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Original Research

Abnormal Changes Diagnosis and its Control Factors of Water and Sediment Discharge in the Lower Reaches of the Three Largest Rivers in China from 1960 to 2020

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Abstract

There are general trends and significant and abnormal changes in water and sediment discharge in rivers and estuaries, and the abnormal changes have been diagnosed frequently. Here we clarified the time node and mechanism of abnormal changes in water and sediment discharges in the lower reaches of the three largest rivers in China, which occurred with the increase of strong human activities and climate change. Using the Mann-Kendall test, Pettitt test, and double cumulative curve methods, we analyzed the data change characteristics of 5 hydrological stations: Lijin (Yellow River), Datong (Yangtze River), Gaoyao, Shijiao, and Boluo (Pearl River) from 1960 to 2020. The results showed that the Yellow River had significant and abnormal changes in water discharge in 1976 and 1986 separately, while the Yangtze River and Pearl River didn't show abnormal changes due to being located in different climatic zones. In addition, the Yellow and Yangtze Rivers had abnormal changes in sediment discharge in 1997 and 1992, separately, the West and East branch rivers of the Pearl River showed abnormal changes in 2000 and 1989, separately, and the North branch rivers of the Pearl River only showed significant changes in 1999. Most sediment abnormal changes for the three rivers occurred in 10 years, from 1990-2000, when there were strong human activities, including water and soil conservation, sand mining, and dam construction. Dam construction plays the most important role in sediment abnormal changes. The intensity after the sediment abnormal change is around 5 times that before the abnormal change in the Yellow River, but the intensity is only 2-3 times in the Yangtze River and Pearl River. The Yellow River shows a higher vulnerability to water and sediment changes than the other two rivers under the influence of strong human activities and thus needs to be carefully protected for sustainable use.

Keywords: water and sediment discharges, abnormal change, Mann-Kendall trend analysis, Pettitt test, the three largest rivers in China

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Introduction

The processes of water and sediment have an important impact on social development. With climate change and intensive human activities, global water and sediment changed significantly and had a profound impact on the temporal and spatial distribution of water resources, riverbed evolution, and estuary ecosystem [1, 2]. As a densely populated and economically important area, water security and ecosystem evolution in the estuarine delta are closely linked to water and sediment discharge into the sea. The water and sediment discharge are not only affected by reservoirs, deforestation, and soil and water conservation measures in the upstream and midstream, but also by sand mining in the river network, reclamation at the mouth, and river dredging in the estuary area. Therefore, the dynamic changes in water and sediment discharge have always been the focus of scholars.

Milliman concluded that there are geographical differences in water discharge from several European rivers due to a combination of climatic and topographic factors. Deforestation, agricultural farming, and mining activities have led to an increase in sediment, while soil protection, reforestation, river diversions, and dam construction have reduced sediment discharge [3]. Panin and Jipa analyzed the trends in sediment in the Danube River and found that it was reduced to 30-40% under the interception of the Iron Gate Dam, leading to intense erosion along the delta [4]. In addition, sediment discharge in the Mississippi River decreased by 75% from 1940 to 2007, which was due to dams, bends, soil conservation, and other factors [5]. The suspended particulate matter in the Mekong River also decreased by 5% annually, which was mainly affected by the hydropower development project after dam construction [6, 7]. What's more, the estuarine deltas in East and Southeast Asia were also at risk of erosion due to the reduction of sediment discharge [8].

Domestic studies mainly focused on the Yellow River, Yangtze River, and Pearl River. For example, Liu et al. first compared the temporal and spatial trends of sediment in the sea of three major rivers from 1950 to 2011. The results showed the variability of water discharge in the past 60 years was not obvious, while sediment discharge decreased significantly. Specifically, water and sediment decreased abruptly in 1985 for the Yellow River, and sediment discharge decreased abruptly in the mid-1980s and early 1990s for the Yangtze River. The sediment discharge of the East River and West River dropped abruptly in 1987 and 1998, respectively, while that of the North River did not change significantly [9]. Chu et al. only compared the relationship between precipitation and water discharge in the Yellow River and Yangtze River. Due to the differences in climate types and human activities, the water discharge of the Yellow River was not significantly affected by precipitation, while the water discharge cycle of the Yangtze River was closely related to the precipitation cycle [10]. Besides that, comparative studies on water and sediment discharge in the three rivers are rare, and most studies focus on a single river. For example, Wang et al. used the MK test and wavelet analysis to evaluate the trend, variability, and periodicity of water and sediment in the Yellow River. The results showed water and sediment discharge had changed abruptly in 1985 and 1996, respectively [11]. Peng et al. found that water and sediment occurred abruptly around 1968 and the early 21st century, respectively, in the mainstream of the Yangtze River [12]. Liu et al. analyzed the characteristics of water and sediment in the Pearl River, and the results showed that water discharge was relatively stable while sediment discharge decreased significantly [13-15]. There are many other studies on water sediment changes in the three rivers, but most of them are not limited to the estuary. Wang et al. (2022) and Xu et al. (2022) studied the characteristics of long-term changes in water and sediment in the Yellow River basin at different periods since the 1950s [16, 17]. Other studies focused on the characteristics of water and sediment discharge in the Weihe River basin from 1956-2010, the main stream of the Yellow River from 1950-2013, and the source area of the Yellow River from 1960-2013, respectively [18-20]. Li et al. (2023) explored the dynamic changes of sediment and the influencing factors in the Yangtze River basin and simulated future trends [21]. Dai et al. (2016) analyzed the variation characteristics of the suspended sand concentration in the Yangtze River from 1956 to 2013 [22]. Zhou et al. (2019) analyzed the characteristics of water-sediment changes in the Pearl River basin from 1953-2017 [23]. Wan (2020) only analyzed the characteristics of water-sediment changes in the West River from 1957-2016 [24].

In general, there are few comparative studies of the water and sediment discharge of the three major rivers in China, and there is no unified diagnostic method to judge their variability. Given the dynamic characteristics of water and sediment, it is necessary to compare the differences between them on the basis of data updating. Therefore, we collected water and sediment data from five hydrological stations in the three major rivers from 1960 to 2020 and used a unified diagnostic method to judge the variation of estuaries. In addition, we further discussed and compared the control factors in different rivers.

Material and Methods

Study Area

The Yellow, Yangtze, and Pearl Rivers, located from north to south, are the three largest rivers in China. The freshwater, sediment, and dissolved solids delivered by the three rivers to the sea account for 3%, 9%, and 7% of the world total, respectively [25]. The Yellow and Yangtze Rivers originate from the Qinghai-Tibet

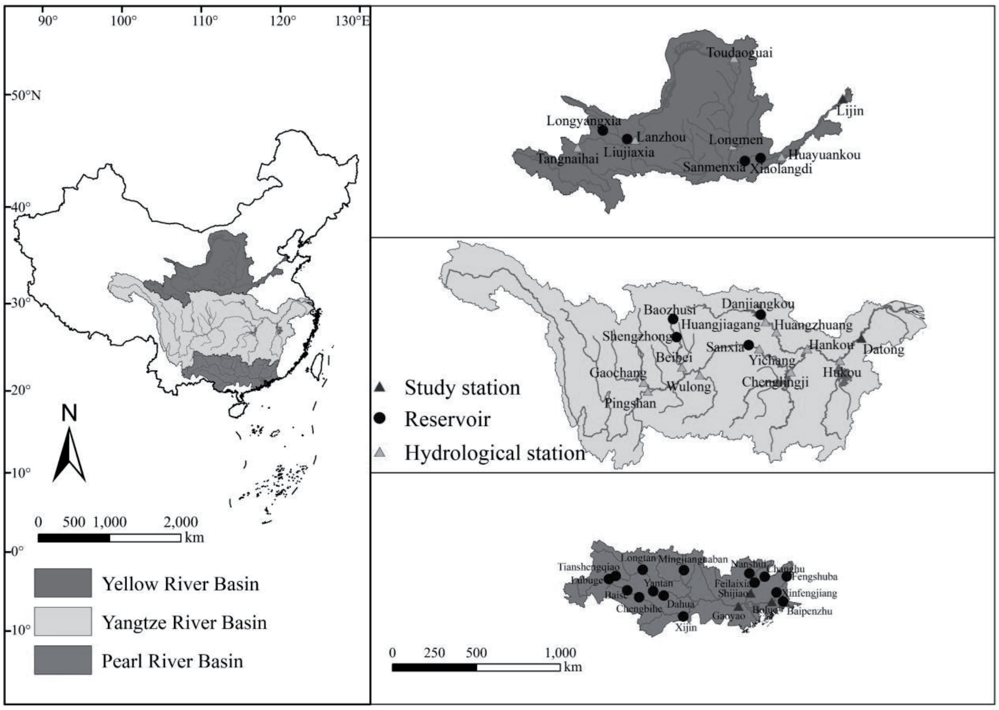

Fig. 1. A schematic map of the Yellow River, Yangtze River, and Pearl River basins.

