

Impact of the Xiaolangdi Reservoir Operation on Sediment Transport and Aquatic Organisms in the Lower Yellow River

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Abstract: The operation of reservoirs has prompted rivers to transition from natural ecosystems to 'natural-artificial' composite ecosystems, which has not only altered the water-sediment processes but has also affected river ecology in the downstream river channels. To reveal the impact of the Xiaolangdi Reservoir (China) on sediment transport and aquatic organisms in the Lower Yellow River (LYR), this paper analyzes the changes in the water-sediment processes and sediment transport characteristics before and after the construction of the reservoir, based on measured water-sediment data from 1960 to 2023. It derives a theoretical expression for the sediment discharge ratio (SDR) of flood events based on the sediment transport rate equation and evaluates the living environment of aquatic organisms in the LYR. The results indicate that after the construction of the Xiaolangdi Reservoir, the range of average flow discharge during floods decreased, the frequency of high sediment concentration floods significantly declined, and floods with average sediment concentration below 20 kg/m³ accounted for approximately 89.03%. The SDR of flood events significantly correlates positively with the average flow discharge and the runoff variation coefficient. Conversely, it negatively correlates with the average sediment concentration and the incoming sediment coefficient. The operation of the Xiaolangdi Reservoir has increased the sediment transport capacity of the river upstream of Gaocun and decreased the downstream of Gaocun. Additionally, the water-sediment process after the construction of the Xiaolangdi Reservoir has improved the living environment for aquatic organisms, which is conducive to restoring biodiversity and improving the ecological environment of the river.

Keywords: Sediment transport; Aquatic organisms; Reservoir operation; Sediment discharge ratio; The Lower Yellow River

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1. Introduction

Since the dawn of human civilization, society has constructed a history of survival and growth around rivers, developing methods to utilize river runoff and mitigate water shortages and drought disasters by creating reservoirs [1]. Since the 1950s, large-scale reservoir construction has been undertaken globally [2]. There are over 45,000 large

reservoirs, each exceeding a height of 15 m, which are primarily distributed across 140 countries [3,4]. The construction of river reservoirs has altered downstream water-sediment processes, disrupted the original hydrological balance [5], and prompted various adjustments in the sediment transport characteristics and river ecology of downstream rivers [6], not only major rivers like the Mississippi River [7], Colorado River [8], Yellow River [9,10], and Yangtze River [11,12]. Following the construction of reservoirs on alluvial rivers, the processes and mechanisms of sediment transport in downstream rivers have consistently been a topic of significant interest among river scholars and engineers [5,13]. The impact of large reservoirs on sediment transport characteristics is mainly observed in water-sediment conditions, and channel boundaries [14,15]. Regarding water-sediment conditions, the incoming water is primarily defined by flood interception, lowered peak flow discharges, water storage during plentiful periods to aid drier seasons, and a notable increase in mid-flow discharge duration. In contrast, the incoming sediment exhibits a marked reduction in both the downstream sediment load and the size of the suspended fine-grained particles [4]. Concerning riverbed boundaries, on one hand, after constructing the reservoir, it will intercept sediment, and the downstream channel will receive insufficient fine sediment recharge. This causes the river to continue eroding, which leads to the coarsening of the riverbed. As the riverbed resistance increases, the flow velocity decreases, resulting in a significant reduction in sediment transport efficiency [16]. On the other hand, the performance of the continuous erosion effect shows that the downstream channel has both lateral widening and increased vertical depth. However, the overall depth increase is significantly greater than the width increase, indicating that the river continues to erode downward mainly. From the near-dam section onward, the flood discharge capacity continues to increase significantly [17,18]. In addition, the construction and operation of reservoirs lead to the redistribution of water and sediment [19], which alters the processes of river material transport [20], hydrological cycle [21], and biological life activities [22], resulting in changes in the ecological structure of the river environment. The effects of reservoir operations on downstream sediment transport and aquatic organisms are a crucial concern when developing water and sediment control measures aligned with current river erosion and aggradation patterns. This also aims to enhance the water environment in the basin, which remains a crucial issue in water science both nationally and internationally [5,6,23].

