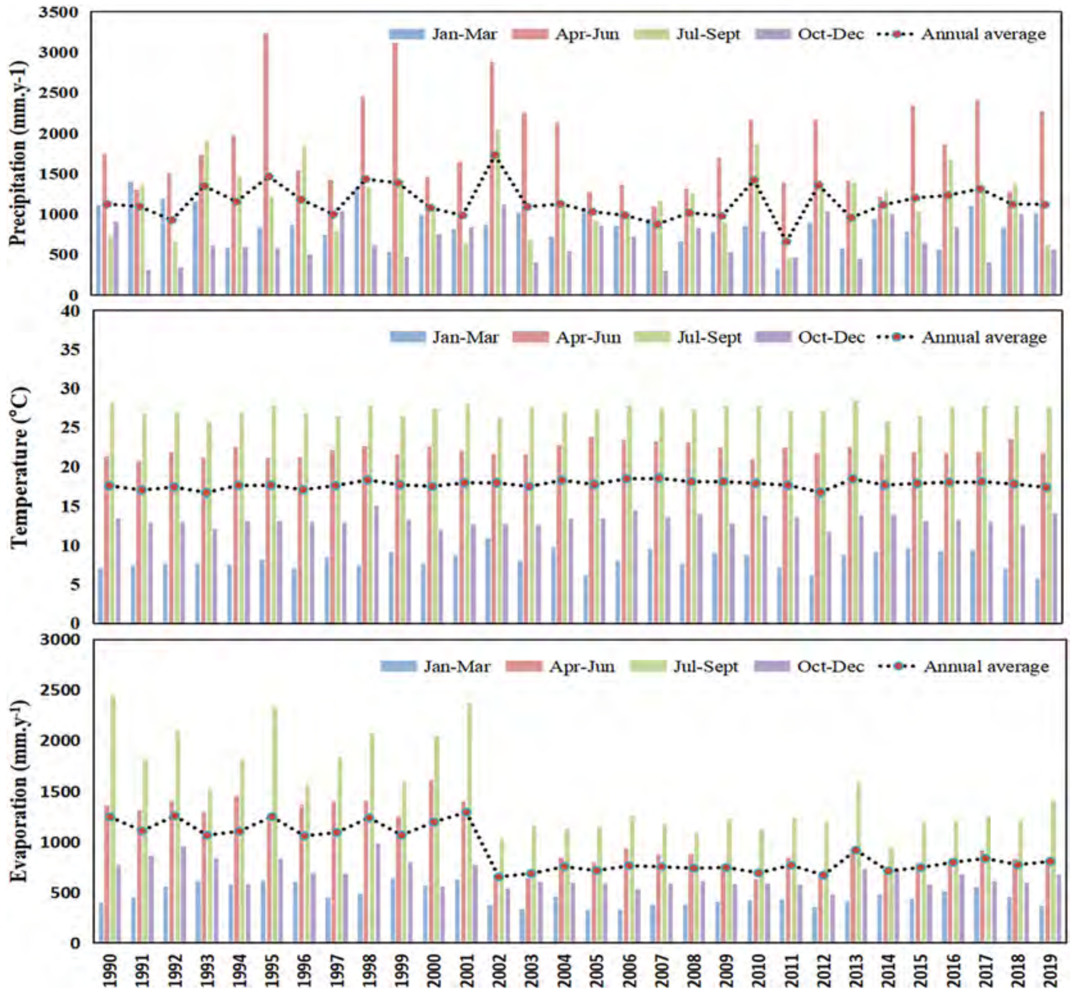

Fig. 2. The trends and seasonal changes of annual precipitation, temperature and evaporation in Dongting Lake from 1990 to 2019.

2020). The SEM construction process mainly includes observation variables and latent variables (Yang et al., 2020). We used the path analysis method to estimate the direct, indirect, and total impacts (the sum of direct and indirect) affecting the water level of Dongting Lake from 1990 to 2019. Path analysis method is a statistical procedure that can establish equations by analyzing the causal effects of hypotheses between

