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Article

Differential Changes in Water and Sediment Transport Under the Influence of Large-Scale Reservoirs Connected End to End in the Upper Yangtze River

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Abstract

The analysis of changing trends of river runoff and sediment discharge and the exploration of their causes are of great significance for formulating sustainable development measures for river basin systems. Based on methods such as trend test, mutation detection, and regression analysis, this study conducts a systematic comparative research on the water-sediment processes in the river reach where large-scale cascaded reservoirs connected end to end are located in the upper Yangtze River, and obtains the following key research progress: For the study reach (between Sanduizi and Xiangjiaba Stations) during the period of 1966–2023, the change rates of annual incoming and outgoing runoff were $2.88 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$ and $-0.186 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$ respectively, accounting for 0.017% and 0.013% of the annual average runoff. The changing trends were not significant. During the same period, the change rates of suspended sediment load (SSL) at the inlet and outlet of this river reach were $-8.0 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ and $-46 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ respectively, accounting for 1.25% and 2.45% of their respective annual average sediment discharge. The SSL showed a significant decreasing trend, which was particularly characterized by a sharp reduction at the outlet. The massive sediment retention and multi-mode operation of cascaded reservoirs are the fundamental reasons for the variation of the water-sediment relationship and the sharp decrease in annual SSL in this reach, and they also lead to an obvious adjustment of water and sediment in the river basin that “cuts peaks and fills valleys” within a year. Climate change and other human activities have reduced the sediment input in the study reach. Looking forward to the next few decades, climate factors will remain the dominant factor affecting the inter-annual variation of runoff in the study area. In contrast, human activities such as reservoir operation will continue to fully control the sediment output of the river reach and also restrict the annual distribution of water and sediment. The results of this study can provide a reference for predicting the changing trends of water and sediment in similar river reaches with cascaded reservoir groups and formulating effective river management measures.

Keywords: runoff; suspended-sediment load; changing trend; influencing factor; cascade reservoirs; upper Yangtze River

1. Introduction

As transport channels for terrestrial water and sediment, rivers exhibit periodic fluctuations in their runoff and sediment transport, often in response to climate variability. With the intensification of global changes and the growing impact of human activities, these patterns of river water and sediment undergo profound alterations, manifested as either enhanced trends or abrupt changes. A sudden reduction in river runoff exerts significant negative effects on riparian ecosystems, navigation, and agricultural irrigation. Conversely, a substantial increase elevates flood control risks

and may even trigger direct flood disasters [1–3]. A marked decrease in river sediment transport typically lowers the sediment concentration of the flow; such unsaturated sediment-laden flow causes severe erosion in alluvial channels of the middle and lower reaches of river basins, frequently leading to bank collapse and increased chances of bank breaching. In contrast, a significant increase in river sediment results in heavy sedimentation in channels with gentle slopes, which in turn makes the channels wider and shallower. This is unfavorable for flood conveyance, thereby raising the risk of flood disasters [4]. Evidently, abrupt or trending changes in river water and sediment pose a severe threat to the lives and property of residents along the riverbanks. Therefore, analyzing the variation characteristics of river runoff and sediment transport and exploring their causes hold great practical significance for environmental protection, flood control safety, economic development, and social stability within river basin systems [3].

Originating from the Qinghai-Tibet Plateau, the “Third Pole of the World,” the upper reaches of the Yangtze River feature a large riverbed drop and abundant discharge, boasting enormous hydropower generation potential. Consequently, this section has become a renowned clean energy production corridor not only for the Yangtze River Basin but also globally. Five giant dams, including the Three Gorges Dam, have been built on an 1,800-kilometer-long river reach in the upper reaches of the Yangtze River, and the storage capacities of these reservoirs all rank within the top 11 in the world. These reservoirs, with a total storage capacity of $86.75 \times 10^9 \text{ m}^3$ and a total annual power generation of $295.9 \times 10^9 \text{ kWh}$ (in 2024), form the “Capital of Artificial Reservoirs” and a clean energy production corridor in the upper Yangtze River. Their total installed hydropower capacity exceeds $71.595 \times 10^6 \text{ kW}$, accounting for approximately 18.5% of the total installed hydropower capacity in mainland China. It is thus clear that the giant cascade reservoirs in the upper Yangtze River play an irreplaceable role in clean energy production, reducing greenhouse gas emissions, facilitating navigation, promoting economic development, and improving the ecological environment. Their massive water storage capacity provides crucial support for flood control safety in the middle and lower reaches of the Yangtze River, while the operation of these reservoirs also exerts a profound impact on water allocation in the downstream channels of the dams and the erosion and sedimentation processes of the riverbeds.

A series of studies have shown that the construction and operation of the Three Gorges Reservoir exert a significant seasonal regulation effect on runoff, characterized by “cutting peaks and filling valleys” [3,5,6], while also causing extensive sedimentation within the reservoir area [7]. This heavy sedimentation in the Three Gorges Reservoir leads to a substantial reduction in sediment transport in the downstream channels of the dam [8,9]. This new modified regime of water and sediment processes triggers significant adjustments in downstream channels, such as riverbed scouring, channel sedimentation, and main stream migration [10–12]. Sediment trapping by the dam, which reduces sediment transport, even affects sedimentation processes at the river estuary [13]. All these new changes in hydrology and geomorphology present new challenges for flood control efforts.

Compared to the Three Gorges Dam, which was completed in 2003, four giant cascade reservoirs (Wudongde, Baihetan, Xiluodu, and Xiangjiaba; see Figure 1 and Table 1) have been successively built between 2012 and 2021 along a 1,020-kilometer stretch upstream of the Three Gorges Reservoir, with their reservoirs connected end-to-end. Their total storage capacity ($45.868 \times 10^9 \text{ m}^3$) is approximately 1.17 times that of the Three Gorges Reservoir, and their total power generation in 2024 ($195.59 \times 10^9 \text{ kWh}$) is even 2.36 times that of the Three Gorges Hydropower Station. While these cascade hydropower stations generate economic, social, and ecological benefits, they also exert a significant impact on the water and sediment processes of this river section. Several studies have preliminarily revealed the influence of specific dams in the study area on water and sediment processes. A series of research works have focused on the Xiangjiaba Dam—the first completed and the most downstream dam in the study area—whose extensive sediment trapping effect has caused a sharp decline in sediment transport below this river section [4,14,15]. This result has significantly reduced the sediment input into the Three Gorges Reservoir downstream [14,16,17] and triggered differential adjustments in the geomorphology of the middle and lower reaches of the Yangtze River

[12]. Some scholars have conducted preliminary studies on the sediment trapping extent, sedimentation characteristics, or changes in downstream sediment flux of individual reservoirs within this cascade reservoir group. For example, research has been carried out on the sedimentation characteristics of the Xiluodu Reservoir [18,19] and the multi-source nature of sediment deposited in the Baihetan Reservoir [20]. The findings of Li et al. [21] indicate that in the early stage after the completion of the Baihetan Dam, the sediment deposited in the reservoir was mainly derived from sediment inflow from the basin, supplemented by sediment generated from gravitational erosion processes—such as sliding and collapse of the bank slopes in the reservoir’s drawdown zone. However, two years later, the bank slopes stabilized [21], leading to a significant reduction in sediment inflow into the reservoir caused by gravitational erosion. Wang [22] identified the variation characteristics of sedimentation rates in the Xiluodu and Xiangjiaba Reservoirs within the study area, and based on this, further analyzed the changing trend of the longitudinal slope of the reservoir channels in response to sedimentation [23]. The aforementioned studies, along with others, have provided diverse insights into the changes in water and sediment and the geomorphic responses induced by large-scale cascade reservoirs in the upper Yangtze River. Nevertheless, there remains a lack of systematic research on the patterns and mechanisms through which these reservoirs synergistically influence the water and sediment processes of the river section.

