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Hydrological Changes and Sediment Dynamics in the Inner Mongolia Section of the Yellow River: Implications for Reservoir Management

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Abstract: The Inner Mongolia section of the Yellow River is a primary alluvial segment of the main channel. The variations in water and sediment not only alter the cross-sectional morphology and flow capacity of the river but also impact the scheduling of upstream cascade reservoirs. Based on runoff and sediment load data and topographic information from typical hydrological stations, the characteristics of runoff and sediment load variations and the evolutionary pattern of siltation in the Inner Mongolia River section were analyzed via trend analysis methods, Mann–Kendall test methods, the sediment load transport rate method, and the water level–flow relationship. The results showed that the water and sediment loads at the hydrological stations in the Inner Mongolia River section significantly changed from the 1960s to after 2000, with runoff decreasing by approximately 22% to 32% and the sediment load decreasing by approximately 65% to 73%. Sedimentation in the river section generally increased, and the average annual siltation amount reached 0.144 billion t. The joint utilization of the Longyangxia and Liujiaxia reservoirs in 1987 was the main reason for the rapid increase in siltation, and siltation in the Inner Mongolia River section was slightly reduced after 2005. In addition, the critical sediment load coefficients of the Bayangaole–Sanhuhekou and Sanhuhekou–Toudaoguai River sections were 0.0073 and 0.0051 kg·s/m^6, respectively, from 1952 to 1968, and 0.0053 and 0.0037 kg·s/m^6, respectively, from 1969 to 2020. This study could provide technical support for river flood control and reservoir water sediment regulation in Inner Mongolia.

Keywords: Inner Mongolia reach; sediment load variation; erosion; sedimentation

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1. Introduction

Rivers are the origin of human civilizations and an important support for national economic and regional development, with multiple applications such as irrigation, navigation, and power generation [1]. The evolving understanding of rivers has propelled a developmental trend focusing on their utilization and transformation [2]. In particular, the construction of a series of water projects has realized the comprehensive utilization of river resources [3].

Large-scale water conservancy projects, integral for flood control and power generation, induce alterations in the dynamics of water and sediment discharge, disrupting the adaptive equilibrium between water and sand conditions and river morphology [4–6], leading to responsive siltation adjustments in the riverbed downstream of the dam [7]. So far, more than tens of thousands of dams have been constructed worldwide, changing the natural runoff and sediment processes [8]. However, due to the differences in reservoir capacity, operation mode, and main construction purposes, the response phenomena and mechanisms of downstream riverbed erosion and sedimentation adjustments to changes in water and sediment processes are not entirely the same [9,10].

The main impact of the impoundment of the Gongola River is a significant reduction of 11.5% in flood peaks below the reservoir, resulting in a reduction of 38.3% in the width of channel bankfull and 72.2% in the width of the riverbed, respectively [11]. E. B. Campbell Dam is located in the Saskatchewan River in Canada, with the dam downstream of the 0~81 km range of river width, whereby the water depth increase is small from the dam mileage of more than 81 km section of the riverbed deformation [12]. Fortore River, Italy, saw the construction of the Occhito Dam from 1958 to 1966, wherein the upstream and downstream channels were narrowed up to 81% and 98%, respectively, and the channel planform was transformed from a multi-branch channel to a single river type [13,14]. After the construction of the Massanjore Reservoir in India, the channel downstream of the dam exhibited narrowing of the river width bundle, coarsening of the riverbed, reduction in lateral stability, and an increase in the branching index [15]. After the impoundment of the Xiaolangdi Reservoir on the Yellow River, the downstream river continued to be flushed, the bankfull discharge increased, and the river situation was adjusted [16–18]. Since the construction of the Danjiangkou Reservoir, the downstream has been transformed from an accretionary channel to a scouring channel, with weakening of wandering characteristics and strengthening of deep erosion in the bending section [19]. After the completion of the Aswan Dam, sand delivery from the Nile Delta dropped by nearly 98% [20]. The storage of water in the Three Gorges Reservoir has led to a change in the hydrological situation in the middle and lower reaches of the Yangtze River, with a significant reduction in the amount of sand transport, which has an impact on the downstream river [21]. Large reservoir impoundment usage has changed the water and sand conditions, and the characteristics of the downstream erosion and siltation adjustment of the dam have received widespread attention [22,23].

The Yellow River is the second longest river in China and is known for its outstanding sediment problems. The upper reaches of the Yellow River are the main water area of the whole river, and its rich hydroelectric resources support the economic and social development of the basin [24]. The Inner Mongolia reach is an alluvial river section in the upper reaches of the Yellow River and is characterized by high sand delivery, severe sediment siltation, and frequent channel migration [25,26]. In recent years, under the influences of climate change and human activities in the basin, the incoming runoff and sediment load in the Inner Mongolia reach of the Yellow River have changed, which in turn has led to problems such as siltation and channel shrinkage. In particular, the joint use of reservoirs in the upper reaches of the Yellow River, a continuous reduction in incoming water in the basin, and an increase in water consumption for industry and agriculture, have led to a significant reduction in the amount of water in this river section during the flood season. This has caused the main river channel to shrink annually and the riverbed to silt up continuously [27–29]. Sediment siltation and a reduced flow capacity have caused the water level (a flow rate of 2000 m^3/s) to rise by 0.5 to 2.0 cm per year, resulting in frequent breakout events even when the water volume is low in the Inner Mongolia reach of the Yellow River [30–32]. Since 1986, there have been seven breaches in this reach, causing severe damage. For example, in 2008, the highest water level since the establishment of the Sanhuhekou hydrological station resulted in river embankment breakout in the Inner Mongolia River section, affecting 10,241 people and causing a direct economic loss of 691 million yuan. Therefore, it is a major demand of the country to carry out joint scheduling of reservoirs to improve the river flood discharge capacity and sand transfer efficiency, as well as to ensure the safety of flood control and bullying.

Water–sediment changes and siltation evolution in alluvial rivers have long remained popular research topics. Several scholars have studied sediment siltation and its causes in the Inner Mongolia reach using measured data [33,34] and quantified the contributions of various influencing factors by determining the relationships between water–sediment conditions and sedimentation [35]. Sliding *t*-test method, M–K nonparametric mutation test, cumulative distance level method, double cumulative curve method, and water sediment relationship curves were used to analyze the trend of annual runoff and annual sand transport, mutation trend, and correlation analysis. The operation of upstream reservoirs has significantly impacted the hydraulic conditions of the Inner Mongolia reach [36], such as reducing the flood frequency, increasing the channel width/depth ratio, and restoring the channel flow capacity [27,37]. Therefore, the effects of silt flats and brush channels can be realized by joint reservoir dispatching in the downstream section of a river.

The study of runoff and sediment load change patterns constitutes the basis for understanding the characteristics of rivers. In recent years, the water and sediment loads in the Inner Mongolia section of the Yellow River have considerably changed under the influences of climate change and human activities. There is still much uncertainty in the characteristics of water and sand changes and the evolution of river channel siltation in the Inner Mongolia River section. Therefore, in this paper, the trends in water and sediment load changes in the Inner Mongolia River section from 1950 to 2020 were systematically analyzed by using runoff and sediment load data from representative hydrological stations. Moreover, the volume of silt in the trunk channel was calculated according to the sediment volume balance method, thereby elucidating the spatial and temporal distributions of the siltation process in this reach. The coupled relationship between the amount of incoming water and the sediment and riverbed evolution was analyzed, and the threshold value of the water sediment factor was subsequently calculated when the Inner Mongolia reach exhibited flushing and siltation equilibrium. This study could provide technical support for river flood control and reservoir water–sediment regulation in Inner Mongolia.