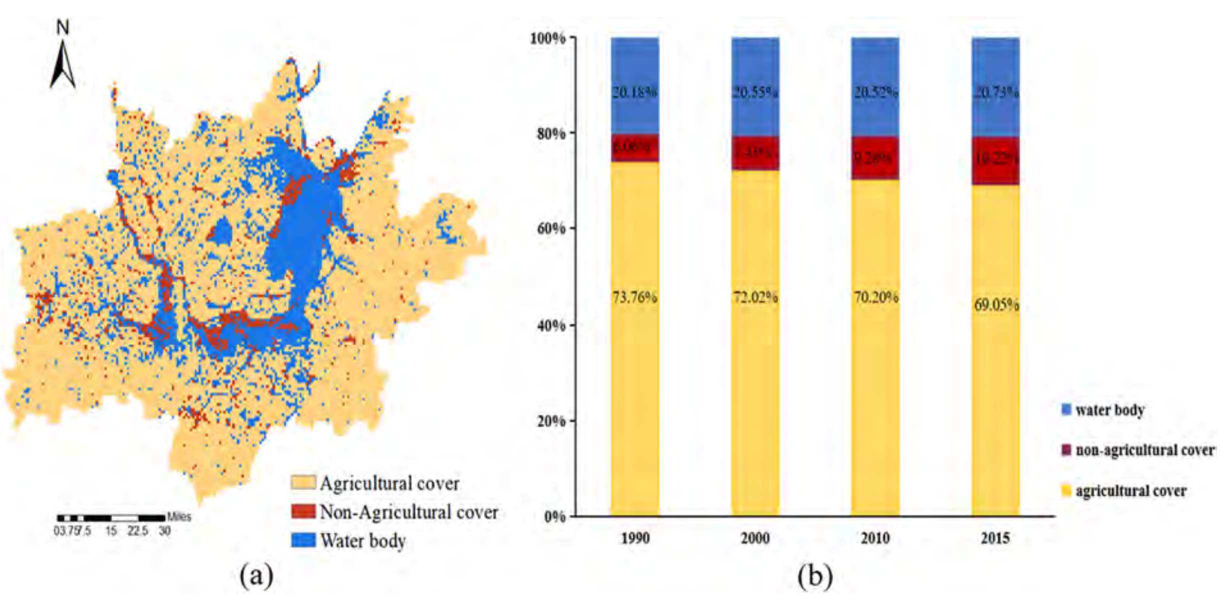

Fig. 3. Land cover classification maps in Dongting Lake area (a) and proportions in 1990, 2000, 2010 and 2015 (b).

variables. The seven independent variables were taken into consideration (precipitation, evaporation, temperature, agricultural cover and non-agricultural cover, In-YR, and In-HN), the outlet water level of Dongting Lake was used as the dependent variable. According to the existing research and actual situation, the hypothetical correlation equations of these causal variables were constructed with the "piecewiseSEM" R package. The *P* value indicates a significant impact. The Std.Estimate indicates the influence value of each factor, and a positive value means the positive influence, while the negative values are the opposite. The V value represents the standard path coefficient, that is, the intensity of direct and indirect effects from an exogenous variable to an endogenous variable.

2.4. Hydrodynamic model simulation

Based on the analysis results of the structural equation model, we combined with the MIKE21 hydrodynamic model to discuss the internal factors affecting the water level. The topographic data of the Dongting Lake area comes from the 3 arc-second (about 90 m) Global Land Cover Facility (GLCF) of the United States Earth Observation Database. The Dem data was collected in mid-February 2000. At this time, there was the dry season in Dongting lake, and had the high-quality lake bottom elevation data. The extracted high-level data of the lake was used for direct modeling, which uneven terrain will cause the flow unsmoothly. Therefore, the Filling Sink function in the geospatial data model (Arc Hydro) supported by ArcGIS was used to correct the elevation data to fix this trouble (Gong et al., 2007; Li et al., 2019). The mesh was created through MIKE Zero Mesh Generator, importing the boundary area of Dongting Lake and interpolating the terrain data to generate a simulation area. The calculation area was 109 km × 113 km. The settings of model parameters and the results of model calibration and validation are shown in Fig. S1 and Table S1 (see the supplementary information for specific methods).

2.5. Quantitative analysis of the impact of key factors

Combining the results of Structural Equation causality analysis, we have identified the key driving factors that have affected the water level of Dongting Lake in recent decades, namely In-YR. We used the MIKE21 hydrodynamic model to simulate and analyze the spatial and temporal changes of the In-YR on the water level of Dongting Lake under the condition of eliminating other disturbances. Therefore, two simulation schemes were devised to reveal the influence of the In-YR on the hydrological conditions of Dongting Lake. Scenario 1 (S1) means the status of Dongting Lake during the period 2003–2019 after the river-lake relationship changed. During this period, by calculating the daily average inflows, the annual series of time-varying daily flow were obtained. The input data of Chenglingji was obtained from 2003 to 2019 average daily water levels. Scenario 2 (S2) was a hypothetical state, the In-YR was changed to the average flow for 1990–2002, the In-HN and the daily water level at Chenglingji were the same as S1. We defined scenario 2 as a natural condition, while scenario 1 was more reflecting the changed river-lake relationship. Therefore, by comparing the difference between the results of S1 and S2, the effect of In-YR on the water level of Dongting Lake can be quantitatively evaluated.

