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Characteristics and influencing factors of sediment deposition-scour in the Sanhuhekou-Toudaoguai Reach of the upper Yellow River, China

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ABSTRACT

The annual changes of sediment deposition-scour on the riverbed in the Sanhuhekou-Toudaoguai Reach of the upper Yellow River during the years 1952–2010 were investigated based on runoff and sediment transport observations from the Sanhuhekou and Toudaoguai hydrological stations. Multiple influencing factors such as reservoir operations, tributary inflows, as well as runoff and sediment loads from the Shidakongdui area were analyzed. The results show that even though the sediment loads from the major sources, the Shidakongdui area as well as the upstream tributaries such as the Qingshui River and the Zuli River have reduced especially since the 2000s as a result of enhanced water-soil conservation measures and improvement of vegetation cover, the study reach was still generally in a status of cumulative aggradation. This is mainly due to the joint operations of the Liujiaxia Reservoir and the Longyangxia Reservoir, which significantly reduced the annual runoff and sediment loads at the Sanhuhekou Crosssection. The reservoirs also remarkably altered the summer flood characteristics of the study reach, inducing the shape of the annual flow curve changing from a ‘single-peak’ into a ‘double-peak’. These alternations sharply decreased the sediment transport capacity of flooding in the summer flood season which yields more than 90% of the sediment loads, leading to an unbalanced relation between the water and sediment. In addition, the estimated incoming sediment coefficient of the Sanhuhekou Crosssection ranged from 0.003 to 0.014 kg s/m^6, of which 0.004 kg s/m^6 was suggested as a rough critical value to determine the scour or deposition status of the study reach.

1. Introduction

The Ningxia-Inner Mongolia Reach of the upper Yellow River starts from Xiaheyan in Ningxia Hui Autonomous Region and ends at Hekou Town in Inner Mongolia Autonomous Region with a total channel length of about 1000 km (Qin et al., 2011). The flow-sediment relation of the reach is very complicated and the channel has undergone dramatic changes in recent decades (Ran et al., 2010; Xu, 2013). The sediment deposition rate along the reach has increased resulting in rapid shrinkage of the main channel and a remarkable decrease in the sediment transport capacity of flow induced by climate change, reservoir regulation, as well as incoming sediment from its tributaries (Fan et al., 2013; Qin et al., 2011; Ta et al., 2013; Zhang et al., 2017). The instability of the river regime, severe bank collapse, and deposition at tributary entrances result in serious problems for flood control (Chen et al., 2017; Yao et al., 2011). Therefore, studies on the changes in the flow-sediment relations and deposition-scour characteristics of riverbed in the reach as well as the major influencing factors are very important and have aroused wide concern (Fang et al., 2008; Huang et al., 2017; Ran et al., 2012; Ren et al., 2002; Si et al., 2017; Wang et al., 2016; Zhang et al., 2005).

The Sanhuhekou-Toudaoguai Reach is an important part of the Ningxia-Inner Mongolia Reach. It is the transitional part of the upper Yellow River which changes from wandering to meandering channel form as a result of sediment deposition in the upstream areas. The channel receives runoff from a number of tributaries originating from the Loess Plateau, especially the ten seasonal rivers (i.e. Shidakongdui) which enter the mainstream on the right bank with a supply of millions of tons of sediment annually. In recent decades, the reach has experienced an increasing deposition trend as a result of multiple reasons, such as reduction in runoff from upstream and increasing water demand from industry

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and agriculture (Qin et al., 2011), resulting in increasing the rate of change of the main channel and the risk of silting up (Yao et al., 2011).