2. Study Area

The Inner Mongolia reach is located in the lower part of the upstream zone of the Yellow River and exhibits a total length of approximately 823.0 km (Figure 1). This region includes the Shizuishan–Bayangaole reach and the Bayangaole–Toudaoguai reach. The main stream comprises four major hydrological stations arranged in sequence from upstream to downstream: Shizishan, Bayangaole, Sanhuhekou, and Toudaoguai. The former is a valley river section, while the latter is a typical plain river section and the main river section studied. The Bayangaole–Sanhuhekou reach is located in the alluvial plain area, wherein the river channel is wide and shallow, sandbars are scattered, and the river section is a wandering river section. The Sanhuhekou–Toudaoguai reach is narrow and deep, exhibits a low river gradient, and is a meandering river section.

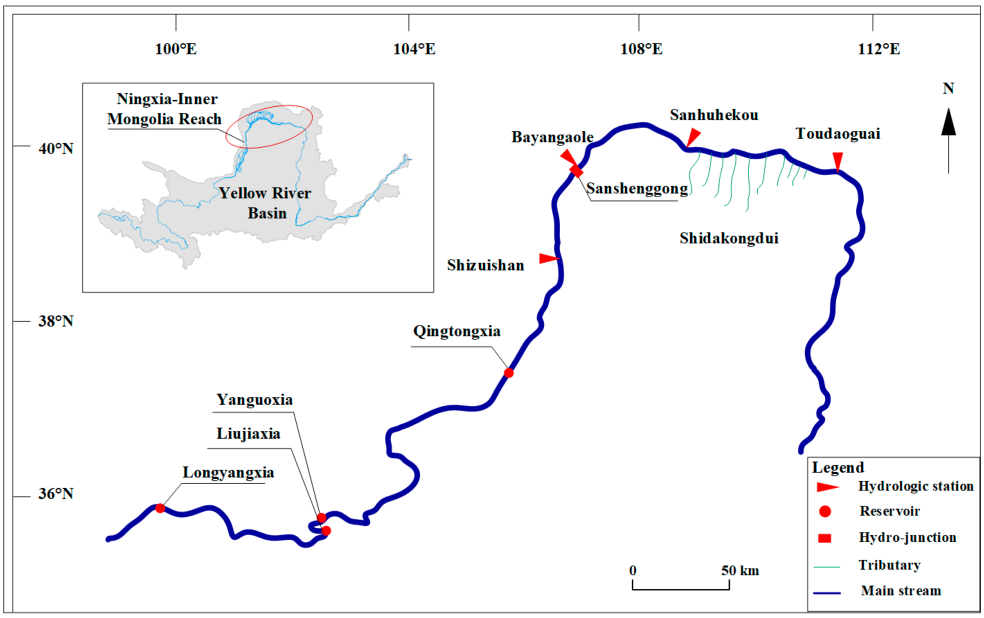

Figure 1. Inner Mongolia section of the Yellow River.

The upper reaches of the Yellow River comprise the major hydropower development area, and the construction and joint operation of cascade reservoirs inevitably alters the water and sediment processes in the river. Starting from 1961, a series of reservoirs were built in the upper reaches of the Yellow River, such as Yanguoxia, Sanshenggong, Qingtongxia, Liujiaxia, and Longyangxia (Table 1), such that the conditions of water and sand coming from the Inner Mongolia river section have been adjusted considerably. Especially after the Longyangxia Reservoir was put into operation, the amount of water in the upper reaches of the Yellow River during the flood season was significantly reduced compared with that during the operation of the Liujiaxia Reservoir. The Bayangaole–Sanhuhekou section is distributed within the Kubuqi Desert and Shidakongdui, the flood sediment problem is prominent in the Shidakongdui, and a large amount of sediment enters the Yellow River during heavy rains.

Table 1. Basic information on reservoirs in the study area.

Name	Completion Time (Year)	Regulation Mode	Reservoir Storage (Billion m^3)
Yanguoxia	1961	Daily regulation	0.22
Sanshenggong	1961	/	0.08
Qingtongxia	1967	Daily regulation	0.61
Liujiaxia	1969	Annual regulation	5.7
Longyangxia	1986	Multi-year regulation	24.7

3. Method

3.1. Calculation of River Sedimentation

The sediment transport balance method refers to the use of the balance principle to calculate the amount of river erosion and sedimentation. This approach is one of the main methods for calculating the amounts of channel scour and fill. In the Inner Mongolia River section, the region is dry and windy year-round, and the Ulanbuhe Desert and Kubuqi Desert occur along both banks of the Yellow River and are among the main areas of wind and sand activity in the Yellow River basin. Therefore, the sediment in this river section originates not only from upstream and tributary sediments but also from wind-generated sand. Therefore, the amount of channel scour and fill in the Inner Mongolia River section can be calculated as follows:

$$\Delta W_s = W_{si} + \sum W_{si} - W_{so} \tag{1}$$

where ΔW_s is the amount of channel scour and fill, billion t; W_{si} is the imported sediment transport in the river section, billion t; and W_{so} is the sediment transport at the river outlet. $\sum W_{si}$ is the amount of sediment that enters the reach, which mainly includes aeolian sand from the desert and sediment from Shidakongdui, which refers to the ten tributaries of the Yellow River. Among them, aeolian sand should be included in the Bayangaole–Sanhuhekou reach, and the sediment load originating from the tributaries of Shidakongdui should be included in the Sanhuhekou–Toudaoguai reach.

3.2. Incoming Sediment Coefficient

The incoming sediment coefficient (ISC) is an important parameter that represents the coordination of incoming water and sediment conditions, and it is an important parameter that affects the sediment transport capacity of a river. It denotes the sand content per unit flow, indicating the concurrence of water and sand in the river. A lower incoming sand coefficient signifies easier river flushing and a more favorable alignment of water and sand conditions. The value determines the variation characteristics of sediment transport and channel erosion and deposition. In alluvial rivers, the relationship between the ISC and the amount of channel erosion and deposition is often analyzed to determine the effect of different water–sand combinations on the river channel. The ISC can be calculated as follows:

$$\xi = S/Q \tag{2}$$

where S is the sediment concentration of the suspended load, kg/m^3; and Q is the discharge, m^3/s.

3.3. Mann–Kendall Test

The Mann–Kendal l nonparametric rank order correlation test is used to establish the M–K test statistic for a sequence of hydrological variables.

$$U = \tau/[Var(\tau)]^{1/2} \tag{3}$$

$$\tau = 4P/N(N-1) \tag{4}$$

$$Var(\tau) = 2(2N+5)/9N(N-1) \tag{5}$$

where P is the number of $(x_i < x_j)$ in the sequence of hydrological variables $(x_i, x_j, i < j)$; N is the total number of sequences of hydrological variables.

U is the standard normal distribution, $U > 0$, the hydrological series is increasing trend; $U < 0$, the hydrological series is decreasing trend. The larger $|U|$ is, the more significant is the trend of the hydrological series.

Let the confidence levels be $\alpha = 0.05$. From the normal distribution table, U is 1.96.

3.4. Data Sources

In this study, the measured runoff and sediment load data of four hydrological stations in the Inner Mongolia section of the Yellow River, including Shizishan, Bayangaole, Sanhuhekou, and Toudaoguai, were collected for analyzing the relationship between water and sand changes during the period of 1950–2020, and the data were obtained mainly from the Hydrological Yearbook of the People's Republic of China.

To comprehensively investigate flushing and siltation characteristics in diverse river sections, this study compiled measured data encompassing cross-sectional morphology (elevation), consistent-flow water levels, flood flow, and sediment load data from Maobula Kongtui and Xiliugou at the hydrological stations. These data, obtained directly from the hydrological stations, were supplemented by information on wind-formed sands and tributaries' uninformative Kongtui data, acquired through a literature review, aiding in the derivation of sand quantities entering the Yellow River.