3. Results

3.1. Trend and change-point analysis of water level

Based on Mann-Kendall test, the inter-annual change and mutation point of water level during entire study period were showing in Fig. 4. The negative UF value mean that the sequence has a decreasing trend, but not significant (UF value did not exceed the significance level −1.96). The intersection point where the UF and UB curves intersect was determined as a change point, showing that has undergone a sudden change. There were three intersections in 1990–2019, namely 1991, 1993, and 2003 (Fig. 3a). Considering the instability of initial data detection and the actual situation of Dongting Lake, we determined the 2003 as the change year. Fig. 3b shows that the annual variations of the water level was relatively stable during 1990–2002, fluctuate up and down around 25.33 m. But after the change point in 2003, the decline fluctuation increased, and annual average water level drops 0.35 m compare the previous period. Combining the changing periods and change point of Dongting Lake, the sequence (1990–2019) were divided into two sub-sequences, 1990–2002 and 2003–2019, respectively.

3.2. Direct and indirect effects of the climate, land cover and dam construction on water level

To quantitatively reveal their direct and indirect effects on lake hydrology, we designed a causal equation to connect various factors with the water level of Dongting Lake. According to the results (Fig. 5a and Table 1), from 1990 to 2002, precipitation shown significant positive direct effect ($V = 0.469$, $P = 0.0134$) on the water level. In contrast, the evaporation and temperature have a significant negative direct effect ($V = -0.424$, $P = 0.0291$) and negative indirect effect ($V = -0.408$). The conclusion shows that the stronger precipitation input, the higher the water level will be, while the temperature and evaporation had the opposite results. Furthermore, the land use change also played a relatively important role in changing the lake water level. The agricultural cover had a significant positive direct effect ($V = 0.235$, $P = 0.0334$) on the water level, while the non-agricultural cover shows a significant negative effect ($V = -0.334$, $P = 0.0248$) (Fig. 5a). At the same time, our results also show that precipitation, evaporation, temperature, and non-agricultural cover can also indirectly affect hydrology change by altering agricultural cover. During this period, the impact of the In-YR and In-HN on the water level of Dongting Lake was not very obvious. In short, during 1990–2002, the main factors affecting the water level change were climate and land cover changes, and the latter has a weaker impact.

In another phase of analysis (2003–2019), shown in Fig. 5b and Table 1, with the continuous expansion of human influence, the factors affecting the water level of Dongting Lake had undergone great changes. The inflow of river-lake system had become the dominant factors affecting the water level of Dongting Lake, In-YR and In-HN had a significant positive effect ($V = 0.436$, $P = 0.007$ and $V = 0.431$, $P = 0.012$), respectively. The result of SEM shows that the precipitation had a significant direct effect ($V = 0.349$, $P = 0.045$) on the lake water level, but the evaporation and temperature shown relatively weak indirect negative effects ($V = -0.093$, $V = -0.069$). Different from the results in 1990–2002, the impact of land cover is relatively weak, both agricultural cover and non-agricultural cover shows an insignificant indirect effect on lake water levels ($V = -0.372$, $V = -0.470$). Another important pathway that the non-agricultural cover on the water level ($V = -0.459$) was to affect the agricultural cover ($V = -0.929$, $P = 0.000$). At this stage, the In-YR became the dominant factor affecting the water level, followed by In-HN and precipitation.

In short, the SEM analysis results of the two-stage time series show that the In-YR was the key factor in the change of the Dongting Lake water level from 1990 to 2019.

3.3. Temporal and spatial characteristics in water level under the key factor

Through the simulation of two scenarios (S1, S2), the spatio-temporal characteristics of the influence of In-YR on the water level were shown in Fig. 6. It can be clearly seen from the dynamic graph that the In-YR mainly affects the water level during the wet season (Jun - Aug) and the recession period (Sep–Nov), thus the water level showed the downward trend obviously. By contrast, the distribution of the water level during the dry season (Dec - Mar) and water supplement period (Apr–May) in S1 was almost coincident with the