Plateau, with mainstream lengths of 5,464 km and 6,300 km, respectively, and catchment areas of 750,000 km^2 and 1800,000 km^2, separately. The Pearl River originates from the Yunnan Plateau, with a length of 2,400 km and a catchment area of 450,000 km^2 (Fig. 1).

The Yellow River is divided into the upper, middle, and lower reaches at Toudaoguai and Huayuankou, which are characterized by less water and more sediment. The upper and middle reaches generate almost all the runoff for the river basin, and the sediment primarily originates from the middle reach, which provides approximately 90% of the total sediment discharge. Lijin Station is the last hydrometric station of the river into the sea, located in Lijin County, Shandong Province. The Yangtze River is also divided into three reaches at Yichang and Hukou, and approximately half of the runoff and all of the sediment come from upstream Yichang. Datong Station is a reference station for the runoff and sediment flowing into the sea from the Yangtze River, located in Guichi County, Anhui Province, which is basically not affected by tidal currents. The Pearl River is a compound river system involving three main tributaries: the West River, the North River, and the East River. The West River is the largest tributary and provides approximately 77% and 89% of the total water and sediment of the Pearl River, respectively. The West River and North River flow into the Pearl River Delta through Sixianjiao, while the East River flows into the Pearl River Delta at Shilong Town, Dongguan City. The main hydrological control stations before the confluence of three rivers are Gaoyao Station (West River), Shijiao Station (North River), and Boluo Station (East River).

Datasets

The hydrological data was collected from the Yellow River Conservancy Commission (YRCC), the Yangtze Water Conservancy Committee (YWCC), and the Water Bureau of Guangdong Province (WBGP) (Table 1). The data on main dams in three rivers (Table 2) was taken from the Chinese National Committee on Large Dams (http://www.chincold.org.cn/).

Table 1. Water and sediment data of 5 hydrological stations in the Yellow, Yangtze, and Pearl Rivers.

River	Hydrological station	Location	Data range
Yellow River	Lijin	118°18′18″E,37°31′20″N	1964-2020
Yangtze River	Datong	117°36′43″E,30°46′41″N	1950-2020
Pearl River	Gaoyao	112°27′13″E,23°02′43″N	1960-2020
	Shijiao	112°56′59″E,23°33′39″N	
	Boluo	114°17′42″E,23°09′50″N	

Methodologies

Mann-Kendall Test

The Mann-Kendall (MK) trend test method is a rank-based nonparametric statistical test that is widely used to identify the trends of hydrological and agro-meteorological time series [26]. For time series $X = \{x_1, x_2, x_3, ..., x_n\}$, the MK test statistic S is given by:

$$s_k = \sum_{i=1}^{k} r_i, \quad k = 2, 3, \dots, n \tag{1}$$

Table 2. Large scale dams in the Yellow, Yangtze, and Pearl River basins.

River		Dam	Capacity ($10^8 m^3$)	Running time
Yellow River	Upstream main stream	Qingtongxia	6.06	1967
		Liujiaxia	57	1969
		Longyangxia	247	1986
		Lijiaxia	16.5	1997
	Middle main stream	Sanmenxia	162	1961
		Wanjiazhai	8.96	1998
		Xiaolangdi	126.5	2000
Yangtze River	Jinsha River Main Stream	Xiluodu	126.7	2007
		Xiangjiaba	51.9	2012
	Jinsha River Tributary	Ertan	58	2000
	Jialing River Tributary	Shengzhong	13.9	1982
		Baozhusi	25.5	1998
		Bikou	5.2	1976
	Minjiang River Main Stream	Zipingpu	11.1	2002
	Minjiang River Tributary	Pubugou	53.9	2009
		Gongzui	3.7	1979
	Han River Main Stream	Yahekou	13.2	1960
		Danjiangkou	290.5	1968
		Ankang	25.9	1993
	Han River Tributary	Huanglongtan	11.6	1978
	Wujiang River Main Stream	Goupitan	55.6	2008
		Wujiangdu	23	1983
		Hongjiadu	49.5	2002
	Xiangjiang River	Dongjiang	91.5	1986
	Yuanjiang River	Wuqiangxi	42	1996
		Fengtan	17.3	1979
	Zi Shui	Zhexi	36.6	1962
	Li Shui	Jiangya	17.4	1998
	Ganjiang River	Wan'an	22.2	1990
	Poyang Lake System Tributary	Zhelin	79.2	1972
		Hongmen	12	1961
	Yangtze River main stream	Gezhouba	15.8	1981
		Three Gorges	393	2003

Table 2. Continued.

Pearl River	West River	Dawangtan	5.85	1960
		Mingjiangnaban	7.02	1960
		Xijin	30	1964
		Chengbi River	11.3	1966
		Dahua	9.64	1982
		Lubuge	1.11	1988
		Yantan	33.8	1992
		Tianshengqiao	108	1997
		Baise	56	2006
		Longtan	273	2006
	North River	Nanshuir	12.43	1971
		Changhu	1.49	1973
		Jinjiang	1.9	1990
		Feilaixia	19.5	1999
	East River	Xinfengjiang	138.96	1962
		Fengshuba	19.4	1973
		Baipenzhu	12.2	1985

Where

$$r_i = \begin{cases} 1, & x_i > x_j \\ 0, & x_i \le x_j \end{cases}, \qquad j = 1, 2, \ldots, n \tag{2}$$

Assuming that the data is independent and identically distributed, the mean and variance of S_k are:

$$\begin{cases} E(s_k) = \dfrac{n(n+1)}{4} \\ \operatorname{var}(s_k) = \dfrac{n(n-1)(2n+5)}{72} \end{cases} \tag{3}$$

The normalized equation for S_k is:

$$UF_k = \frac{[s_k - E(s_k)]}{\sqrt{\operatorname{var}(s_k)}}, \qquad k = 1, 2, \ldots, n \tag{4}$$

where $UF_1 = 0$, $\alpha = 0.05$, if $|UF| > U\alpha$, indicating a significant trend change in the series. The inverse series normalization is represented by UB_k. When UF_k and UB_k have an intersection, the intersection may be a change point.

Pettitt Test

The Pettitt test is used to test an unknown change point by considering a sequence of random variables, X_1, X_2, ..., X_n, that have a change point at m. The null hypothesis, H_0: no change or $m = n$, is tested against the alternative hypothesis, H_a: change or $1 \le m < n$, using the nonparametric statistic. Where,

$$U_{t,n} = U_{t-1,n} + \sum_{j=1}^{n} \operatorname{sgn}(x_i - x_j) \quad t=2, \quad ,n$$

$$\begin{gathered} if\ x_i - x_j > 0;\ \operatorname{sgn}(x_i - x_j) = 1 \\ if\ x_i - x_j = 0;\ \operatorname{sgn}(x_i - x_j) = 0 \\ if\ x_i - x_j < 0;\ \operatorname{sgn}(x_i - x_j) = -1 \end{gathered} \tag{5}$$

$U_{t,n}$ is the statistic and *sgn* is the sign function.