4. Results

4.1. Trends of Runoff and Sediment Load Variations

The average annual runoff values at the Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai hydrological stations in the Inner Mongolia reach from 1950 to 2020 were 27.671 billion m^3, 22.45 billion m^3, 21.49 billion m^3, and 21.6631 billion m^3, respectively (Figure 2a). The sediment loads at each hydrological station were 105 million tons, 965 million tons, 918 million tons, and 986 million tons, respectively (Figure 2b). The runoff and sediment transport values at each hydrological station fluctuated with peaks and valleys at different times but showed an overall decreasing trend. Runoff decreased from 32.625 billion m^3, 27.176 billion m^3, 26.983 billion m^3, and 27.103 billion m^3 in the 1960s to 25.485 billion m^3, 18.602 billion m^3, 18.801 billion m^3, and 18.686 billion m^3, respectively, from 2000–2020, which represents a decrease ranging from 22% to 32% at the Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai hydrological stations. The sediment load at each station decreased from 171 billion t, 148.8 billion t, 173 billion t, and 182.7 billion t in the 1960s to 0.601 billion t, 0.405 billion t, 0.520 billion t, and 0.528 billion t, respectively, from 2000–2020, which represents a decrease of approximately 65~73%.

The ISC is more sensitive to channel erosion and deposition than to runoff or sediment transport. The average annual sediment inflow coefficients at the Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai hydrological stations from 1950 to 2020 were 0.004614767, 0.006486497, 0.00582, and 0.00589 (kg·s)/m^6, respectively. The change process of the ISC was basically similar at each station (Figure 3). For example, at the Bayangaole hydrological station, the ISC was high and increased annually before 1960. In addition, it was low and not highly variable from 1961–1986. After 1986, it continuously increased and reached a maximum value of 0.0225 (kg·s)/m^6 in 1997, which is 3.47 times the average value, indicating that the water–sand relationship was not harmonized during this period. Since 2005, the ISC has progressively decreased, indicating more favorable conditions for incoming water and sediment in the river.

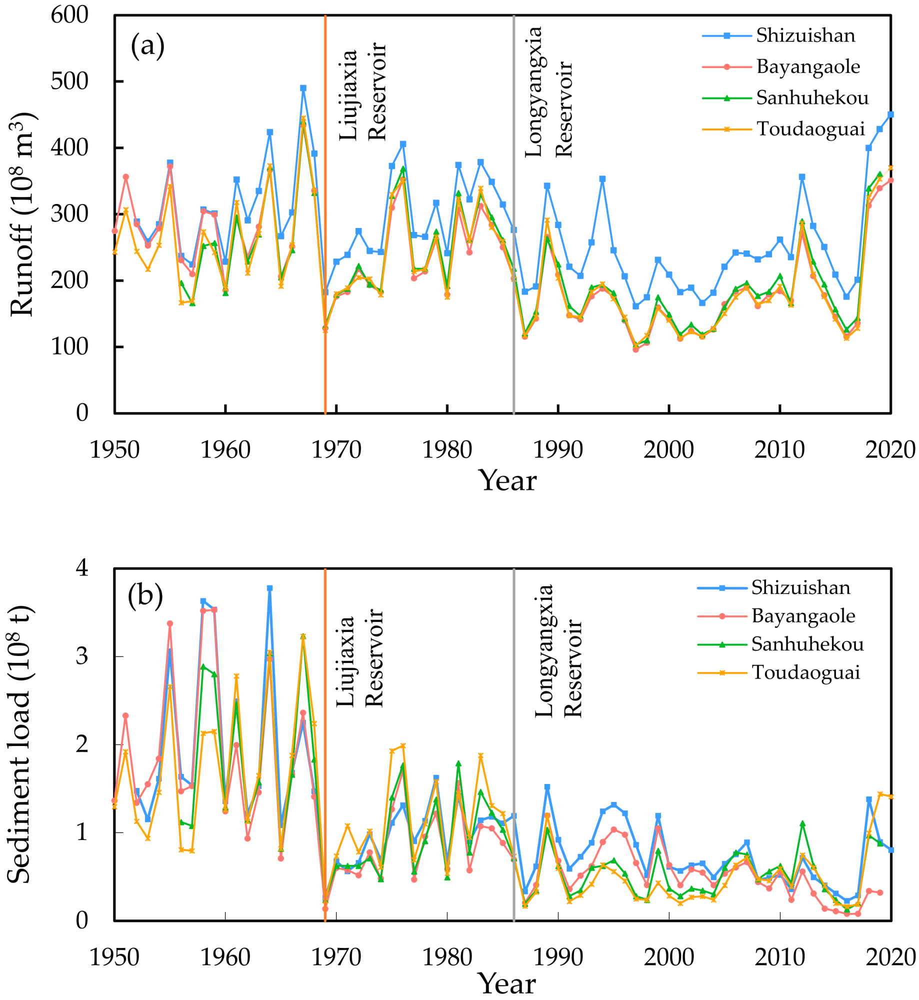

Figure 2. Runoff and sediment transport in the Inner Mongolia section of the Yellow River: (**a**) Runoff and (**b**) sediment load.

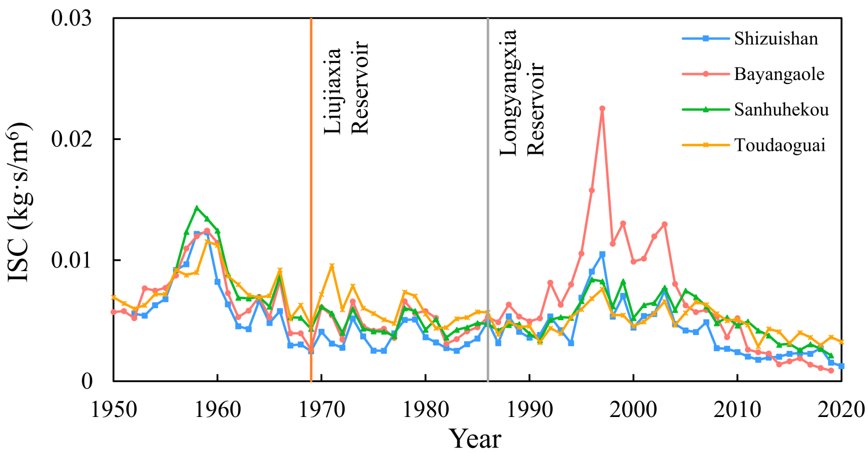

Figure 3. ISC in the Inner Mongolia section of the Yellow River.

4.2. Mutation Test of Runoff and Sediment Load Variations

The M–K statistical variables of runoff at Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai are basically the same, experiencing the process of decreasing-increasing-decreasing-increasing before 1986, and then decreasing in 1986, with the absolute value less than 1.96 before 1996, and then continuing to decrease after 1996, with a rebound but with final values of −2.23, −4.12, −2.77, and −3.27, respectively (Figure 4a), with absolute values greater than 1.96. The corresponding double cumulative curves continued to deviate downward to the right after 1995, indicating that the annual runoff volume at each station had a decreasing trend (Figure 5).