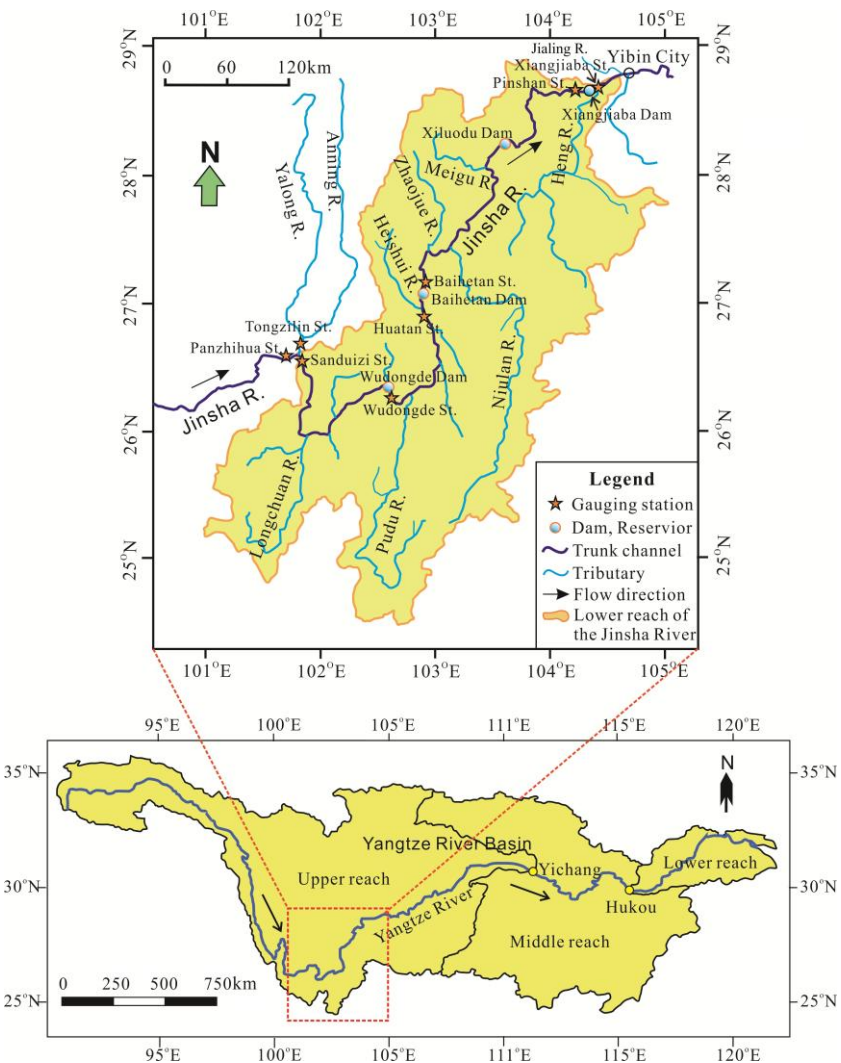


Figure 1. Location map of cascade reservoirs connected end to end and hydrological gauging stations in the upper Yangtze River.

Table 1. Main parameters of completed cascade reservoirs in the study area.

Reservoirs	Initial storage	Controlled basin area (10 ⁵ km ²)	Storage Capacity (10 ⁹ m ³)	Regulating capacity (10 ⁹ m ³)	Installed capacity (GW)	Global ranking
Wudongde	Jan. 2020	4.068	7.408	3.0	10.2	7
Baihetan	Apr. 2021	4.303	20.627	10.4	16.0	2
Xiluodu	May 2013	4.544	12.670	6.46	13.9	4
Xiangjiaba	Oct. 2012	4.588	5.163	0.903	6.4	11
Sum			45.868	20.763	46.5	

To address this gap in current research, this study analyzes how the large-scale, end-to-end cascade reservoirs in the upper Yangtze River synergistically influence or constrain the mechanisms of water and sediment changes in the study area, based on the latest observational data covering the period after the completion of these cascade reservoirs. The main objectives of this study are as follows: (1) To explore the trending variation characteristics of water and sediment at the river section scale by examining the long-term variation trends of inflow and outflow runoff and sediment transport in the study reach over the past nearly 60 years; (2) To compare the different impacts of the existing reservoirs on water and sediment processes during different periods—before, during, and after dam construction—based on the shorter time scales of the reservoir group’s construction period and the periods preceding and following it; (3) To reveal the mechanisms through which large-scale cascade reservoirs affect water and sediment changes in their controlled areas. The results of this study can provide a reference for predicting the trends of water and sediment changes in similar cascade reservoir reaches and formulating effective river management measures.

2. Study Area, Dataset and Methods

2.1. Study Area

The Yangtze River originates from the Qinghai-Tibet Plateau, flows from west to east, and empties into the East China Sea (Figure 1). It has a total length of approximately 6,397 km and a total drainage area of 1.8×10⁶ km². Taking the Yichang and Hukou hydrological stations as boundaries, the Yangtze River is divided into three reaches: the upper reach with a length of 4,504 km, the middle reach with 955 km, and the lower reach with 938 km. Since 1950, more than 50,000 reservoirs of various types have been built in the Yangtze River Basin [3], with a total storage capacity exceeding 83×10⁹ m³. Among them, the upper reaches of the Yangtze River are a “rich mining area” for hydropower resources. The world’s largest Three Gorges Dam is located at the downstream end of the upper Yangtze River, with a storage capacity as high as 39.3×10⁹ m³.

Approximately 1,020 km upstream of the Three Gorges Dam, the river reach where four large-scale cascade reservoirs—namely Wudongde, Baihetan, Xiluodu, and Xiangjiaba—are connected end to end serves as the study area of this paper. The Sanduizi Hydrological Station and Xiangjiaba Hydrological Station are the controlling hydrological stations at the inlet and outlet of this reach, respectively. The drainage areas controlled by these two hydrological stations are 388,571 km² and 458,800 km², respectively, with the drainage area between them being 70,229 km² [4]. This river reach is characterized by high mountains and deep valleys, with the riverbed elevation ranging from 216 m to 4,281 m. The maximum depth of the river valley can reach 3,100 m, presenting a typical “V”-shaped eroded valley landform.

The four large-scale cascade reservoirs (Wudongde, Baihetan, Xiluodu, and Xiangjiaba) distributed along the study reach were completed and began impounding water in January 2020, April 2021, May 2013, and October 2012, respectively (Table 1). Before the construction of these large reservoirs, the sediment transport modulus of this reach was as high as 2,200 t·km⁻²·yr⁻¹, making it a major source of sediment inflow into the Three Gorges Reservoir [17]. During the period from 2003 to 2012, the average annual sediment transport of this reach was 234 million tons, accounting for 84.2% of the average annual sediment inflow from the main stream into the Three Gorges Reservoir during the same period.

2.2. Dataset

There are three types of water and sediment data used in this research: annual runoff and annual suspended-sediment load (SSL) with a long-term time series (1966–2023); monthly average discharge and monthly average sediment concentration with a short-term time series (2008–2023); and daily water discharge and daily sediment concentration for typical years (e.g., 1971, 1999, 2020).

The hydrological stations in the study area that involve long-time scale data series include: Panzhihua Station, a main stream control hydrological station located above the studied river reach; Tongzilin Station, the outlet hydrological station of the Yalong River (the largest tributary of the Yangtze River above the Xiangjiaba Station); Sanduizi Station, the inlet hydrological station at the entrance of the studied river section; and Xiangjiaba Station, the outlet hydrological station of this river reach. Sanduizi Station, Wudongde Station, Baihetan Station and Xiangjiaba Station also have short-time scale data series, such as monthly average data series and daily data series of typical years.

For the data of Tongzilin Station before its establishment in 1998, observation data from Luning Station were adopted and converted to Tongzilin Station data using the area-weighted method. For the historical hydrological data of Sanduizi Station before its establishment, the basic observation data of Panzhihua Station and Tongzilin Station were used for proportional calculation via the area-weighted method. For the data of Xiangjiaba Station before its establishment, the observation data from Pingshan Station (located near its upper stream) were directly used.

The time series of data adopted by the above-mentioned hydrological stations are shown in Table 2. The basic hydrological and suspended-sediment observation data of each hydrological station are derived from the field-measured data by the professional team of the Changjiang Water Resources Commission, which are recorded in the *Hydrological Data of the Yangtze River Basin* and *China River Sediment Bulletin* over the years. Other types of data involved in this paper, such as sediment inflow coefficient and cumulative data, are obtained through relevant methods based on the basic data, because the difference in the drainage area controlled by the two stations is only 0.05%.

