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Notes

Evolutionary law of the relatinship between Dongting

Lake and three outlets of Jingjiang River in recent 60

years

Ley evolutiva de la relación entre el lago Dongting y las tres desembocaduras del río Jingjiang en los últimos 60 años

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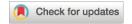
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Abstract

The Three Gorges Reservoir has begun to play a comprehensive role in power generation, flood control, shipping and other aspects, since June 1, 2003. Using long time series runoff and sediment transport data, the evolution of the relationship of the Dongting Lake and the three outlets of the Jingjiang River after operation of the Three Gorges Project was analyzed using Back Propagation neural networks, Mann-Kendall trend test, and double cumulative curves. The results show that: 1) On interannual and interdecadal scales, the decrease in runoff from Dongting Lake is mainly caused by the sharp decrease in runoff from the three outlets. To some extent, the siltation of the Dongting Lake was alleviated because of the reduction of sediment transport coming from the three outlets; 2) by analyzing the consistency of runoff and sediment transport in and out of Dongting Lake, it was found that the influence of the hydraulic engineering in the Yangtze River on runoff and sediment entering and leaving Dongting Lake is asynchronous. The rate of decay of sediment into the Lake is much greater than the decay rate of sediment







out of the Lake; 3) from the trend change of the dried-up days of the three outlets, the three outlets tend to be silted, and the Ouchi River and the Hudu River gradually decline; 4) From the sedimentation process line of Dongting Lake, cumulative sedimentation of Dongting Lake from 2003 to 2018 was -2 829×10⁴ t, and the Dongting Lake changed from siltation state to erosion state; 5) a back propagation neural network model was used to simulate the runoff and sediment transport of Dongting Lake, and the results show that the simulation accuracy met the needs of Dongting Lake runoff and sediment transport prediction.

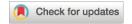
Keywords: Back propagation neural network, runoff and sediment variation, Jingjiang three outlets, Dongting Lake, the Three Gorges Reservoir

Resumen

El embalse de las Tres Gargantas ha comenzado a desempeñar un papel integral en la generación de energía, el control de inundaciones, el transporte marítimo y otros aspectos desde el 1º de junio de 2003. Utilizando datos de escorrentía y transporte de sedimentos de series temporales largas, la evolución de la relación del lago Dongting y las tres desembocaduras del río Jingjiang después de la operación de las Tres Gargantas, el proyecto se analizó utilizando redes neuronales de propagación posterior, prueba de tendencia de Mann-Kendall y curvas acumulativas dobles. Los resultados muestran lo siguiente: 1) a escala interanual e interdecadal, la disminución de la escorrentía del lago





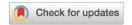


Dongting se debe principalmente a la fuerte disminución de la escorrentía de las tres desembocaduras; hasta cierto punto, la sedimentación del lago Dongting se alivió debido a la reducción del transporte de sedimentos procedentes de las tres desembocaduras; 2) al analizar la consistencia de la escorrentía y el transporte de sedimentos dentro y fuera del lago Dongting, se encontró que la influencia de la ingeniería hidráulica en el río Yangtze en la escorrentía, y el sedimento que entra y sale del lago Dongting es asincrónico; la tasa de descomposición del sedimento en el lago es mucho mayor que la tasa de descomposición del sedimento fuera del lago; 3) a partir del cambio de tendencia de los días secos de las tres desembocaduras, éstas tienden a estar sedimentadas, y los ríos Ouchi y Hudu disminuyen gradualmente; 4) desde la línea de proceso de sedimentación del lago Dongting, la sedimentación acumulada del lago Dongting desde 2003 hasta 2018 fue de -2 829 \times 10⁴ t, y el lago Dongting cambió de estado de sedimentación a estado de erosión; 5) se utilizó un modelo de red neuronal de propagación trasera para simular la escorrentía y el transporte de sedimentos del lago Dongting, y los resultados muestran que la precisión de la simulación satisfizo las necesidades de predicción de la escorrentía y el transporte de sedimentos del lago Dongting.

Palabras clave: red neuronal de propagación trasera, escorrentía y variación de sedimentos, tres salidas de Jingjiang, lago Dongting, embalse de las Tres Gargantas.







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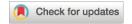
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Introduction

For nearly 100 years, under the dual effects of human activities and nature, Dongting Lake has been shrinking and the flood control situation is grim. Especially after the Three Gorges Project was in function, the runoff and sediment transport from the three outlets into Dongting Lake has undergone dramatic changes, and the river-lake relationship is more complicated. A lot of scholars have had many research results in relation of Yangtze River and Dongting Lake (Chen, 2016; Han, 2014; Hu & Wang, 2014; Hu, Mao, Li, Tan, & Feng, 2013; Li & Wang, 1997; Lu, 2005; Lu & Luo, 1999; Lu & Yao, 2018; Wan, Yang, Wang, Qin, & Dai, 2014). Especially in the past 10 years, many scholars have made a lot of explorations on the impact of human activities on the Dongting Lake, such as reclamation of land from the lake, construction of the Three Gorges Project, etc. (Ban et al., 2014; Chen, 2016; Dai, Lu, Li, & Wang, 2017; Hu et al., 2013; Hu, Mao, Li, Tian, & Feng, 2014a; Hu, Mao, Li, Zeng, & Feng, 2014c; Hu & Zhang, 2018; Shuai, Li, Li, & Li, 2018; Xi et al., 2014; Zhang, Wang, & Tian, 2016). Most studies focus on sedimentation calculations (Guo, Yao, & Yan, 2011; Hong, Dong, & Li, 2007; Hu & Wang, 2014; Jiang,







Huang, & Sun, 2009; Lu & Yao, 2018; Shi, Xia, & Yang, 1999); flood and flood control (Hu & Mao, 2017; Lu, 2009; Mao & Xia, 2005); lake water situation (Hu & Mao, 2017; Huang, Sun, & Jiang, 2011; Sun et al., 2018a); water environment (Hu, 2014; Hu & Zhang, 2018; Shuai et al., 2018; Wang, Ou, Zhang, & Lu, 2015); water level (Hong et al., 2007; Jiang & Huang, 1996; Sun et al., 2018b); ecosystem service function (Deng, Zhong, Xie, Wan, & Song, 2019); wetland (Wu, 2016); aguatic organisms (Wang et al., 2018), etc. The existing literatures have analyzed the time dynamic characteristics of the annual sediment transport in the three outlets and the sediment transport out of the Dongting Lake in recent decades. The results show that the Jingjiang Bending Project and the Three Gorges Project are the fundamental reasons for the substantial reduction of the sediment transport out of the Dongting Lake. However, there are few relevant articles that simultaneously analyze and study the sediment loads of Jingjiang's three outlets and Four Rivers entering the lake, the outflow of Dongting Lake, and the sedimentation of Dongting Lake. Therefore, the systematic study of the response of the lake systems to runoff and sediment variation under the combined effects of natural and human activities is still a frontier field of Dongting Lake research. BP neural networks, M-K test, double cumulative curve and other methods are used to analyze the evolution law of the relationship between Dongting Lake and Jingjiang three mouths in the past 60 years after the operation of the Three Gorges Project, in order to provide reference for the study of Dongting Lake water and sediment.







