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Quantitative assessment of hydrological alteration over multiple periods caused by human activities at the Jingjiang Three Outlets, China

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ABSTRACT

The Jingjang Three Outlets (JTO) play a major role in the water-sediment transport from the Yangtze River to Dongting Lake. The hydrological regimes at the JTO (Songzi, Taiping, and Ouchi) had been changed due to the Jingjiang Cutoffs (JC), the Gezhou Dam (GD), and the Three Gorges Dam (TGD). Based on hydrological data from 1955 to 2019, the variation trend in annual streamflow was detected using three techniques, and the hydrological alteration was assessed with the Range of Variability Approach. Conclusions are as follows: (1) the inflection points consistent with human activities and the time series were divided into periods of P1 (1955–1971), P2 (1972–1985), P3 (1986–2002), and P4 (2003–2019); (2) human activities made a greater contribution to streamflow change than climate change; (3) the hydrological alteration degree caused by the JC, GD, and TGD projects were 56%, 47%, and 52% at the Songzi outlet; 57%, 41%, and 57% at the Taiping outlet; and 57%, 41%, and 57% at the Ouchi outlet; and (4) the ability of division from the Yangtze River to Dongting Lake is weakening and the hydrological regimes at the JTO are deteriorating due to the JC, GD, and TGD, resulting in negative impacts on the biotic composition, structure, and function of riparian ecosystems. This study provides useful insight for ecosystem protection under hydrological alteration.

Key words: hydrologic alteration, Jingjiang Three Outlets, range of variability approach, Three Gorges Dam

HIGHLIGHTS

- Quantitative assessment of hydrological alteration over multiple periods.
- Differentiated the influence of cutoffs projects and dam construction on hydrological alteration.
- Discussed the negative impacts of hydrological alteration on ecosystems and the countermeasures for future.

1. INTRODUCTION

Human activities such as damming and cutoff exert a global impact on river streamflow and sediment regimes (Han & Endreny 2014; Kellogg & Zhou 2014; Guo *et al.* 2018). The increased flow gradients due to cutoffs leads to riverbed degradation in the upstream direction and aggradation in the downstream reach (Zinger *et al.* 2011; Han & Endreny 2014). The closure and water storage capability of dams changes water and sediment regimes of the downstream reach and subsequently affects the geomorphology of the riverbed (Zhang *et al.* 2013; Han *et al.* 2017). The Jingjang Three Outlets (JTO), which is the water and sediment connecting channels between the Yangtze River and Dongting Lake (Zhang *et al.* 2015), play a major role in flood control (Hu *et al.* 2015; Sun *et al.* 2018), Dongting Lake evolution (Chang *et al.* 2010; Ou *et al.* 2014; Wang *et al.* 2017), and in the ecological environment (Wu *et al.* 2017; Yu *et al.* 2018; Wu *et al.* 2019); however, hydrological regimes at the JTO (Songzi, Taiping, and Ouchi) has changed over the last 60 years due to the Jingjiang Cutoffs (JC), the Gezhou Dam (GD), and the Three Gorges Dam (TGD) (Li *et al.* 2016; Zhu *et al.* 2016; Wang *et al.* 2017).

The Yangtze River, the third-longest river in the world, is expected to have a capacity of 300 billion cubic meters by 2030 (Dai *et al.* 2015). The Dongting Lake is the second-largest freshwater lake in China; however, due to human activities, the amount of water-sediment diverted into the Dongting Lake has decreased, the number of zero streamflow days has increased at the JTO, and the dry season of the Dongting Lake came early, which influences flood disasters control, water resources management, and the protection of aquatic ecosystem (Zhu *et al.* 2016; Wu *et al.* 2017; Sun *et al.* 2018). Specifically, several studies have been conducted on the variation in streamflow and driving factors at the JTO. For instance, Zhu *et al.* (2016) found that streamflow diverted at the JTO continuously decreased over 4 or 5 years after major human activities (i.e. the

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JC, GD, and TGD). From 2003 to 2014, streamflow diverted at the JTO increased by 0.8×10^8 m^3/s every year due to the water supply at TGD in the dry season, but deceased by 2.9×10^8 m^3/s every year because of impounding water at TGD after the flood season. Moreover, the pattern and connectivity of the water system changed and must be optimized to maintain the connected river–lake relationship at the JTO (Wang *et al.* 2017; Huang *et al.* 2019). Without phytoplankton recruitment from the JTO to the Dongting Lake, the species diversity of the Dongting Lake will decrease (Ma *et al.* 2019; Yan *et al.* 2019). Previous studies have mainly focused on streamflow diversion ratio, river–lake relationship, and aquatic ecosystem, and argued that the major human activities are vital factors in facilitating the decline of streamflow at the JTO (Zhu *et al.* 2016; Wang *et al.* 2017; Ma *et al.* 2019). However, few attempts have been made to systematically evaluate the hydrological alteration degree at the JTO as a result of large-scale hydro-projects over multiple periods. Further studies are needed to assess the hydrological alteration degree over time and to study the diverse variations of streamflow caused by cutoff projects and dam construction at the JTO.

The Indicators of Hydrological Alteration (IHA) and the Range of Variability Approach (RVA) are the most effective approaches used to quantitatively evaluate the changes in the hydrological regimes caused by hydro-projects, climate change, and other activities or events (Richter *et al.* 1996, 1997). The RVA uses 33 hydrological indicators to assess the hydrological alteration, which are divided into five groups addressing the magnitude, timing, frequency, duration, and rate of change (Yang *et al.* 2008). The RVA method has been widely used in assessing changes in the hydrological regimes of global rivers and lakes (Galat & Lipkin 2000; Magilligan & Nislow 2004; Cheng *et al.* 2019). Papadaki *et al.* (2015) used the RVA method to highlight that climate change will reduce the summer flow in mountain rivers in the southwestern Balkans and have potential impacts on typical biota habitats. Tian *et al.* (2019) used the RVA method to analyze the driving factors leading to the change in the hydrological regimes in the Wuding River. The RVA method can therefore be considered as a good solution for the quantitative assessment of hydrological alteration degree at the JTO.

This study has the following objectives: (1) to detect inflection points and segment periods of annual streamflow from 1955 to 2019; (2) to assess the impact of climate and human activities on streamflow alteration; (3) to characterize the temporal and spatial hydrological alteration; and (4) to provide a good reference for the management of river networks and ecosystems protection under hydrological alteration at the JTO.