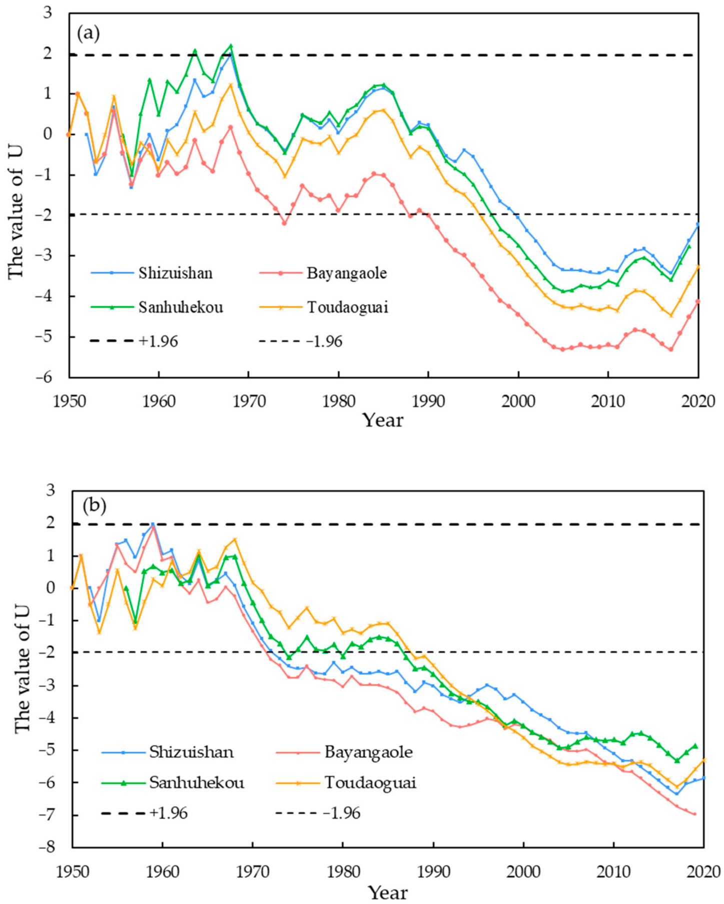

Figure 4. M–K test for runoff and sediment transport in the Inner Mongolia section of the Yellow River: (**a**) runoff and (**b**) sediment load.

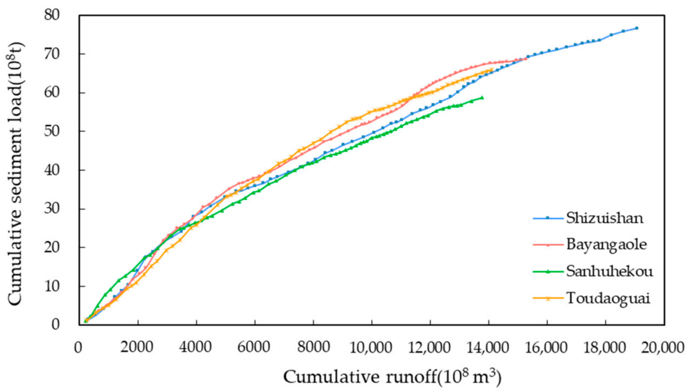

Figure 5. Changes in runoff and sediment transport accumulation in the Inner Mongolia section of the Yellow River.

Although the M–K statistical variables of sediment load at Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai began to decrease at the end of the 1960s, the absolute values were still less than 1.96 before 1973 and 1986, respectively, and then continued to decrease to −5.86, −6.98, −4.86, and −5.30 (Figure 4b), and the bicumulus lines of sand and water were all upwardly convex. This indicates that the annual sand transport at the two stations is obviously decreasing (Figure 5).

4.3. Amount of Sand Entering the Inner Mongolia Reach

The southern bank of the Inner Mongolia section of the Yellow River is close to the Kubuqi Desert, which is one of the main windy desert areas of the Yellow River [38]. There are three ways for wind-generated sand to reach the Inner Mongolia reach: (1) Sand from the Kubuqi Desert is blown directly into the Yellow River, whereby the sands entering the Yellow River are coarse, basically deposited in the riverbed, and seldom form suspended materials. (2) Sediment flows into the Yellow River through the ten tributaries of the Kubuqi Desert. Sand is blown by wind into the tributaries and then carried by floodwaters into the main stream of the Yellow River during flood periods. After complex sorting, coarse sediment is deposited in the riverbed, while some of the fine sediment forms into a suspended mass that is carried by the river to be deposited downstream. (3) Sand originating from quicksand covering the riverbank alluvial plain is blown into the main stream by strong winds. These sediments comprising relatively coarse particle sizes are the main component of the sediment deposited in the Inner Mongolia River section [39,40].

Sediment enters the Bayangaole–Sanhuhekou reach of the Yellow River mainly through the first and third pathways. According to the data, the annual amount of sand blown by wind entering the Ningmeng River reach reached 37.1 million tons, 15.4 million tons entered the Qingtongxia–Shizuishan reach, 18 million tons entered the Shizuishan–Bayangaole reach, and 3.7 million tons entered the Bayangaole–Sanhuhekou reach [41].

Sediment entered the Sanhuhekou–Toudaoguai reach mainly through the second pathway, which involves the convergence of the tributaries of Shidakongdui. Water and soil loss in the Shidakongdui basin is severe, accounting for 82% of the watershed area. In addition, the river reach exhibits a high gradient, and the water flow is rapid, leading to the tributaries carrying a large amount of sediment into the Yellow River during the flood season. However, among the ten tributaries, only two tributaries, namely Maobula Kongdui and Xiliugou, have sediment observation data. Therefore, the sediment transport amount from each tributary was measured separately based on the different geomorphological and rainfall conditions, and the sediment transport was subsequently summed to obtain the total annual sediment transport (Figure 6). The average annual sand inflow from the tributaries of Shidakongdui into the Inner Mongolia reach reached approximately 0.237 billion t. This inflow was mainly concentrated in a few years, while the inflow in the remaining years was very low [42].

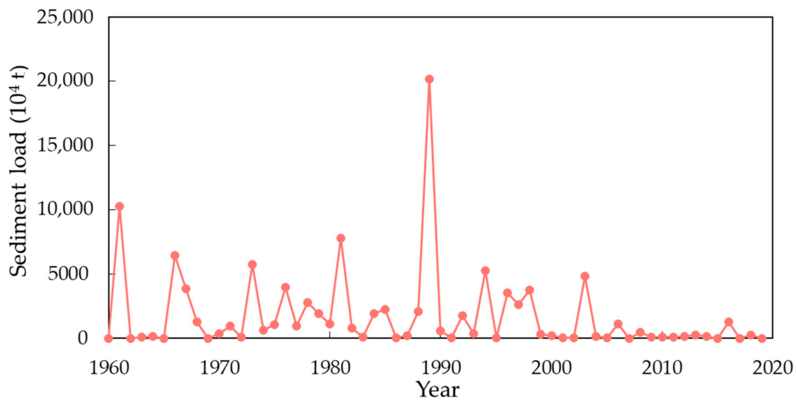

Figure 6. Sediment load in the tributaries of Shidakongdui.

4.4. Change in Siltation

4.4.1. Siltation in the River Reaches

The average annual siltation in the Inner Mongolian River channel from 1950 to 2020, calculated using the sediment transport balance method, reached 0.144 billion t (Figure 7). Notably, the river channel was dominated by scouring or a balance between scouring and siltation from 1960 to 1985, siltation from 1986 to 2004, and siltation after 2005. Among the different reaches, the downstream reaches were more susceptible to siltation than the upstream reaches which are influenced by the confluence of the tributaries of Shidakongdui. The average annual siltation amounted to 0.011 billion tons in the Bayangaole–Sanhuhekou reach and 0.133 billion tons in the Sanhuhekou–Toudaoguai reach.