Materials and methods

Study area

Dongting Lake is located in the northeastern of Hunan Province, on the southern bank of Jingjiang River, spanning Hunan and Hubei provinces. Dongting Lake is located closely with the middle reaches of the Yangtze River. Changes in lake runoff and sedimentation caused by the river-lake interaction have been the focus of attention of hydrologists and geographers. Dongting Lake is an important river-linked lake in the middle of Yangtze River, distributing runoff and sediment from the three outlets of Songzi, Taiping, and Ouchi, and bringing together the Sishui Rivers of Xiang, Zi, Yuan, and Li, as well as the surrounding Miluo River and the Xinqiang River and other small rivers, which forms a complicated river-lake relationship (Figure 1). Dongting Lake is an area which has significant role in regulating floods and protecting wetland ecosystems. The total catchment area of Dongting Lake is 259 430 km², of which the water area of the Lake is 2 625 km².







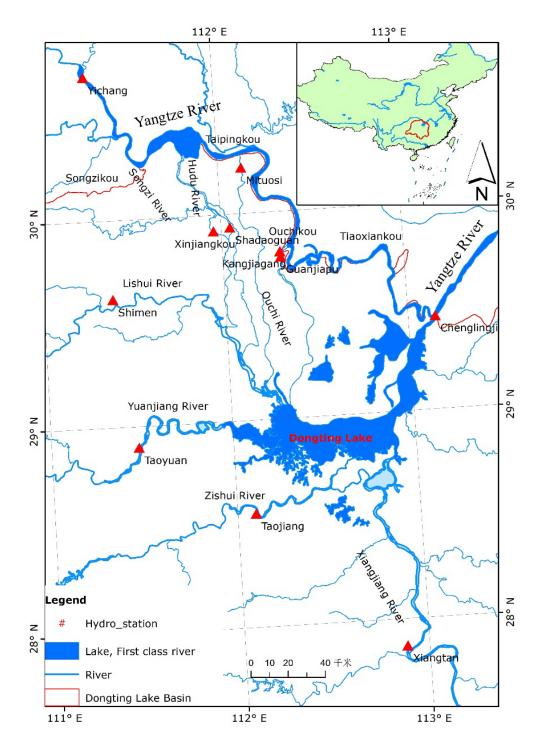


Figure 1. Water system structure of Dongting Lake Basin.







Data

The measured runoff and sediment data of the major control stations were selected as the basic data for the variation analysis of runoff and sediment process at Dongting Lake during 1956-2018 (http://yzt.hnswkcj.com:9090/#/). The control stations in and out of the Dongting Lake include Xiangtan, Taojiang, Taoyuan, Shimen, Xinjiangkou, Shadaoguan, Mituosi, Kangjiagang, Guanjiapu, Chenglingji. measured water and sediment data over the years came from the Hunan Provincial Hydrology and Water Resources Survey Bureau and the "Changjiang Sediment Bulletin 2000-2018" (http://www.cjw.gov.cn/zwzc/bmgb/nsgb/). The cut off data of the three outlets over the years comes from the daily water situation report on the website of the Hunan Provincial Department of Water Resources (https://slt.hunan.gov.cn/slt/hnsw/index.html).

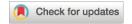
Methods

The following research methods are applied in this paper:

1. Back propagation (BP) neural network. At present, artificial neural networks have been broadly applied in the analysis and simulation







of hydrology and water resources systems, and the BP artificial neural network model is the most widely used (Karunanithi, Grenney, Whitley, & Bovee, 1994). The essence of BP algorithm is to transform a set of system input-output fitting problems into a nonlinear optimization problem. The learning process of neural networks consists of forward propagation of signals and back propagation of errors. The forward and back propagation processes alternate until the neural networks model output reaches our expectations and the network reaches convergence.

After the optimization selection of model training parameters, the runoff and sediment BP neural networks models are trained on the input sample data using a 3-layer network. The input layer of the runoff artificial neural model is the runoff of three outlets and Four Rivers with a total of 9 nodes. The output of the system is 1 node of the sediment transport from the lake in Chenglingji, the number of hidden layer nodes is 9, and the maximum training step is set at 20 000 steps; the input layer of the sand transport artificial neural networks model is the runoff and sediment transport of nine hydrological control stations in three outlets and Four Rivers. A total of 18 nodes are used to transport sediment from 1 node of the lake in Chenglingji is the output of the system, the number of hidden layer nodes is 19, and the maximum training step size is 20 000 steps.

2. Mann-Kendall (M-K) trend test method is used to test and analyze the trend mutation of long sequence data. Please refer to the literature for the specific calculation process (Hu, Mao, Li, & Xu, 2014b). M-K trend test method is widely accepted by hydrologists because it not







expected that the raw material data obey a specific probability distribution and satisfies only the stochastic independence of time series.

In the case of the null hypothesis H_0 : No change in the hydrological sediment time series, let the time series $X = \{x_1, x_2, x_3, ..., x_n\}$ of one n samples, construct an order column m_i , m_i represents the i-th sample $x_i > x_j$ ($1 \le j \le i$) The cumulative number defines the statistic:

$$dk = \sum_{i=1}^{k} mi, (2 \le k \le n)$$

Under the premise that the original sequence is random and independent, the mean and variance of dk are defined as:

$$E[dk] = k(k-1)/4$$

$$Var[dk] = k(k-1)(2k+5)/72, (2 \le k \le n)$$

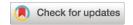
Further normalization of dk, defining statistics:

$$UF_k = \frac{dk - E[dk]}{\sqrt{var[dk]}}, (k = 1, 2, 3, \dots, n)$$

Inverse the time series x { x_n , x_{n-1} , x_{n-2} ,..., x_1 }, $UB_k = -UF_k$ (k = n,







n - 1, ..., 1).

The UB_k and UF_k curves intersect at a certain point in the time series, and the intersection point is the mutation point. If the mutation point is between the given 95 % confidence level, the mutation time is statistically significant.