The Lower Yellow River (LYR) starts from the Tiexie downstream of Xiaolangdi Dam, joins tributaries such as the Yiluo River and the Qin River along the way, passes through the North China Plain, and flows into the Bohai Sea of China near Lijin [9,10]. The Yellow River has typically low runoff and a high sediment load, leading to an imbalance between water and sediment. Historically, large sediment loads have accumulated in the LYR, forming the famous "hanging river on the ground" [24,25]. The Xiaolangdi Reservoir (China) started impounding water in October 1999. The downstream river reach was reshaped by the water-sediment regulation of the reservoir. This effectively reduced aggradation in the LYR and restored the sediment transport capacity [26,27]. Fish habitat stabilization is essential for the recovery of fish resources, and proper flows are a key hydrologic factor in maintaining habitat scale [28]. In the 1990s, the LYR frequently dried up, causing severe damage to fish resources [29]. In recent years, ecological regulation of the Xiaolangdi Reservoir has increased the protection of the ecological base flow at key cross-sections of the downstream river from about 56% in the 1990s to 100% today [30,31]. At the same time, through continuous water-sediment regulation, the flow capacity of the main channel has increased from 1,800 m³/s in 2002 to 4,700 m³/s in 2024, providing a stable habitat for fish growth and reproduction [23]. Research shows that since the water-sediment regulation of Xiaolangdi Reservoir, fish biodiversity in the LYR has recovered significantly [30]. The sediment transport characteristics and the changes in the river

ecological environment in the LYR due to the regulation and operation of the Xiaolangdi Reservoir have consistently captured attention. Accurately predicting the sediment transport process and its distribution along the LYR is crucial for enhancing river management strategies, optimizing reservoir operation methods, and improving the river ecological environment [9,10].

The objectives of scientific river channel management involve maintaining the stability of river channel morphology, optimizing water resource allocation, ensuring flood control safety, and supporting ecological balance [27]. The characteristics of sediment transport in river channels serve as the basis for scientific management of rivers, and the sediment discharge ratio (SDR) is a comprehensive indicator for describing these characteristics [32,33]. Floods are a fundamental aspect of river channel water-sediment processes, serving as the primary periods for downstream sediment transport. They are influenced by various factors, including reservoir operations, river morphology, and river regulation projects [34]. Through the continuous use of sediment interception and the regulation of water-sediment in Xiaolangdi Reservoir, the reservoir's operation mode influences the hydrodynamic conditions and sediment processes during flood events. Studying the SDR during floods can reveal how reservoir operations affect the sediment transport characteristics of downstream rivers. Many experts and researchers have conducted thorough studies on sediment transport characteristics during flood events in recent years. There are generally two methods for establishing the SDR equation: one is to analyse the influencing factors and then verify the equation through direct statistical regression with the measured SDR [35–40]. The other method involves deriving the structural form of the SDR equation through its relationship with sediment transport rate, and then calibrating the parameters using measured data to finalize the equation expression [32,33,41,42]. Current research has given little attention to analyzing the impact of the Xiaolangdi Reservoir's operation on the SDR during flood events, resulting in a lack of comprehensive understanding of the sediment transport characteristics of the river channel before and after the reservoir's construction. Regarding the ecological effects of the Xiaolangdi Reservoir, since 2008, the impact of its operation on downstream fish resources has been the focus of attention. Researchers conducted a survey on the composition and distribution of fish in the LYR [29], assessing fish resources during water-sediment regulation [44]. This provided supportive data for evaluating the ecological effects of the Xiaolangdi Reservoir. Systematic research on the impact of the Xiaolangdi Reservoir on the ecological environment of downstream rivers has been lacking. In summary, the construction of the Xiaolangdi Reservoir has a direct impact on sediment transport and river ecology in the downstream river. Based on these [13,23,25], this paper will establish a simple theoretical expression for the SDR during flood events that directly reflects the impact of reservoir operation, providing a basis for understanding the comprehensive effect of Xiaolangdi Reservoir operation on sediment transport and aquatic organisms in the downstream river channel.