The constructions and operations of reservoirs in the upstream of the Yellow River basin are thought to be one of the major factors that contribute to the remarkable reduction in the runoff and sediment loads entering the Sanhuhekou–Toudaoguai Reach (Ran et al., 2010; Teng et al., 2015; Wang et al., 2006; Xu, 2013). A series of reservoirs have been built in the upper Yellow River basin since the 1960s, such as the Longyangxia Reservoir, the Liujiaxia Reservoir, the Yanguoxia Reservoir, and the Qingtongxia Reservoir, and the reach has been completely regulated and highly fragmented since the 1990s. Thus, the water-sediment equilibrium has changed and the magnitude of discharge peaks in the summer flood season has been significantly reduced (Milliman et al., 1987; Ta et al., 2008). Among these reservoirs, the Liujiaxia Reservoir and the Longyangxia Reservoir were mainly built for hydroelectric power generation and have enough storage and regulation capacities to operate inter-annually, which are thought to have notable impact on the runoff and sediment load in the downstream channel especially after their joint operations since 1986 (Teng et al., 2015; Wang et al., 2006). The other reservoirs such as the Qingtongxia Reservoir and the Sanshenggong Hydro Project have much smaller storage and regulation capacities and can have limited influence on the downstream fluvial system (Ran et al., 2010).

Meanwhile, the sediment loads of the Sanhuhekou-Toudaoguai Reach also are notably affected by the sediment yield from its tributaries, especially some of the tributaries prone to hyper-concentrated flows such as the Qingshui River and the Zuli River originating from the loess plateau in central China which carry large quantities of sediment into the reach in the flood season. Since the 1960s, a serial of soil and water conservation measures have been applied in the drainage areas of some tributaries where soil erosion is strong, and sediment loads from these areas have been reduced to a certain degree (Chen et al., 2007; Li et al., 2010; Zhao et al., 2013). In addition, a long-term trend of reduction in precipitation as well as rainfall intensity in the past several decades also is considered as a factor leading to the changes in runoff and sediment load of the reach (Shi et al., 2017; Xu et al., 2007).

Previous studies (Fan et al., 2013; Wang et al., 2015; Wu et al., 2015; Zhang et al., 2005) have given some discussion on the temporal changes of runoff, sediment load, and sediment deposition characteristics of the Sanhuhekou-Toudaoguai Reach. However, there is still a lack of knowledge on the sediment deposition-scour changes of the riverbed of the reach, especially why the reach is still in a status of cumulative aggradation in the recent decades even though the sediment loads from the upstream tributaries and the Shidakongdui area are notably reduced. Therefore, the current study gives some further discussion on the runoff and sediment load characteristics on the reach based on historical data, and tries to find the major factors influencing the sediment deposition in this reach. The results can give some useful information on the management and conservation of the Sanhuhekou-Toudaoguai Reach.

2. Study area

The upper Yellow River, extending from the source to Hekou Town, is located on the Qinghai-Tibet Plateau and the Loess Plateau. It is 3472 km long with a relief of 3496 m and a drainage area of about 0.39 million km^2 (Wang & Li, 2011). The study area is the Sanhuhekou-Toudaoguai Reach, which is located in the Great Bend of the Yellow River, starting from the Sanhuhekou Crosssection and ending at the Toudaoguai Crosssection, with a total length of about 300 km. The study reach lies in the terminal mainstream channel of the upper Yellow River, and also is the transitional zone transforming from a meandering channel to a straight channel.

The major sediment source within the study reach is the Shidakongdui area which is located on the south bank. It consists of ten seasonal rivers prone to hyper-concentrated flows that drain through the Kubuqi Desert from south to north and then enter the reach (see Fig. 1). The Shidakongdui area has a total catchment area of 7385.5 km^2 and an average annual sediment load of about 0.2×10^8 t (Lin et al., 2014). The upstream of the catchment lies in the hilly and gully regions of Ordos Loess Plateau, which is covered with thin sand residual soil and about 60% of the soil particles are larger than 0.05 mm. Large areas of underlying sandstone are exposed and are vulnerable to erosion. At midstream the rivers flow across the Kubuqi desert where both sediment concentration and size are further increased in flood seasons. The downstream area is an alluvial plain which is flat and wide. The channels are shallow and easily experience siltation. The major land use types are grassland, farmland, and unused land, which account for about 90% of the total area (Liu et al., 2016).