Results

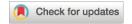
Analysis of water and sediment evolution characteristics of Yichang station

Annual runoff

The multi-year average runoff of Yichang station from 1956 to 2018 was $4\ 271\times10^8\ m^3$, and the annual runoff was in a state of fluctuating decline (Figure 2a). From the different periods when major human disturbances occurred, the overall trend is relatively stable, except for a decline from 2003-2018 ($4\ 092\times10^8\ m^3$) after the operation of the Three Gorges Dam and for the period of 1967-1972 ($4\ 164\times10^8\ m^3$) during the cutting phase has declined. For example, it was $4\ 404\times10^8\ m^3$ before bending from $1956\ to\ 1966,\ 4301\times10^8\ m^3$ after bending from $1973\ to\ 1980,\ 4\ 354\times10^8\ m^3$







after the operation of Gezhouba Dam from 1981 to 2002. The low runoff from 2003 to 2018 may be closely related to the low rainfall of the upper and middle Yangtze River during this period. M-K statistical analysis showed that the annual runoff from Yichang station had been fluctuating in the 63 years, but always changed within the confidence interval (|U| < 1.96, a = 0.05), indicating that no significant changed in annual runoff have occurred.





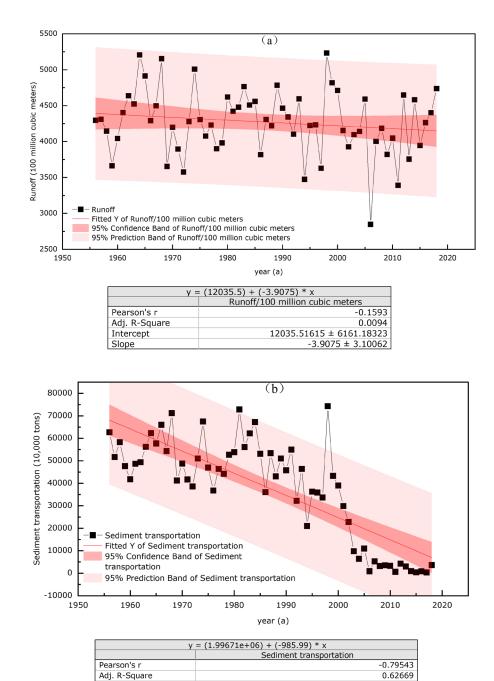


Figure 2. The variation of annual runoff and sediment transport in Yichang station during 1956-2018.

1996709.54047 ± 191129.15104

-985.98968 ± 96.18578

Slope







Annual sediment transport

The annual average value of sediment transport at Yichang station from 1956 to 2018 is $37\,548\times10^4$ t, the fluctuation downward trend is obvious, especially after 2003 (Figure 2b). From different periods, the annual sediment transport showed a downward trend, and it was $54\,764\times10^4$ t from 1956 to 1966 (before bending), $49\,300\times10^4$ t in 1967-1972 (during bending), $49\,925\times10^4$ t in 1973-1980 (after bending), $45\,936\times10^4$ t from 1981 to 2002 (after the operation of Gezhouba dam), only $3\,583\times10^4$ t in 2003-2018 (after the operation of the Three Gorges Dam). M-K statistical analysis shows that in the past 63 years, the annual sand discharge of Yichang station presents a very obvious downward trend. The mutation point occurred in 2003 and exceeded the $95\,\%$ confidence interval in 1995. It can be seen that after the Three Gorges Project impoundment, the annual sediment transport downstream of the reservoir decreased significantly.

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Runoff and sediment transportation evolution in Dongting Lake

Annual runoff

The runoff and sediment in Dongting Lake largely derived from Four Rivers in Hunan (Xiang, Zi, Yuan, Li River), and three outlets of Jingjiang River. The Measured runoff and sediment data of the Dongting Lake from 1956 to 2018 (Table 1) show that the average runoff into the lake is 2 446×10^8 m³/a from the three outlets and Four Rivers, and that of Chenglingji is 2 753×10^8 m³/a, of which the inflow of the three outlets is 792×10^8 m³/a, accounting for 28.78 % of the total runoff of the Lake, and the runoff of the Four Rivers is 1 654×108 m³/a, accounting for 60.07 %, and the interval recharge is 307×10⁸ m³/a, accounting for 11.15 % of the total water of the lake. In the early stage of the operation of the Three Gorges Project (1994-2002), the average runoff of the Four Rivers was 1 908×10^8 m³/a, and after the operation of the Three Gorges Project (2003-2018), the average runoff of the Four Rivers was 1 604×108 m³/a, and the attenuation rate was 15.93 %. The average runoff of the three outlets is 616×10^8 m³/a in the early stage of impoundment operation (1994-2002) and 481×10^8 m³/a in the post-storage period, with a decay rate of 22.3 and 39.3 %, respectively, compared to multi-year averages. The average runoff out of the lake at the beginning of the Three Gorges water storage







was 2 748×10^8 m³/a, while the average runoff out of the lake after the Three Gorges impoundment dropped to 2 400×10^8 m³/a. The amount of runoff coming from the Four Rivers has not changed much, while the amount of water entering three outlets has decreased significantly. M-K trend test (Figure 3) results show that the runoff from the Four Rivers into the lake did not change significantly, while the runoff from the three outlets into the Lake changed abruptly in 1980 and decreased significantly, indicating that the decrease in the amount of runoff in the Dongting Lake is mainly due to the sharp decrease in the amount of runoff from the three outlets (Figure 4a).

Table 1. Runoff and sediment statistics into and out of the Dongting Lake during 1956-2018.

Statistical period/year	The volume of runoff entering the lake/10 ⁸ m ³			The volume	The volume of sediment entering the lake /10 ⁴ t			The volume of	The amount of	sedimentation
	Three outlets	Four rivers	three outlets + four rivers	of the lake/10 ⁸ m ³	three outlets	Four rivers	three outlets + four rivers	sediment in the lake/10 ⁴ t	sedimentation /10 ⁴ t	rate/%
1956-1966	1 313	1 517	2 830	3 126	19 564	2 921	22 485	5 690	16 795	74.69
1967-1972	1 010	1 729	2 739	2 982	14 108	4 081	18 190	5 263	12 926	71.06
1973-1980	8 27	1 699	2 526	2 789	11 075	3 663	14 737	3 839	10 899	73.95
1981-2002	6 86	1 722	2 408	2 748	8 574	2 128	10 702	2 757	7 946	74.24
2003-2018	481	1 604	2 085	2 400	867	814	1 680	1 857	-177	-10.52
1956-2018	792	1 654	2 446	2 753	9 380	2 314	11 694	3 416	8 277	70.78







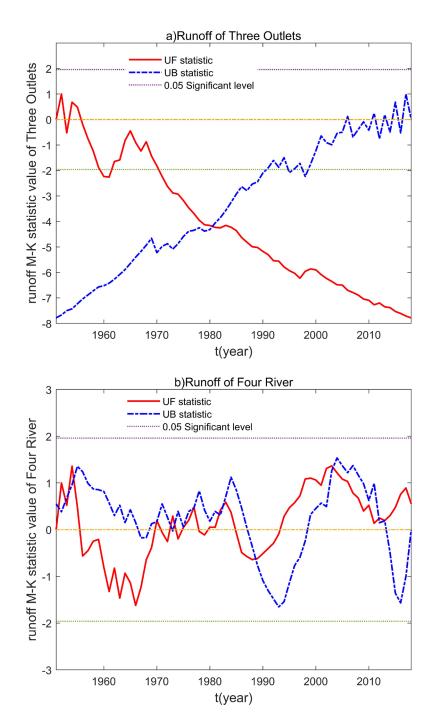


Figure 3. The M-K test statistics of runoff of three outlets and four rivers.