This paper is based on measured water-sediment data in the LYR from 1960 to 2023. It compares and studies the water-sediment processes and sediment transport characteristics of the LYR before and after the construction of the Xiaolangdi Reservoir. It analyses and explores the water-sediment factors that affect the SDR of flood events, derives a theoretical expression for the SDR of flood events based on the sediment transport rate equation, and analyses and studies the sediment transport characteristics of each section of the LYR after the construction of the Xiaolangdi Reservoir, and assesses the ecological environment of aquatic organisms. The research findings will provide a theoretical basis and scientific support for improving downstream river management strategies, optimizing reservoir operation modes, and enhancing the river's ecological environment.

discharge exceeding 500 m³/s. The principles for classifying flood events are consistent with those outlined in the “Documented data of fluvial processes of the lower Yellow River” [53]. The selected flood events can represent various water-sediment combinations, and the theoretical expression for SDR established using these data has a wide range of applications.

There are a total of 340 large cross-sections in the LYR. The cross-section elevation is measured once before and after the flood season each year. A total of 126 sets of cross-sectional terrain data were used in this paper. The cross-sectional terrain and bed material particle size data are both from the Yellow River Basin Hydrological Yearbook [51].

3.2. Methods

The SDR is a significant indicator for describing sediment transport characteristics [33,39]. It refers to the ratio of the output sediment load to the input sediment load during a specific period, reflecting the comprehensive indicators of sediment transport capacity and the erosion and aggradation characteristics of the river reach [32]. The SDR is expressed as:

$$SDR = W_{s,out} / W_{s,in} \quad (1)$$

where $W_{s,in}$ is the imported sediment load, 10⁸ t; $W_{s,out}$ is the exported sediment load, 10⁸ t. When $SDR > 1$, the river reach is mainly dominated by erosion; When $SDR < 1$, the river reach is mainly characterized by aggradation; When $SDR = 1$, the river section approaches the equilibrium of erosion and aggradation.

Due to sediment diversion caused by human activities in downstream rivers, the SDR derived from Equation (1) usually indicates the apparent SDR rather than the true one, thus diminishing its original importance. Given the significant sediment diversion in the downstream river channel, it is essential to restore the sediment load at the river reach's outlet cross-section [32]. The following equation can be used to calculate the actual SDR under natural conditions and accurately describe the sediment transport characteristics of the river reach.

$$SDR_a = \left(\frac{W_{s,out}}{W_{s,in}} \right) / \left(1 - \frac{W_{s,d}}{W_{s,in}} \right) \quad (2)$$

where SDR_a is the actual SDR; $W_{s,d}$ is the sediment load diversion, 10⁸ t. Data regarding sediment load diversion is obtained from the Yellow River Basin Hydrological Yearbook [51]. In Equation (2), $W_{s,d}$ is less than $W_{s,in}$, and SDR_a will not have negative values.

The incoming sediment coefficient indicates the sediment concentration per unit of flow discharge:

$$\xi = S_{in} / Q_{in} \quad (3)$$

where S_{in} is the inlet sediment concentration, kg/m³; Q_{in} is the import flow discharge, m³/s. The sediment concentration per unit flow discharge is greater if the incoming sediment coefficient is larger. This may result in the river channel being supersaturated where aggradation occurs. Conversely, it may exist in a sub-saturated state, resulting in scouring [24].

The runoff variation coefficient refers to the ratio between the inlet runoff and the outlet runoff:

$$\eta = W_{w,out} / W_{w,in} \quad (4)$$

where $W_{w,in}$ is the inlet runoff, 10⁸ m³; $W_{w,out}$ is the outlet runoff, 10⁸ m³. A runoff variation coefficient greater than 1.0 indicates that the runoff at the outlet cross-section exceeds that at the inlet cross-section. Conversely, a coefficient lower than 1.0 suggests that the runoff at the outlet cross-section is less than that at the inlet cross-section.

Xiaoheiwu Station refers to the general term for Xiaolangdi Station, Wuzhi Station, and Heishiguan Station. Xiaolangdi Station is located on the main stream of the Yellow