Table 2. The data sequences of the hydrological stations in the study river reach.

Station name	Location	Start year	Controlled drainage area		Data sequence
			Size (km ²)	Rate (%)	
Luning	Lower Yanlong River	1959	108277	23.59	1966–2008
Tongzilin	Above the outlet of the Yalong River	1998	128363	27.98	2009–2023
Panzhihua	Above the confluence of Yangtze and Yalong Rivers	1965	259177	56.49	1966–2023
Sanduizi	Inlet of the study river reach	2006	388571	84.69	2009–2023
Wudongde	Upper part of the study river reach	1998	406347	88.57	2008–2023
Baihetan	Middle part of the study river reach	2014	430308	93.79	2015–2023
Pingshan	Above the outlet of the study river reach	1954	458592	99.95	1966–2008
Xiangjiaba	Outlet of the study river reach	2008	458800	100.00	2009–2023

2.3. Methods

2.3.1. Cumulative Anomaly Method

Cumulative anomaly is a statistical method used to analyze the trends and changes in time series data X_t . Its basic principle is to accumulate the differences between each observed value and the multi-year average value, thereby obtaining a new cumulative anomaly series X_t :

$$X_t = \sum_{i=1}^t (x_i - \bar{x}) \quad t = 1, 2, \dots, n, \quad \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \tag{1}$$

This method can help identify trend changes and abnormal times in data sequences. The cumulative anomaly method is a commonly used data analysis method in fields such as meteorology and hydrology [24,25]. When the cumulative anomaly curve formed by a set of interrelated

cumulative data sequences shows an upward trend, it indicates that the values of the original data sequence have an increasing trend; conversely, they have a decreasing trend. When there is an obvious sudden change from rising to falling or vice versa, it indicates that the data sequence shows a reversal change (abrupt change), and the corresponding time is the abrupt change time.

The most obvious abrupt change point obtained by analyzing the entire sequence of data as mentioned above can be called the main abrupt change point, and its corresponding time is called the main abrupt change time. If the data sequence is long enough and there are obvious reversal changes on one or both sides of the main abrupt change point, independent cumulative anomaly analysis can be performed on the anomaly values of these sub-regions. Thus, the secondary abrupt change points of the sub-sequence data can be obtained, and their corresponding times can be called the secondary abrupt change times. This is also an extension of the application of this method.

2.3.2. Double Mass Curve Method

The double mass curve method, proposed by Merriam [26], is one of the simplest, most intuitive, and widely used methods in analyzing the consistency or long-term evolution trends of hydrometeorological elements [24]. If two sets of variables are proportional (directly or inversely) within the same period, the cumulative value sequence of one variable and the corresponding cumulative value sequence of the other variable can be represented as a straight line in a rectangular coordinate system, with its slope being the proportional constant of the corresponding points of the two elements. If there is an abrupt change in the slope, it means that the proportional constant between the two variables has changed. If the fact that the slope has changed is recognized, the time (such as the year) corresponding to the slope mutation point is the time when the cumulative relationship between these two variables undergoes a mutation. The runoff and sediment data of rivers have a highly correlated proportional relationship, and this method can be used when analyzing whether the relationship between the two has undergone a mutation.

2.3.3. Mann-Kendall Method

As one of the methods recommended by the World Meteorological Organization (WMO), the Mann-Kendall method [27,28] is a non-parametric statistical analysis method for abrupt change detection and trend testing of long-term data series. Its ability to detect abrupt changes is less convenient compared to the two aforementioned methods; however, its trend detection is more distinct due to its ability to quantitatively determine indicators based on significance under different confidence levels, and it has achieved good application results in the analysis of hydrological parameter change trends.

2.3.4. Regression Analysis Method

According to the needs of correlation analysis between hydrological data, regression analysis methods such as linear and nonlinear regression were also used in this research. The application of these methods can clearly reveal the intrinsic relationships between relevant parameters, and help people gain an in-depth understanding of the variation mechanism of hydrological and sediment parameters in the study area in response to the construction and operation of cascade reservoirs.

3. Results

3.1. The Variation Trend of Long-Series Water and Suspended-Sediment

3.1.1. Average Rate of Change

The annual runoff of Panzhihua Station and Tongzilin Station both showed a fluctuating increasing trend during 1966–2023 (Figure 2a), with their average growth rates being $1.185 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$ and $1.697 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$, respectively. Except for a few individual years, the annual runoff of Panzhihua Station was slightly higher than that of Tongzilin Station.

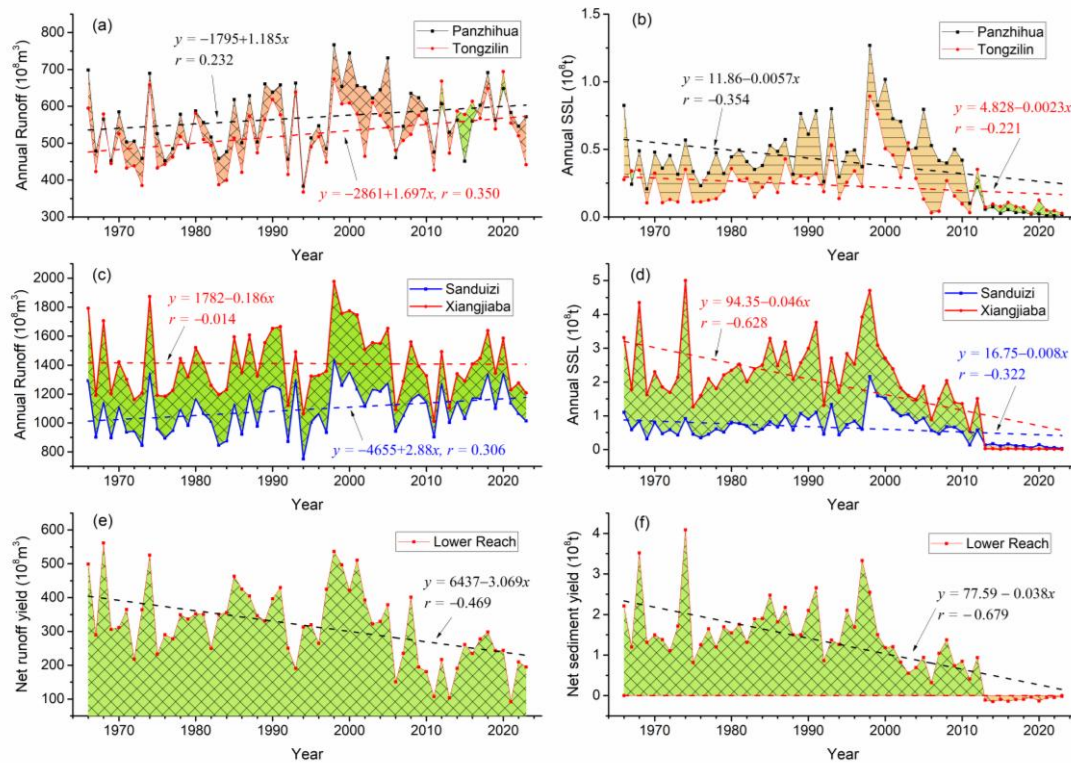


Figure 2. Variations of annual runoff and suspended sediment load (SSL) at Panzhihua Station (located at the trunk channel about 5 km upstream of the Sanduizi Station), Sanduizi Station (located at the entrance of the study river reach), Xiangjiaba Station (located at the exit of the study river reach), and Tongzilin Station (at the exit of the Yalong River which is a tributary of the Yangtze River) in the period from 1966 to 2023.

The annual SSL of these two hydrological stations showed a slight increase with fluctuations before 1998, and since then, it has exhibited a fluctuating decreasing trend (Figure 2b). During the entire period of 1966–2023, an obvious decreasing trend was observed, with their average decreasing rates being $5.7 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ and $2.3 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$, respectively. Among them, the decreasing rate of SSL at the main stream (Panzhihua Station) was 2.48 times that at the Yalong River (Tongzilin Station), a tributary.