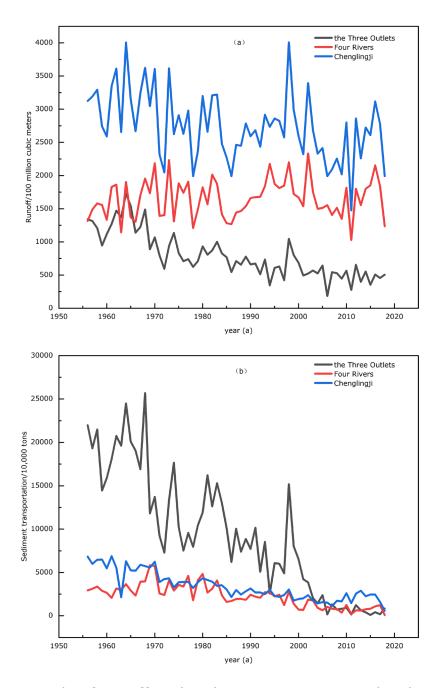


Figure 4. Trends of runoff and sediment transport at the three outlets, four rivers, and Chenglingji during 1956-2018.







Annual sediment transport

The multi-year average sediment transport of three outlets and Four Rivers is 11 694×10⁴ t/a, of which the sediment transport of the three outlets into the Lake is 9 380×10^4 t/a, accounting for 80.22 % of the total sediment transport into the Lake, and sediment transport from Four Rivers into the Lake is 2.314×10^4 t/a, accounting for 19.78 % of the total sediment transport into the Lake. The annual average sediment transport of Chenglingji out of the Lake is 3 416×10⁴ t/a, and the annual siltation amount of the Lake is 8277×10^4 t/a, with a siltation rate of 70.78 %. Before the Three Gorges Project operation, sediment transport into the Lake at three outlets was stable at 75-87 %, but after the Three Gorges Project operation, the sediment volume in Jing River decreased, and sediment entering the Lake from three outlets dropped significantly. The mean sediment transport in the Three Gorges operation period (2003-2018) is only 867×10^4 t/a, accounting for 51.57 % of the incoming sediment transport, which is 5.507×10^4 t/a lower than the average value of 6374×10⁴ t/a in the early stage of the Three Gorges operation period (1994-2002), with a reduced rate of 86.40 %. In addition, from the perspective of changes in the amount of sediment in and out of the Lake over the years (Figure 4b), the amount of sediment flowing out of the Lake has exceeded the amount of sediment in the Lake since 2006, and







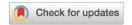
Dongting Lake starts to change from siltation to scouring, indicating that the Three Gorges Project operation has a significant effect on sediment interception in the downstream, which reduces the siltation of Dongting Lake to a certain extent.

Consistency analysis of annual runoff and sediment transport in the three outlets and Chenglingji

Figure 5 shows the double accumulation curves of annual runoff and sediment transport from three outlets into Dongting Lake and Chenglingji out of the Lake, which show that the runoff and sediment in and out of Dongting Lake have changed significantly in the past 63 years. According to the slope of the double accumulation curve, the slope K of the double accumulation curve of runoff and sediment entering the Lake attenuates from 14.4 in the first period to 1.5 in the fifth period, with a decay rate of 89.6 %; while the slope K of the double accumulation curve of runoff and sediment decreases from 1.8 in the first period to 0.8 in the fifth period, with a decay rate of 55.6 %. In particular, it should be noted that the slope of the lake sand curve K decreased from 12.1 to 1.5, indicating the change of the lake sand in Dongting Lake from 2003 to 2018 and the Three Gorges Storage Water operation is closely related, and the trend of the runoff and sediment curve out the lake is not strong. It can be seen that the influence of the water conservancy project of the Yangtze River







on runoff and sediment entering and leaving Dongting Lake is not synchronized, and the attenuation rate of sediment entering the Lake is much greater than that of sediment exiting the lake.



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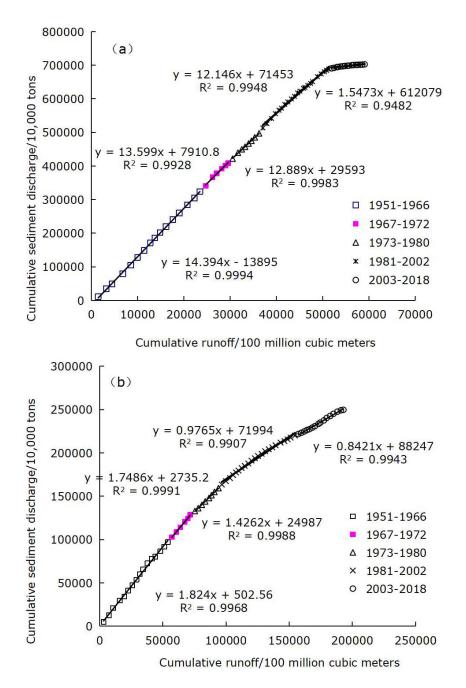


Figure 5. Double cumulative curve of runoff and sediment in and out of Dongting Lake: a) Cumulative runoff and sediment into the lake; b) cumulative runoff and sediment out of the lake.







Impact of Three Gorges Project operation on the relationship between Dongting Lake and Jingjiang River

On June 1, 2003, the Three Gorges Project was officially lowered to store water and began to operate at 135-139 m, which had a profound impact on the relationship between three outlets and Dongting Lake.

Impact on the inflow of the Lake from three outlets

Variation of the runoff of the three outlets

The attenuation of runoff and sediment distribution from three outlets is the direct cause of the change of runoff and sediment in Dongting Lake. With the Lower Jingjiang Cutting Bend, construction of Gezhouba dam, and the Three Gorges Reservoir operation, the amount of runoff entering the Dongting Lake from the three outlets continues to decrease. Before the Three Gorges Dam operation (1994-2002), the total amount of runoff diversion from three outlets was 616×10^8 m³/a, while during the Three Gorges Dam operation (2003-2018), the runoff from the three outlets into the Dongting Lake has dropped to 481×10^8 m³/a, with a reduction of







22.00 %. The total diversion ratio of three outlets decreased from 29.82 % before the lower Jingjiang River cutting bend to 11.77 % at the initial stage of the Three Gorges operation (Table 2). Among them, the runoff diversion and split ratio of the Ouchikou outlet have the fastest attenuation rate among the three outlets. From 1956 to 1966, its multi-year average runoff diversion was $629 \times 10^8 \,\mathrm{m}^3/\mathrm{a}$. From 2003 to 2018, its multi-year average runoff diversion was only $105 \times 10^8 \,\mathrm{m}^3/\mathrm{a}$, which was reduced by 83.3 %. The corresponding shunt ratio dropped from 14.29 to 2.58 %.