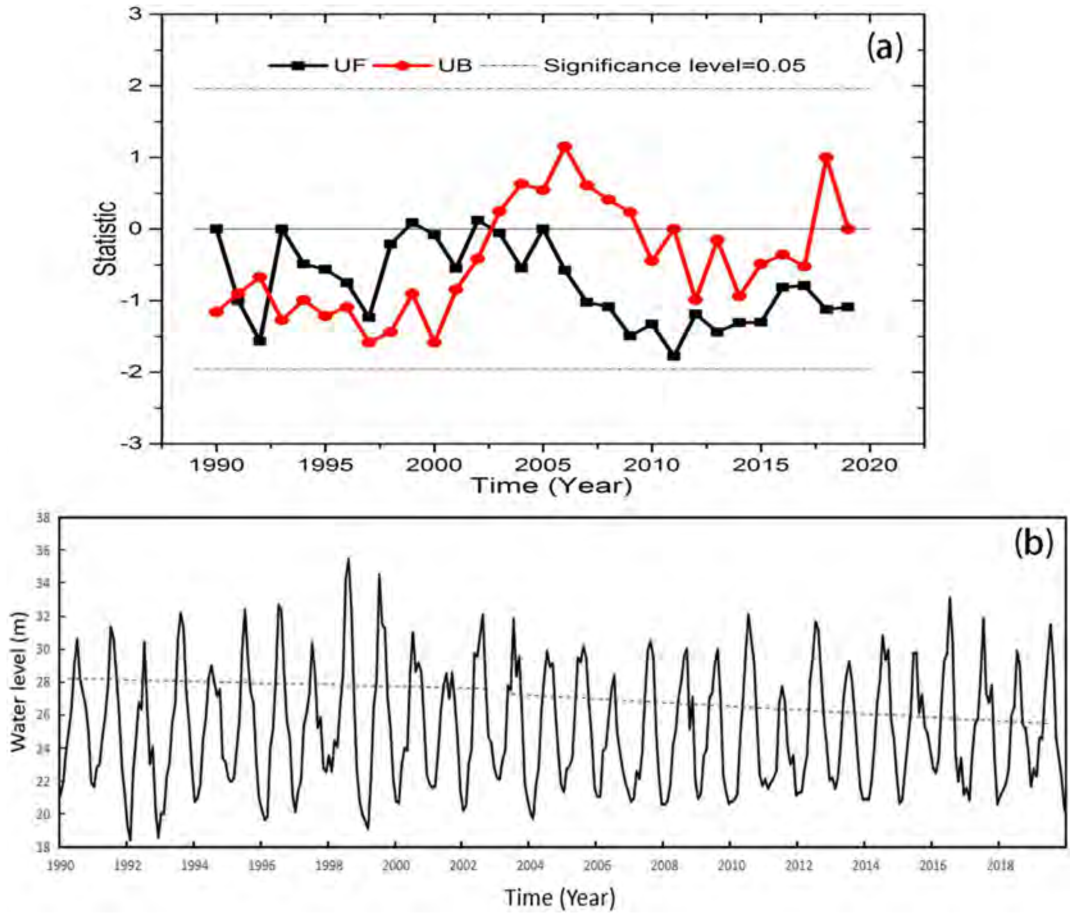

Fig. 4. Mann–Kendall test and trend analysis of water level in Dongting lake. In Figure (a), the positive UF shows that the water level has an increasing trend, and the negative values are the opposite. The intersection between UF and UB at the level of significance, and the UF statistical value passes the ±1.96 significance level, that considered a mutation point. In Figure (b), shows the trend of water level change in Dongting Lake from 1990 to 2019.

distribution in S2, water level fluctuations were not obvious. The affected area of water level changes was most obvious in East Dongting Lake.

In order to quantitatively reveal the changes of water level in different regions of Dongting Lake, we selected three hydrological stations (Yueyang, Yingtian, Caowei) to represent East, South, and West Dongting Lake, respectively. We compared the water level difference between the S1 and S2 of each station, as the Fig. 7 shows. Before and after the operation of the TGD, the water level of the Dongting Lake area fluctuated significantly in different periods, which has an obvious phenomenon of weakening during the high water season and replenishment during in the low water period. At Yueyang station, the water level of S1 during the dry period and water supplement period increased by about 0.25 m compared with S2, and the highest was over