2. STUDY AREA AND DATASET

The Jingjiang River refers to the middle reaches of the Yangtze River from Zhicheng to Chenglingji. The Jingjiang River is the most significant natural habitat and breeding location for four major Chinese carps (grass carp, herring fish, silver carp, and bighead carp). Dongting Lake is the second-largest freshwater lake in China, with a strong flood storage capacity and abundant fish resources, and it plays a crucial role in flood control. Additionally, the Jingjiang River delivers water-sediment to Dongting Lake via the Songzi, Taiping, and Ouchi outlets which are distributed from top to bottom on the Jingjiang River (Figure 1).

The daily runoff at five hydrological stations (Xingjiagkou, Shadaoguan, Mituosi, Kangjiagang, and Guanjiapu) was collected from 1955 to 2019 by the Hunan Hydro and Power Design Institute. Rainfall data was collected from 1955 to 2019 by the China Meteorological Data Network.

3. METHODS

3.1. Detection of inflection points

To reliably detect the inflection points of a long time series, three techniques, i.e., Mann–Kendall (M–K) Test (Mu *et al.* 2020), Accumulative Anomaly Method (AAM) (Wang *et al.* 2012), and moving t-test (Mu *et al.* 2020), were used in this paper. These tests have been confirmed in previous studies as useful techniques to identify the inflection points of streamflow data (Wang *et al.* 2012; Mu *et al.* 2020). More details of the calculation procedures used in the three techniques can be obtained from Wang *et al.* (2012) and Mu *et al.* (2020).

3.2. Slope change ratio of accumulative quantity (SCRAQ)

The SCRAQ is put forward to estimate quantitatively the impact of climate and human activities on streamflow change (Wang *et al.* 2012). The slope of the linear relation between year and accumulative streamflow before and after a turning year is S_{Rb} and S_{Ra}, respectively, and the slope of the linear relation between year and accumulative precipitation before and after the turning year is S_{Pb} and S_{Pa}, respectively.

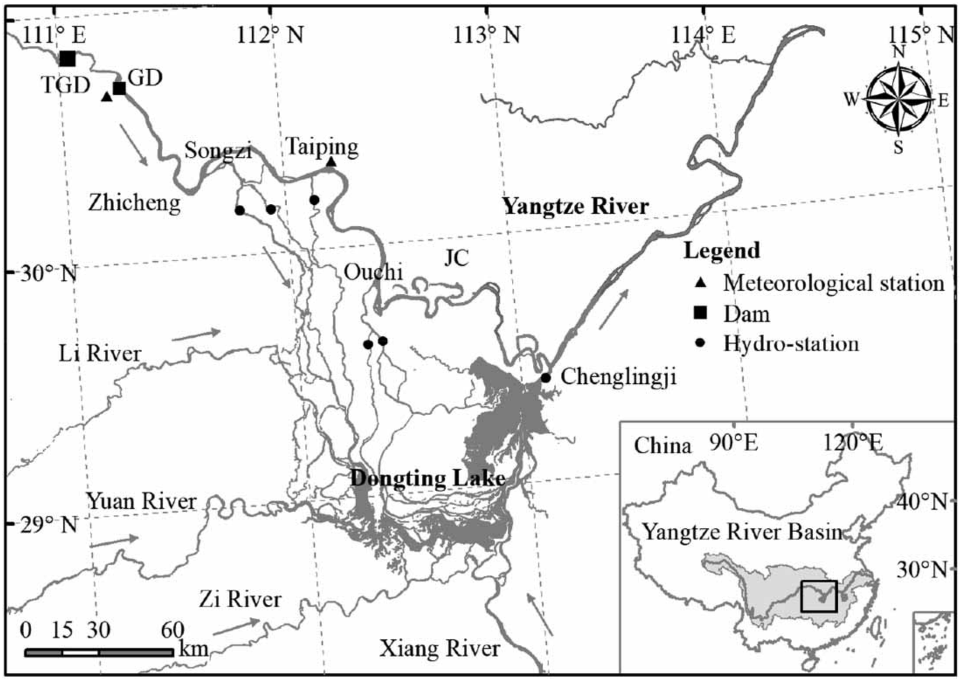

Figure 1 | Study area showing the locations of the JC, GD, TGD, and JTO.

S_{SR}, the slope change rate of the accumulative streamflow, can be calculated in Equation (1).

$$S_{SR} = \frac{(S_{Ra} - S_{Rb})}{S_{Rb}} \times 100 \tag{1}$$

S_{SP}, the slope change rate of the accumulative precipitation, can be calculated in Equation (2).

$$S_{SP} = \frac{S_{Pa} - S_{Pb}}{S_{Pb}} \times 100 \tag{2}$$

C_P, the contribution rate of precipitation to streamflow change, can be calculated in Equation (3).

$$C_P = \frac{S_{SP}}{S_{SR}} \times 100 \tag{3}$$

C_H, the contribution rate of human activities to streamflow change, can be calculated in Equation (4).

$$C_H = 100 - C_P \tag{4}$$

3.3. IHA

IHA was used to evaluate the degree of hydrological alteration in terms of flow magnitude, timing, frequency, duration, and rate of change, with 33 hydrological indicators classified into five groups (Richter *et al.* 1997; Yang *et al.* 2008). The hydrological indicators and their features are listed in Table 1. Their impacts on the ecosystem are very common and are discussed in Ma *et al.* (2014) and Cheng *et al.* (2019).