Table 2. Runoff and the split ratio at the Yichang Station and the three outlets during different periods.

Statistical period			runoff /×10) ⁸ m ³	split ratio /%				
	Yichang Station	Songzikou	Taipingkou	Ouchikou	Total runoff of the three outlets	Songzikou	Taipingkou	Ouchikou	Total runoff of the three outlets
1956-1966	4 404	479	205	629	1 313	10.87	4.66	14.29	29.82
1967-1972	4 164	441	186	383	1 010	10.58	4.46	9.21	24.25
1973-1980	4 301	423	160	244	827	9.83	3.72	5.68	19.23
1981-2002	4 354	370	132	183	686	8.51	3.04	4.20	15.75
2003-2018	4 092	294	82	105	481	7.18	2.01	2.58	11.77
1956-2018	4 271	383	141	268	792	8.97	3.30	6.28	18.55







The characteristics and trend changes of the number of dried-up days of the three outlets

After the Three Gorges Project operation, three outlets cutoff has changed to varying degrees. Since a long time, the sediment of the flood channel and entrance in the three outlets of the Jingjiang River has been silting and shrinking year by year, so that the other entrances (Shadaoguan, Guanjiapu, Kangjiagang, and Mituosi) have been cut off year after year during the dry period, except for a small amount of diversion into Dongting Lake at the Xinjiangkou of Songzikou (Table 3 and Figure 6), and the number of dried up days at the three outlets showed an increasing trend. In recent years, the dry-flow time of the three outlets has been maintained at about 5-6 months every year, and the average dry-flow time of the Kangjiagang station has exceeded 8 months for many years. According to statistics from 2003 to 2018, the annual average number of dried-up days at Shadaoquan, Mituosi, Guanjiapu, and Kangjiagang has reached 186 days, 138 days, 175 days, and 269 days respectively, compared to the multi-year average, the number of dried-up days has increased by 70 days, 34 days, 44 days, and 20 days respectively. Among them, in 2006, due to comprehensive factors such as low precipitation in upstream Yangtze River and water storage in the Three Gorges Project, the number of dried-up days at three outlets was the highest over the years, and the number of dried-up days at Shadaoguan, Mituosi,







Guanjiapu, and Kangjiagang reached 269d, 206d, 235d, and 336d, respectively. The cut-off time mainly occurs in dry months such as January-April and November-December, which coincides with the adjustment and replenishment operation period of the Three Gorges Project. Therefore, according to the length of the dry season, optimize the water replenishment dispatch scheme of the Three Gorges Reservoir, and while ensuring the demand for the power generation, shipping, and irrigation during the dry period of the reservoir, increase the discharge flow of the reservoir in due course or pre-discharge in advance, to increase the runoff of the Yichang-Zhicheng section of the Yangtze River and ensure the safety of industrial and agricultural production and domestic water in the Dongting Lake area.

Table 3. Variation of average dried up days at the three outlets during different periods.

Statistical period	_		_	mber of dried up tlets by period (d)	the corresponding flow of Zhicheng station when the flow is cut off at each station (m³/s)				
	Shadaoguan	Mituosi	Guanjiapu	Kangjiagang	Shadaoguan	Mituosi	Guanjiapu	Kangjiagang	
1956-1966	0	36	18	212	/	4 292	3 925	13 070	
1967-1972	0	3	80	240	/	3 470	4 958	15 950	
1973-1980	75	70	145	257	4 660	5 180	7 790	18 350	
1981-2002	172	155	167	252	8 920	7 676	8 665	17 390	
2003-2018	186	138	175	269	10 824	7 321	8 788	14 500	
1956-2018	117	104	131	248	8 594	5 932	7 337	16 000	







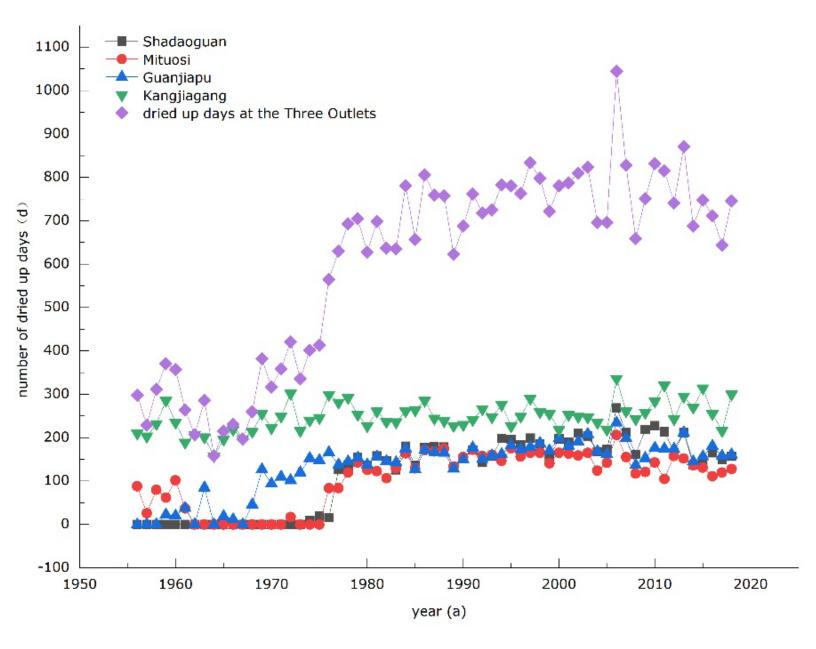
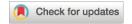


Figure 6. Trend of dried-up days at the three outlets in the Jingjiang River.