Defining the statistic $K_{t,n}$ by the maximum value of the $U_{t,n}$ sequence to represent the most likely mutation point.

$$K_{t,n} = max|U_{t,n}| \qquad (1 \le t \le n) \tag{6}$$

Establishing a test statistic p to determine the significance of correlation probability mutation points:

$$p = 2e^{\frac{-6K_{t,n}^2}{n^2+n^3}} \tag{7}$$

$\alpha = 0.05$. When $p < \alpha$, the detected variant is a significant mutation [27].

Classification of Water and Sediment Variation

According to the results of the MK and Pettitt tests, the variation degree in water and sediment is classified (Table 3) [28].

Table 3. Diagnostic classification of water and sediment variation.

MK (Within 0.05 significant level) test	Pettitt test	Classification
UF intersects with UB	Exceeds the 0.01 significant level and reaches the peak	Abnormal change
	Exceeds the 0.5 significant level and reaches the peak	Significant change
	Not exceeding the 0.5 significant level	General trend change
UF does not intersect with UB	Exceeds the 0.01 significant level and reaches the peak	Abnormal change

Results

Abnormal Changes in Water and Sediment in the Yellow River

Time and Intensity of Abnormal Change

As shown in Fig. 2, in the MK test of water discharge in the Yellow River (Lijin), UF and UB intersected in 1976 at a significant level of 0.05; the value of PT in 1969-2001 exceeded the 0.5 significant level. According to the diagnostic rules, 1976 was identified as the significant change point. There was no intersection of UF and UB after 1980, while the PT value exceeded the 0.01 significant level and reached its peak in 1986. Therefore, we judged that the water discharge changed abnormally in 1986. Before the significant change, the range of water discharge from 1964 to 1976 was 706-3,085 m^3/s, with a mean value of 1,429 m^3/s (Fig. 3). Before the abnormal change, the range of water discharge from 1977 to 1986 was 499-1,556 m^3/s, with a mean value of 980 m^3/s. After the abnormal change, the range from 1987 to 2020 was 59-1,140 m^3/s, with a mean value of 531 m^3/s (Fig.3). The water discharge before the significant change is 1.5 times of that after, and it is 1.8 times that of the abnormal change (Table 4).

The result of the MK test for sediment discharge showed that there was no intersection between UF and UB within the 95% confidence interval. The value of PT from 1978 to 2007 exceeded the 0.01 significant level and reached its peak in 1997. Therefore, it was judged that the sediment t discharge in the Yellow River changed abnormally in 1997. Before the abnormal change, the sediment discharge in 1964-1997 ranged from 3,035 to 66,054 kg/s, with an average of 25,253 kg/s. However, the variation from 1998 to 2020 was 245-11,711 kg/s, with an average value of 4,645 kg/s after the abnormal change (Fig. 3). In general, the sediment t discharge before the anomaly was about 5 times that after (Table 4), and the slope of the double cumulative curve changed from 25.3 to 7.8.

Control Factors for Abnormal Changes in Water and Sediment Discharge

The differences in the temporal abnormal points of water and sediment discharges in the Yellow River may be the result of the heterogeneity of their sources and the impacts of human activities. According to the precipitation-water discharge double accumulation curve (Fig. 3), the correlation coefficients for 1964-1976, 1977-1986, and 1987-2020 were 1.85, 1.89, and 0.81, respectively, which showed the water discharge variation dominated by precipitation gave way to the influence of human activities.

Water discharge from the Yellow River into the sea is affected by the upper, middle, and lower reaches. The upstream area is high in terrain and cold in climate, and its water discharge is mainly affected by precipitation [29]. The basin below Huayuankou is a “river hanging on the ground”, whose water discharge is affected by human activities. The middle reaches flow through the Loess Plateau. Since the 1950s, the population explosion has led to a fivefold increase in water consumption in the basin, with the largest water consumption for agricultural irrigation. The annual average water consumption of the Yellow River Diversion Irrigation Area on both sides of the Ningmeng Plain is 335×10^8 m^3, accounting for 90.4% of the surface water withdrawal. And the annual average industrial water consumption is about 26.77×10^8 m^3, accounting for 7.2%. In addition, the water and soil conservation measures implemented since the 1950s have reduced the average annual water discharge of the Yellow River. The reduction in the 1960s was 7×10^8 m^3/a and increased to 32×10^8 m^3/a in the 1990s [30]. In comparison, human consumption of water resources is still greater than the interception of water discharge by water and soil conservation measures [30]. Liujiaxia, Qingtongxia, and Sanmenxia Reservoirs were built and put into operation before 1976, with a designed capacity of 225.06×10^8 m^3, which was less than the consumption of runoff by human beings. Therefore, the control factor for the significant change in 1976 was the consumption of water resources. In 1986, Longyangxia Reservoir was completed with a capacity of 247×10^8 m^3. The downstream water discharge was reduced by 60% to 70% [31], which triggered the abnormal change.

The sediment discharge of the Yellow River (Lijin) changed abnormally in 1997, which was affected by the reduction of water discharge and the implementation of water and soil conservation measures on the Loess Plateau. By 1986, Liujiaxia and Longyangxia Reservoirs were built upstream of the Yellow River, with a cumulative capacity of 310.06×10^8 m^3. Since sediment from the Yellow River into the sea originates from the Loess Plateau in the midstream, reservoirs upstream did not trigger the abnormal change in sediment discharge. Water and soil conservation measures and watershed management projects, which began in the 1950s, had a more significant impact on sediment discharge [32, 33]. Statistics showed that the average annual sediment discharge of the Yellow River was 16×10^8 T (1919-1975), and the average annual sediment reduction under the influence of water and soil conservation measures was 4.35×10^8 T. Therefore, the amount of sediment reduction was about 144×10^8 T from 1964 to 1997, accounting for 58% of the total sediment discharge at Lijin Station (2000 China River Sediment Bulletin, Ministry of Water Resources of the People's Republic of China, http://www.mwr.gov.cn/index.html). Consequently, water and soil conservation measures became the control factors for sediment discharge variation in 1997. Although Sanmenxia (1961), Wanjiazhai (1998), and Xiaolangdi Reservoir (2000) were also built in the midstream, they were not control factors for the anomaly of sediment discharge. The time of their completion does not coincide with the time of the anomaly diagnosed in this paper.