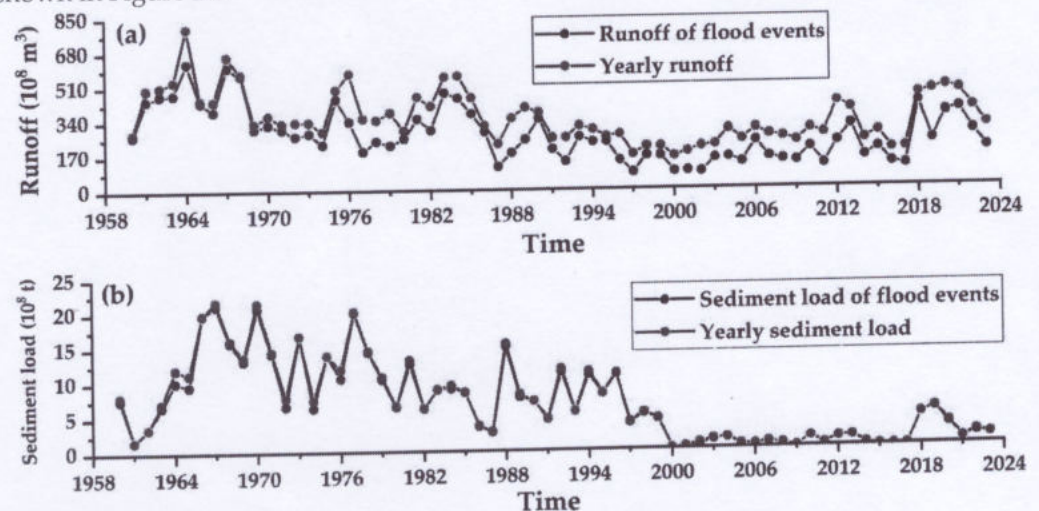
River, Wuzhi Station is located on the Qin River, and Heishiguan Station is located on the Yiluo River [25]. Flood propagation from the Xiaolangdi Reservoir to Huayuankou, Gaocun, Aishan, and Lijin occurs over 1, 2, 4, and 5 days, respectively. When selecting the flood event at Xiaoheiwu Station, the corresponding flood processes for 1, 2, 4, and 5 days are applied to the flood events at Huayuankou, Gaocun, Aishan, and Lijin, thus ensuring the completeness of the flood event [54].

4. Results

4.1. Water-sediment characteristics of flood events in downstream rivers

Figure 2 shows the water-sediment process of the flood events in the LYR. From 1960 to 2023, the annual runoff flowing into the LYR first declined before rising, reaching a minimum of 15.6 billion m^3 around 2000. Flood events contribute approximately 72% of the yearly runoff, as indicated in Figure 2a. From 1960 to 2023, the sediment load entering the LYR steadily declined. Flood events account for approximately 94% of the average sediment load each year. The research shows that the sediment load is predominantly concentrated during annual flood events, illustrated in Figure 2b.

Before the construction of the Xiaolangdi Reservoir, average flow discharges entering the downstream river channel ranged from 507 to 6778 m^3/s . In contrast, this range changed to an average flow discharge of 519 to 3992 m^3/s after its construction. Before the construction of Xiaolangdi Reservoir, the flow discharge entering the downstream river channel showed fluctuating changes. However, after the construction of Xiaolangdi Reservoir, the range of average flow discharge entering the downstream river channel significantly decreased, and the flow was controlled within 4000 m^3/s , as shown in Figure 2c. Before the Xiaolangdi Reservoir's construction, the sediment concentration variation in the downstream river channel floods ranged from 0.0 to 340.98 kg/m^3 . In contrast, this variation decreased to 0.0 to 103.71 kg/m^3 after its construction. Before the construction of Xiaolangdi Reservoir, the flood events in the downstream river channel could be regarded as a 'natural flood'. During this period, the channel faced considerable sediment load, resulting in frequent floods with high sediment concentrations. After the construction of the Xiaolangdi Reservoir, it adopted a "long-term sediment regulation and timely precipitation flushing" mode, significantly reducing the occurrence of high sediment concentration floods. This is due to the reservoir's water storage and sediment interception significantly reducing the sediment concentration of flood events flowing downstream, as shown in Figure 2d.