3.4. RVA

RVA was used to measure the degree of hydrological alteration of streamflow after the dam construction (Richter *et al.* 1997). Hydrological alteration (HA) of each indicator is calculated in Equation (5), where the observed frequency is the post-impact

Table 1 | Hydrological indicators of IHA and their features

IHA groups	Regime features	IHA parameters
1. Magnitude of monthly water level conditions	Magnitude, timing	Mean value of each calendar month
2. Magnitude and duration of annual extreme water level conditions	Magnitude, duration	Annual minimum and maximum 1, 3, 7, 30, and 90-day mean number of zero-flow days Baseflow index
3. Timing of annual extreme water level conditions	Timing	Julian date of each annual 1-day minimum and maximum
4. Frequency and duration of high and low pulses	Magnitude, frequency, duration	Number of low and high pulses with each year Median duration of low and high pulses
5. Rate and frequency of water level condition changes	Frequency, rate of change	Rise and fall rates Number of hydrologic reversals

value of indicators actually falling within the RVA target range, and the expected frequency is the post-impact value of indicators that should fall within the RVA target range. The RVA target range of each IHA indicator can be defined as 75% and 25% of their probability.

$$\mathrm{HA} = \frac{\text{observed frequency} - \text{expected frequency}}{\text{expected frequency}} \times 100\% \tag{5}$$

When the observed frequency (after the dam construction) falls within the RVA target equals the observed frequency, $\mathrm{HA} = 0$. When indicators fall within the RVA target more often than expected, the deviation is positive. When indicators fall within the RVA target less often than expected, the deviation is negative. An absolute value of hydrological alteration that falls within the range of 0–33%, 34–67%, and 68–100% is defined as little (slight) alteration (L), moderate alteration (M), or high alteration (H), respectively. The classification of hydrological alteration indicates that the ecosystem is low risk, moderate risk, and high risk. An overall degree of hydrological alteration, D_O, is defined in Equation (6).

$$D_O = \left(\frac{1}{33}\sum_{i=1}^{33}\mathrm{HA}^2\right)^{\frac{1}{2}} \tag{6}$$

4. RESULTS

4.1. Detection of inflection points and division of periods

Figure 2 illustrates the annual streamflow variations at the JTO. The annual streamflow decreased significantly ($p < 0.05$) from 1955 to 2019. Streamflow decreased most significantly at the Ouchi outlet, and the slope of the linear trend was

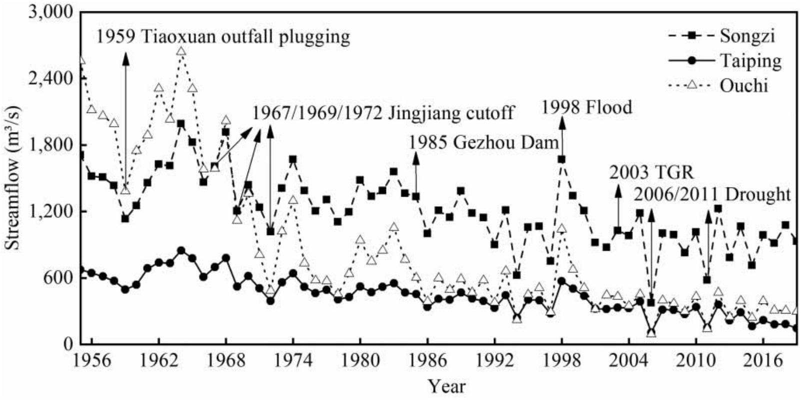

Figure 2 | Annual streamflow variations at the JTO from 1955 to 2019.

−29.57. The Taiping outlet showed the gentlest downward trend, and the slope of the linear trend was −7.78. The slope of the linear trend in the Songzi outlet was −12.00. It can be seen from Figure 2 that the decrease in streamflow at the JTO was affected by many events, and a single inflection point cannot reliably reveal the change in streamflow. Therefore, in this paper, a long sequence of streamflow changes was assessed three times with three techniques (M–K test, AAM, and moving t-test). The inflection points detected with these three techniques are shown in Table 2, which also shows that the inflection points are consistent with the operation of hydro-projects.

Artificial JC projects (1967 and 1969) and natural JC (1972) were carried out, which reduced the total length of the Jingjiang River by approximately 74 km. The GD, which is located approximately 53 km upstream of the Jingjiang River, was built in 1981, and by 1985, the GD reservoir had a basic balance between erosion and deposition. Approximately 60 km upstream of the Jingjiang River, the TGD began impoundment in 2003. The inflection points were 1971, 1985, and 2003. In addition, according to the inflection points, the series was divided into four periods: P1 (1955–1971), P2 (1972–1985), P3 (1986–2002), and P4 (2003–2019).

4.2. Contribution rate of climate and human activities to streamflow alteration

A method of SCRAQ was proposed to calculate the contributions of different factors to the streamflow change (Wang *et al.* 2012). In this paper, precipitation represents climate change. The relationships between the year and cumulative streamflow and between the year and cumulative precipitation at the JTO are shown in Figure 3. The calculated impact of climate change and human activities on the process of streamflow evolution are displayed in Table 3. Note that the effect on streamflow from human activities was far greater than climate change except at the Songzi outlet during P1, indicating the main factor for the decrease in streamflow was human activities. The main reasons for the inflection points of annual streamflow at the JTO were human activities (the JC, GD, and TGD).

4.3. Characterization of streamflow regimes before and after human activities

The full range of streamflow regimes including magnitude, duration, timing, frequency, and rate of change at the JTO were calculated. The hydrological alteration of streamflow regimes at the JTO is shown in Table 4, which highlights the hydrological alteration of 33 IHA indicators from P1 to P2, from P2 to P3, and from P3 to P4.

After the JC project, high and moderate alterations were observed for most indicators. For example, the absolute value of alteration in October at the Ouchi outlet was 100%, which fell outside the RVA boundaries (Figure 4(a)). To be specific, in group 1, nearly all of the monthly indicators (except for May, June, and September at the Songzi outlet) decreased at the JTO (Figure 5). The average alteration (absolute value) of monthly streamflow at the Ouchi outlet was 85%, which was the highest among the values at the JTO.

In group 2, the median values of annual 1, 3, 7, 30, and 90-day minimum and maximum streamflow noticeably decreased at the JTO, whereas the number of zero days increased except for the Songzi outlet. The medians of the number of zero-flow days increased to 129 days and the alteration was 100% at the Ouchi outlet, which was higher than the value at the Taiping outlet.

In group 3, the date of minimum streamflow advanced 20 days at the Songzi outlet, whereas it was delayed by 38 days at the Taiping outlet and by 37 days at the Ouchi outlet. However, the date of maximum streamflow only altered slightly.

In group 4, the low pulse count was shortened at the Songzi outlet and Ouchi outlet, but other indicators altered slightly.

Table 2 | Detection of inflection points by three techniques

	Inflection points											
	M–K			**AAM**			**moving t-test**			**Inflection points**		
Outlet	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
Songzi	1970	1987	2001	1968	1985	2003	1972	1985	2003	1971	1985	2003
Taiping	1972	1985	2005	1970	1985	2005	1972	1985	2003	1971	1985	2003
Ouchi	1969	1986	2004	1968	1984	2003	1972	1983	2003	1971	1985	2003

Note: I (1955–1984); II (1970–1999); III (1985–2019).