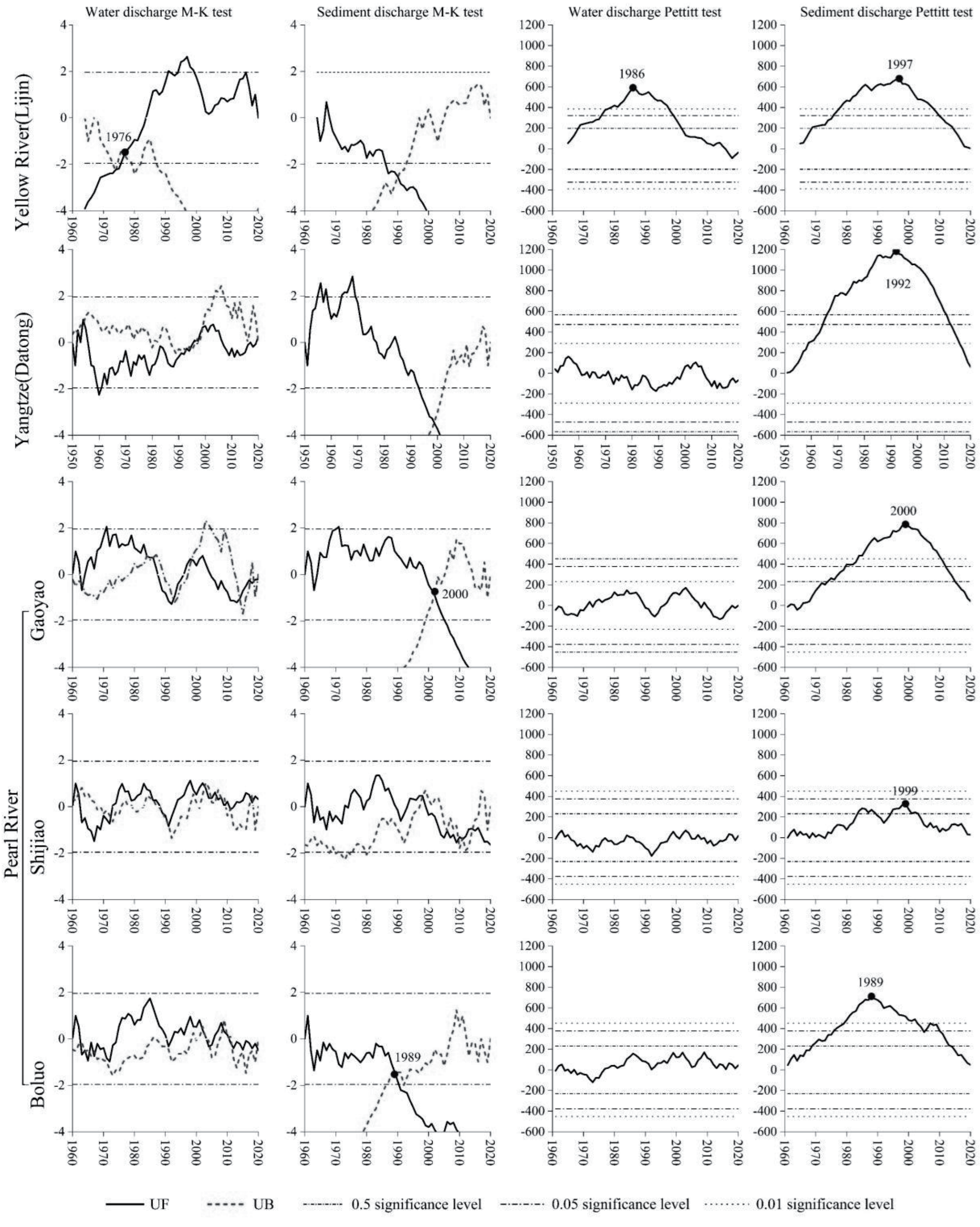

Fig. 2. M-K and Pettitt tests in water discharge and sediment t discharge of 5 hydrological stations in the Yellow River, Yangtze River, and Pearl Rivers.

Abnormal Changes in Water and Sediment in the Yangtze River.

Time and Intensity of Abnormal Change

As shown in Fig. 2, the UF and UB intersected several times at the 0.05 significant level in the MK test of water discharge in the Yangtze River (Datong), and none of the PT values exceeded the 0.5 significant level line. Therefore, the water discharge of the Yangtze River (Datong) showed a general trend variation. From 1950 to 2020, the variation range of water discharge was 21,154-43,100 m³/s, with an average value of 28,480 m³/s (Fig. 3).

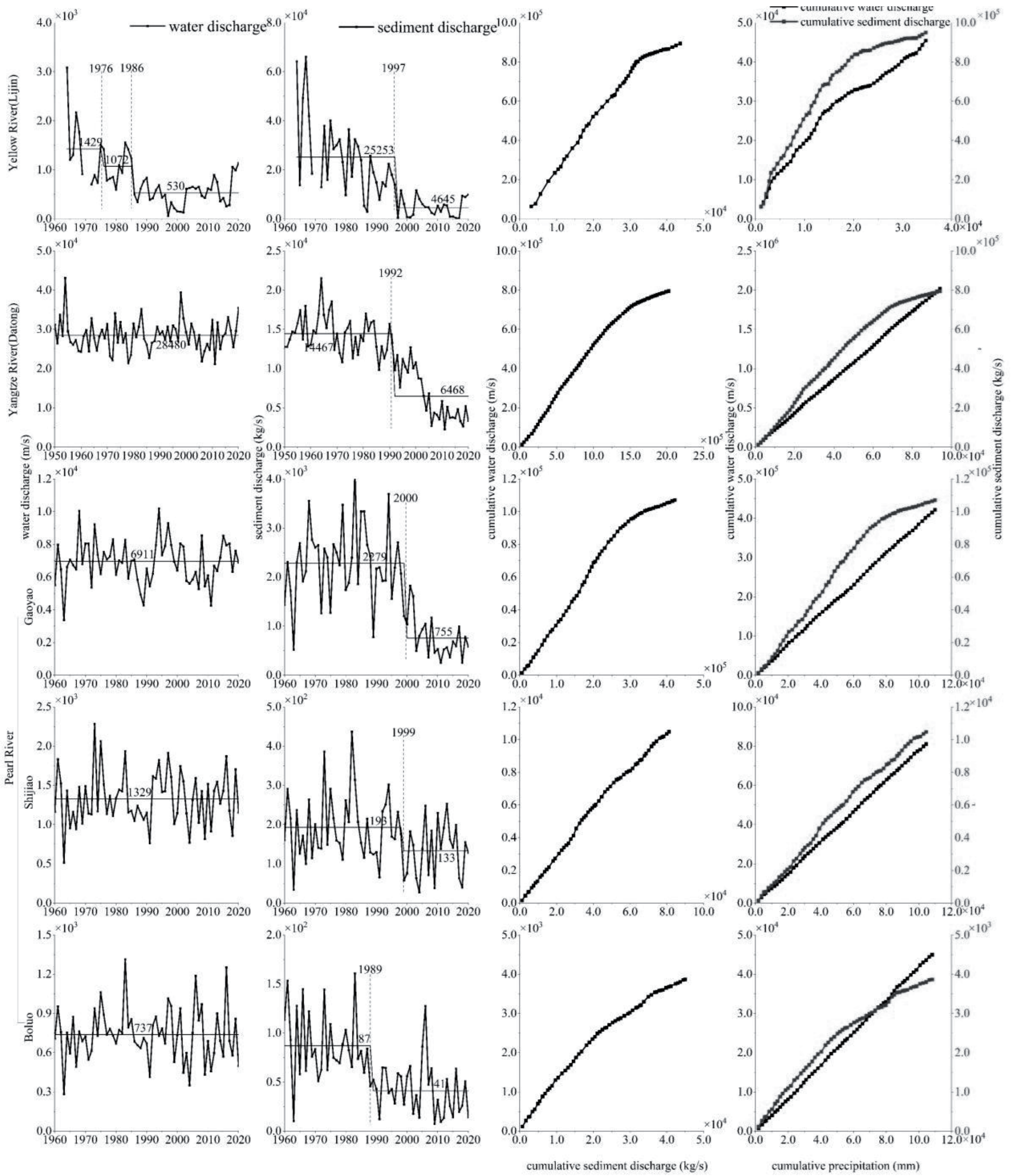

Fig. 3. Flow sediment discharge process, cumulative flow sediment discharge curve, and cumulative precipitation flow (sediment discharge) curve of 5 hydrological stations in the Yellow River, Yangtze River, and Pearl River.

In the MK test of sediment discharge, there was no intersection point between UF and UB within the 95% confidence interval. While the value of PT from 1966 to 2010 exceeded the 0.01 significant level line and reached its peak in 1992, which was determined to be the abnormal change point (Fig. 3). Before the abnormal change (1950-1992), the variation range of sediment discharge was 9,798-21,531 kg/s, with an average value of 14,359 kg/s. After the abnormal change (1993-2020), the variation range was 2,277-12,716 kg/s, with an average of 6,350 kg/s. In general. the sediment discharge before the anomaly was 2.3 times that after the anomaly (Table 4), and the slope of the double accumulation curve changed from 0.52 to 0.21.