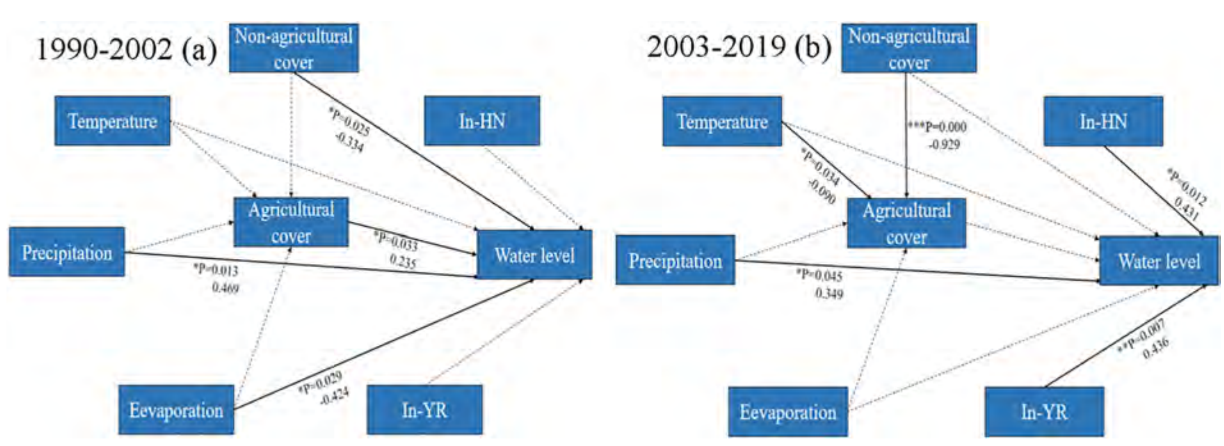

Fig. 5. Path diagrams of the Structure Equation Model for the water level, (A) represents the result of causal analysis from 1990 to 2002, and (B) represents the period 2003–2019. The solid line represents a significant ($P < 0.1$) effect, the dashed line represents an insignificant effect, *** Correlation is significant ($P < 0.01$), ** Correlation is significant ($P < 0.05$), * Correlation is significant ($P < 0.1$). Where In-YR represents three inlets inflow of Yangtze River and In-HN is four waters inflow of Hunan.

Table 1
The direct, indirect and total impacts of different driving factors on the water level of Dongting Lake.

Year	Response	Predictor variable	Std. direct	Std. indirect	Std. total
1990–2002	Water level	Temperature	0	−0.4076	−0.4076
		Precipitation	0.4686	0	0.4686
		Evaporation	−0.4244	0	−0.4244
		Agricultural cover	0.2348	0	0.2348
		Non-agricultural cover	−0.3337	0	−0.3337
		In-HN	0	0.6306	0.6306
		In-YR	0	0.5100	0.5100
2003–2019	Water level	Temperature	0	−0.0685	−0.0685
		Precipitation	0.3491	0	0.3491
		Evaporation	0	−0.0934	−0.0934
		Agricultural cover	0	0.3491	0.3491
		Non-agricultural cover	0	−0.4695	−0.4695
		In-HN	0.4312	0	0.4312
		In-YR	0.4359	0	0.4359

0.50 m. The average drop of water level was about 1.11 m during wet period and recession period, and the height was close to 2 m in August and mid-September. The water level difference at Yingtian station shown a little changes during the dry period and water supplement period, but fluctuates around 0.85 m during the wet period and recession period. In comparison, Caowei station showed the smallest water level impact, but the distribution of increase and decrease were obvious in the period of low and high water level. The average water level increased by about 0.09 m in December–April and decreased by about 0.58 m in June–November.

4. Discussion

4.1. Relative importance of climate and human activities on water level

Water resources are jointly effected by climate changes and human transformation (Donnelly, 2020). The purpose of this article is to explore the relative importance of climate variability and human activities to the changes in the water level of Dongting Lake. The impact of climate and human activities on the water resources of rivers and lakes changes over time (Li et al., 2016). Studies have been conducted on the Sweden River (Berit and Göran, 2019), Luan River (Wang and Hejazi, 2011), and the lower reaches of the Yangtze River (Yuan et al., 2016), implying that the human activities have gradually become the dominant factor (59–78%) on fresh water. In other areas, however, such as the Columbia River (Naik and Jay, 2011) and Midwestern United States River (Wang and Hejazi, 2011), the climate plays a dominant role (53–72%) in water resources. Our results show that the impact of climate change in Dongting area is gradually weakening, while the impact of dam operation is gradually increasing.