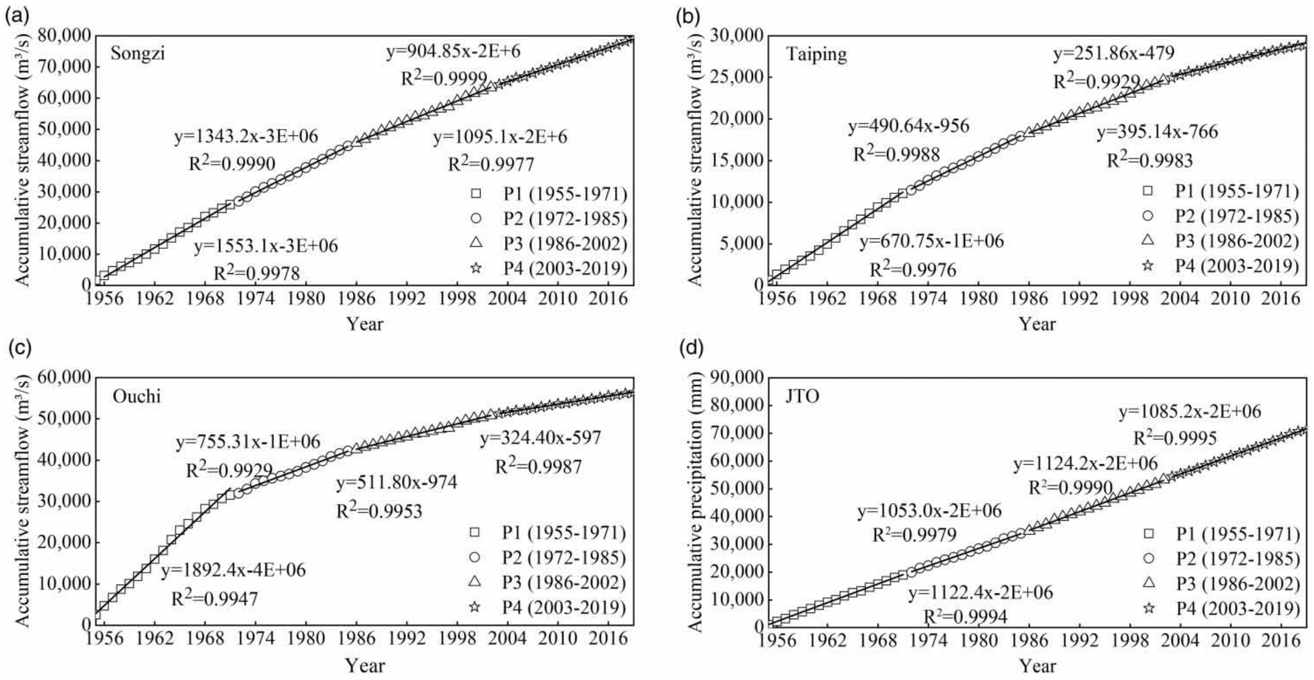

Figure 3 | The relationships between the year and accumulative runoff (a, Songzi; b, Taiping; c, Ouchi), and between the year and accumulative precipitation of the JTO (d).

Table 3 | Contribution rate of precipitation and human activities to streamflow change

				Comparison of the slope from 1955 to 1971 (%)		Contribution rate	
Outlet	**Period**	**Slope of flow m/a**	**Slope of precipitation mm/a**	**Runoff**	**Precipitation**	**Precipitation %**	**Human activities %**
Songzi	P1	1,553.1	1,122.4	–	–	–	–
	P2	1,343.2	1,053.0	–13.5	6.2	45.9	54.1
	P3	1,095.1	1,124.2	–29.5	0.2	0.7	99.3
	P4	904.8	1,085.2	–41.7	3.5	8.4	91.6
Taiping	P1	670.8	1,122.4	–	–	–	–
	P2	490.6	1,053.0	–26.9	6.2	23.0	77.0
	P3	395.1	1,124.2	–41.1	0.2	0.5	99.5
	P4	251.9	1,085.2	–60.5	3.5	5.8	94.2
Ouchi	P1	1,892.4	1,122.4	–	–	–	–
	P2	755.3	1,053.0	–60.1	6.2	10.3	89.7
	P3	511.8	1,124.2	–73.0	0.2	0.3	99.7
	P4	324.4	1,085.2	–82.9	3.5	4.2	95.8

In group 5, low and moderate alterations are observed for most indicators except for the number of reversals at the Ouchi outlet. In general, the outlet that was primarily influenced by the JC project was the Ouchi outlet.

After the GD installation, low and moderate alterations were observed for most indicators. For instance, as shown in Figure 6, the slightly altered (L) indicators accounted for 48%, 55%, and 73% at the JTO, respectively. The highly altered (H) indicators accounted for 15%, 9%, and 12% at the JTO, respectively. Specifically, the absolute value of alteration in July at the Ouchi outlet was 45% and the date of maximum streamflow was 4%, which fell within RVA boundaries (Figure 4(b) and 4(c)).

In group 1, nearly all of the monthly indicators (except for March and August at the Songzi outlet) decreased at the JTO (Figure 5). The average alteration (absolute value) of monthly streamflow at the Ouchi outlet was 26%, which was the lowest among the values at the JTO.