A series of reservoirs are present in the upstream areas of the study reach, among which the Longyangxia Reservoir and the Liujiaxia Reservoir are the most important. The Liujiaxia Reservoir was finished in 1968 and has a total storage capacity of 57.1×10^8 m^3. The Longyangxia Reservoir was completed in 1986, and has a total water storage capacity of 247×10^8 m^3 at the normal level and a regulation capacity of 193.5×10^8 m^3. The two reservoirs have operated jointly since 1986.

The two major tributaries that may affect the channel flow and sediment yield of the study reach are the Qingshui River and the Zuli River. The Qingshui River is the largest tributary of the Yellow River in the Ningxia Hui Autonomous Region, with a length of 320 km and an average slope of 1.49‰. The average annual runoff and sediment load of the river are 1.09×10^8 m^3 and 0.236×10^8 t, respectively. The Zuli River is one of the tributaries most prone to hyper-concentrated flows of the Yellow River in Gansu Province, with an average annual suspended sediment concentration of 440.63 kg/m^3. Soil erosion in the catchment is very serious, and the erosion area composes about 7559 km^2 which makes up 71% of the total catchment area.

3. Data sources

The data used in this study are mainly from the Hydrological Data of the Yellow River Basin (1952–2010) published by the Yellow River Conservancy Commission (YRCC) of the Ministry of Water Resources (MWR), China, including the time series of runoff and suspended sediment load at the Sanhuhekou Crosssection and the Toudaoguai Crosssection. The sediment loads from the Shidakongdui area are based on the report of Lin et al. (2014).

To discuss the impact of the upstream reservoirs (i.e. the Liujiaxia Reservoir and the Longyangxia Reservoir) on the runoff, sediment load, and sediment deposition-scour changes of the riverbed of the study reach, the data are divided into three different time periods as follows: (I) 1952–1968, no regulation, i.e. before the construction of the two reservoirs discussed previously; (II) 1969–1985, regulation by the Liujiaxia Reservoir, i.e. after the construction of the Liujiaxia Reservoir but before that of the Longyangxia Reservoir; and (III) 1986–2010, joint operations of the two reservoirs, i.e. after the construction of the Longyangxia Reservoir.