The annual runoff at Sanduizi Station showed a fluctuating increasing trend, with an average growth rate of $2.88 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$ (Figure 2c). The annual average increment only accounted for 0.017% of the annual average runoff ($1094.2 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$) during the period 1966–2023. In contrast, the annual runoff at Xiangjiaba Station fluctuated significantly and exhibited an extremely insignificant decreasing trend, with a decreasing rate of only $0.186 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$. The annual average decrement only accounted for 0.013% of the annual average outflow runoff ($1410.88 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$).

The annual sediment discharge at both hydrological stations showed a decreasing trend (Figure 2d), with decreasing rates of $8.0 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ and $46 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ respectively. The annual average decrement of sediment discharge accounted for 1.25% and 2.45% of the annual average inflow sediment ($0.64 \times 10^8 \text{ t} \cdot \text{yr}^{-1}$) and annual average outflow sediment ($1.88 \times 10^8 \text{ t} \cdot \text{yr}^{-1}$) during the above-mentioned period, respectively.

For the studied river reach (between Sanduizi and Xiangjiaba Stations), both the annual net runoff yield and annual net SSL showed decreasing trends (Figures 2e, f), with average decreasing rates of $3.069 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$ and $3.8 \times 10^6 \text{ t} \cdot \text{yr}^{-1}$, respectively.

3.1.2. Variation Trend and Significance

The results of the Mann-Kendall (M-K) trend test for the interannual variations in annual runoff and annual SSL at the aforementioned hydrological stations during 1966–2023 are presented in Table

3. Among these stations, the interannual variation of runoff at Tongzilin Station showed a significantly increasing trend, while that at Sanduizi Station exhibited a relatively significant increasing trend; these two trends passed the significance test at the 0.05 and 0.10 confidence levels, respectively. In contrast, the interannual variations of runoff at Xiangjiaba Station and Panzhihua Station failed the significance test at the 0.10 confidence level, indicating their changing trends were not significant.

All four hydrological stations mentioned above showed a significant decreasing trend in SSL. Specifically, the decreasing trends at Sanduizi Station and Xiangjiaba Station were extremely significant, both passing the significance test at the 0.01 confidence level.

Table 3. Test results of the variation trends of runoff and sediment transport at typical gauging stations.

Gauging station	Runoff			Suspended sediment load		
	Time span	<i>S</i>	<i>Z</i>	Time span	<i>S</i>	<i>Z</i>
Tongzilin	1966–2023	378	2.53**	1966–2023	–370	–2.48**
Panzhihua	1966–2023	232	1.55	1966–2023	–381	–2.55**
Sanduizi	1966–2023	340	2.27*	1966–2023	–418	–2.79***
Xiangjiaba	1966–2023	52	0.34	1966–2023	–701	–4.70***

Note: The *Z* value with superscript *, **, or *** indicates passing the 0.10, 0.05, and 0.01 confidence test, respectively.

3.1.3. Abrupt Change Time and Its Characteristics

The cumulative anomaly curves of annual runoff and annual SSL from 1966 to 2023 at the hydrological stations at the inlet (Sanduizi Station) and outlet (Xiangjiaba Station) of the study area are shown in Figure 3. A main abrupt change in the runoff at Sanduizi Station occurred in 1997, with the trend shifting from a decreasing one before 1997 to an increasing one afterward (Figure 3a). A cross-check with the Mann-Kendall (M-K) trend test results confirms that this abrupt change year is statistically significant.

The main abrupt change year for both the annual runoff at Xiangjiaba Station and the annual net runoff yield in the studied river reach was 2005; before this inflection year, the trend was increasing, and after that, it turned to decreasing. However, a cross-check with the M-K trend test results shows that this abrupt change year is not statistically significant.

The annual SSL at Sanduizi and Xiangjiaba Stations, and the annual net SSL in the studied river reach all experienced an abrupt change from an increasing to a decreasing trend (Figure 3b), with their main abrupt change years being 2005, 1999, and 2001, respectively. A cross-check with the M-K trend test results verifies that all these main abrupt change years are statistically significant.

Separate cumulative anomaly analyses were conducted on the sub-sequence data of annual runoff and annual SSL before and after the main abrupt change years. The variation characteristics of these cumulative anomaly curves are presented in Figures 3c–f. For the annual runoff sequence before the main abrupt change year, a secondary abrupt change year was only clearly observed at Xiangjiaba Station, which was 1997 (Figure 3c). The secondary abrupt change years (shifting from a decreasing to an increasing trend) for the annual SSL sequences at Xiangjiaba and Sanduizi Stations were 1988 and 1984, respectively (Figure 3d).

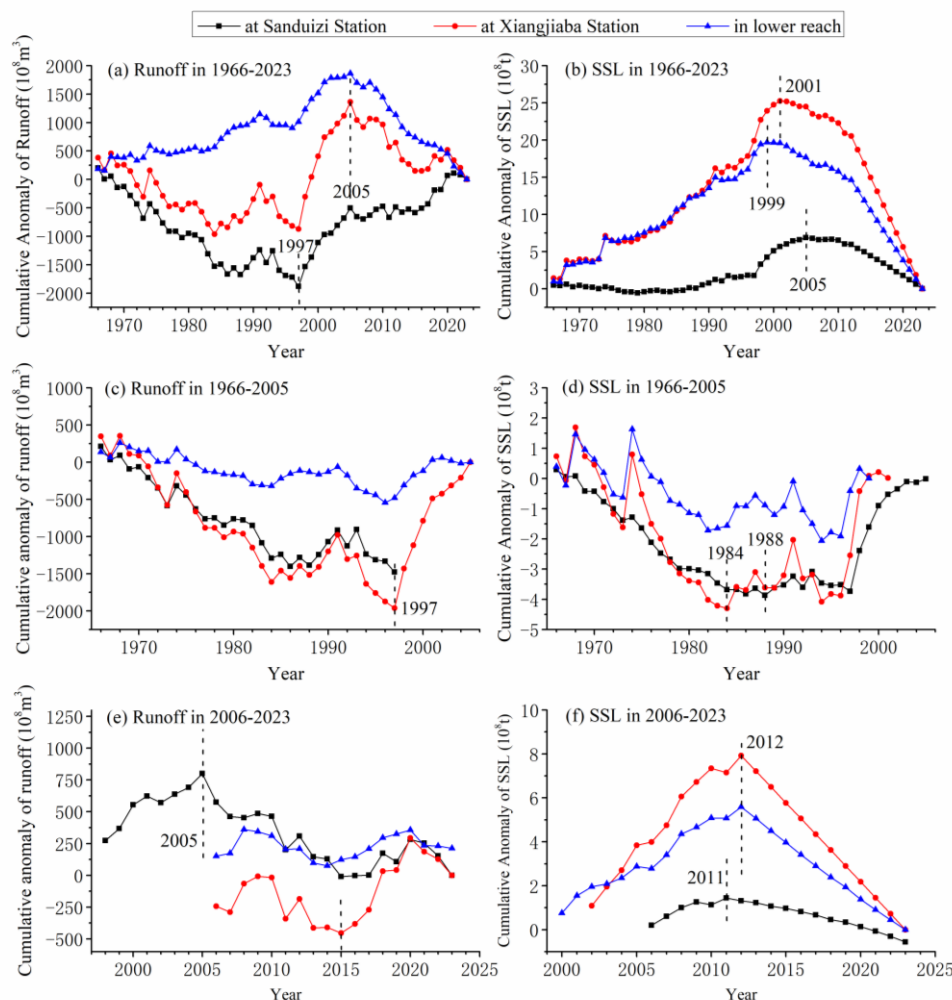


Figure 3. Cumulative anomaly curves of runoff and sediment transport at the inlet and outlet hydrological stations in the lower reaches of the Jinsha River, as well as the cumulative anomaly curves of net runoff production and net sediment transport in the lower reach.

After the main abrupt change year, the annual runoff at Sanduizi Station had an insignificant secondary abrupt change year in 2005 (Figure 3e). The secondary abrupt change years (shifting from an increasing to a decreasing trend) for the annual SSL at Xiangjiaba and Sanduizi Stations, and the net SSL in the studied river reach were 2011, 2012, and 2012, respectively (Figure 3f). As can be seen from the overall variation trends in Figures 3a and 3b, all secondary abrupt changes are relatively insignificant compared with the main abrupt changes.