Table 4 | The degree of IHA indicators at the JTO

	Songzi hydrological alteration (%)			Taiping hydrological alteration (%)			Ouchi hydrological alteration (%)		
Indicators	**P1–P2**	**P2–P3**	**P3–P4**	**P1–P2**	**P2–P3**	**P3–P4**	**P1–P2**	**P2–P3**	**P3–P4**
January	−100	−53	−29	−100	40	−6	−100	0	0
February	−100	−73	−86	42	27	0	42	0	0
March	−65	−4	−29	−100	40	0	−100	0	0
April	−48	−86	−43	−48	−73	−36	−83	24	7
May	39	−59	−43	4	−4	57	−83	−18	0
June	39	−59	−43	39	−31	−57	−100	10	−71
July	4	−45	0	−87	10	−71	−100	−73	−29
August	−83	−18	−29	−65	−59	−29	−83	−100	29
September	39	10	−29	−31	−31	−14	−31	10	−29
October	−48	−18	−71	−13	24	−71	−100	10	−57
November	−83	−45	29	−83	−73	43	−100	−73	33
December	−65	−100	−14	−83	40	0	−100	0	0
1-day minimum	−83	−31	−75	42	0	0	42	0	0
3-day minimum	−83	−31	−71	42	17	0	42	0	0
7-day minimum	−83	−45	−75	42	17	0	42	0	0
30-day minimum	−83	10	−86	−31	40	0	42	0	0
90-day minimum	−65	−59	−14	−65	40	−41	−100	8	0
1-day maximum	−13	−4	−71	−31	−31	−71	−100	−31	−86
3-day maximum	−13	−18	−29	−13	−4	−57	−100	−18	−86
7-day maximum	−13	−4	−14	−31	−4	−71	−100	−4	−100
30-day maximum	39	37	0	−83	−18	−71	−100	−4	−86
90-day maximum	−48	10	14	−83	−45	−43	−100	−45	−57
Number of zero days	0	−6	6	−60	−100	−88	−100	−73	−43
Base flow index	−83	−59	−86	42	17	0	42	0	0
Date of minimum	−48	−59	−50	−83	40	0	−100	0	0
Date of maximum	4	−4	−13	4	24	0	4	24	0
Low pulse count	−29	−18	−64	−27	5	0	−22	0	0
Low pulse duration	−70	10	−43	−100	65	0	−31	0	0
High pulse count	−15	−31	−63	−24	24	−56	−33	41	−36
High pulse duration	39	−45	−45	21	−59	−43	−13	−65	0
Rise rates	−13	−73	−71	−39	−29	−100	−13	−73	−86
Fall rates	−13	−86	−29	−31	37	−86	−48	−45	−57
Number of reversals	4	−59	−100	−48	−65	−29	−73	−29	29

In group 2, the median values of annual 1, 3, 7, 30, and 90-day minimum and maximum streamflow slightly altered at the JTO, whereas the number of zero days increased except for the Songzi outlet. The medians of the number of zero days increased by 48 days and the alteration was 100% at the Taiping outlet, which was higher than the value at the Ouchi outlet.

In group 3, the date of minimum streamflow advanced 22 days at the Songzi outlet, whereas other indicators altered slightly.

In group 4, the median of high pulse duration significantly increased at the Ouchi outlet, but other indicators altered slightly.

In group 5, high and moderate alterations were observed for most indicators except for the number of reversals at the Ouchi outlet and rise rate at the Taiping outlet. In general, the outlet primarily influenced by the GD project was the Songzi outlet.

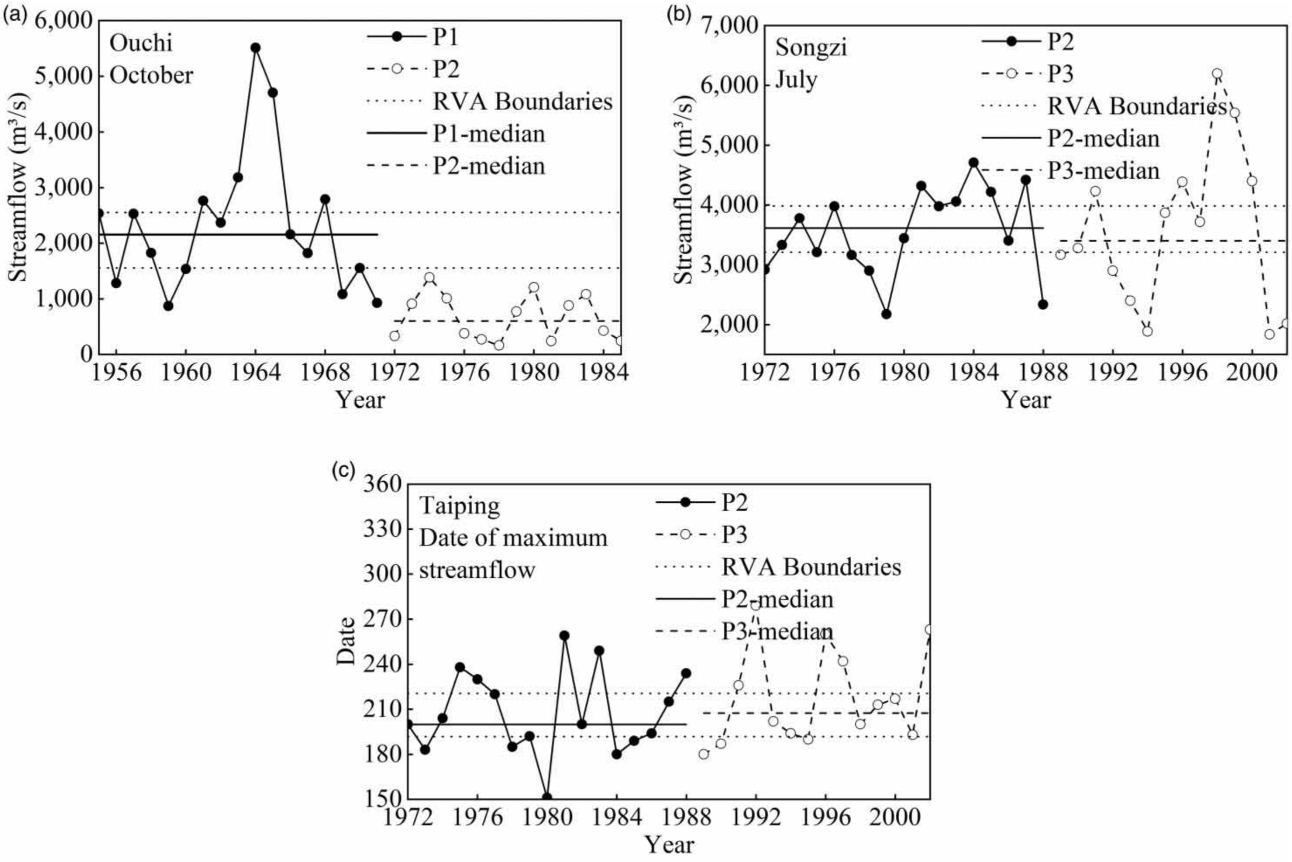

Figure 4 | Variation in high (a), moderate (b), and low (c) alterations of streamflow at the JTO.