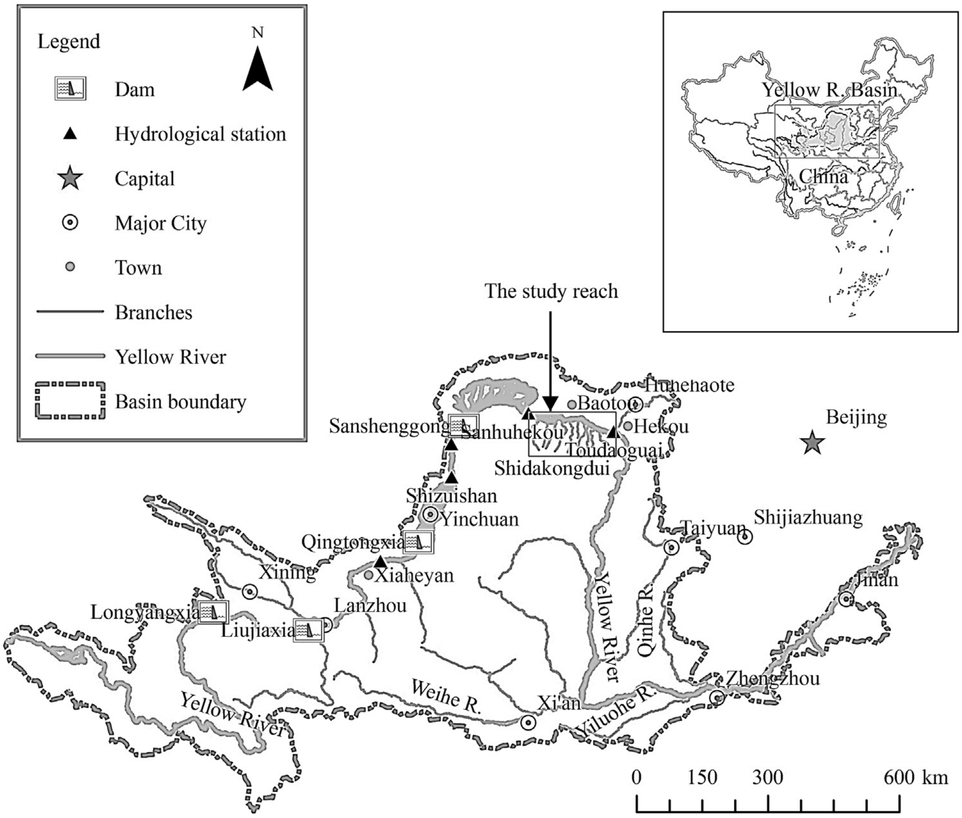

Fig. 1. A map of the study area and the study reach.

4. Methods

4.1. Mann-Kendall trend test

The Mann-Kendall trend test (Hamed, 2008; Mann, 1945) is used to investigate the temporal variations of annual runoff and sediment load of the Sanhuhekou Crosssection. It is based on the correlation between the ranks of a time series and their time order. The test statistic for the kth data of a time series, $X = \{x_1, x_2, \ldots, x_n\}$, is given by:

$$d_k = \sum_{i=1}^{k} m_i \qquad (2 \le k \le n) \tag{1}$$

where

$$m_i = \sum_{j=1}^{j \le i} \text{sign} \begin{Bmatrix} x_i > x_j, & 1 \\ x_i \le x_j, & 0 \end{Bmatrix} \tag{2}$$

where *sign* is a sign function, which equals 1 when $x_i > x_j$ or 0 when $x_i \le x_j$.

The mean and variance of d_k are calculated as:

$$E(d_k) = k(k-1)/4 \tag{3}$$

$$\text{var}(d_k) = k(k-1)(2k+5)/72 \tag{4}$$

The Mann-Kendall statistic, *UF*, can then be described as:

$$UF_k = \frac{d_k - E(d_k)}{\sqrt{\text{var}(d_k)}} \tag{5}$$

in which positive and negative *UF* values indicate upward and downward trends, respectively. The Mann-Kendall *UB* values can be calculated in the same way using the reverse order of the time series, and the intersection of the *UF* and *UB* curves within the confidence intervals is the jump change point.

4.2. Annual deposition-scour amount

The amount of the annual sediment deposition-scour in the study reach is estimated as follows:

$$W_s = W_{s,s} - W_{s,t} + S_3 - S_4 \tag{6}$$

where W_s is the sediment deposition/scour amount in the Sanhuhekou-Toudaoguai Reach; $W_{s,s}$ and $W_{s,t}$ are sediment load at the Sanhuhekou Crosssection and the Toudaoguai Crosssection, respectively; and S_3 and S_4 are source and sink of sediment in the study reach, respectively. All of the terms are expressed in the unit of 10^8 t/yr. The term S_3 is roughly estimated as the sediment load discharging from the Shidakongdui area, which is estimated base on to the report by Lin et al. (2014). S_4 is considered to be zero as the major sediment diversion in the study reach is from Baotou City, which is relatively small compared to the other terms in the equation, and, thus, can be neglected. Positive W_s values indicate that the reach is experiencing sediment deposition, and negative values suggest the reach is experiencing scour.

4.3. Fit to deposition-scour amount

The sediment deposition-scour amount of the study reach is affected by the runoff and sediment load from both upstream of the Sanhuhekou Crosssection and the Shidakongdui area. However, as the annual runoff from the Shidakongdui area only comprises less than 1% of that from the upstream channel, its effect can, thus, be neglected. In order to quantitatively investigate these factors, a multiple linear regression is carried out as follows:

$$W_s = a_0 + a_1 Q_s + a_2 W_{s,s} + a_3 W_{s,k} \tag{7}$$

where a_0, a_1, a_2, and a_3 are the regression coefficients, all dimensionless except for a_1 which is in t/m^3; Q_s is the annual runoff of the Sanhuhekou Crosssection, 10^8 m^3/yr; and $W_{s,s}$ and $W_{s,}$

$_k$ are the annual sediment loads of the Sanhuhekou Crosssection and the Shidakongdui area, respectively, 10^8 t/yr. The regression was carried out by Origin® Pro 8.5, from which the coefficients as well as other statistics (e.g., standard error and R-square) were determined.