Control Factors for Abnormal Changes in Sediment Discharge

About 22% of the sediment in global rivers was intercepted in the reservoir each year, influenced by human activities [1]. The change in sediment discharge in the Yangtze River (Datong) affected by human activities reached 97.37% [12]. Specifically, deforestation and land reclamation in the Yangtze River basin led to an increase in the surface erosion area from 350,000 km² in 1951 to 560,000 km² in 1985 [34], and the forest coverage rate decreased from 60-80% to 10% in 1986 [35]. As a result, the soil erosion area in the Yangtze River basin reached 24×10^8 T in 1980 [36]. In order to solve these problems, a key project of water and soil conservation in the upper reaches of the Yangtze River (referred to as the "Changzhi" project) has been implemented since 1989. The project mainly covered the lower reaches of the Jinsha River and Bijie area, the middle and lower reaches of the Jialing River, the south area of Gansu and Shaanxi, and the Three Gorges reservoir area. Since 1994, reserves have been expanded to the Danjiangkou Reservoir Area, Dongting Lake Water System, Poyang Lake Water System, and the southern foot of the Dabie Mountains in the middle reaches [12]. From 1999 to 2003, the project reduced soil erosion by 0.6×10^8 T/a, and the total sediment reduction from 1989 to 1992 was about 1.80×10^8 T [37, 38]. In addition, 14 reservoirs had been built on the main and tributaries of the Yangtze River with a cumulative capacity of 635.7×10^8 m³ from the 1960s to the 1990s, which intercepted 55% of sediment. Consequently, reservoirs were the control factor for the abnormal change in sediment discharge in 1992.

Abnormal Changes in Water and Sediment in the Pearl River

Time and Intensity of Abnormal Change

The characteristics of water and sediment discharges in the Pearl River were analyzed from the tributaries of the West River, North River, and East River, respectively. Firstly, there were multiple intersection nodes between UF and UB at the 0.05 significant level in the MK test for the water discharge of West River (Gaoyao), while the PT value did not exceed the 0.5 significant level line, which indicated that an abnormal change in the water discharge in West River had not occurred (Fig. 2). The range of water discharge from 1960 to 2020 was 3,367-10,198 m³/s, with an average value of 6,911 m³/s.In the MK test of sediment discharge, UF and UB intersected between 2000 and 2001 at the 0.05 significant level and the statistical value of PT from 1984 to 2010 exceeded the 0.01 significant level and reached its peak in 2000. Accordingly, 2000 was determined as the abnormal change point of the sediment discharge in the West River (Fig. 3). In general, the variation of sediment discharge before the abnormal change (1960-2000) ranged from 521 to 4,167 kg/s, with an average of 2,249 kg/s. The range after the variation (2001-2020) was 255-1,823 kg/s, with an average of 742kg/s (Fig. 3). The sediment discharge before the anomaly was about 3 times that after the anomaly (Table 4), and the slope of the double cumulative curve changed from 0.34 to 0.10.

According to the judgment criteria, the water discharge of the North River (Shijiao), showed a general variation trend. The range of variation was 515-2,280 m³/s, with an average value of 1,329m³/s (Fig. 3). In the MK test of sediment discharge, UF and UB had five intersection points. The statistical value of PT in 1984-1989 and 1995-2001 exceeded the 0.5 significant level line and reached its peak in 1999, which was identified as the significant change point. From 1960 to 1999, the sediment discharge increased slowly, with an average of 190 kg/s. After 1999, the sediment discharge decreased, with an average of 137 kg/s (Fig. 3). The sediment discharge before the significant change was about 1.4 times that after the significant change (Table 4), and the slope value of the double cumulative curve changed from 0.15 to 0.11, with a small change.

Like the West and North Rivers, the water discharge of the East River also showed a general trend. The range of variation was 284-1,313 m³/s, with an average value of 737 m³/s (Fig. 3). In the MK test of sediment discharge, UF and UB intersected in 1989 at the 0.05 significant level. The value of PT in 1980-2002 exceeded the 0.01 significant level line and reached its peak in 1989, which was identified as the abnormal change point of sediment discharge in the East River (Boluo). The range of variation before the abnormal change (1960-1989) was 10-161 kg/s, with an average of 87 kg/s. The range after the variation (1990-2020) was 7-128 kg/s, with an average of 42 kg/s (Fig. 3). In general, the sediment discharge before the anomaly was about 2 times that after the anomaly (Table 4), and the slope of the double cumulative curve changed from 0.11 to 0.06.

Control Factors for Abnormal Changes in Sediment Discharge

The sediment discharge of the Pearl River changed abnormally in 2000, which was due to reservoirs upstream [13, 14]. The sediment discharge of the West River did not change significantly before 1990 because of the balance between reservoir sediment retention and sediment increase caused by soil erosion. Statistics showed that the area of soil erosion in Guangxi Province increased from 12,000 km² in 1950-1960 to 30,600 km² in the 1980s, while that in Guangdong Province increased from 7,444 km² to 17,070 km² [39, 40]. At the same time, several reservoirs were built upstream of the West River to intercept sediment [41]. In 1992, the construction of Yantan Reservoir led to sediment deposition at a rate of 1×10^7 t/a at Gaoyao Station [42, 43]. Tianshengqiao Reservoir was built in 1997 with a capacity 3 times that of Yantan Reservoir, which directly led to the abnormal change in sediment discharge in 2000. In addition, Longtan Reservoir was completed in 2006, with a capacity of about 2.5 times that of Tianshengqiao Reservoir. However, since Tianshengqiao Reservoir intercepted a large amount of sediment upstream, Longtan Reservoir downstream only played a role in maintaining the basic stability of water and sediment [44, 45].

In 1999, the sediment discharge of the North River changed significantly, which was affected by the Feilaixia Dam (with a storage capacity of about 20×10^8 m³). Since the mid-1980s, the forest coverage of the North River has increased from 73% to 77% [46], and has been affected by the policy of water and soil conservation. Although the increased forest land could reduce the sediment discharge, its impact was far less than that of the dam. It is noteworthy that sand excavation in the North River also reduced sediment; however, the impact of these activities that occurred from 2003-2014 is not significant. The impact of sand excavation activities from 2003 to 2014 was not significant. Thus, the control factor for the significant change in sediment discharge in the North River is the Feilaixia Dam.

Since the 1960s, Xinfengjiang Reservoir (1962), Fengshuba Reservoir (1973), and Baipenzhu Reservoir (1985) have been built upstream of the East River, which guarantees the stability of the water and sediment discharge [41]. However, with the implementation of projects such as the treatment of mountains and rivers, the development of "four wastelands", and the return of farmland to forests in the 1990s, vegetation coverage increased from 30% to 65% [47]. Although sand excavation would also reduce the sediment discharge, large-scale dredging occurred in the East River from 1998 to 2008, which was less related to the abnormal change in sediment discharge in 1989 [45]. In general, the control factors for the abnormal change in sediment discharge in the East River in 1989 were water and soil conservation measures.

On the whole, water discharge in the Pearl River showed a general trend change, while sediment discharge was different. Specifically, the West River and North River changed abnormally and significantly in 2000 and 1999, respectively, and were influenced by dams and reservoirs. The East River changed abnormally in 1989, and the control factor was the promotion of water and soil conservation measures.

Discussion

In this paper, the water and sediment discharges of 5 hydrological stations in the Yellow River, Yangtze River, and Pearl River were diagnosed by a unified method, which basically solved the problem of differences in the results caused by different data time series, stations, and analysis methods. Most importantly, the characteristics and control factors were compared, which supplemented the deficiencies of previous studies.

Differences in Time and Intensity of Water-Sediment Anomalies in Three Rivers

The meaning of a water-sediment anomaly is that water and sediment discharges are significantly reduced due to large events. Our results showed that the water and sediment discharge in the Yellow River changed abnormally, while only the sediment discharge in the Yangtze River and Pearl River changed abnormally. The time of water discharge change in the Yellow River coincided with the reform and opening up of China, which indicated that it was significantly affected by extensive human activities (Fig. 4). As the Yellow River flows through agricultural areas such as the Loess Plateau and the North China Plain, a large amount of water is consumed by agriculture, industry, and humans, which led to significant change in 1976. Furthermore, the joint regulation of Longyangxia Reservoir and Liujiaxia Reservoir caused the water discharge of the Yellow River to change abnormally in 1986. In addition, the time of change in sediment discharge of the three rivers was concentrated in 1990-2000, which corresponded to the construction of reservoirs and the effective time of water and soil conservation projects (Table 3).