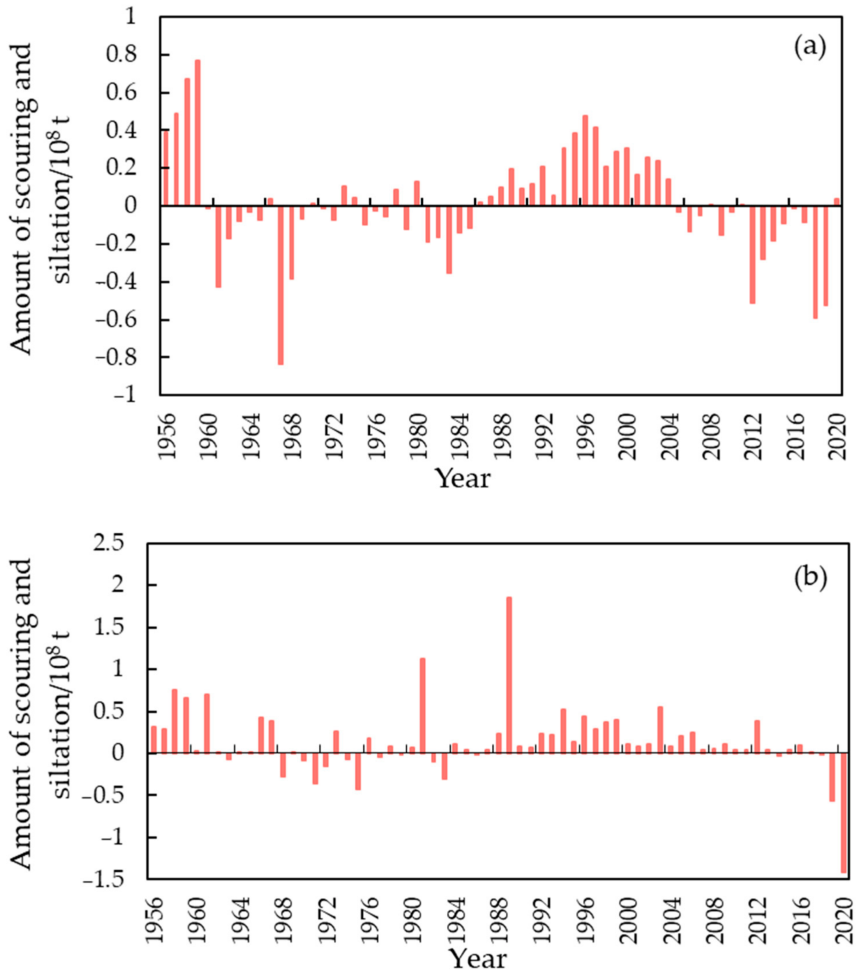

Figure 7. Erosion and sedimentation in the Inner Mongolia River section: (**a**) Bayangaole–Sanhuhekou reach; (**b**) Sanhuhekou–Toudaoguai reach (note: "+" denotes sedimentation; "–" denotes erosion).

4.4.2. Siltation in the Hydrological Station Section

The evolution of channel erosion and siltation is generally manifested as adjustments in the cross-sectional morphology, increase and decrease in water levels at the same flow rate, and changes in the river regime. Figure 8 shows the cross-sectional morphology of the Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai hydrological stations. The figure reveals the following:

(1) The cross section at the Shizuishan hydrological station is a U-shaped cross section with a basically constant cross-sectional morphology, with siltation dominating from 1992 to 2004 and scouring dominating from 2004 to 2020, and the depth of the main trough in 2020 was greater than that in 1992.

(2) The cross section at the Bayangaole hydrological station is a deviated V-shaped cross section, the main trough shifted to the right from 1992 to 2005, and the right bank beach was seriously silted and elevated, with an average silt thickness of approximately 1.1 m. The right side of the section was gradually washed away from 2005 to 2020.

(3) The cross section at the Sanhuhekou hydrological station was seriously silted from 1987–2002, with the width of the main channel decreasing by approximately 150 m. The main channel generally shifted to the left and silted from 2002–2010, while the cross section was flushed and silted with little change from 2010–2015. However, the cross section was seriously scoured after 2015, and the cross-sectional area below the post flood elevation of 1019.37 m in 2020 increased by approximately 880 m^2 compared to that in 2002.

(4) Compared with those during the same period in 1987, the main channel of the cross section at the Toudaoguai hydrological station shifted to the right in 2005, the left side of the channel was elevated by siltation, and the right side was flushed. However, there was little change in erosion and sedimentation in the cross section from 2005 to 2020.

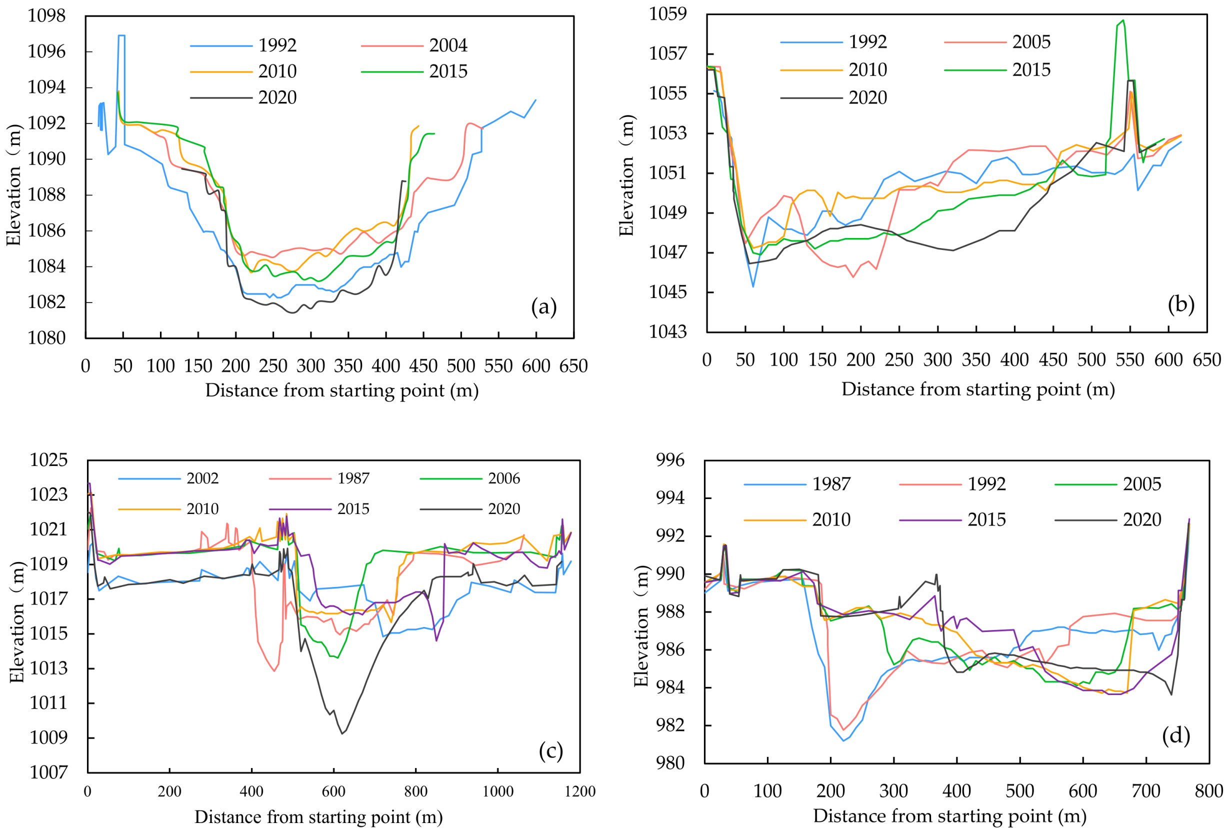

Figure 8. Cross-sectional morphology of the typical hydrological stations: (**a**) Shizuishan hydrological station, (**b**) Bayangaole hydrological station, (**c**) Sanhuhekou hydrological station, and (**d**) Toudaoguai hydrological station.