4.4. *Incoming sediment coefficient*

The incoming sediment coefficient is an important parameter to express the correlation between runoff and sediment loads, and is widely used in studies on sediment transport in the Yellow River. It is defined as the ratio of suspended sediment concentration to flow discharge:

$$\xi = S/Q \tag{8}$$

where ξ is the incoming sediment coefficient, kg s/m^6; S is the concentration of suspended sediment, kg/m^3; and Q is the channel flow discharge, m^3/s.

5. Results

5.1. *Annual changes of runoff and sediment load*

The temporal changes of annual channel flow and suspended sediment load at the Sanhuhekou Crosssection and the Toudaoguai Crosssection are shown in Fig. 2. It can be seen that the runoff and sediment load of the two crosssections have good correlations, in which the linear correlation coefficients (R^2) are 0.98 and 0.88, respectively. Obvious inter-annual variations can also be found especially before the 1970s, which became smaller between the 1970s and 1980s and even smaller since the 1990s. In general, both the channel flow and sediment load at the two crosssections exhibit a notable decreasing trend. The jump change points for the annual runoff and sediment load determined by the Mann-Kendall test are at the years of 1987 and 1979, respectively, and obvious decreasing trends started from around the years of 1990 and 1970, respectively (see Fig. 3). In the third period, the average annual runoff and sediment load at the two crosssections significantly reduced to about 2/3 and 1/4 of those in the first period (1952–1968), respectively.

In addition, the relations between annual runoff and sediment load of the two crosssections experienced notable alternations as well in the past several decades (shown in Fig. 4). In particular, the sediment load under the same runoff has significantly reduced since the second time period, indicating reductions in the sediment transport capacity of the flow in the study reach.

5.2. *Monthly variations of flow discharge and sediment transport rate*

The monthly-average flow discharge and sediment transport rate of the Sanhuhekou Crosssection and the Toudaoguai Crosssection in different periods are shown in Fig. 5. It can be seen that both of them have experienced significant changes during the past 60 years, in which the most notable alteration is the remarkable reduction in the summer flood season (from July to October). Comparing to the situations before 1968, the maximum monthly-average channel flow discharge (in September) for the two crosssections reduced from 2500 m^3/s to 2000 m^3/s, and the sediment transport rate from the amount of 20,000 kg/s to 15,000 kg/s during the period from 1969 to 1985. Even more sharp decreases occurred after 1985, in which the channel flow discharge and sediment transport rate reduced to the amount below 1000 m^3/s and 5000 kg/s, respectively. These sharp decreases lead the annual distributions of channel flow discharge and sediment transport rate to change from a “single-peak” into a “double-peak” shape, in which the amount during the summer flood season is very close to that in the spring (usually in March and April).

These changes significantly altered the annual distributions of runoff and sediment load for the two crosssections (see Tables 1 and 2), in which the percentage of runoff in the summer flood season at the Sanhuhekou Crosssection reduced from 71.8% in the first period to 58.9% and 39.2% in the two later periods, respectively. Meanwhile, the sediment load in the flood season