After the TGD began operating, as showed in Figure 6, the slighted altered (L) indicators accounted for 45%, 48%, and 64% at the JTO, respectively. The highly altered indicators (H) accounted for 30%, 24%, and 18% at the JTO, respectively. In group 1, the streamflow slightly increased from January to March at the Songzi outlet, whereas it significantly decreased at other outlets. The average alteration (absolute value) of monthly streamflow at the Songzi outlet was 37%, which was the highest among the values at the JTO. In group 2, the median values of annual 1, 3, 7, and 30-day minimum and maximum streamflow decreased at the JTO. The medians of the number of zero days decreased by 28 days and the alteration was 88% at the Taiping outlet, whereas it increased by 6 days and the alteration was 43% at the Ouchi outlet. In group 3, the date of minimum streamflow advanced 14 days at the Songzi outlet, whereas other indicators altered slightly. In group 4, the frequency and duration of high and low pulses decreased at the Songzi outlet, but other indicators altered slightly except for high pulse duration at the Ouchi outlet. In group 5, the rate and frequency of streamflow altered significantly at the JTO. In general, the outlet primarily influenced by the TGD was the Songzi outlet.

4.4. Characterization of spatio-temporal hydrological alteration

The streamflow at the JTO was influenced by the JC, GD, and TGD projects. To provide a better understanding of the 33 IHAs, the distribution of the degree of streamflow change at the JTO is shown in Figure 7. Different colors represent different degrees of hydrological alteration, green (0, 255, 0) indicates that the hydrological alteration degree was 0; yellow (255, 255, 0) indicates that the hydrological alteration degree was 50%; and red (255, 0, 0) indicates that the hydrological alteration degree was 100%. The overall degree of hydrological alteration (D_O) was also calculated.

At the Songzi outlet, all of the water conservancy projects exerted a significant effect on streamflow. The overall degree of hydrological alteration caused by the JC, GD, and TGD projects was 56%, 47%, and 52%, respectively. Horizontally, the indicators with a high or moderate degree of hydrological alteration were mainly concentrated on the change in minimum

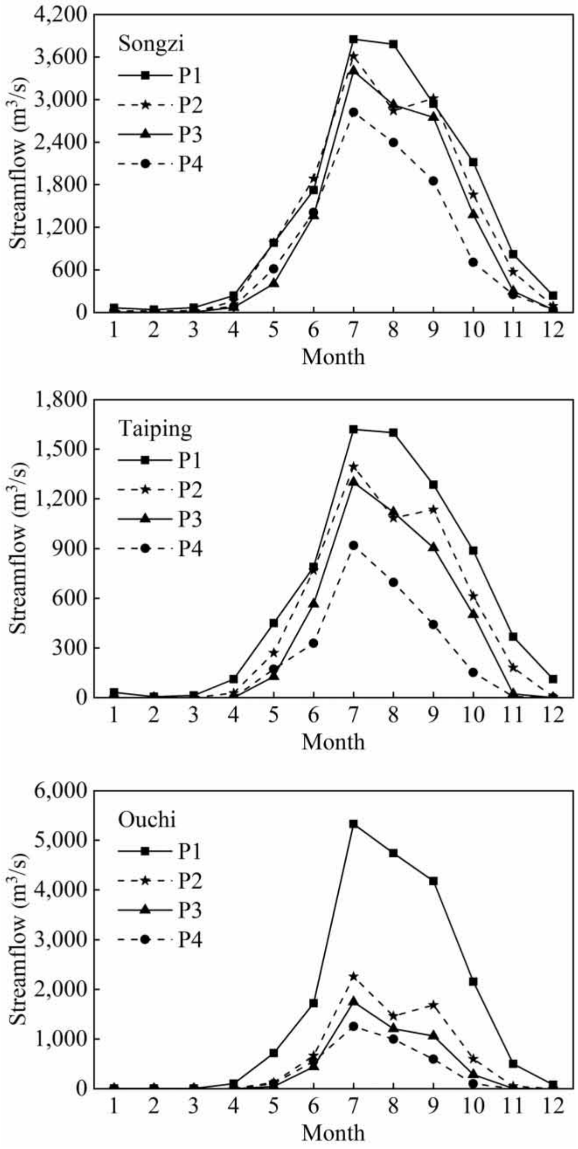

Figure 5 | Changes of monthly median streamflow at the JTO before and after human activities.

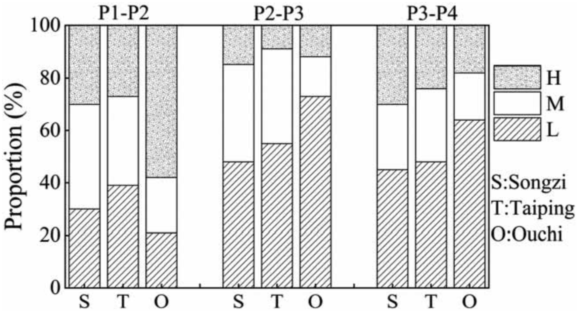

Figure 6 | Distribution of hydrological indicators within the three classes of alteration at the JTO. (L, slight alteration; M, moderate alteration; H, high alteration).

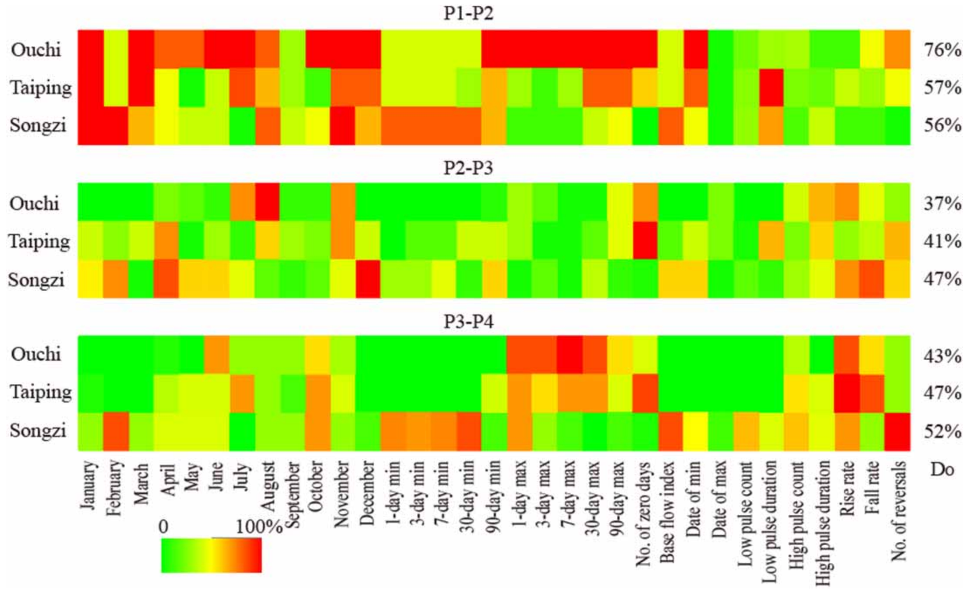

Figure 7 | Distribution of hydrological alteration at the JTO after human activities.

streamflow. However, after the JC and GD projects, the minimum streamflow decreased, whereas the minimum streamflow increased after the TGD project.