The increases and decreases in the water level (with the same discharge) in the cross section not only reflect the changes in riverbed elevation and discharge area but also reflect the changes in the flood carrying capacity and adjustment in riverbed scouring and siltation. The water level changes (a flow rate of 1000 m^3/s) at the four hydrological stations in the Inner Mongolia reach are shown in Figure 9. The water level decreased from 1950 to 1985, increased from 1986 to 2004, and subsequently decreased after 2005.

(1) The average water level (at the same discharge) in the 1950s at the Shizuishan hydrological station was 1086.14 m, and the amplitude of river siltation was approximately

0.2 m. Since the construction of the Liujiaxia and Longyangxia reservoirs upstream, the siltation in this section has been basically balanced, and the change in the water level varied between 0 and 0.1 m from 1960 to 1985, with an average of 1085.97 m. From 1987 to 2020, the water level slightly increased, with an average water level of 1086.02 m. In the long term, the water level in this river section has remained relatively stable.

(2) The changes in the water level (at the same discharge) at the Bayangaole and Sanhuhekou hydrological stations were basically the same over time. From 1961 to 1986, the total amount of erosion in the Bayangaole–Sanhuhekou reach was 0.30 billion tons, and the water levels at the two hydrological stations decreased by 1.09 and 0.84 m, respectively. From 1984 to 2004, the total amount of sedimentation in the Bayangaole–Sanhuhekou reach was 0.22 billion tons, and the water levels at the two hydrological stations increased by 1.31 and 0.66 m, respectively. From 2005 to 2020, the total amount of erosion in the Bayangaole–Sanhuhekou reach was 0.16 billion tons, and the water levels at the two hydrological stations decreased by 2.06 and 0.68 m, respectively.

(3) The change process of the water level at the Toudaoquan hydrological station varied. The water level (under the same discharge conditions) did not remain constant but rather fluctuated within a relatively small range. This occurs because the erosion benchmark section in the Inner Mongolia River section is located approximately 30 km below the Toudaoquan hydrological station, so the water level in this section fluctuates within only a small range.

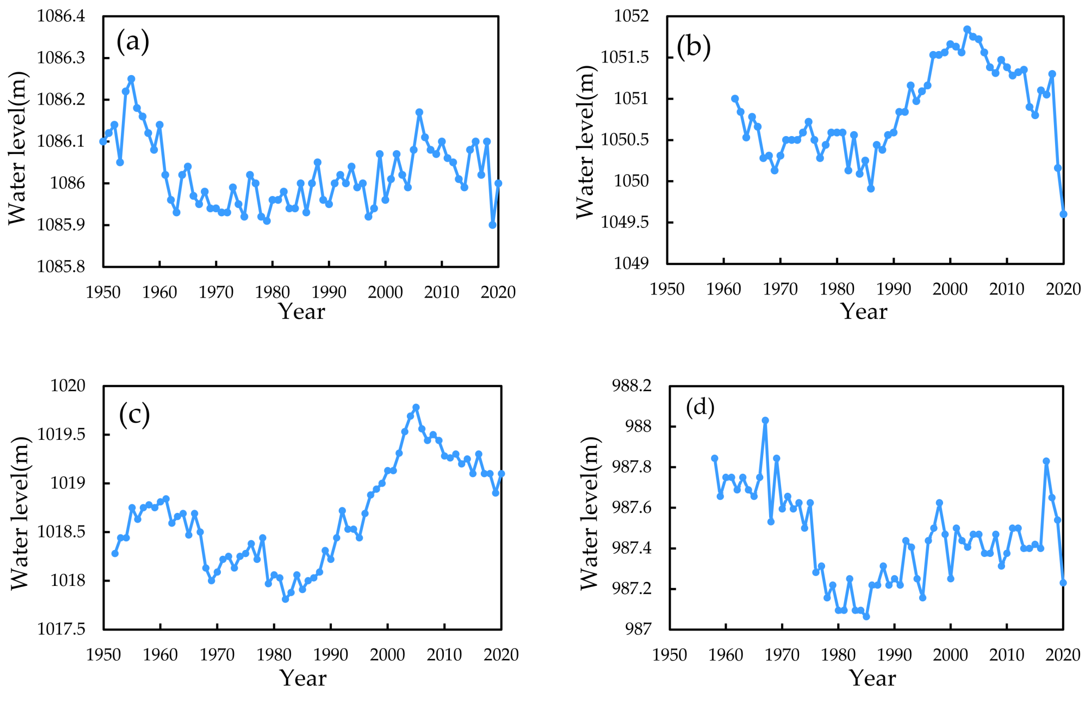

Figure 9. Water level (at a flow rate of 1000 m^3/s) after flooding in the Inner Mongolia section: (**a**) Shizuishan hydrological station, (**b**) Bayangaole hydrological station, (**c**) Sanhuhekou hydrological station, and (**d**) Toudaoguai hydrological station.

5. Discussion

5.1. Reliability Analysis

Relevant studies have shown that the critical ISC of the Inner Mongolia reach for the balance between erosion and siltation during different periods ranges from 0.004 to 0.009 (Table 2). The critical ISC calculated in this paper ranged from 0.0037 to 0.0073 from 1952 to 2020, which is basically consistent with the results of previous studies [43,44].

In addition, the small specific drop, low flow velocity, and large sediment grain size in the Inner Mongolia reach resulted in a low sediment transport capacity of the river. The critical ISC of the Inner Mongolia reach for the balance between erosion and siltation was only approximately one third of that of the lower Yellow River during the flood period, increasing the sensitivity of this reach to incoming water and sand changes [48]. Therefore, optimizing the incoming water and sand conditions can easily affect the river erosion and sedimentation conditions by regulating upstream reservoirs.

Table 2. Critical ISC of the Inner Mongolia reach for the balance between erosion and siltation.

Year	Reach	Critical *ISC* (kg·s/m^6)	Reference
1952–2003	Inner Mongolia reach	0.005~0.009	[45]
1950–2010	Bayangaole–Sanhuhekou reach	0.006	[46]
1952–2012	Bayangaole–Sanhuhekou reach	0.007	[47]
	Sanhuhekou–Toudaoguai reach	0.005	

5.2. Trend Analysis of Runoff and Sediment Load Variations

The runoff process and values were similar at the Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai hydrological stations. After the construction of the Liujiaxia Reservoir in 1968, the annual runoff from 1969–1986 decreased by 14%, 15%, 14%, and 17% compared to that from 1960–1968 (Figure 2a). After the Longyangxia Reservoir was impounded and utilized in 1986, the annual runoff from 1987–2000 decreased by 21%, 33%, 32%, and 32% compared to that from 1969–1986. This occurs because the Liujiaxia Reservoir provides a low capacity and limited ability to regulate the annual runoff. In contrast, the Longyangxia Reservoir provides a higher capacity and is a multiyear regulating reservoir, with a greater impact on the annual runoff. After 2010, there was a trend toward an increasing annual runoff at each station as rainfall increased in the watershed.

The sediment load decreased overall at each hydrological station, but the magnitude of the decrease varied during different periods. The Longyangxia Reservoir focuses on regulating runoff, and the sediment retention effect of the Liujiaxia Reservoir is highly significant. The annual sediment loads at the hydrological stations from 1969–1986 decreased by 48%, 53%, 51%, and 45% compared to those from 1960–1968 before the construction of the Liujiaxia Reservoir. The annual sediment loads at the hydrological stations from 1987 to 2000 decreased by 8%, 21%, 47%, and 61% compared to those before the operation of the Longyangxia Reservoir (Figure 2b).