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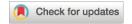




To more intuitively reveal the trend change of the number of dried up days of three outlets, using M-K trend test method, taking the largescale hydro project on the mainstream of Yangtze River as the node, the number of dried up days of the three outlets have been divided into 6 stages. The first stage is 1951-1958 (the Tiaoxiankou blocked), and the Kandel rank correlation test value is |U| = 1.359 < U (0.05/2) = 1.96, the number of dried-up days has an increasing trend, but the increasing trend is not significant. In the second stage, from 1959 to 1973 (the Lower Jingjiang River cutting period), the Kandel rank correlation test value |U| = 1.039 < U(0.05/2) = 1.96, showing an ascending trend, but the trend is not obvious, and it can be seen that the blockage of Tiaoxiankou has no fundamental impact on three outlets interruption. In the third stage, from 1974 to 1981 (Gezhouba dam for power generation), the relevant test values of Kandel rank were |U| = 2.473 > U (0.05/2) = 1.96, the number of dried-up days showed an increasing trend, and the increasing trend was significant, indicating that the Lower Jingjiang Cutting Project had a significant impact on the three outlets interruption. In the fourth stage, from 1982 to 2003 (before the impoundment of the Three Gorges Reservoir), the Kandel rank correlation test value |U| = 3.016 > U(0.05/2)= 1.96, the number of dried-up days of the three outlets showed a significant increasing trend, indicating that the construction of Gezhouba has a significant impact on the three outlets interruption. In the fifth stage, from 2004 to 2018 (the operation period of the Three Gorges Reservoir), the Kandel rank correlation test value |U| = 0.842 < U (0.05/2) = 1.96,







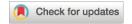
the number of dried-up days of the three outlets has an increasing trend, but the trend is not significant, indicating that the Three Gorges Reservoir water storage has not had a fundamental impact on the three outlets interruption. In a comprehensive analysis, the number of dried-up days of the three outlets showed an increasing trend from 1956 to 2018, but the increasing trend was not significant from 2004 to 2018, indicating that the increase in the number of dried-up days of the three outlets has slowed down since the Three Gorges Reservoir operation. This shows that the dispatch of the Three Gorges Reservoir during the dry period has an obvious resupply effect on the downstream water volume, which is beneficial to the stability of the runoff of the three outlets.

Effect on the change of erosion and siltation in Dongting Lake

From sediment statistics data from 1956 to 2018 and the sedimentation process line of the Dongting Lake (Figure 7), it is evident that the sediment distribution at three outlets has contracted significantly under the influence of the Three Gorges Project. The sediment deposition in the Dongting Lake showed a clear decay trend, and the average annual sediment deposition amount has decreased from 11 155 \times 10⁴ t/a before the Three Gorges operation (1956-2002) to 29 \times 10⁴ t/a during the Three Gorges operation period (2003-2018), with a decrease of 99.8 %. The







sediment deposition rate decreased from 72.01 % before the Three Gorges operation to -43.38 % during the Three Gorges operation. In 2006, the sediment volume out of the Lake was 1 520×10⁴t, and the amount of sediment from the three outlets and Four Rivers was 1 188×10⁴t, ignoring the amount of sediment coming from the interval, the Dongting Lake began to turn into a washout state in 2006, except for the slight siltation in 2007 and 2018, the Dongting Lake showed an erosion state from 2008 to 2017. It can be seen from Figure 7 that the siltation amount of the Dongting Lake has been decreasing year by year, especially after the Three Gorges Dam operation, the decrease has shown an increasing trend, and a sudden change is shown in 2006.







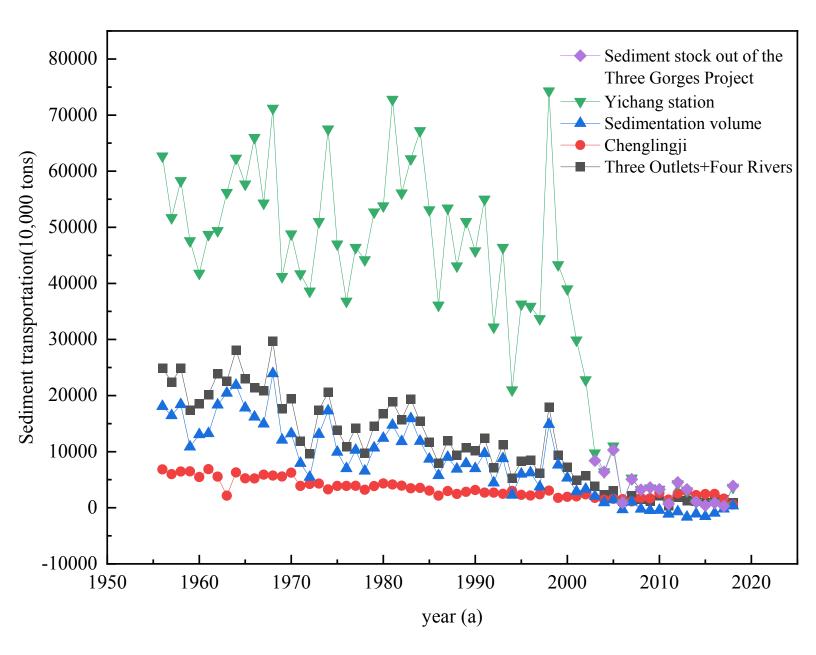


Figure 7. Process line of sediment deposition in Dongting Lake during 1956-2018.







The average annual sediment inflow of three outlets into the Lake decreased from 19 590×10^4 t (1956-1966), 6 960×10^4 t (1966-2002) to 867×10^4 t (2003-2018), with a decrease of 95.6 and 87.6 %, respectively. Without considering the interval sediment input, the average annual sediment into the Dongting Lake was $1\,917.65\times10^4$ t in 15 years after the Three Gorges Project operation, which is 16.4 % of the multi-year average sediment inflow of $11\,694\times10^4$ t. From 2003 to 2018, the accumulated siltation volume of the Dongting Lake was $-2\,829\times10^4$ t, showing a washed-out state, which was $55\,154\times10^4$ t less than the accumulated siltation sediment volume of $52\,325\times10^4$ t from 1994 to 2002, with a reduction of 105.4 %.

Effects on the area and volume changes of Dongting Lake

Three outlets and Four Rivers of Hunan are the main sources of runoff and sediment in Dongting Lake. Due to the small amount of runoff and sediment changes in Four Rivers, the runoff and sediment variation at three outlets has a significant effect on Dongting Lake (Hu *et al.*, 2013; Hu & Zhang, 2018). Through the comparative analysis of the relationship between runoff and sediment volume of three outlets and the area and volume of the Lake in different years, it was found that there was a positive correlation between the magnitude of the runoff and sediment volume transported into the lake by three outlets and the area and volume