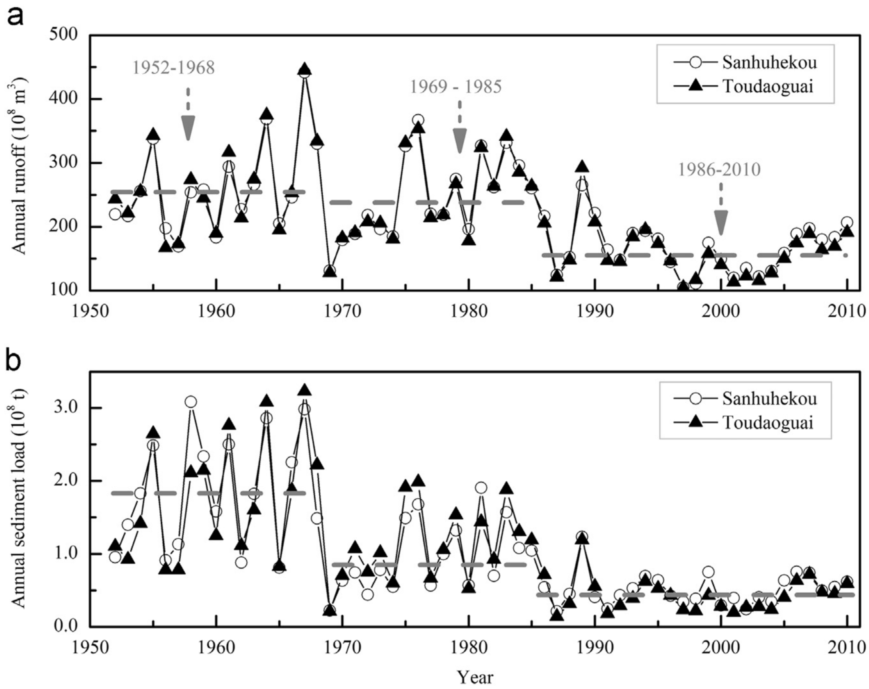

Fig. 2. Annual changes of the runoff (a) and suspended sediment load (b) at the Sanhuhekou Crosssection and the Toudaoguai Crosssection between 1952 and 2010.

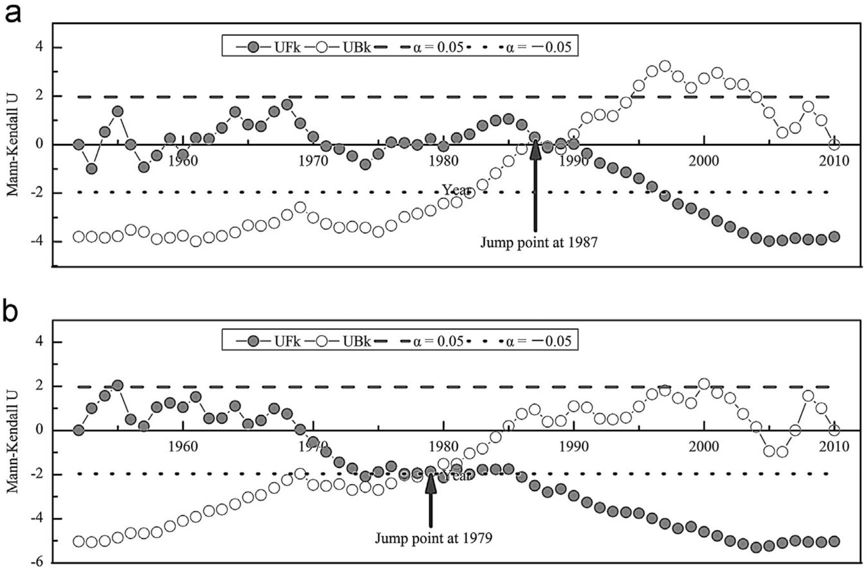

Fig. 3. The Mann-Kendall trend and jump point tests for annual runoff (a) and sediment load (b) at the Sanhuhekou Crosssection. *UF* and *UB* are statistics of the Mann-Kendall tests. α is the significance level.