Climate oscillations can cause changes in precipitation, temperature, and evaporation, which further influence the annual changes in water level (Zhao et al., 2015). Actually, the annual precipitation has a significant direct impact on the water level, but the impact weakened a lot during 2003–2019, which implied the influence on the water level of Dongting Lake was gradually being occupied by other factors (such as dam construction). Generally, the effect of land cover changes on the hydrological cycle was crucial to the sustainable development of rivers and lakes. Furthermore, the relationship between land cover change and water and energy flux was designated as one of the 23 unresolved issues in hydrology in 2019 (Blöschl et al., 2019). Dongting Lake was mainly based on agriculture, thus the land cover was divided into agricultural and non-agricultural cover for analysis. We proved that the impact of land use from 1990 to 2002 on the water level was significantly higher than that of 2003–2019. It may be attributed to the measures of returning farmland to lake implemented in the Dongting Lake area in the early 1990s. In fact, from 1990 to 2019, the land cover changes in the Dongting Lake area were not obvious (Fig. 3). Although the non-agricultural cover showed an increasing trend during the latter stage, the ratio no more than 11% of the total coverage area. In addition, due to other human activities, the impact of land cover changes might be hard to spot in large river-lake systems, thus reducing or masking the impacts on water level (Zhang et al., 2008).

Dam construction, especially large-scale dam construction, will bring new challenges to the hydrological system of rivers and lakes (Zhang et al., 2011). Compared with changes in climate and land cover, the dam construction had the characteristics of shorter time and greater impact, therefore attracted a lot of attention (Gu et al., 2019; Li et al., 2020b). Numerous dams have been built in the upper reaches of the Yangtze River, but the most striking is the TGD (Xie et al., 2015). Since the operation of the TGD in 2003, the water level of Dongting Lake has dropped significantly, and the downward is more marked than before (Han et al., 2016). Moreover, the result of the SEM shows that TGD was the dominant factor changing the water level of Dongting Lake from 2003 to 2019. The reasons are summarized

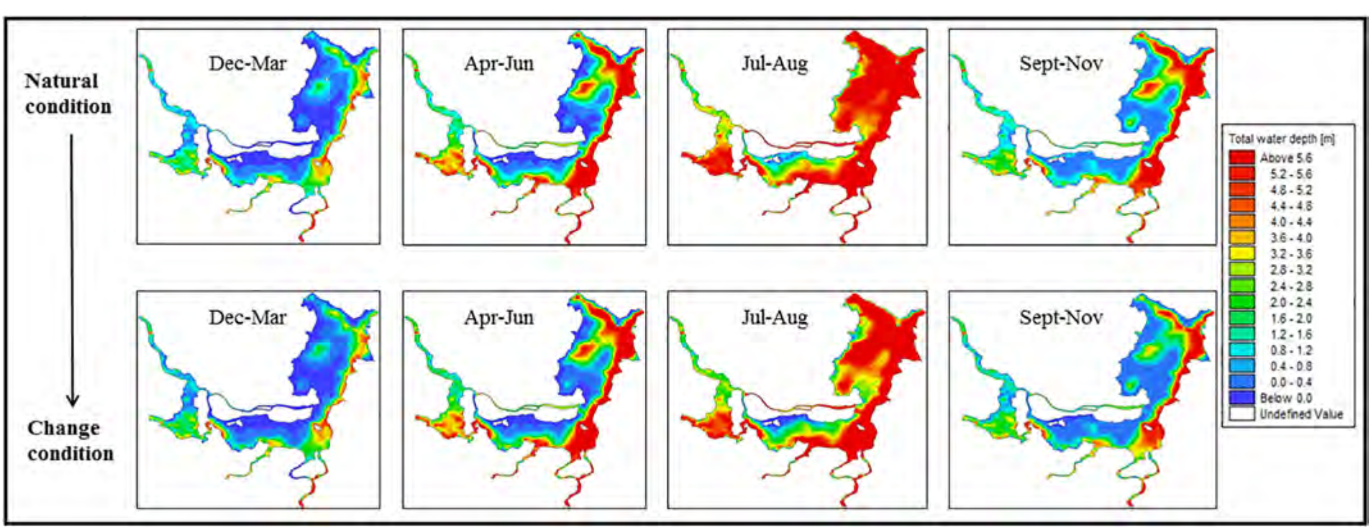

Fig. 6. Spatial distribution map of the water level of Dongting Lake before and after the impact of the TGD. According to the dispatch of the TGD, it is divided into four periods: December–March, April–June, July–August and September–November.