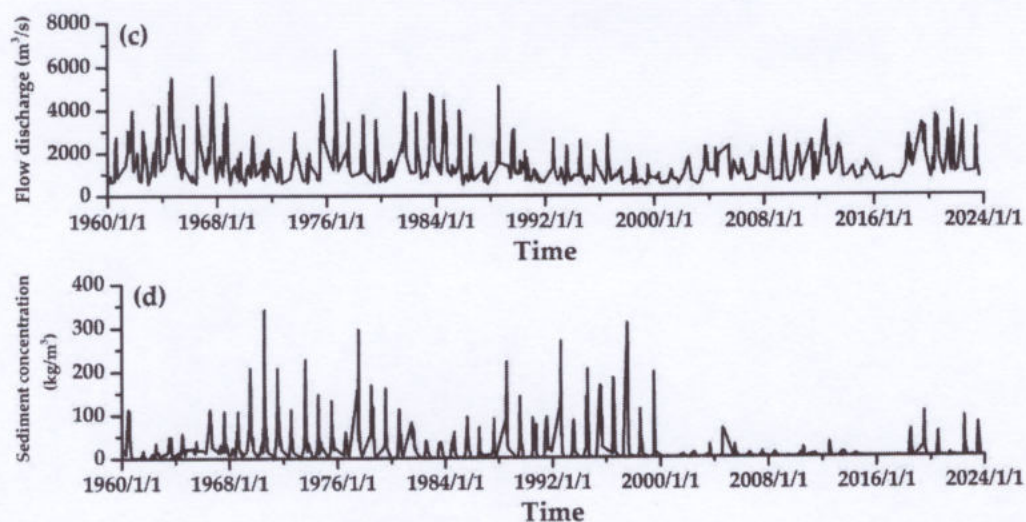


Figure 2. Water-sediment processes of flood events entering the LYR. (a) Runoff volume. (b) Sediment load. (c) Average flow discharge. (d) Average sediment concentration.

Figure 3 shows the proportions of different flow discharge levels and sediment concentration levels for flood events. Before and after the construction of the Xiaolangdi Reservoir, the proportions of three flow discharge ranges—1000 to 2000 m³/s, 2000 to 3000 m³/s, and 3000 to 4000 m³/s—entering the downstream river channel exhibited negligible variation. In contrast, the proportions of flow discharge ranging below 1000 m³/s and above 4000 m³/s exhibited significant differences. Before the construction of the Xiaolangdi Reservoir, the proportion of flood events with flow discharge below 1,000 m³/s was 26.08%, which was lower than the proportion of the same flow discharge category after the reservoir was constructed (37.42%). Flood events with flow discharge above 4,000 m³/s accounted for 4.69% of all flood events, which is significantly higher than the proportion of flood events with the same flow discharge after the Xiaolangdi Reservoir was constructed (0.0%), as shown in Figure 3a. Before the construction of the Xiaolangdi Reservoir, floods with sediment concentrations below 20 kg/m³ accounted for approximately 46.34% of all flood events, which was significantly lower than the proportion of floods with the same sediment concentration level after the reservoir was constructed (89.03%). For the Yellow River, a river with relatively high sediment concentrations, floods with sediment concentrations below 20 kg/m³ are generally considered to be low sediment concentration floods [55,56], indicating that after the construction of the Xiaolangdi Reservoir, the sediment concentration of floods entering the downstream area was generally lower, almost resembling a clear water erosion pattern. The proportion of flood events with sediment concentrations above 20 kg/m³ was consistently lower than that before the reservoir's construction, particularly for sediment concentrations above 100 kg/m³, as shown in Figure 3b. In summary, after the construction of the Xiaolangdi Reservoir, the flow discharge and sediment concentration of floods have decreased significantly, demonstrating the reservoir's water storage and sediment retention functions [57].