The aforementioned abrupt changes are caused by the independent variation of runoff or SSL; the combined variation of the two will inevitably exhibit differences. This can be further revealed through the following analysis.

The variation characteristics of the double mass curves of annual runoff and annual SSL show (Figure 4) that Panzhihua Station exhibited one upward deflection (abrupt change) in 1987 and one downward deflection (abrupt change) in 2010, respectively. Tongzilin Station showed one upward deflection, one upward deflection, and one downward deflection in 1979, 1997, and 2003, respectively. After the water and sediment flowing through the above two hydrological stations converge, they directly affect the water-sediment process at Sanduizi Station. Sanduizi Station had one upward deflection in 1984 and 1997 respectively, and one downward deflection in 2002 and 2010 respectively. Xiangjiaba Station had one downward deflection in 2001 and 2012, respectively.

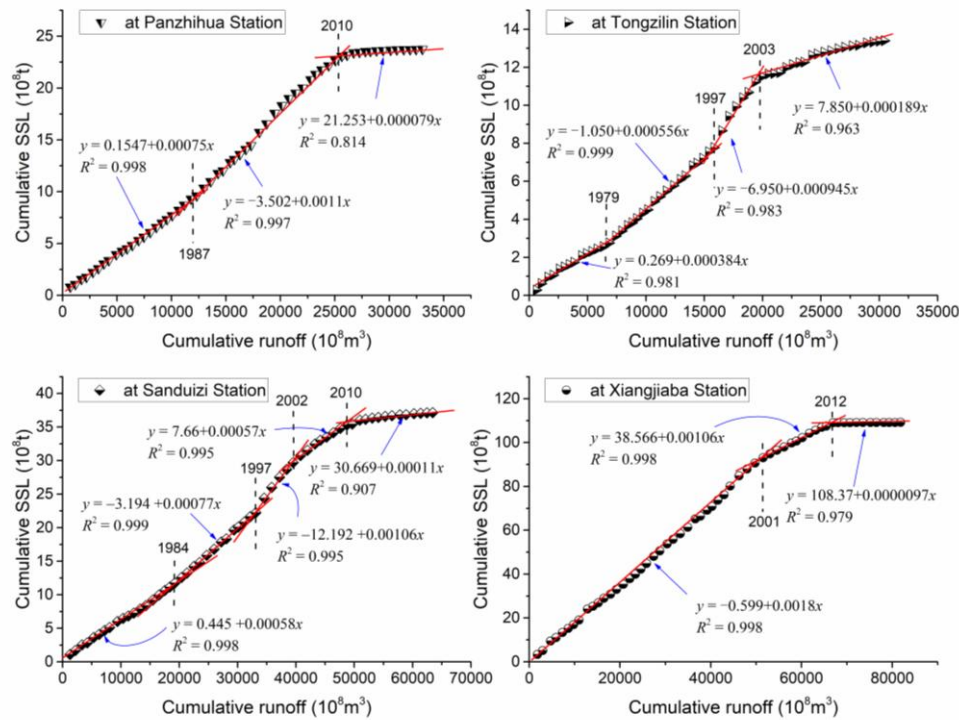


Figure 4. Variation characteristics of the double mass curves of annual runoff and suspended sediment load (SSL) of the hydrological stations.

All deflections occurring before 2000 were characterized by the growth rate of cumulative SSL being greater than that of cumulative runoff, which was manifested as an overall upward deflection of the double mass curve. All deflections after 2000 were characterized by the growth rate of cumulative SSL being less than that of cumulative runoff, which was manifested as a downward deflection of the curve after the inflection point.

3.2. Comparison of Water-Sediment Processes Before and After Dam Construction

Considering that these cascade dams were constructed between 2012 and 2021, this study focuses on investigating the characteristics of water and sediment changes since 2008 to reveal the direct impact of dam construction on water and sediment.

3.2.1. The Trend of Interannual Changes

Since 2008, the annual runoff at typical hydrological stations in the study area has shown well-synchronized fluctuation characteristics (Figure 5a), with an obvious increasing trend along the river course in terms of spatial distribution. The construction of cascade dams has not affected the interannual variation trend of runoff.

In general, the annual SSL has shown a decreasing trend (Figure 5b). When a certain dam was completed in a specific year, annual SSL at the hydrological stations downstream of the dam decreased suddenly accordingly. This indicates that the sediment trapping effect of the dam becomes prominent immediately after its completion, which directly affects the changes in sediment flux in the studied river section. For example: The Xiangjiaba Dam was completed in October 2012, and the annual SSL of the river downstream of the dam dropped sharply from 1.51×10^8 t·yr⁻¹ in 2012 to 2.03×10^6 t·yr⁻¹ in 2013, a decrease of 98.7%. The Wudongde Dam was completed in January 2020, and the annual SSL of the river downstream of the dam plummeted from 1.62×10^7 t·yr⁻¹ in 2019 to 1.25×10^6 t·yr⁻¹ in 2020, a decrease of 92.3%. The Baihetan Dam was completed in April 2021, and the annual SSL at Baihetan Station (downstream of the dam) fell sharply from 4.38×10^7 t·yr⁻¹ in 2020 to 5.5×10^6 t·yr⁻¹ in 2022, a decrease of 87.4%.

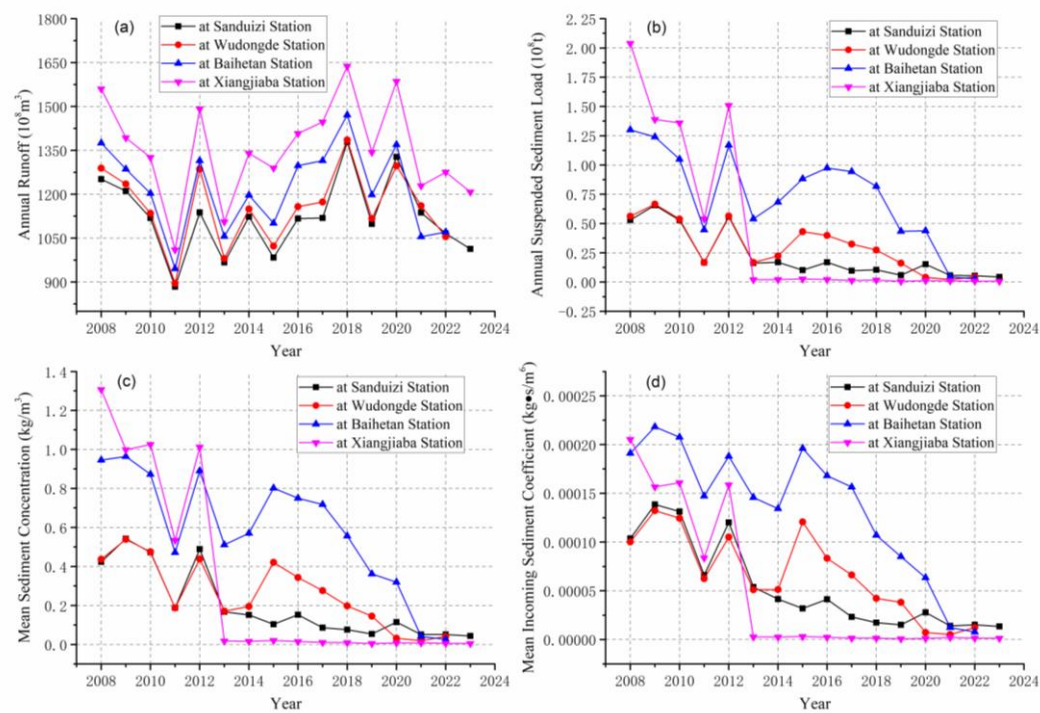


Figure 5. Annual variation characteristics of (a) runoff, (b) suspended sediment load, (c) sediment concentration, and (d) sediment inflow coefficient of the hydrological stations in the study river reach during the period from 2008 to 2023.

The sharp decreases in the annual average sediment concentration (Figure 5c) and annual average sediment inflow coefficient (Figure 5d) at the aforementioned hydrological stations also coincide with the completion timelines of the adjacent dams upstream of these stations, respectively, and their variation trends are similar to that of SSL.