It was found that the decrease in sand delivery from 1969 to 1986 was 34 percentage points higher than the decrease in runoff, and the decrease in sediment load from 1987 to 2000 was 4 percentage points higher than the decrease in runoff, which is relatively close to the decrease in runoff. However, the decrease in sediment load at Toudaoguai station from 1987 to 2000 was 29% higher than the decrease in runoff, and the decrease in sediment at Bayangaole station was 15% lower than the decrease in runoff. This is closely related to reservoir regulation and rainfall. Liujiaxia Reservoir is an incomplete annual regulating reservoir, with an effective regulating capacity of 4.15 billion m^3, which is relatively small and has a relatively small effect on the regulation of runoff, while its effect on the regulation of sediment is more obvious. Longyangxia Reservoir is a multi-year regulation reservoir, with effective regulation of the reservoir capacity of 19.36 billion m^3, whereby as the reservoir capacity is larger, the larger the impact on the annual runoff [34]. From the water–sand change mutation test, two of the mutation points are consistent with the time nodes when Longyangxia Reservoir and Liujiaxia Reservoir were put into operation, which also indicates that the reservoir regulation has a greater impact on the water–sand relationship of the river downstream of the project [28].

5.3. Reasons for the Changes in River Siltation

The water–sand process is the driving condition for river evolution, and the incoming sediment load and the average annual amount of scouring and siltation in the Inner Mongolia reach during the different periods are given in Table 3.

Table 3. Incoming sediment load and the average annual erosion and sedimentation volume in the Inner Mongolia reach.

Year	Sediment Load (Billion Tons)					Erosion and Sedimentation Volume (Billion Tons)	
	Shizuishan	Bayangaole	Sanhuhekou	Toudaoguai	Shidakongdui	Bayangaole–Sanhuhekou Reach	Sanhuhekou–Toudaoguai Reach
1961–1968	1.94	1.69	1.97	2.10	2768.44	−0.24	0.15
1969–1986	0.97	0.84	0.93	1.10	1865.41	−0.06	0.01
1987–2004	0.83	0.64	0.46	0.39	2563.68	0.22	0.32
2005–2020	0.603	0.368	0.582	0.614	266.194	−0.16	−0.0428
1950–2020	1.05	0.965	0.9177	0.9865	1764.41	0.011	0.1336

(1) From 1961 to 1968.

From 1961 to 1968, several reservoirs in the Inner Mongolia River reach were put into operation, with a scouring volume of 24 million tons in the Bayangaole–Sanhuhekou reach and a siltation volume of 15 million tons in the Sanhuhekou–Toudaoguai reach. Although the amount of water and sand in the main stream and the amount of sand in the tributaries of Shidakongdui were large during this period, the average annual siltation was very low, which is basically consistent with that during the natural period. The influence of human activities during this period was relatively limited. Although the upstream Yanguoxia Reservoir, Qingtongxia Reservoir, and Sanshenggong Water Conservancy Hub were built and put into operation in 1961, 1967, and 1961, respectively, the regulating capacities of the Yanguoxia, Qingtongxia, and Sanshenggong reservoirs are 0.22, 0.61, and 0.08 billion m^3, respectively. They are all power stations without storage and with a low ability to regulate the flow rate and intercept the sediment load. The impact of reservoir construction on water–sediment processes during this period was insignificant. Therefore, the water–sediment conditions of the river during this period were similar to those during the natural period.

(2) From 1969 to 1986 (reservoir impoundment).

The 1969 to 1986 period was the operation period of the Liujiaxia Reservoir, with an annual erosion volume of 0.06 billion tons in the Bayangaole–Sanhuhekou reach and an annual siltation volume of 0.01 billion tons in the Sanhuhekou–Toudaoguai reach. With the construction of water conservancy projects in the upper reaches of the Yellow River, the reservoir's ability to store water and stop sand has gradually increased, and the amount of incoming sand has obviously decreased, whereby the annual average silt deposition of sediment in the Liujiaxia Reservoir is 0.58 billion m^3 [34]. Moreover, the amount of sand originating from the tributaries of Shidakongdui decreased during this period. The Inner Mongolia reach experienced overall erosion, indicating that the impact of the incoming sediment load on scouring and siltation was very significant.

(3) From 1987 to 2004 (joint scheduling of reservoirs).

After 1986, the joint use of the Longyangxia and Liujiaxia reservoirs affected the water and sand conditions in the Inner Mongolia River section, resulting in siltation in the river section during this period, with siltation amounting to 0.22 billion tons in the Bayangaole–Sanhuhekou reach and 0.32 billion tons in the Sanhuhekou–Toudaoguai reach. This occured because reservoir regulation caused a reduction in the amount of water and high-flow processes during the flood season, weakening the dynamic conditions for sediment transport and triggering siltation in the river. For example, before 1986, the flood peak flow at the Shizuishan Station was higher than 2000 m^3/s in 92% of the years, while after 1986, the proportion decreased to 25% due to the reduction in the peak flow caused by the joint use of the reservoirs (Figure 10). Moreover, the amount of sand fed into the Yellow River stemming from the tributaries of Shidakongdui was larger during this period, especially in 1989, 1994, 1998, and 2003, leading to obvious siltation in the river channel.

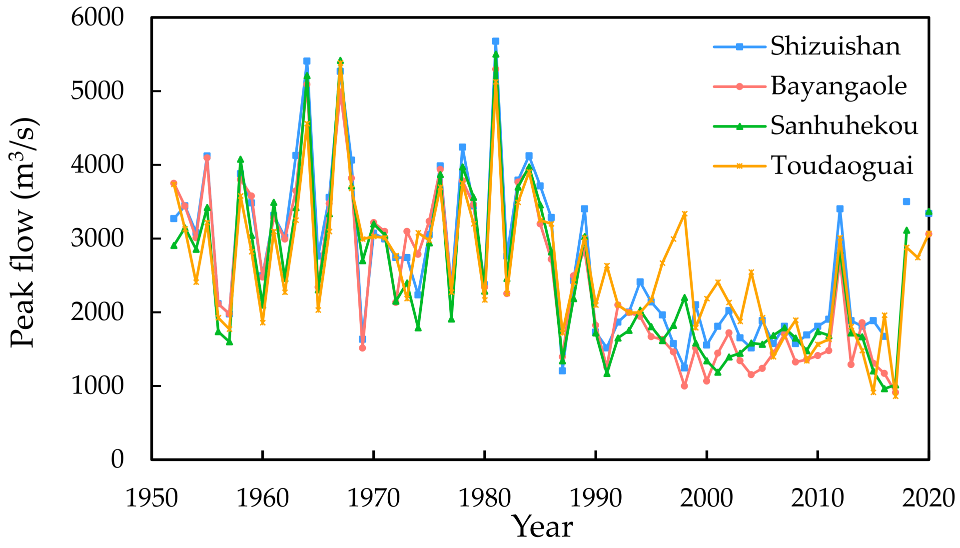

Figure 10. Peak flow in the Inner Mongolia reach.

(4) From 2005 to 2020.

From 2005 to 2020, the Bayangaole–Sanhuhekou reach was dominated by scouring, with an average annual erosion volume of 0.16 billion tons, while the Sanhuhekou–Toudaoguai reach experienced scouring or siltation, with an average annual erosion volume of 0.0428 billion tons. This mainly occured because since the 21st century, the sediment load in the upper reaches of the Yellow River has significantly decreased, reaching only approximately 20% of the amount from 1959–1968. In addition, the river experienced high-flow processes in 2010, 2018, and 2020, imposing greater scouring effects on the river.

5.4. Response of River Channel Siltation and Water–Sediment Processes

The morphology of a natural river is shaped by the movement of water and sediment under certain boundary conditions. The incoming water is the main driving force of sediment transport, and the incoming sediment is the main factor of erosion and sedimentation in rivers. The river channel responds to accommodate this change when the ISC changes. In general, river erosion and sedimentation are influenced not only by single factors, such as the flow rate or sediment concentration, but also by complex water–sediment relationships. The correlations between the erosion and siltation volume per unit of water volume and the ISC in the Inner Mongolia reach during the different periods are shown in Figure 11.