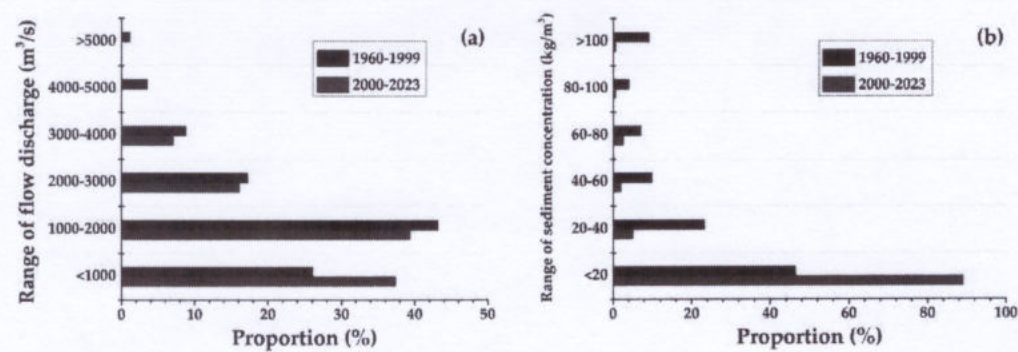
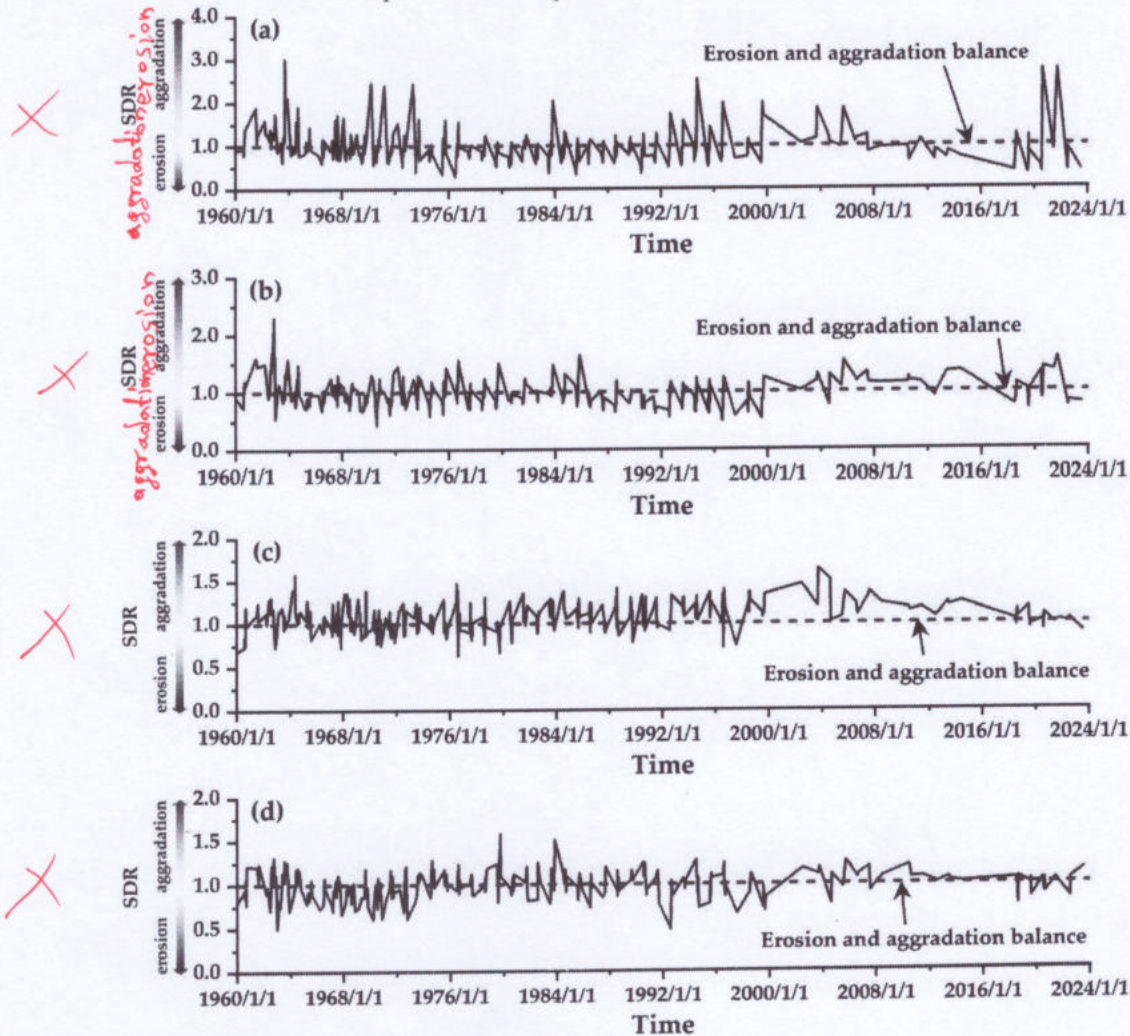


Figure 3. Proportion of flow discharge and sediment concentration ranges of flood events entering the LYR (a) Proportion of flow discharge ranges. (b) Proportion of sediment concentration ranges.