The variation characteristics of annual net runoff yield, net SSL, net runoff yield modulus, and net sediment discharge modulus in the three sub-sections of the study area during 2008–2023 are shown in Figure 6. The annual net runoff yield exhibited significant fluctuations of increase and decrease in 2012 and 2021, respectively (Figure 6a), while fluctuations in other years were weak with no obvious variation trend.

The annual net SSL of the studied river reach dropped sharply in 2013 (Figure 6b), which is closely related to the completion of the Xiangjiaba Dam in 2012. The annual net SSL in the two sub-reaches (from Sanduizi Station to Wudongde Station, and from Wudongde Station to Baihetan Station) decreased significantly in 2020 and 2021, respectively. These decreases coincide with the completion and the start of sediment trapping of the Wudongde Dam (in January 2020) and the Baihetan Dam (in April 2021), respectively.

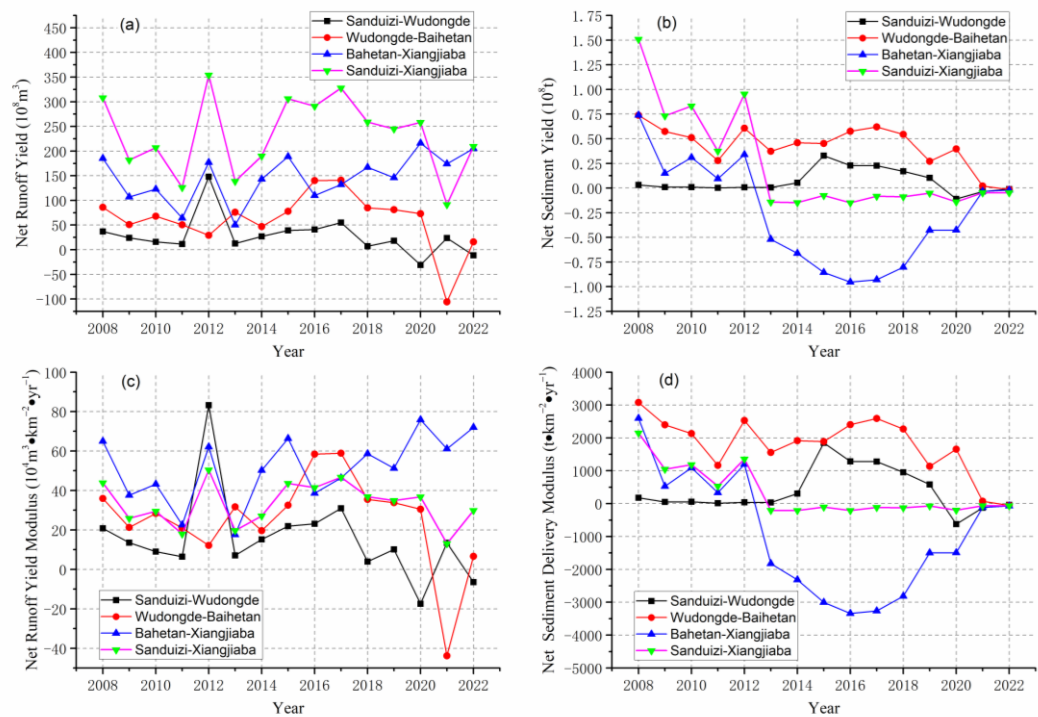


Figure 6. Variation characteristics of (a) net runoff production, (a) net sediment transport, (a) net runoff production modulus, and (a) net sediment transport modulus in different reaches of the study river during the period from 2008 to 2023.

The interannual variation of the net runoff yield modulus in this river reach (Figure 6c) is roughly similar to the fluctuation characteristics of its annual net runoff yield, while the interannual variation of the net sediment discharge modulus (Figure 6d) is basically consistent with the variation trend of the annual net SSL in the corresponding sub-sections.

3.2.2. The Trend of Monthly Variation

Three periods, before construction (2008–2012), during construction (2013–2021), and after completion (2022–2023) of cascade dams, were used for comparative analysis. The calculated proportions of the monthly average discharge and monthly average sediment transport rate of the hydrological stations at the inlet and outlet of the studied river reach (relative to the total values of the three periods) are overlaid in Figure 7.

At Sanduizi Station (inlet of the river reach) and Xiangjiaba Station (outlet of the river section), the percentage of monthly average discharge during the main flood season (from June to September) generally decreased (Figure 7a, b). Specifically, the percentages dropped from 33.6% and 38.7% (before dam construction) to 29.4% and 27.4% (after dam construction), respectively. Moreover, the magnitude of the decrease at the outlet station (–11.1%) was greater than that at the inlet station (–7.1%). In contrast, during the non-main flood season (from November to December and from January to May), the monthly average proportions increased: from 29.1% and 27.4% (before dam construction) to 38.3% and 40.0% (after dam construction), respectively. Meanwhile, the magnitude of the increase at the outlet station (12.6%) was larger than that at the inlet station (9.6%).

During the main flood season, the relative percentage of the monthly average sediment transport rate at Sanduizi Station changed from 33.0% (before dam construction) to 32.3% (after dam construction), with a negligible decrease of –0.7% (Figure 7c). At Xiangjiaba Station, however, this percentage fell from 39.7% (before dam construction) to 25.8% (after dam construction), showing a significant decrease of –13.9% (Figure 7d). In months other than the main flood season, the relative percentage of the monthly average sediment transport rate at Sanduizi Station increased slightly from

34.6% (before dam construction) to 37.5% (after dam construction), with an increase of 3.0%. In contrast, at Xiangjiaba Station, this percentage surged from 15.7% (before dam construction) to 54.2% (after dam construction), representing a substantial increase of 38.5%.

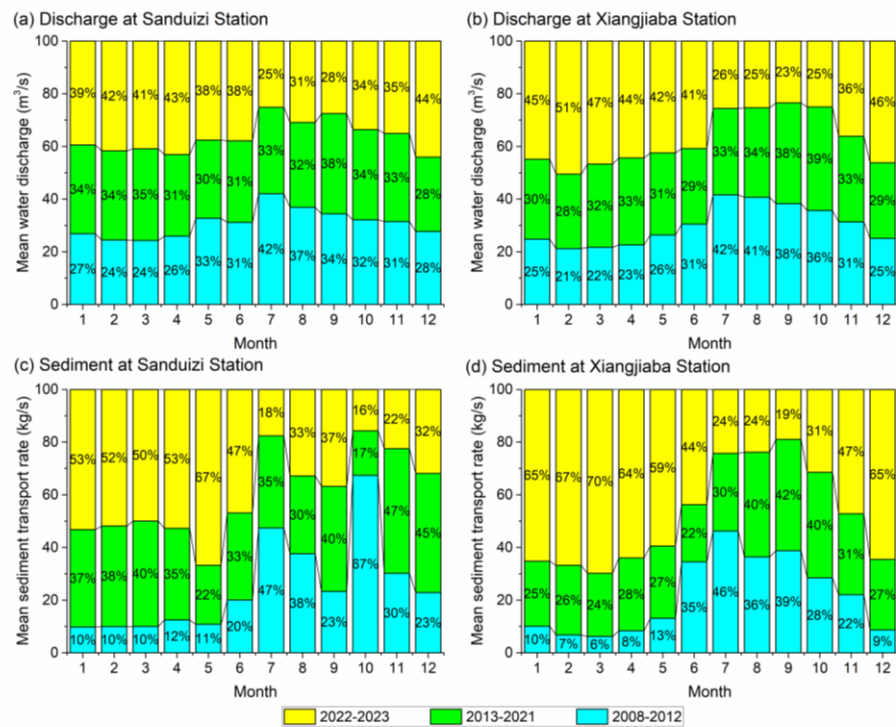


Figure 7. The 100% stacked columns of relative percentage of monthly mean discharge and suspended sediment transport rate (SSTR) at the entrance (Sanduizi Station) and exit (Xiangjiaba Station) of the river section in the pre-construction period (2008–2012), construction period (2013–2021), and post-completion period (2022–2023) of large-scale cascade dams in the study river reach.