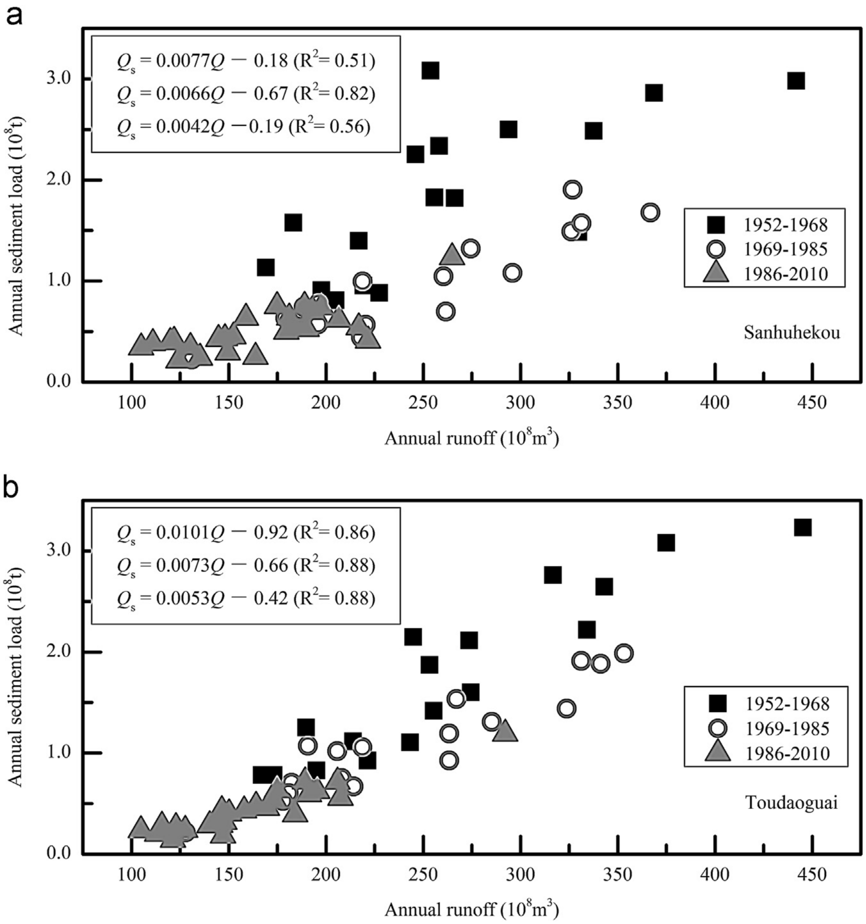

Fig. 4. Changes of relation between annual runoff and sediment load at the Sanhuhekou Crosssection (a) and the Toudaoguai Crosssection (b) in different time periods, in which the linear regression equations are arranged in the same order of the time periods, and Q and Q_s represent annual runoff and sediment load, respectively.