The intensity of water-sediment varied significantly due to the difference between the natural environment and human activities. Chu et al. believed that human activities led to a total reduction of 500×10^8 T of sediment in China's nine major rivers from 1959 to 2007, of which dams and reservoirs had the most significant impact, about 280×10^8 T, followed by water and soil conservation projects, about 115×10^8 T [48, 49]. Our findings are similar to this. Generally, the reservoir capacity designed according to the actual situation has a significant effect on the interception of water and sediment. For example, the water discharge of the Yellow River and the sediment discharge of the Yangtze River and Pearl River before the abnormal change were

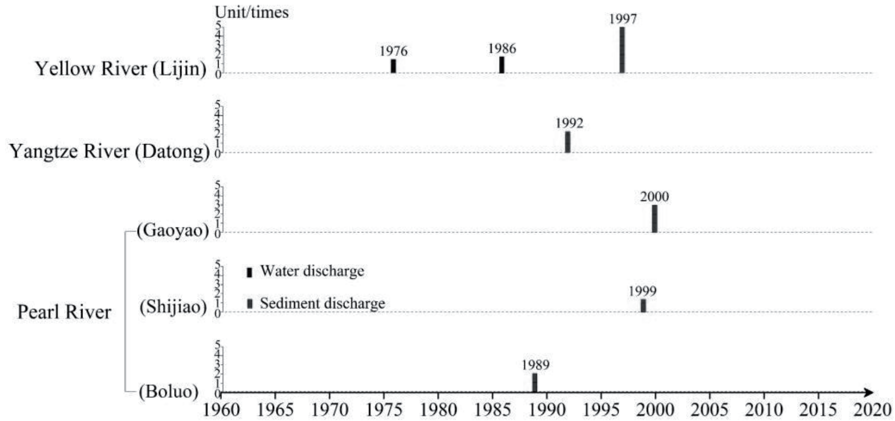

Fig. 4. Differences in water and sediment variability in the Yellow River, Yangtze River, and Pearl River.

1.8, 2.3, and 3 times that after the abnormal change, respectively. While the effect of the water and soil conservation projects was not obvious because of the uncertainty of natural environments. It was noteworthy that the intensity of sediment discharge at Lijin Station on the Yellow River (before the variation (1964-1997) was 5 times that after the variation (1998-2020)) (Fig. 4). The reason was that serious soil erosion on the Loess Plateau resulted in a higher sediment content base in the Yellow River than in the two other rivers.

Differences in Factors of Water-Sediment Anomaly in Three Rivers

According to our results, the water discharge of the Yellow River changed significantly and abnormally in 1976 and 1986, respectively, while the Yangtze River and Pearl River showed general trend changes (Table 4). It was related to the climate types and the differences in the underlying surface. First of all, the Yellow River is located in the arid zone with an average annual precipitation of 615mm, while the Yangtze River and Pearl Rivers are located in the humid zone with an average annual precipitation of 1,325mm and 1,761mm, respectively. Affected by precipitation and other factors, the water discharge of the Yellow River (Lijin) is only 1/36 of that of the Yangtze River (Datong) and 1/11 of the Pearl River (Gaoyao+Shijiao+Boluo). Thus, the smaller base water discharge of the Yellow River led to a more sensitive variation [2, 50]. Then, the growth of population, cultivated land, and GDP in the Yellow River basin consumed a lot of water [51]. Most of the farmland in the Yangtze River and Pearl River is paddy; the increase in the irrigation area and water consumption didn't lead to a significant reduction in water discharge. On the contrary, due to the progress of urbanization, soil compaction, and crusting have reduced infiltration rates and soil water storage content. The naturally permeable ground becomes an impermeable hard ground surface after ground hardening and the impermeable area increases greatly, adding to the surface flow [52-54]. In addition, reservoirs led to an increase in evaporation

Table 4. Variation of water and sediment in the Yellow River, Yangtze River, and Pearl River.

		Water discharge				Sediment discharge			
		Type	Time	Intensity	Reason	Type	Time	Intensity	Reason
Yellow River		Significant change	1976	1.5 times	Human consumption	Abnormal change	1997	5 times	Water and soil conservation
		Abnormal change	1986	1.8 times	Longyangxia Reservoir				
Yangtze River		General trend change	—	—	—	Abnormal change	1992	2.3 times	Reservoirs
Pearl River	West River	General trend change	—	—	—	Abnormal change	2000	3 times	Yantan Reservoir (1992) Tianshengqiao Reservoir (1997)
	North River		—	—	—	Significant change	1999	1.4 times	Feilaixia Dam (1999)
	East River		—	—	—	Abnormal change	1989	2 times	Water and soil conservation

in the Yellow River basin, which reduced water discharge. However, it was different in the Yangtze River and Pearl River, where water discharge increased due to the reduction of forest and the weakening of the water interception effect of the forest canopy. Although reservoirs would increase evaporation, the effect of forest canopy throttling on the increase in water discharge was more significant due to the influence of the humid climate [2]. In general, the differences in climate as well as basin substrate conditions led to significant changes in the water discharge of the Yellow River.

The sediment discharge of the Yangtze River (Datong), West River (Gaoyao), and North River (Shijiao) changed significantly due to reservoirs and dams, while the Yellow River (Lijin) and East River (Boluo) were significantly affected by water and soil conservation [55]. Specifically, erosion caused by the Loess Plateau accounted for 89.15% of the Yellow River basin. Reservoirs such as Longyangxia and Liujiaxia had intercepted 32% of the sediment by 1997, which was less than the sediment intercepted by water and soil conservation measures (58%). Therefore, water and soil conservation measures were control factors for the abnormal sediment discharge of the Yellow River. Unlike the Yellow River basin, more than 50,000 reservoirs and dams have been built in the Yangtze River basin since the 1950s, with a total capacity of more than $3,600\times10^8$ m^3, which intercepted a lot of sediment [56]. Water and soil conservation measures that started in 1989 have only intercepted a small amount of sediment (1.8×10^8 T by 1992), which was less than reservoirs (55%). In addition, the abnormal change in sediment discharge in the West River and North River was affected by the Yantan Reservoir (1992), Tianshengqiao Reservoir (1997), and Feilaixia Dam (1999); however, the significant change in sediment discharge in the East River was influenced by vegetation coverage.

Comparison of Water-Sediment Anomalies from Other Regions of the World

Our research found that sediment changes in the Yellow River, Yangtze River, and Pearl River were strongly affected by human activities, which might lead to both an increase and a decrease in sediment yield. Similar to the results, Degens et al. found that sediment in the Black Sea had increased by three times over the past 20,000 years, which was caused by deforestation and agricultural development [57, 58]. The interception effect of reservoirs on river sediment led to annual sediment transport to the Nile Delta dropping from 10^8t to almost zero. In addition, five dams built in the Missouri River basin in North America from 1953 to 1963 led to a 3/4 reduction of water entering the Mississippi River. In 1984, the sediment in the estuary was less than half of that before 1953 [59, 60]. Meade and Moody also found that sediment discharge in the Mississippi River decreased by 75% from 1940 to 2007, which was influenced by dams and soil conservation measures [5, 61]. In addition, the sediment of the Danube River had been reduced by 60-70% due to the interception of the Iron Gate Dam [4, 62]. The sediment capacity of the Mekong River in Asia also decreased by 5% annually, which was mainly affected by hydropower development [6, 7, 63-66].

To sum up, the variation characteristics of water and sediment discharges in three rivers in China are similar to those in other estuaries of the world, and the variation of water discharge is smaller than that of sediment discharge. The control factor for the variation was human activity. For example, land development increased sediment, while reservoirs could intercept sediment. The natural environment leads to differences in the extent and timing of human activities on sediment discharge. The variation of three rivers in China was concentrated from the 1990s to the 21st century, while that of other estuaries in the world was concentrated from the 1970s to the 1980s.