3.2.3. Water-Sediment Relationships Before and After Dam Construction

The construction of large dams in the study area has a significant impact on the changes in the flow-sediment processes of this river reach and the adjustment of the relationship between them. The Wudongde Dam was completed in January 2020; since then, the area where the Wudongde Dam is located has become a region with strict control over flow and sediment. Naturally, the flow-sediment relationship at the Sanduizi Station, which is situated at the entrance of the study river reach, is not directly affected by the construction of this dam. This is clearly reflected in the fact that the fitting curves of the flow-sediment relationship at the Sanduizi Station in 2019 and 2020 show little difference (Figure 8a). However, the flow-sediment relationship at the Wudongde Station (located near the downstream of the Wudongde Dam) in 2020 was significantly different from that in 2019 (Figure 8b). The most notable change is that after the dam construction, the sediment concentration of the flow decreased drastically, and the large-amplitude fluctuations that still existed in the previous year completely disappeared.

The completion of the Wudongde Dam and its significant sediment-trapping effect will also affect the changes in the flow-sediment relationship in the downstream river reaches. When the Baihetan Dam was completed in April 2021, the flow-sediment relationship of the output from its reservoir reach had already undergone fundamental changes under the influence of the Wudongde Dam (Figure 8c). For instance, the fitting curve of its flow-sediment relationship in 2020 was very similar to that in 2019, but showed a huge difference compared with that in 1971. It can be predicted that after the completion of the Baihetan Dam, the changed state of the flow-sediment relationship downstream of the dam will continue. If daily-scale hydrological observation data from the

downstream of the Baihetan Dam (Baihetan Station) after 2021 can be collected, a flow-sediment relationship fitting curve similar in shape to that of 2020 will also be obtained.

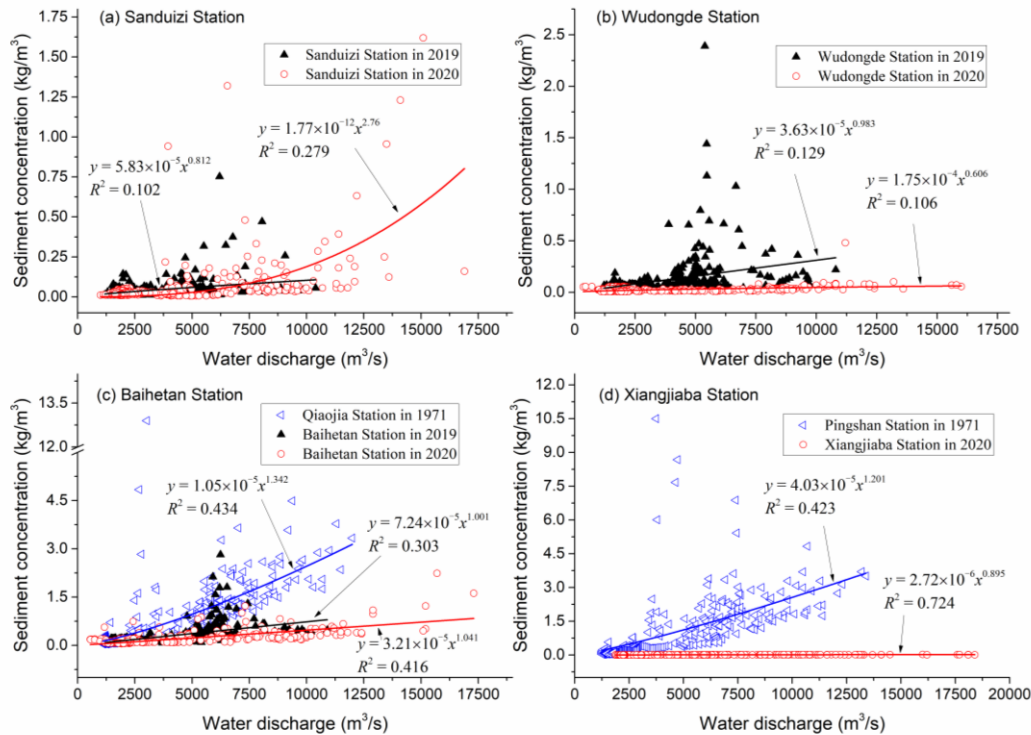


Figure 8. Changes in the relationships between daily discharge and sediment concentration in typical years before and after the construction of the cascade dams in the study river reach.

The change in the flow-sediment relationship at the Xiangjiaba Station is particularly significant (Figure 8d). This is not only a continuous response to the sediment-trapping capacity of the Xiangjiaba Dam, which was the first to be completed, but also an inevitable result of the coordinated sediment-trapping by all large dams in the study river reach.

In summary, the construction of large dams in the study area, with their strong sediment-trapping capacity and the huge storage capacity of the corresponding reservoirs, has significantly reduced the sediment concentration of the outflow and its intra-annual and inter-annual fluctuations. This not only leads to a marked decrease in the slope of the fitting curve for the flow-sediment relationship of the downstream flow but also a significant improvement in the correlation between flow and sediment.

4. Discussion

4.1. Sediment Trapping Effect of Cascade Dams Causes Abrupt Changes in SSL

A notable abrupt change in the annual inflow runoff of the study reach occurred in 1997 (a shift from decrease to increase), which resulted from the increase in precipitation and glacial-snow meltwater in the area upstream of the reach. The variation in runoff at the reach outlet was insignificant and showed no abrupt change. Similarly, the annual net runoff yield within the reach (between Sanduizi and Xiangjiaba Stations) exhibited no significant trend of change. This indicates that the inter-annual variations in runoff at different hydrological stations in the study reach were not significantly affected by the construction of large-scale cascade dams. However, the intra-annual distribution of runoff at each station underwent relatively obvious changes, which is associated with complex operation modes such as water storage for power generation, water storage for flood control, pre-flood water discharge, and water replenishment to the downstream during dry seasons. In other

words, human activities in the study area significantly altered the intra-annual distribution of runoff; nevertheless, due to the abundant incoming flow in the study area, the construction of dams and operation of reservoirs did not change the inter-annual natural pattern of runoff.

The annual SSL at the reach inlet (Sanduizi Station), reach outlet (Xiangjiaba Station), and the annual net SSL within the reach (between Sanduizi and Xiangjiaba Stations) all experienced an abrupt change from increase to decrease (Figure 3b). The main abrupt change years were 2005, 1999, and 2001, respectively, which were primarily attributed to the substantial sediment trapping by the Ertan Dam (with a total storage capacity of $58 \times 10^8 \text{ m}^3$) built on the Yalong River (a tributary) in 1998. From 1982 to 1996, the average annual SSL of the Yalong River was $37.70 \times 10^6 \text{ t}$ [29]. During 1999–2020, with the coordinated sediment-trapping effect of subsequent dams, the average annual SSL of this tributary decreased to $12.23 \times 10^6 \text{ t}$ [30]. Dam-induced sediment trapping reduced the sediment input from the Yalong River to the study reach by more than two-thirds.

A secondary abrupt change in sediment discharge at the inlet of the reach where large-scale cascade reservoirs are located (Sanduizi Station) occurred in 2011, which was related to the Jinping-I Reservoir (with a total storage capacity of $79.9 \times 10^8 \text{ m}^3$) built in the lower reaches of the Yalong River in 2009. The completion of this dam further reduced the sediment discharge of the Yalong River, thereby decreasing the sediment input to the study reach. The secondary abrupt change years for sediment discharge at the outlet of the reach with large-scale cascade reservoirs (Xiangjiaba Station) and the net SSL within the reach were both 2012, which perfectly coincided with the completion of the Xiangjiaba Dam and the start of its large-scale sediment trapping [31]. Evidently, the abrupt changes in sediment discharge in the river reach where large-scale cascade reservoirs are situated are a direct result of dam construction in different regions and their efficient sediment-trapping function.

4.2. Cascade Dams Alter Hydrological and Sediment Connectivity in a Differential Manner

The river reach where the cascade reservoirs are located is a steep canyon section in the upper reaches of the Yangtze River. Historically, it has been not only an efficient transport channel for river flow and sediment but also a main site for erosion and downcutting in the river valley area [22,32]. Therefore, under natural conditions in historical periods, this reach could not only fully transport the incoming sediment from upstream but also carry the eroded sediment from its own river valley downstream.