At the Taiping outlet, the JC and TGD projects exerted a significant effect on streamflow. The overall degree of hydrological alteration caused by the JC, GD, and TGD operation was 57%, 41%, and 57%, respectively. It is worth noting that the absolute value of hydrological alteration of the number of zero days exceeded 60%. However, after the JC and GD projects, the number of zero-flow days increased, whereas the number of zero days decreased after the TGD project. The increased streamflow caused by JC and GD projects was partially offset by the increased streamflow associated with the TGD.

At the Ouchi outlet, the JC project exerted a significant effect on streamflow. The overall degree of hydrological alteration caused by the JC, GD, and TGD operation was 76%, 37%, and 43%, respectively. The indicators with a high or moderate degree of hydrological alteration were mainly concentrated on the change in maximum streamflow (P1–P2 and P3–P4). The absolute values of hydrological alteration of the number of zero days were 100%, 73%, and 43%, respectively. The difference with the Taiping outlet is that the number of zero days increased after all of the engineering projects.

The proportion and variation of mean annual streamflow at the JTO during P1, P2, P3, and P4 are shown in Figures 8 and 9. Figure 8 shows that the proportion of diversion increased at the Songzi outlet after the JC, GD, and TGD projects. The proportion of diversion increased at the Taiping outlet after the JC and GD projects, whereas it decreased after the TGD project. The proportion of diversion decreased at the Ouchi outlet after the JC and GD projects, whereas it increased after the TGD project. Figure 9 shows that the mean annual streamflow decreased sharply from P1 to P4 at the JTO, especially at the Ouchi

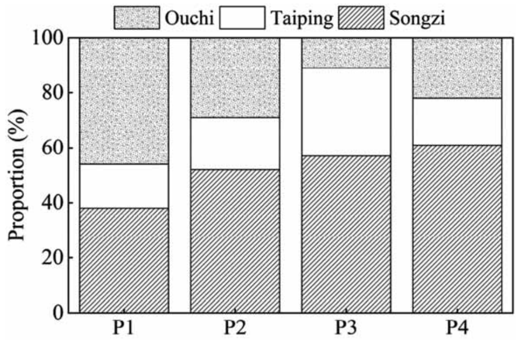

Figure 8 | Proportion of mean annual streamflow at the JTO during P1, P2, P3, and P4.

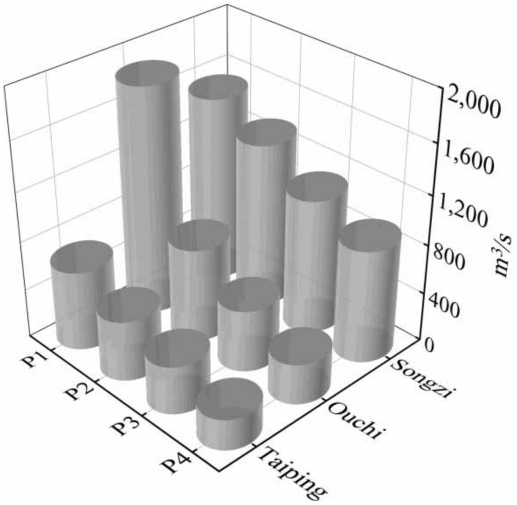

Figure 9 | Variation of mean annual streamflow at the JTO during P1, P2, P3, and P4.

outlet. After the JC project, the annual streamflow decreased by 185.74 m^3/s (Songzi), 158.51 m^3/s (Taiping), and 1,086.41 m^3/s (Ouchi), indicating that the JC project had the most impact out of the three human activities. After the GD project, the annual streamflow decreased by 240.58 m^3/s (Songzi), 99.28 m^3/s (Taiping), and 259.56 m^3/s (Ouchi), suggesting that the GD project had the second-most impact. After the TGD project, the annual streamflow decreased by 177.64 m^3/s (Songzi), 139.67 m^3/s (Taiping), and 176.58 m^3/s (Ouchi), indicating that the TGD project had the least impact out of three human activities.

5. DISCUSSION

5.1. Responses of spatial regions to multiple engineering projects

The difference with the hydrological alteration caused by dam construction is that the effects induced by cutoff projects are often morphologic alterations. A host of investigations indicated that the cutoff disturbed the natural state of water and sediment and led to riverbed degradation and aggradation, which caused adjustments in sediment, streamflow, and water level after the cutoff (Zinger *et al.* 2011; Han & Endreny 2014). After the JC project, the length of the Jingjiang River was shortened by 78 km, the amount of sediment scoured in the Jingjiang River was 6.82×10^8 t, and the water level gradually increased downstream of the JC (Han *et al.* 2017). Consequently, as shown in Figures 1, 7, and 8, the JC project exerted a significant effect on streamflow at the Ouchi outlet, which was the closest outlet in the reach upstream of the JC compared with other outlets. The hydrological alteration was the lowest at the Songzi outlet, which is the farthest outlet in the reach upstream of the JC.

The GD, a runoff hydroelectric station, had a slight effect on streamflow processes and suspended sediment, whereas it had an obvious effect on bedload (Zhang *et al.* 2013). As a result of a slight effect on suspended sediment, river erosion occurred downstream of the GD. Consequently, the GD project exerted a significant effect on streamflow at the Songzi outlet, which was the closest outlet downstream of the GD, compared with other outlets (Figure 7). The hydrological alteration was the lowest at the Ouchi outlet, which is the farthest outlet downstream of the GD.