Conclusions

We unified the Mann-Kendall test, the Pettitt test, and the double cumulative curve to divide the water and sediment discharges into three levels: abnormal, significant, and general trend changes. The water discharge of the Yellow River changed significantly in 1976 and abnormally in 1986, while the Yangtze River and Pearl River showed a general trend change. The control factors for the variation in the Yellow River were water consumption in agriculture and industry at midstream and upstream and the construction of Longyangxia Reservoir, respectively. In comparison, the Yellow River was influenced by temperate climate types, whose water discharge was more susceptible to human activities and other external factors.

For the sediment discharge, except for the North River, where only significant changes occurred, the other four rivers had abnormal changes from 1990 to 2000. There are two control factors for the variation: one is the sediment regulation function after the completion of hydraulic facilities and the other is the sediment retention function of vegetation after the promotion of water and soil conservation. Among them, the variation rate of sediment discharge is more significant than that of water and soil conservation projects due to the clear design of reservoir capacity and the stable impact process of hydraulic projects. During the ten years (1990-2000) affected by water and soil conservation, sand mining, and dam construction, the intensity after sediment abnormal change is around 5 times that before the abnormal change in the Yellow River, while the intensity is only 2-3 times in the Yangtze River and Pearl River. The Yellow River shows higher vulnerability to water and sediment changes than the other two rivers, which need to be carefully protected for sustainable use in the future.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. SYVITSKI J.P.M., VÖRÖSMARTY C.J., KETTNER A.J., GREEN P. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science, **308** (5720), 376, **2005**.
2. WANG Y., DING Y., YE B., LIU F., WANG J., WANG J. Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. Science China-Earth Sciences, **56** (8), 1398, **2013**.
3. MILLIMAN J.D. Delivery and fate of fluvial water and sediment to the sea: a marine geologist's view of European rivers. Scientia Marina, **65**, 121, **2001**.
4. PANIN N., JIPA D. Danube River sediment input and its interaction with the north-western Black Sea. Estuarine Coastal and Shelf Science, **54** (3), 551, **2002**.
5. MEADE R.H., MOODY J.A. Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940-2007. Hydrological Processes, **24** (1), 35, **2010**.
6. LOISEL H., MANGIN A., VANTREPOTTE V., DESSAILLY D., DINH D.N., GARNESSON P., OUILLON S., LEFEBVRE J.-P., MéRIAUX X., PHAN T.M. Variability of suspended particulate matter concentration in coastal waters under the Mekong's influence from ocean color (MERIS) remote sensing over the last decade. Remote Sensing of Environment, **150**, 218, **2014**.
7. MANH N.V., DUNG N.V., HUNG N.N., KUMMU M., MERZ B., APEL H. Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. Global and Planetary Change, **127**, 22, **2015**.
8. SAITO Y., CHAIMANEE N., JARUPONGSAKUL T., SYVITSKI J.P.M. Shrinking megadeltas in Asia sea-level rise and sediment reduction impacts from case study of the Chao Phraya Delta. Land-Ocean Interactions in the Coastal Zone (LOICZ), **2** (39), 169, **2007**.
9. LIU F., YANG Q., CHEN S., LUO Z., YUAN F., WANG R. Temporal and spatial variability of sediment flux into the sea from the three largest rivers in China. Journal of Asian Earth Sciences, **87**, 102, **2014**.
10. CHU Z., LI Y., LI B. Human impacts could affect natural periodicity of river runoff entering the sea. Journal of Coastal Research, 369, **2015**.
11. WANG J., SHI B., BA Y. Evolution characteristics of runoff and sediment fluxes of Yellow River into Bohai Sea in recent 70 years. Research of Soil and Water Conservation, **27** (3), 57, **2020**.
12. PENG T., TIAN H., QIN Z., WANG G. Impacts of climate change and human activities on flow discharge and sediment load in the Yangtze River. Journal of Sediment Research, **43** (6), 54, **2018**.
13. LIU F., HU S., GUO X., LUO X., CAI H., YANG Q. Recent changes in the sediment regime of the Pearl River (South China): Causes and implications for the Pearl River Delta. Hydrological Processes, **32** (12), 1771, **2018**.
14. LIU F., YUAN L., YANG Q., OU S., XIE L., CUI X. Hydrological responses to the combined influence of diverse human activities in the Pearl River delta, China. Catena, **113**, 41, **2014**.
15. LIU Z., FAGHERAZZI S., LIU X., SHAO D., MIAO C., CAI Y., HOU C., LIU Y., LI X., CUI B. Long-term variations in water discharge and sediment load of the Pearl River Estuary: Implications for sustainable development of the Greater Bay Area. Frontiers in Marine Science, **9**, **2022**.
16. WANG J., SHI B., ZHAO E., YUAN Q., CHEN X. The long-term spatial and temporal variations of sediment loads and their causes of the Yellow River Basin. Catena, **209, 2022**.
17. XU M., WANG G., WANG Z., HU H., SINGH D.K., TIAN S. Temporal and spatial hydrological variations of the Yellow River in the past 60 years. Journal of Hydrology, **609**, **2022**.
18. CHANG J., LI Y., WEI J., WANG Y., GUO A. Dynamic changes of sediment load and water discharge in the Weihe River, China. Environmental Earth Sciences, **75** (12), **2016**.
19. WEI Y., JIAO J., ZHAO G., ZHAO H., HE Z., MU X. Spatial-temporal variation and periodic change in streamflow and suspended sediment discharge along the mainstream of the Yellow River during 1950-2013. Catena, **140**, 105, **2016**.
20. XIAO H., ZHANG J. Multi-temporal relations between runoff and sediment load based on variable structure cointegration theory. International Journal of Sediment Research, **38** (2), 216, **2023**.
21. LI B., WANG Y. Dynamics of sediment transport in the Yangtze River and their key drivers. Science of the Total Environment, **862**, **2023**.
22. DAI Z., FAGHERAZZI S., MEI X., GAO J. Decline in suspended sediment concentration delivered by the Changjiang (Yangtze) River into the East China Sea between 1956 and 2013. Geomorphology, **268**, 123, **2016**.
23. ZHOU H., WANG Z., WU X., CHEN Y., ZHONG Y., LI Z., CHEN J., LI J., GUO S., CHEN X. Spatiotemporal variation of annual runoff and sediment load in the Pearl River during 1953-2017. Sustainability, **11** (18), **2019**.
24. WAN J. Characteristics of water and sediment variation of main streams in Xijiang River basin in recent years. Port & Waterway Engineering, (6), 120, **2020**.
25. MILLIMAN J.D., SYVITSKI J.P.M. Geomorphic tectonic control of sediment discharge to the ocean - the importance of small mountainous rivers. Journal of Geology, **100** (5), 525, **1992**.
26. NURWANDA A., ZAIN A., RUSTIADI E. Analysis of land cover changes and landscape fragmentation in Batanghari Regency, Jambi Province. Procedia - Social Behavioral Sciences, **227**, 87, **2016**.