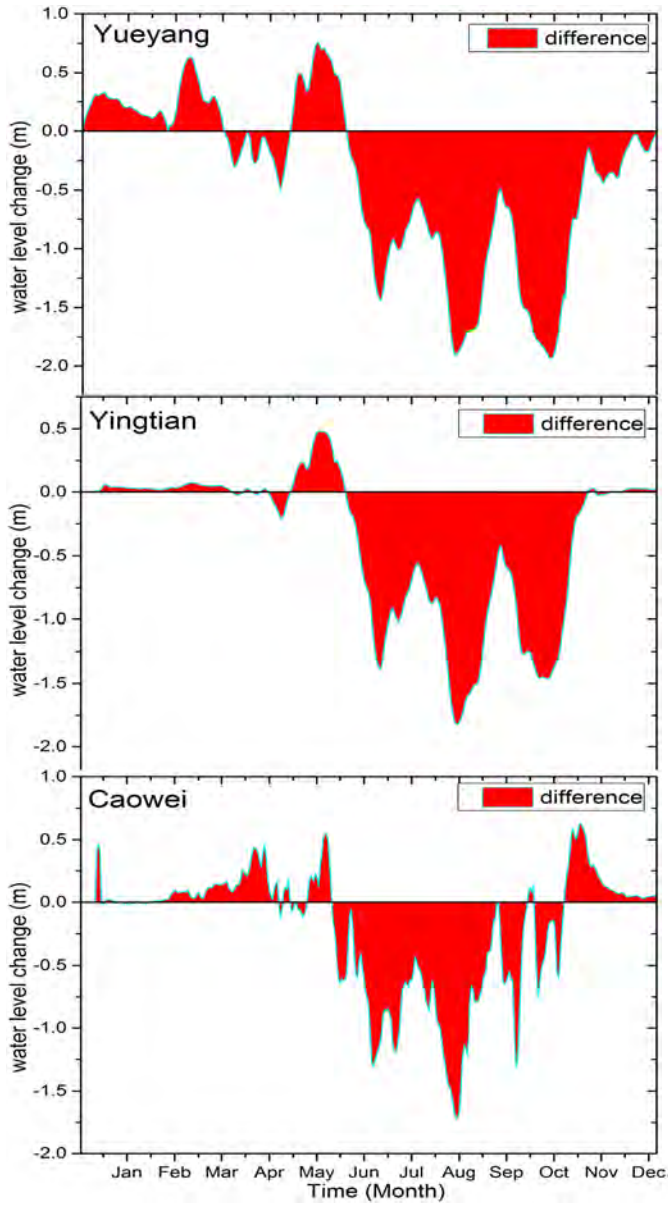

Fig. 7. Distribution map of the water level difference before and after the operation of the TGD. Yueyang station represents East Dongting Lake, Yingtian station represents South Dongting Lake, and Caowei station represents West Dongting Lake.

as follows. First of all, after 2003, the total inflow of the three inlets of the Yangtze River, especially in the wet season, has been greatly reduced, which may be due to the combined effect of the regulation of the TGD and the reduction of precipitation in the Dongting Lake area. Secondly, the operation of the TGD led to a sudden decrease of sediment in the downstream, riverbed scouring, and a drop in the water level of the Yangtze River (Zhang et al., 2017). These changes have accelerated the outflow from the Dongting lake to the Yangtze River, resulting in a rapid decline in the lake's water level. This implied that dam construction played a decisive role in affecting the water level of river-lake system, at least in the short term.

4.2. Impact of dam construction on the spatio-temporal characteristics of water level

The analysis of the importance of climate change and human activities illuminates that the TGD plays a decisive role in the change of Dongting Lake water level. Whether dam construction has a positive or negative impact on river and lake hydrology has always been a key topic of concern (Shen and Xie, 2004; Xie et al., 2015). Therefore, it was necessary to reveal the spatiotemporal characteristics of the water level of Dongting Lake under the key factor. In fact, the hydrodynamic model method (MIKE21) was used to quantitatively show the temporal and spatial characteristics of the water level under the influence of the inflow (Li and Li, 2020). In this study, natural conditions (1990–2002) were compared to variable conditions (2003–2019), the inner-annual water level changes mainly occur during the flood adjustment period (July–August) and the water storage period (September–November), which had a very obvious weakening effect. Due to the dispatching function of the TGD, which blocked large quantity water from the mainstream of the Yangtze River during the flood regulation and impoundment period, was resulted in a significant reduction in the water flowing into the downstream lakes (Li et al., 2020a). On the other hand, the TGD had little effect on the water level during the dry season on the spatial scale, but it still had a weak supplementary effect from the quantitative difference (Fig. 7).

Most of the previous studies focused on a series of ecological crises caused by the TGD changing the hydrological changes in our study area, making it a target of public criticism (Zhang et al., 2017) . But from another point of view, the operation of TGD seems to have a positive impact on the seasonal changes in the water level. Firstly, the weakening of the peak water level during July–August effectively reduced the flood rate during the flood period. Secondly, although there was a weak replenishment effect during low water level, dam replenishment plays a positive role in drought. Actually, agriculture was the main productive force in our research area, the peak of the farmland water consumption was in September–November (Zhao et al., 2018). This was superimposed on the peak water level drop caused by TGD impoundment from September to November, which will inevitably aggravate the impact of water resources and affect the value of agricultural output. Changes in the temporal and spatial characteristics of the water level are related to all aspects, and will have completely different effects from different perspectives. In addition, future research should be continued, due to the ongoing human activities and constantly updated hydrological data.