After the completion of the cascade dams, the intra-annual distribution of the runoff process has undergone significant seasonal adjustments due to reservoir operation [33]. Generally, this is manifested in a slight decrease in the monthly average runoff during the main flood season and a significant increase in the monthly average runoff during the non-main flood season. Meanwhile, the flood control operation measures of the reservoirs have reduced the peak flood discharge, making the occurrence of large flood discharges that were common in history extremely rare. Obviously, the joint operation of cascade reservoirs has significantly altered the intra-annual runoff process and plays a key role in intra-annual runoff regulation [34]. This has led to a certain reduction in the original connectivity of monthly average runoff within the reach, but has had a limited impact on the inter-annual runoff connectivity. A study by Yang et al. [6] showed that when comparing the 10 years before and after the completion of the Three Gorges Dam in 2003, the contribution rate of the dam to the reduction in the annual runoff of the Yangtze River was only 8%.

In the study river reach, the completion of large-scale cascade reservoirs and severe sedimentation in the reservoirs have led to a substantial decrease in the sediment discharge leaving the reach. The coordinated sediment reduction by multiple reservoirs has reduced the outgoing sediment by 99% [4,17,23], meaning that the inter-annual sediment process is completely controlled by the cascade reservoirs. At the same time, the cascade reservoirs have also changed the intra-annual distribution of sediment flux, resulting in a significant decrease in the relative proportion of sediment discharge during the main flood season and a notable increase during the non-main flood season. In any case, the monthly sediment flux within the year is significantly lower than that before dam

construction; in other words, the completion of cascade reservoirs has greatly reduced the longitudinal connectivity of sediment in the study area.

It is worth emphasizing that once the Xiangjiaba Dam, the first completed dam in this reach and located at the outlet, was built, it almost completely intercepted the incoming sediment from the upstream basin of the dam due to its huge storage capacity, with a sediment interception rate as high as 99% [17,23]. Subsequent other large-scale cascade reservoirs built later intercepted and deposited large amounts of incoming sediment from the upstream basins and the areas between dams to varying degrees, significantly reducing the sediment inflow, sedimentation amount, and reservoir deposition rate of the Xiangjiaba Reservoir [23]. However, there was almost no further change in the total sediment output and sediment transport ratio of the entire reach (with the Xiangjiaba Station as the control station). The extremely high sediment interception efficiency of these cascade reservoirs has greatly reduced the sediment inflow into the Three Gorges Reservoir at the terminal section of the upper Yangtze River, leading to a 50% reduction in the annual average sediment amount in the Three Gorges Reservoir area (from 1.4×10^8 t to 0.7×10^8 t) [35]. This has significantly slowed down the rate of storage capacity loss of the Three Gorges Reservoir, which implies an extension of its effective period for flood control and clean energy production.

Large-scale cascade reservoirs exhibit significant differences in the degree to which they alter runoff and sediment connectivity. The reduction in sediment discharge caused by dam construction is of a much larger magnitude than that of runoff, which is reflected in the fact that the exponent of the inherent power function relationship between flow and sediment in the study area decreased sharply after dam construction (Figure 8) and tended to show a linear relationship with an extremely small gradient. This means that the construction of large dams has made the artificial control over the sediment-laden flow in the study area far greater than the inherent sediment transport capacity of the river, thereby completely changing the internal mechanism of the flow-sediment process in the controlled river reach.

4.3. The Impacts of Climate and Other Human Activities

In the basin of the Yangtze River above the Xiangjiaba Dam, the annual precipitation from 1950 to 2022 showed an increasing trend, with a significant increasing trend in the upper sections of the river reach where large-scale cascade reservoirs are located and an insignificant increasing trend in the inter-reach area [36]. After 2000, the precipitation at most stations had a main cycle of 20–40 years, and the precipitation was mainly affected by long-cycle climate change. The multi-year average actual evapotranspiration in this region was 447.30 mm, and showed an insignificant increasing trend from 2002 to 2016. The rapid increase in forestland evapotranspiration was the main reason for this change [37]. Obviously, the increase in evapotranspiration, which has a negative impact on runoff changes, has offset the positive impact of precipitation on runoff changes to a certain extent. Based on the positive correlation between runoff and sediment transport, it can be considered that the impact of climate on sediment transport is also extremely limited. As pointed out by Ye et al. [31] and others, the contribution rate of climate to the changes in sediment discharge in the study area is only between 0.78% and 8.98%.

The contribution rate of human activities to the reduction of sediment discharge in the study area was as high as 91.02%–99.22% [31]. In addition to the large amount of sediment trapped by large-scale cascade reservoirs, the implementation of slope soil and water conservation measures, the construction of small and medium-sized reservoirs, and vegetation restoration in the basin above the Xiangjiaba Dam also reduced the sediment inflow into the study river reach to a certain extent. However, the reduction of such sediment is gradual and there is no significant abrupt change. In the basin of the Yangtze River above the Xiangjiaba Station, the total storage capacity of large reservoirs, including these four cascade reservoirs with a total storage capacity of 458.7×10^8 m³, was 709.2×10^8 m³ [4]. The total storage capacity of all 2,645 small and medium-sized reservoirs in this region was only 41.2×10^8 m³ [15], accounting for merely 5.49% of the total storage capacity of all types of reservoirs. Therefore, their overall sediment-trapping capacity and sediment-trapping amount are

very limited compared with large reservoirs. It can be seen from this that the sediment trapping by large-scale cascade reservoirs in the study area is the real reason for the sharp reduction in sediment discharge [4].

Under normal circumstances, based on the insight that glacial recharge accounts for at least 10% of river runoff [38], global warming may lead to an increase in the proportion of glacial recharge in river runoff, and an expansion of the time span of glacial ablation within a year, extending to spring and winter. This will enhance the seasonal variation of runoff [3,39–41], and rivers usually show a slight increase in discharge in spring and winter. For the study area, due to the integrated operation mechanism of large-scale cascade reservoirs for water storage, power generation, flood control, navigation, and other purposes, the seasonal changes of runoff and sediment as well as the inter-annual changes of sediment are almost completely controlled by the impact of human activities. Climate factors will only continue to play a dominant role in the inter-annual changes of runoff.

5. Conclusions

Based on the analysis results of hydrological data from relevant hydrological stations in the river reach where large-scale cascade reservoirs are located in the upper reaches of the Yangtze River, both before and after dam construction, the following main conclusions are drawn:

1) The annual inflow runoff of the study reach showed an insignificant increasing trend, with an average growth rate of $2.88 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$. The annual average increment only accounted for 0.017% of the annual average runoff ($1094.2 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$) during the period 1966–2023. The outflow runoff of this reach showed an extremely insignificant decreasing trend, with a decreasing rate of only $0.186 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$, and the annual average decrement only accounted for 0.013% of the annual average outflow runoff ($1410.88 \times 10^8 \text{ m}^3 \cdot \text{yr}^{-1}$).

2) During the above-mentioned period, both the annual sediment inflow and outflow of the reach showed a significant decreasing trend with obvious abrupt change characteristics; the decreasing rates of sediment discharge were $8.0 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ and $46 \times 10^5 \text{ t} \cdot \text{yr}^{-1}$ respectively, and the latter was 5.75 times that of the former. The annual average decrement of sediment transport accounted for 1.25% and 2.45% of the annual average inflow sediment ($0.64 \times 10^8 \text{ t} \cdot \text{yr}^{-1}$) and outflow sediment ($1.88 \times 10^8 \text{ t} \cdot \text{yr}^{-1}$) during the above period, respectively.

3) The successive completion of cascade dams and the comprehensive operation mode of reservoirs are the fundamental reasons for the variation in the flow-sediment relationship and the sharp reduction in annual outflow sediment in the study reach. Furthermore, they have led to obvious “peak-shaving and valley-filling” adjustments in the intra-annual variations of runoff and sediment. Climate change and other human activities have reduced the sediment inflow into the study reach.

4) At least in the next few decades, climate factors will remain the dominant factor controlling the inter-annual variation of runoff in the study area; while human activities will completely control the sediment outflow of the reach and also restrict the intra-annual distribution of runoff and sediment.

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