27. TIAN X., ZHAO G., MU X., HU J. Comparison study on hydrological time series change-point testing methods. Journal of Sediment Research, **44** (2), 33, **2019**.
28. WANG Y., PENG J., HUANG C., WU H., CAI S., LIU F. Abnormal changes diagnosis and its control factors of water and sediment discharge in the lower reaches of Pearl River Basin from 1960 to 2019. Research of Soil and Water Conservation, **29** (5), 21, **2022**.
29. CUO L., ZHANG Y., GAO Y., HAO Z., CAIRANG L. The impacts of climate change and land cover/use transition on the hydrology in the upper Yellow River Basin, China. Journal of Hydrology, **502**, 37, **2013**.
30. SHI C., ZHOU Y., FAN X., SHAO W. A study on the annual runoff change and its relationship with water and soil conservation practices and climate change in the middle Yellow River basin. Catena, **100**, 31, **2013**.
31. REN H., LI G., CUI L., HE L. Phases and periodic changes of water discharge and sediment load from the Yellow River to the Bohai Sea during 1950-2011. Acta Geographica Sinica, **69** (5), 619, **2014**.
32. WALLING D.E. Erosion and sediment yield : global and regional perspectives. Iahs Publication, **236**, **1996**.
33. ZHAO G., TIAN P., MU X., JIAO J., WANG F., GAO P. Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin, China. Journal of Hydrology, **519** 387, **2014**.
34. YANG S.L., XU K.H., MILLIMAN J.D., YANG H.F., WU C.S. Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes. Scientific Reports, **5**, 12581, **2015**.
35. ZHANG S., ZHU C. Soil loss and its effect on flooding catastrophe in Yangtze drainage basin. Journal of Soil and Water Conservation, **15** (6), 9, **2001**.
36. LIAO C., HAN F., FENG M. Construction achievement and experience of soil and water conservation. Yangtze River, **41** (13), 16, **2010**.
37. XU K., MILLIMAN J.D., YANG Z., WANG H. Yangtze sediment decline partly from Three Gorges Dam. Eos Transactions American Geophysical Union, **87** (19), 185, **2006**.
38. YANG Z., WANG H., SAITO Y., MILLIMAN J.D., XU K., QIAO S., SHI G. Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam. Water Resources Research, **42** (4), W04407, **2006**.
39. XIA H. Flood disasters soil erosion and eco-restoration of vegetation in the Yangtze and the Pearl River valleys. Tropical Geography, **19** (2), 124, **1999**.
40. PAN J. Review and expectation of water and soil conservation in Guangxi. GX Water Resources & Hydropower Engineering, (B11), 47, **2004**.
41. WU C., JI C., SHI B., WANG Y., GAO J., YANG Y., MU J. The impact of climate change and human activities on streamflow and sediment load in the Pearl River basin. International Journal of Sediment Research, **34** (4), 307, **2019**.
42. DAI S., YANG S., AIMIN C.A.I. Variation of sediment discharge of the Pearl River Basin from 1955 to 2005. Acta Geographica Sinica, **62** (5), 545, **2007**.
43. WU C., YANG S., LEI Y. Quantifying the anthropogenic and climatic impacts on water discharge and sediment load in the Pearl River (Zhujiang), China (1954-2009). Journal of Hydrology, **452**, 190, **2012**.
44. NI P., WEN P., LIU J. Study on variation of annual water discharge and sediment load in Pearl River Delta. Pearl River, **37** (1), 19, **2016**.
45. WANG Y., CAI S., YANG Y., ZHONG Z., LIU F. Morphological consequences of upstream water and sediment changes and estuarine engineering activities in Pearl River Estuary channels over the last 50 years. Science of the Total Environment, **765**, 16, **2021**.
46. TAN C., HUANG B., LIU K., CHEN H., LIU F., QIU J., YANG J. Using the wavelet transform to detect temporal variations in hydrological processes in the Pearl River, China. Quaternary International, **440**, 52, **2017**.
47. LI N., WANG D. Water rights transaction practice in Dongjiang River Basin-Take interregional water rights trading as an example between Huizhou and Guangzhou. Guangdong Water Resources and Hydropower, (12), 1, **2018**.
48. CHU Z., ZHAI S., LU X., LIU J., XU J., XU K. A quantitative assessment of human impacts on decrease in sediment flux from major Chinese rivers entering the western Pacific Ocean. Geophysical Research Letters, **36**, 5, **2009**.
49. WANG H.J., WU X., BI N.S., LI S., YUAN P., WANG A.M., SYVITSKI J.P.M., SAITO Y., YANG Z.S., LIU S.M., NITTROUER J. Impacts of the dam-orientated water-sediment regulation scheme on the lower reaches and delta of the Yellow River (Huanghe): A review. Global and Planetary Change, **157**, 93, **2017**.
50. FRIEDRICHS-MANTHEY M., LANGHANS S.D., BORGWARDT F., HEIN T., KLING H., STANZEL P., JAEHNIG S.C., DOMISCH S. Three hundred years of past and future changes for native fish species in the upper Danube River Basin-Historical flow alterations versus future climate change. Diversity and Distributions, **30**, e13808, **2024**.
51. MIAO J., ZHANG X., ZHAO Y., WEI T., YANG Z., LI P., ZHANG Y., CHEN Y., WANG Y. Evolution patterns and spatial sources of water and sediment discharge over the last 70 years in the Yellow River, China: A case study in the Ningxia Reach. Science of the Total Environment, **838**, 12, **2022**.
52. LI J., LIANG Z., GAO Z., LI Y. Experiment and simulation of the purification effects of multi-level series constructed wetlands on urban surface runoff. Ecological Engineering, **91**, 74, **2016**.
53. ARAGAW H.M., GOEL M.K., MISHRA S.K. Hydrological responses to human-induced land use/land cover changes in the Gidabo River basin, Ethiopia. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, **66** (4), 640, **2021**.
54. LI H., YU C., QIN B., LI Y., JIN J., LUO L., WU Z., SHI K., ZHU G. Modeling the effects of climate change and land use/land cover change on sediment yield in a large reservoir basin in the east Asian monsoonal region. Water, **14** (15), **2022**.
55. XU J., DING W., LIN Q. Characteristics analysis of runoff and sediment variation in Danjiang River watershed. Resources and Environment in the Yangtze Basin, **28** (8), 1956, **2019**.
56. HUANG D., LI H., LIAN W., LIU H., XU L. Variations in runoff and sediment load in middle and lower Beijiang River and impacts of cascade reservoirs. Journal of Hydroelectric Engineeringm, **38** (1), 86, **2019**.
57. DEGENS E.T., KEMPE S., RICHEY J.E. Summary: Biogeochemistry of major world rivers (SCOPE 42), **42**, 323, **1991**.

58. LI S., XU J., NI M. Changes in sediment, nutrients and major ions in the world largest reservoir: Effects of damming and reservoir operation. Journal of Cleaner Production, **318**, **2021**.
59. WU W., WANG R., PENG W., LI S. Sediment management of dams removal in the United States. Journal of Sediment Research, (2), 76, **2016**.
60. SHELLEY J., HOTCHKISS R.H., BOYD P., GIBSON S. Discharging sediment downstream: case studies in cost effective, environmentally acceptable reservoir sediment management in the United States. Journal of Water Resources Planning and Management, **148** (2), **2022**.
61. YIN S., GAO G., LI Y., XU Y.J., TURNER R.E., RAN L., WANG X., FU B. Long-term trends of streamflow, sediment load and nutrient fluxes from the Mississippi River Basin: Impacts of climate change and human activities. Journal of Hydrology, **616**, **2023**.
62. VAS L., TAMAS E.A. Surrogate method for suspended sediment concentration monitoring on the Alluvial reach of the River Danube (Baja, Hungary). Applied Sciences-Basel, **13** (10), **2023**.
63. DANG THI H., OUILLON S., GIAP VAN V. Water and suspended sediment budgets in the lower Mekong from high-frequency measurements (2009-2016). Water, **10** (7), **2018**.
64. SOK T., OEURNG C., ICH I., SAUVAGE S., MIGUEL SANCHEZ-PEREZ J. Assessment of hydrology and sediment yield in the Mekong River Basin using SWAT model. Water, **12** (12), **2020**.
65. GUAN Q., FENG L., TANG J., PARK E., ALI T.A., ZHENG Y. Trends in river total suspended sediments driven by dams and soil erosion: A comparison between the Yangtze and Mekong rivers. Water Resources Research, **58** (10), **2022**.
66. TRUONG THAO S., DAO NGUYEN K. The responses of river discharge and sediment load to historical land-use/land-cover change in the Mekong River Basin. Environmental Monitoring and Assessment, **194** (10), **2022**.