4.3. Conservation management of rive-lake system

In view of the escalating trend of climate change and human activities, the rive-lake system will continue to be threatened for a long time in the future (Vorosmarty et al., 2010). Changes in hydrology status are considered to be one of the most critical factors in river and lake degradation (Kingsford, 2011). Simultaneous research on the influence of climate and human-driven factors are essential to understand their complex interactions and their direct and indirect effects on hydrology, which will provide useful information for future water resources management planning (Liang et al., 2020). Obviously, the impact of TGD on the water level of Dongting Lake has exceeded the impact of climate change. The result undoubtedly provides a direction for water resources management of the river-lake system. Contrary to climate variability, we can optimize the water resources system by reasonably controlling human activities, such as the operation of reservoirs/dams. The optimal goal is to achieve a relatively ideal state of river-lake interaction during the impoundment period and the replenishment period (Yang et al., 2016). The key point is to optimize water storage on the premise of ensuring flood control safety. In the early stage of impoundment (around mid-August), the drainage of the upper reaches of the Yangtze River should be reduced. After the impoundment period (mid-October–early November), the downstream drainage should be gradually increased to satisfy the health of the river-lake ecosystem. As far as possible, the negative effects of dam storage on the river-lake interaction are basically minimized in regular years, and also improved to a certain extent in wet and dry period. To maintain a healthy rive-lake system in the dry season, the water demand of lake ecological environment should be met to the greatest extent. The development of society requires human interference, but we can build a completely and efficient protected area system based on scientific methods to restore the hydrology of the river -lake system.

Nevertheless, climate variability was still an important factor that cannot be ignored in water resources management. Quantitative analysis of the impact of climate variability and human activities are beneficial to reduce the impact of climate by optimizing human transformation. Therefore, this research is very necessary, future research should refine the analysis of the driving factors on the lake level in order to better manage water resources.

5. Conclusions

This study combines M-K test, Structural Equation Modeling (SEM), and MIKE21 Hydrodynamic Simulation to discuss the relative importance of the driving factors in Dongting Lake water level changing from 1990 to 2019, and determines the key factors. Then, the water level of Dongting Lake is simulated under the action of only key factors to analyze its temporal and spatial dynamic characteristics.

The result indicates that the water level of Dongting Lake showed a downward trend from 1990 to 2019, and the change point appeared in 2003. The driving factors of the Dongting Lake water level in the two phases of 1990–2002 and 2003–2019 have undergone tremendous changes. In the early stage, it was mainly affected by climate ($P < 0.1$) and land cover ($P < 0.1$), and later, the dam construction has become the dominant factor, especially the construction of the TGD ($P < 0.01$). The In-YR became a key factor causing the sudden change of water level of Dongting Lake from 1990 to 2019. Under the influence of the changed In-YR, the time period of water level variation was mainly concentrated in the flood period (June–August) and the impoundment period (September–November), and the water level dropped about 0.50 and 0.67 m, respectively. In addition, the effect of water replenishment on the water level uplift in the dry season (December to April) was about 0.09 m. In short, with the continuous development of human society, the driving factors of hydrological changes in rivers and lakes are constantly changing, and the influence of human activities has been gradually taking a leading role.

The results of this study provide a new insight on how to quantify the impact of human activities and climate change on the hydrology of the river-lake system, and can also be used as a scientific reference for water resources planning and management decisions of other similar regions. In addition, although the seasonal dispatch of dams has a more remarkable impact on river-lake system regulation than other factors, climate and other human-induced factors cannot be ignored. In the future, it is necessary to investigate more detailed effects of various environmental factors on water resources management.

CRediT authorship contribution statement

Jie Liang: Writing – review & editing, Conceptualization, Methodology. **Yuru Yi:** Writing – original draft, Software, Data curation. **Xiaodong Li:** Writing – review & editing, Conceptualization, Methodology. **Yujie Yuan:** Data curation. **Suhang Yang:** Data curation. **Xin Li:** Writing – review & editing. **Ziqian Zhu:** Writing – review & editing. **Manqin Lei:** Data curation. **Qianfang Meng:** Data curation. **Yeqing Zhai:** Data curation.

Declaration of competing interest

There is no actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within five years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

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Appendix A. Supplementary data

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