4.2. Spatial and temporal distribution of sediment discharge ratio

Figure 4 shows the spatial-temporal variation of the SDR during flood events. The water-sediment conditions affect the variation in the SDR of the LYR. In years with higher flow discharge and less sediment, river channels tend to erode, resulting in a SDR exceeding 1.0. On the contrary, in years with less runoff and more sediment, the river channel undergoes aggradation, and the SDR remains below 1.0 [58]. The relationship between water and sediment during flood flow downstream significantly changes, leading to notable differences in the spatial and temporal distribution of the SDR.



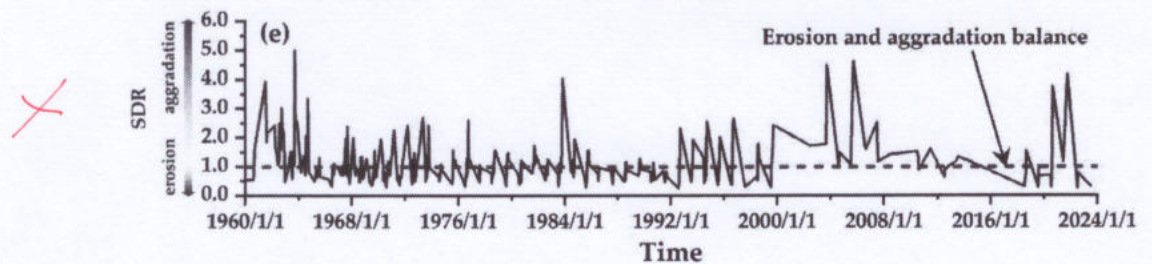


Figure 4. Spatial-temporal variation of SDR during flood events. (a) Tiexie-Huayuankou reach. (b) Huayuankou-Gaocun reach. (c) Gaocun-Aishan reach. (d) Aishan-Lijin reach. (e) Tiexie-Lijin reach.

Before the construction of Xiaolangdi Reservoir, the SDRs of floods show significant fluctuations over time. After the construction of the Xiaolangdi Reservoir, the median particle size of bed material in the downstream river channel increased by 1 to 2 times [38,40]. The overall trend of the SDR has decreased over time due to the coarsening of bed material. From 2018 to 2023, sediment discharge from the Xiaolangdi Reservoir stayed relatively high, resulting in more fine sediment in the river channel and a sharp increase in the SDR of the river reach [54,59]. Comparing SDRs across different river reaches, the ratio for the reach from Tiexie to Huayuankou varied the most (0.277 to 3.012), while that from Aishan to Lijin varied the least (0.222 to 1.578), as shown in Figures 4a~4d.

In the reach from Tiexie to Lijin, the Sanmenxia Reservoir was managed for water storage and sediment retention from 1960 to 1964. Except for the discharge of fine-grained sediment through density currents during the flood season, the flow discharge into the downstream river channel was mainly clear water, resulting in a relatively high SDR. Between 1964 and 1973, the Sanmenxia Reservoir shifted its focus from "water storage and sediment blocking" to "flood control and sediment discharge," resulting in a significant sediment load being released downstream. The unfavorable combination of "more water with little sediment and little water with more sediment" led to considerable aggradation, and the SDR was below 1.0. From 1981 to 1985, the runoff volume was 6% higher than the average annual volume, while the sediment load was 50% lower than the average annual load due to decreased rainfall in the middle reaches and expanded basin management areas. The lower reaches of the river experienced a rare pattern of "more water and little sediment," with the SDR gradually increasing [60]. The Longyangxia Reservoir is located in Gonghe County, Qinghai Province, upstream of the Xiaolangdi Reservoir. After the construction of Longyangxia Reservoir in 1986 [45,61], water-sediment conditions downstream have worsened considerably, and both runoff and sediment load have continued to diminish, leading to a SDR below 1.0. Before the construction of Xiaolangdi Reservoir, the overall SDR of the river reach from Tiexie to Lijin was less than 1.0, indicating a trend of aggradation. From 1961 to 1964 and from 1981 to 1985, the SDR exceeded 1.0, coinciding with periods when the downstream river channel was flushed. The Xiaolangdi reservoir started operating in 2000, with water-sediment regulation beginning in 2002, leading to changes in downstream water-sediment conditions. Between 2000 and 2006, there was a yearly trend in runoff and sediment load; the scouring efficiency improved significantly, and the SDR surged. Following 2006, runoff fluctuated, and the sediment load and scouring efficiency slightly declined. Consequently, there was a minor decrease in the SDR compared to the period before 2006. Since 2018, the Xiaolangdi Reservoir has adopted a water level reduction method for sediment discharge, resulting in a large amount of sediment siltation in the downstream river channel, with 90% of the sediment silted in the reach from Tiexie to Huayuankou [59]. The supply of fine sediment throughout the entire downstream channel has increased, the bed erodibility has risen, and the SDR of the reach has improved. The erosion load from Tiexie to Lijin is the sum of the erosion loads of all individual reaches, so the SDR of the entire reach will reach its maximum, as shown in Figure