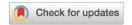




of Dongting Lake (Figure 8a-d). According to the measured data of Dongting Lake, the lake area decreased from 6 000 km² in 1852 to 4 350 km² in 1949, reduced by 1 650 km², and the area of the Lake decreased by 37.6 % and the volume decreased by 42 % during the 63a period from 1949 to 2012, and the Dongting Lake changed from the largest freshwater lake in China to the second largest freshwater lake. From the statistical data of the area of Dongting Lake, it can be seen that from 1825 to 2012, the lake area of Dongting Lake showed a continuous shrinking trend, with the smallest area shrinking to 2 525 km². From 1949 to 1982, the reduction of the Lake area changed significantly, of which the annual reduction rate from 1954 to 1958 was the largest, reaching 10 km²/a, which was related to a large number of reclaiming farmlands from lakes in this stage. From 1977 to 2012, the volume of the Lake was between 165 and 178×108 m³. In 1998, the area and volume of the Lake rebounded. According to the statistics of the Water Resources Department of Hunan Province, since 1998, Dongting Lake has implemented the project of returning farmland to the lake. The flood storage capacity has increased by 27×10⁸ m³, the flood storage area has been expanded by 554 km², and the Lake area has shown an increasing trend. In 2003, the Three Gorges Project was put into operation, and three outlets were discharged with clear water, and Dongting Lake was changed from siltation to scouring with obvious effect, and the area of Dongting Lake has the tendency to continue to increase. Generally, the reduction in runoff and sediment amounts has led to an important factor in the







reduction of the lake area and volume, but it is not the only influencing factor, and the area or volume of the Lake is also significantly affected by the construction of fields around the lake or returning farmland to the lake.







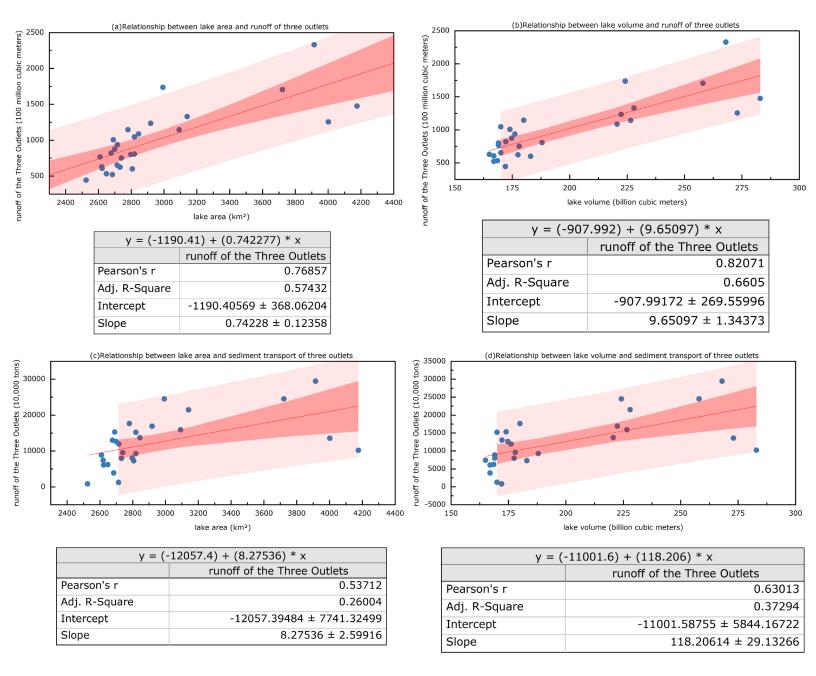


Figure 8. Relationship between area, the volume of the Dongting Lake and runoff, sediment transport at the three outlets.







Prediction of changes in runoff and sand transport out of the Dongting Lake

According to the long-term sequence data of runoff and sediment discharge from three outlets and the Chenglingji, a BP neural network model was constructed to train and analyze runoff and sediment emission of Dongting Lake. In the simulation, a BP neural network prediction model for the prediction of annual runoff and annual sediment delivery was established, and the simulation results are shown in Figure 9.





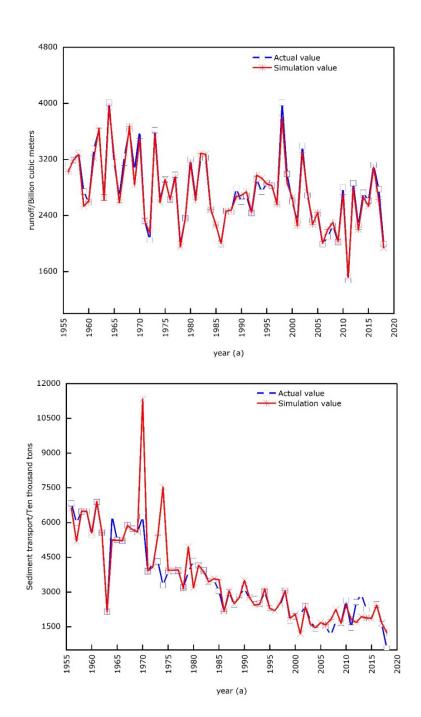
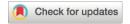


Figure 9. Results of BP network fitting on annual runoff and sediment transport.







According to the results of the model, the average percent error of annual runoff and sand transport were 0.65 and 5.16 %, respectively (Table 4). It can be seen that the runoff prediction results are relatively ideal, and the error percentage is between 0.02 and 7.59 %, however, due to the large interannual variation of sediment transport, the sediment transport forecast results are worse than the runoff forecast results, and the data errors of individual years are larger.







Table 4. Comparison of measured and predicted values of runoff and sediment out of the Dongting Lake basin after the Three Gorges Reservoir operation.

Time after the construction of the reservoir (year)	Runoff (×10 ⁸ m ³)			Sediment transport (×10 ⁴ t)		
	Measured	Simulated	Error	Measured	Simulated	Error
	value	values	percentage	value	values	percentage
1	2 685	2 728.47	1.62	1 750	1 592.08	-9.02
2	2 329	2 274.75	-2.33	1 430	1 460.64	2.14
3	2 415	2 441.06	1.08	1 590	1 676.12	5.42
4	1 990	2 003.94	0.70	1 520	1 586.37	4.37
5	2 094	2 201.38	5.13	1 120	1 806.07	61.26
6	2 256	2 299.70	1.94	1 740	2 247.50	29.17
7	2 018	2 035.58	0.87	1 670	1 642.87	-1.62
8	2 799	2 702.60	-3.44	2 620	2 438.32	-6.93
9	1 475	1 515.60	2.75	1 460	1 819.62	24.63
10	2 860	2 788.02	-2.52	2 560	1 687.99	-34.06
11	2 259	2 202.44	-2.50	2 900	1 934.93	-33.28
12	2 725	2 662.61	-2.29	2 260	1 876.50	-16.97
13	2 610	2 533.36	-2.94	2 450	1 868.12	-23.75
14	3 119	3 085.88	-1.06	2 460	2 432.35	-1.12
15	2 776	2 626.53	-5.38	1 610	1 664.66	3.40
16	1 990	1 936.04	-2.71	575	1 247.27	116.92
17		2 041.45			335.46	
18		2 138.85			216.19	
19		2 153.68			259.90	
20		2 198.67			303.85	
21		2 238.43			367.12	







After the completion of the Three Gorges Reservoir, a large amount of sediment was trapped in the reservoir, and the riverbed downstream of the dam was obviously scoured. According to the calculation of the measured and simulated values of runoff and sediment transport at Dongting Lake, it can be seen that after the Three Gorges operation for 16 years, the riverbed of the Yangtze mainstream has been greatly scoured, the water level has dropped, the sediment separation of three outlets continued to decrease, and the runoff diversion ratio of three outlets dropped from 22.26 % before the operation to 11.77 % after the operation. In terms of sediment transport volume, after the Three Gorges impoundment operation, the sediment transport volume at Yichang Station dropped sharply from 37 356×10⁴ t (1994-2002) before the operation to 3 583×10⁴ t (2003-2018) after the operation, and the sediment transport capacity of the three outlets was sharply reduced to 467×10^4 t, 119×10^4 t, 280×10^4 t, respectively. It is evident that the completion of the Three Gorges Reservoir has had a significant effect on the interception of sediment entering Dongting Lake.