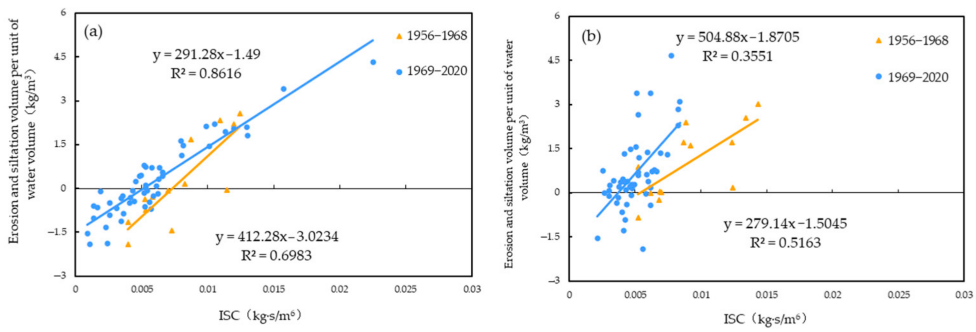

Figure 11. Relationships between the erosion and siltation volume per unit of water volume and the ISC in the Inner Mongolia reach: (**a**) Bayangaole–Sanhuhekou reach; (**b**) Sanhuhekou–Toudaoguai reach.

There exists a favorable correlation between the siltation volume per unit water volume and the ISC in the two reaches of Inner Mongolia. With increasing ISC, channel siltation increases, while when the ISC is low, channel scouring may occur. Therefore, the critical ISC at the equilibrium of flushing and siltation in the river section can be calculated for ΔW_SF equal to zero. According to the regression equation, from 1952–1968 and 1969–2020, the critical ISC at the balance between erosion and siltation was 0.0073 and 0.0051 kg·s/m^6, respectively, in the Bayangaole–Sanhuhekou reach, and 0.0053 and 0.0037 kg·s/m^6, respectively, in the Sanhuhekou–Toudaoguai reach (Table 4).

Table 4. Regression equation between the erosion and siltation volume per unit of water volume and the ISC in the Inner Mongolia reach.

Reach	Year	Regression Equation	Correlation Coefficient	Critical *ISC*
Bayangaole–Sanhuhekou reach	1952–1968	$\Delta W_{SF} = 412.29\xi - 3.02$	0.70	0.0073
	1969–2020	$\Delta W_{SF} = 289.99\xi - 1.47$	0.86	0.0051
Sanhuhekou–Toudaoguai reach	1952–1968	$\Delta W_{SF} = 279.14\xi - 1.505$	0.52	0.0053
	1969–2020	$\Delta W_{SF} = 504.88\xi - 1.87$	0.36	0.0037

In recent years, Bayangaole–Sanhuhekou reach flushing occurs mainly by the upper reaches of the water and sand conditions, while Sanhuhekou–Toudaoguai reach flushing occurs by the wind-sand and sediment inflow from the Shidakongdui, in addition to the upper reaches of the water and sand conditions. The main reason for the recent massive siltation of fine and medium sands is the reduction in water volume and high flow processes during the flood season of the main stream, and the weakening of the power of sediment transport by the water flow. Based on the above analysis, to control the siltation of the river channel in the Inner Mongolia river section, it is advisable to take comprehensive management measures, in accordance with the management idea of "increasing water, reducing sediment, and regulating water and sediment". Firstly, optimize the operation of the upstream terrace reservoirs, increase the discharge flow during the flood season, and reduce the siltation of the river channel [34]. Secondly, the Kubuqi Desert and the upstream areas of the Shidakongdui should be subject to a comprehensive erosion control project, planting shrubs and grasses in the desert areas, strengthening the construction of check dams in the upstream gully areas of Shidakongtui, restoring the vegetation, and intercepting the flood sediments.

5.5. Research Shortcomings and Prospects

The commonly used methods for calculating the amount of river erosion and siltation include the sediment-transport balance method, cross-sectional method, and mathematical modeling. The sediment-transport balance method provides satisfactory spatial and temporal continuity levels and can yield siltation data that reflect the characteristics of river channel siltation within a short period. However, this method requires the consideration of numerous factors and often results in a lower accuracy due to insufficient or erroneous measured data. The cross-sectional method aims to analyze river channel siltation by using a typical large measured cross-sectional set of information, which is useful for analyzing the siltation distribution in a certain cross section or the siltation volume in the river channel between adjacent cross sections. However, this method also suffers limitations, with poor spatial and temporal continuity levels and high measurement effort. This study showed that in the Inner Mongolia River channel, the calculation results of these two methods are similar; each exhibits unique characteristics and can be used as a complement to each other [49]. Therefore, the sediment-transport balance method was adopted in this paper to calculate erosion and siltation in the Inner Mongolia River channel and analyze the erosion and siltation conditions at typical hydrological station sections using cross-sectional morphology data.

In this study, the amount of sand entering the Yellow River in the Inner Mongolia River section was calculated by using the multiyear average without considering the specificity of each year. In addition, the sediment discharge in large irrigation areas along the Inner Mongolia River is insignificant and exerts a relatively limited impact on the overall results [50]. Therefore, the calculations of river erosion and sedimentation did not consider the impacts of water and sediment diversion.

In this paper, the correlation between the average annual sediment load and the ISC was used to calculate the critical threshold for balancing Inner Mongolia River channel siltation. However, siltation in the Inner Mongolia reach is mainly concentrated during the flood season [33], and more accurate results can be obtained if water and sand data for the flood season are used in future studies.

6. Conclusions

This study analyzed the characteristics of runoff and sediment load variations and the evolutionary pattern of siltation in the Inner Mongolia River section by trend analysis methods, Mann–Kendall test methods, the sediment load transport rate method, and the water level–flow relationship. Some central conclusions can be summarized as follows:

(1) The multiyear average runoff values at the Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai hydrological stations in the Inner Mongolia section were 27.671 billion m^3, 22.45 billion m^3, 21.49 billion m^3, and 21.6631 billion m^3, respectively. The multiyear average sediment loads at each hydrological station were 105 million tons, 965 million tons, 918 million tons, and 986 million tons, respectively. The water and sediment loads at the various hydrological stations in the Inner Mongolia River section changed significantly from the 1960s to after 2000, with the runoff decreasing by approximately 22% to 32% and the sediment load decreasing by approximately 65% to 73%.

(2) The decreases in the upstream runoff and lower peak flow due to the joint use of the Longyangxia Reservoir and Liujiaxia Reservoir resulted in severe siltation in the Inner Mongolia reach. The average annual siltation volumes in the Bayangaole–Sanhuhekou reach and Sanhuhekou–Toudaoguai reach from 1960 to 2020 were 0.011 billion tons and 0.133 billion tons, respectively.

(3) In the Inner Mongolia reach, the sedimentation amount per unit water volume increased with increasing ISC. The critical sediment load coefficients of the Bayangaole–Sanhuhekou reach and Sanhuhekou–Toudaoguai reach were 0.0073 and 0.0051 $kg{\cdot}s/m^6$, respectively, from 1952 to 1968, and 0.0053 and 0.0037 $kg{\cdot}s/m^6$, respectively, from 1969 to 2020.

(4) Siltation changes in the Inner Mongolia section of the Yellow River are affected by wind-sand and sediment inflow from the Shidakongdui, in addition to upstream water and sand conditions. The siltation of the river is slowed down by optimizing the operation of the upstream terrace reservoirs and carrying out comprehensive erosion control projects in the Kubuqi Desert and Shidakongdui.

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