The TGD with strong water storage and closure capability for water-sediment changed the geomorphology of the riverbed (Han *et al.* 2017). Previous studies have also indicated that the flow of water coming from the Jingjiang River was constant after the TGD project due to water supply operations from January to March and storage operations from August to October (Zhu *et al.* 2016). For instance, the median of monthly streamflow at the JTO decreased rapidly from September to October, as shown in Figure 4, indicating that the TGD played a role in decreasing peak streamflow. Furthermore, nearly all of the monthly indicators decreased at the JTO after the JC and GD projects; however, the streamflow slightly increased from January to March at the Songzi outlet after the TGD project, indicating that the TGD played a dominant role in water supply from January to March.

Table 5 shows that the outlets are influenced by the JC, GD, and TGD projects according to the above analyses. Many researchers have found that the ability of division at the JTO weakened after the JC, GD, and TGD projects (Ou *et al.* 2014; Hu *et al.* 2015; Wang *et al.* 2017); however, little is known about the proportion of mean annual streamflow at the JTO during P1, P2, P3, and P4. As shown in Figures 1 and 8, the Songzi outlet, the nearest outlet downstream of the TGD, has an advantage over the other outlets in terms of diversion. It can also be seen from Figures 7 and 8 that the operation of the TGD alleviated the downward trend of streamflow at the Songzi outlet. This difference also explains why there were steeper downward trends in streamflow at the Taiping and Ouchi outlets. In addition, the streamflow fluctuation at the Taiping outlet was minimal because it is located in the middle of the JTO. Consequently, this can explain why the number of zero days increased at the Ouchi outlet, whereas it decreased at the Taiping outlet after the TGD project.

5.2. Negative impacts on ecosystems and countermeasures for future

The JTO, as water and sediment connecting channels between the Yangtze River and the Dongting Lake, plays a significant role in flood control, Dongting Lake erosion and deposition, and wetland ecosystems. The ability of division from the Jingjiang River to Dongting Lake is weakening and the hydrological regimes at the JTO are deteriorating due to the JC, GD, and TGD, which will have negative impacts on the ecosystem (Ou *et al.* 2014; Hu *et al.* 2015).

Intra-annual variation in streamflow regimes is significant for fish. To be specific, the magnitude, duration, and timing of extreme water conditions are vital signals for fish spawning (Lytle & Poff 2004; Guo *et al.* 2011; Tao *et al.* 2017). The Yangtze River and Jingjiang River are significant natural havens and important breeding grounds for the four major Chinese carp. Spawning and fertilization activities of the four major Chinese carp require continuous water stimulation (Xu *et al.* 2015). Provided that the water stage rises and the flow rate accelerates, fertilization activities are stimulated, but if the water stage drops and the flow rate slows down, fertilization activities are almost stopped (Tao *et al.* 2017). However, after the TGD project, the hydrological regimes downstream of TGD had changed. For example, the water temperature decreased, the average sediment concentration decreased by 95% over many years, the average spawning time of the four fish species was delayed by 10 days, and the spawning scale also significantly decreased (Guo *et al.* 2011). The JTO is a critical passage for the four major Chinese carp from the Jingjiang River to Dongting Lake. The spawning and fertilization activities of the four major Chinese carp were also inhibited in the Jingjiang River, which will inevitably decrease the numbers of the carp entering the JTO.

As a result of the TGD with strong water storage and closure capability for water-sediment, the regimes of water-sediment transport have changed in the Jingjiang River. The sediment content of water is unsaturated, which results in scouring in the main channel of the Jingjiang River (He 2017). Consequently, the water level difference between the Dongting Lake and the main channel increased, which is the underlying cause of the water stage decline of the Dongting Lake (Lai *et al.* 2013). In addition, due to sediment trapping and the release of clear water by the TGD, clear water now flows into the Dongting Lake from the JTO. Although this clear water alleviated the eutrophication, it promoted the erosion of the Dongting Lake, which has negative impacts on the habitat suitability (Xie 2017; Zhou & Zhang 2018). For example, the landscape pattern of the Dongting Lake changed early after the TGD project, which shifted the migratory waterbird population distributions (Wu *et al.* 2017) and changed the spatial variation in the trophic structure of dominant fish species (Yu *et al.* 2018).

Given this, some countermeasures should be considered to mitigate the negative impacts on ecosystems. The TGD should discharge muddy flow and control excessive scouring of the Jingjiang River to reduce the water stage difference between the Dongting Lake and the main channel of the Jingjiang River (Hu *et al.* 2019). Moreover, the inflow into Dongting Lake was restored to 100 billion m^3/s through the deep excavation of the Songzi outlet and regulation of the Songzi River to improve the water level of Dongting Lake (Zhou & Zhang 2018). Reservoir construction not only provides numerous benefits, e.g. hydropower and flood control, but it also has negative impacts on ecosystems. Nevertheless, the changes discussed here will

Table 5 | Outlets influenced by the JC, GD, and TGD projects

Project	Songzi	Taiping	Ouchi
JC	XXX	XXX	XXX
GD	XXX	XX	X
TGD	XXX	XXX	XX

Note: XXX, strongly influenced outlets; XX, moderately influenced outlets; X, weakly influenced outlets.

increase in the future because the Yangtze River is expected to have a capacity of 300 billion m^3 by 2030 (Dai *et al.* 2015). Therefore, strategies for balancing the relationship between interests and ecology remain a considerable challenge.

6. CONCLUSIONS

In this paper, the hydrological alteration of streamflow at the JTO was quantitively estimated by using three detecting techniques and the RVA method. According to the inflection points, the time series was divided into four periods: P1 (1955–1971), P2 (1972–1985), P3 (1986–2002), and P4 (2003–2019). Human activities (JC, GD, and TGD) played a dominant role in the segmentation of periods and made a far greater contribution to streamflow change than climate change. At the Songzi outlet, cutoff and dam projects exerted important effects on streamflow. The hydrological alteration degree caused by the JC, GD, and TGD operation was 56%, 47% and 52%, respectively. At the Taiping outlet, the JC and TGD projects exerted significant effects on streamflow. The hydrological alteration degree caused by the JC, GD, and TGD operation was 57%, 41% and 57%, At the Ouchi outlet, the JC project exerted a significant effect on streamflow. The overall degree of hydrological alteration caused by the JC, GD, and TGD operation was 76%, 37% and 43%, respectively. The ability of division from the Yangtze River to Dongting Lake is weakening and the hydrological regimes at the JTO are deteriorating due to the JC, GD, and TGD, which have had negative impacts on the ecosystem.

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CONFLICTS OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

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

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