is too broad and shallow, and the relationship between sediment transport capacity and average sediment concentration in this reach is stronger. At the same time, the reach from Aishan to Lijin is too narrow and deep, and the correlation between sediment transport capacity and average flow discharge in this reach is stronger. The cross-sectional morphology of the reach from Gaocun to Aishan varies between being "wide and shallow" and "narrow and deep." The relationship between sediment transport capacity and the ratio of average sediment concentration to average flow discharge is stronger. The correlation coefficient between the incoming sediment coefficient and the SDR of each reach demonstrates explicitly a trend of rising and falling along the channel. The distribution of the runoff variation coefficient from 1960 to 2023 during flood events in the reaches from Tiexie to Huayuankou, from Huayuankou to Gaocun, from Gaocun to Aishan, and from Aishan to Lijin were 1.009, 0.923, 0.918, and 0.833, respectively. Overall, the performance of the runoff variation coefficient decreased along the channel, leading to a gradual increase in its influence on the SDR. For this reason, it is believed that the closer an alluvial river reach is to the estuary, the stronger the correlation between the runoff variation coefficient and the SDR.

Considering the impact of reservoir operations, the correlation coefficients between the average sediment concentration, the incoming sediment coefficient, and the SDR have increased slightly. In contrast, the correlation coefficients between the average flow discharge and the SDR have decreased slightly compared to those before the construction of Xiaolangdi Reservoir. The main reason for this is that the runoff entering downstream, both before and after the operation of the Xiaolangdi Reservoir, was slightly reduced. Simultaneously, the sediment load flowing downstream the channel exhibited a sharp decrease, leading to a gradual increase in the dependence of the SDR on sediment load. Compared to before the construction of the Xiaolangdi Reservoir, the runoff variation coefficient in the reach upstream of Gaocun decreased significantly after the reservoir was constructed, while the decrease in the runoff variation coefficient in the reach downstream of Gaocun was relatively small. This caused a significant increase in how much the upstream reach of Gaocun depended on the runoff variation coefficient, resulting in a higher correlation between the runoff variation coefficient and the SDR.

4.4. Impact of the Xiaolangdi Reservoir operation on the sediment discharge ratio of flood events

There is usually a relatively definite relationship between flow discharge and sediment transport rate. A certain flow discharge has a certain sediment transport rate, as shown in the following Equation [35]:

$$Q_{s,out} = KQ_{out}^{\alpha} \quad (5)$$

where Q_{out} is the outlet cross-sectional flow discharge, m^3/s ; K is the coefficient, which is related to the early erosion and aggradation of the riverbed; α is the index.

The relationship between sediment transport rate and flow discharge typically defines the sediment transport capacity in alluvial river reaches [35]. However, for sandy and fine sediment alluvial river in the LYR, this connection exhibits a relatively scattered pattern as represented by the equation [35]. As early as the 1960s, many scholars proposed that the sediment transport rate in the main channel was not solely a function of flow discharge but was also closely linked to sediment concentration. Qian et al. [35] proposed that the sediment transport dynamics of the LYR differ from those of rivers characterized by low sediment concentrations. They found that the flow discharge and the sediment concentration at the inlet cross-section influence the sediment transport rate at the outlet cross-section.

$$Q_{s,out} = KQ_{out}^{\alpha} S_{in}^{\beta} \quad (6)$$

where $Q_{s,out}$ is the sediment transport rate at the outlet cross-section, kg/s ; S_{in} is the

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