Table 4 provides the forecast data for 21 years after the completion of the Three Gorges Reservoir. This shows that the blocking effect of the Three Gorges Reservoir on sediment is obvious. Due to the obvious decrease in the amount of sediment entering the lake from three outlets, the amount of sediment leaving Dongting Lake has also decreased significantly. It is predicted that the amount of sediment entering the Lake







from Chenglingji in 2023 will only be 367.12×10^4 t. The runoff from the lake is relatively stable, and the amount of runoff out of the Lake will remain at about 2238.43×10^8 m³ by 2023.

Conclusions and discussion

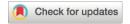
Conclusions

According to the latest observations of water and sand available in Dongting Lake area, an analysis of the variation characteristics of runoff and sediment in Dongting Lake and the interrelationship between rivers and lakes is presented, the impact of Three Gorges Reservoir storage on the relationship between Dongting Lake and three outlets is discussed, and the following main conclusions are drawn:

1. From the perspective of interannual and interdecadal scales, the sharp reduction in the amount of runoff from three outlets is mainly responsible for the decrease in runoff in Dongting Lake. The impoundment of the Three Gorges Dam has a significant intercepting effect on downstream sediments. Hence, Dongting Lake has a reduced degree of siltation. Human activities, such as the Three Gorges Project and the reduction of precipitation in upper Yangtze River reaches, have the largest impact on the lake.





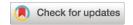


- 2. By analyzing the consistency of runoff and sediment transport in and out of Dongting Lake, it can be seen that the impact of the hydro projects of the mainstream of the Yangtze River on runoff and sediment transport of the Dongting Lake is not synchronized, and the rate of decay and change of sediment entering the lake is much greater than the decay rate of sediment out of the Lake.
- 3. From the characteristics and trend changes of the number of days without flow in three outlets, it can be seen that the changing environment conditions have led to a sharp decline in runoff and sediment diversion of three outlets as a result of the changing of Dongting Lake basin. Three outlets are gradually silting up, and the Ouchi River and Hudu River are slowly declining.
- 4. From the perspective of the sediment sedimentation process line of the Dongting Lake, the cumulative sediment deposition amount of the Dongting Lake from 2003 to 2018 was -2.829×10^4 t, and the lake area was converted from siltation to erosion.
- 5. BP neural network is used to simulate runoff and sediment from Dongting Lake, according to the results, simulation accuracy is sufficient to predict runoff and sediment out of Dongting Lake.

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Discussion

The changes in the relationship between Jingjiang River and Dongting Lake are of great significance to the flood control of the middle reaches of the Yangtze River. Due to the influence of the bending of the Jingjiang River, the construction of the Gezhou Dam, and the impoundment of the Three Gorges Reservoir, the relationship between water and sediment in the Jingjiang River and Dongting Lake has become more and more complicated.

1. The process of water and sediment coming from the three outlets of the Jingjiang River and the Tour Rivers is complex, and the floods from different sources form a mutual top-supporting effect with the Dongting Lake, resulting in a complicated process of water and sediment variation, which aggravates the flood control situation in the Dongting Lake area. The reduction of sediment distribution in the three outlets of the Jingjiang River is mainly caused by the drop of the water level of the Jingjiang River and the change of the rushing of the three outlets flood channels, which is rooted in the change of water and sediment in the main stream of the Yangtze River. In addition to the bending of the Jingjiang River and the Three Gorges impoundment, the construction of Wudongde, Baihetan, Xiluodu and Xiangjiaba hydropower stations had a great impact on the diversion of the three outlets. The total storage capacity of the four hydropower stations exceeds that of the Three Gorges Reservoir, reaching







 $136 \times 10^8 \, \text{m}^3$. Especially in dry years, the situation of the three outlets dry-flow is more serious, which must be paid attention to, and countermeasures should be taken to reduce the impact of the three outlets dry-flow on the water volume of Dongting Lake.

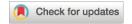
2. Different water conservancy projects have different impacts on the relationship between water and sediment in the Jingjiang River and Dongting Lake. The bending of the Jingjiang River has caused a sharp drop in the diversion of the three outlets, and the Jingjiang River section has been eroded greatly, reducing the amount of water and sediment entering the lake at the three outlets, slowing down the deposition of Dongting Lake. However, with the increase in the amount of water and sediment in the lower reaches of the Jingjiang River, the supporting role of the Jingjiang River on the outlet of Dongting Lake has increased, making the relationship between the rivers and lakes more complicated. The impoundment of the Three Gorges Reservoir also causes the scouring of the Jingjiang River. The difference is that the water level of the Jingjiang River caused by the storage of the Three Gorges Reservoir did not drop much, but the interception effect of the Three Gorges Dam on sediment was obvious, which reduced the siltation of Dongting Lake to a large extent.

It is a long-term systematic study to find out how the Three Gorges

Dam impacts runoff and sediment in Dongting Lake, as there have been
no runoff and sediment process data of the Three Gorges Reservoir over
the years and no topographic map data of the bottom of Dongting Lake.







The relationship between rivers and lakes, as well as sediment, is quite complex. The coupling study of the operation of the Three Gorges Reservoir and the change of runoff and sediment in Dongting Lake, as well as the study of soil erosion and sedimentation changes in Dongting Lake, only involve quantitative statistics. Researchers are only now beginning their study of the impact of the Three Gorges Reservoir operation on three outlets and Dongting Lake, and more observational data tests are needed to support relevant statistical results. It is our goal to conduct spatial coupling studies with complete data and to closely monitor runoff and sediment changes at three outlets as they relate to the evolution of the watershed. Ensure the long-term stability of the Dongting Lake Basin by coordinating reservoirs' and Dongting Lake's operating schedules and implementing flood control and dredging measures in time.

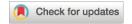
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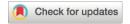




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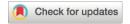




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