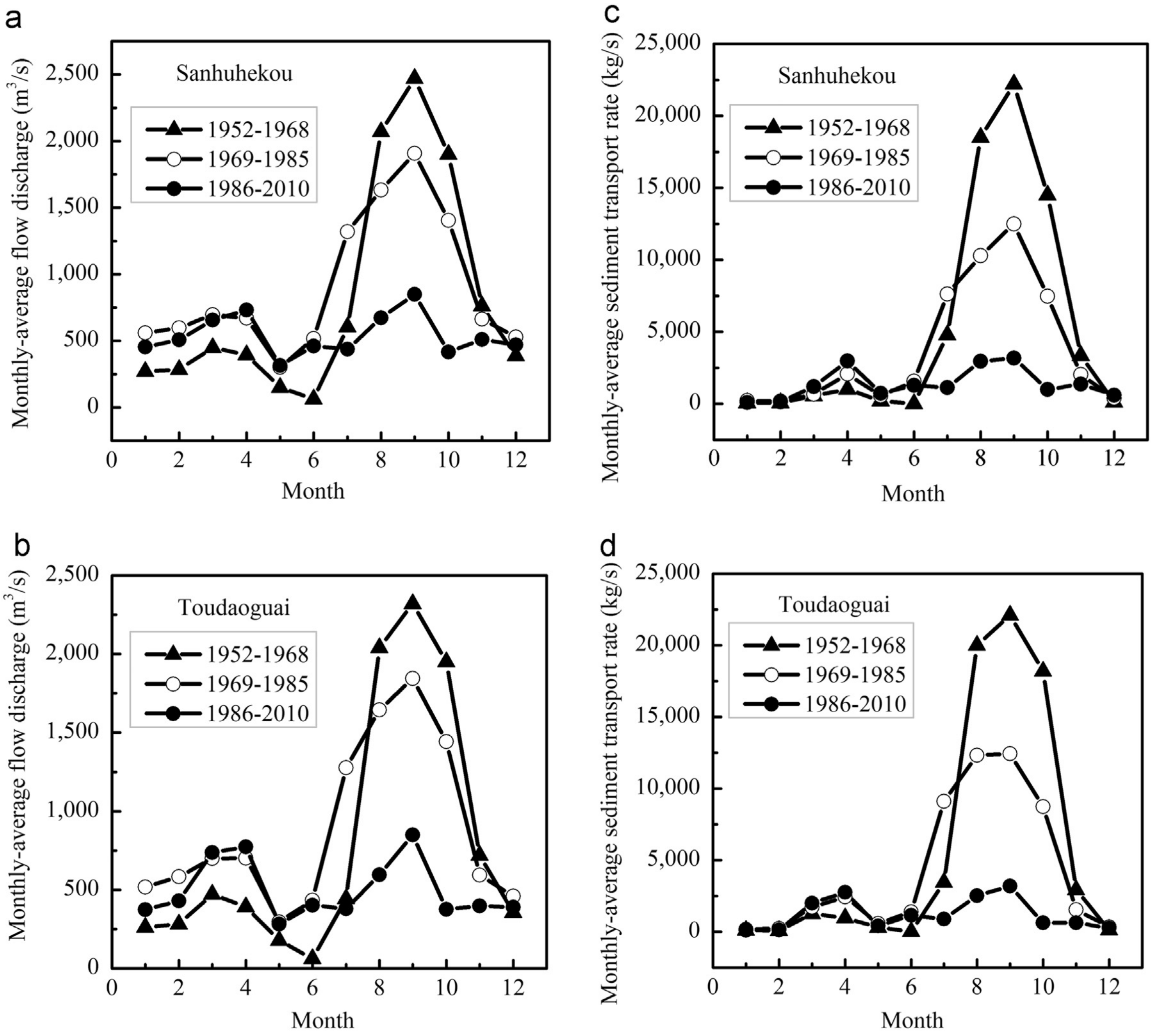

Fig. 5. Monthly-average channel flow discharge and sediment transport rate at the Sanhuhekou Crosssection and the Toudaoguai Crosssection in the three different time periods.

Table 1
Changes of runoff in the flood and non-flood seasons during different time periods.

Time period	Sanhuhekou				Toudaoguai			
	Flood season		Non-flood season		Flood season		Non-flood season	
	10^8 m^3	%	10^8 m^3	%	10^8 m^3	%	10^8 m^3	%
1952–1968	182.6	71.8	71.5	28.2	175.0	71.3	70.5	28.7
1969–1985	170.4	58.9	119.0	41.1	169.0	60.1	112.1	39.9
1986–2010	68.2	39.2	106.0	60.8	64.6	39.7	98.0	60.3

Table 2
Changes of sediment load in the flood and non-flood seasons during different time periods.

Time period	Sanhuhekou				Toudaoguai			
	Flood season		Non-flood season		Flood season		Non-flood season	
	10^8 t	%	10^8 t	%	10^8 t	%	10^8 t	%
1952–1968	1.55	91.7	0.14	8.3	1.65	91.6	0.15	8.4
1969–1985	1.04	83.4	0.21	16.6	1.17	83.7	0.23	16.3
1986–2010	0.28	58.6	0.20	41.4	0.27	59.8	0.18	40.2

reduced from 91.7% to 83.4% and 58.6%, correspondingly. Similar situations are also found at the Toudaoguai Crosssection, suggesting remarkable decreases of runoff and sediment load in the summer flood season.

5.3. Changes in sediment deposition-scour

The estimated annual sediment deposition-scour changes and cumulative sediment deposition in the Sanhuhekou-Toudaoguai Reach are shown in Fig. 6. It can be seen that the annual variations are very significant, and the channel experienced deposition in most of the years. Except for some years (e.g., 1958, 1981, and 1989) in which catastrophic floods occurred and huge amounts of sediment from the Shidakongdui area entered into the reach, the channel sediment deposition amount is roughly less than 0.5×10^8 t/yr. The cumulative deposition curve indicates that the reach channel is generally filled and the total deposition amount is as high as more than 1.2 billion t during the past 60 years. Three different stages can also be found from the sediment accumulation

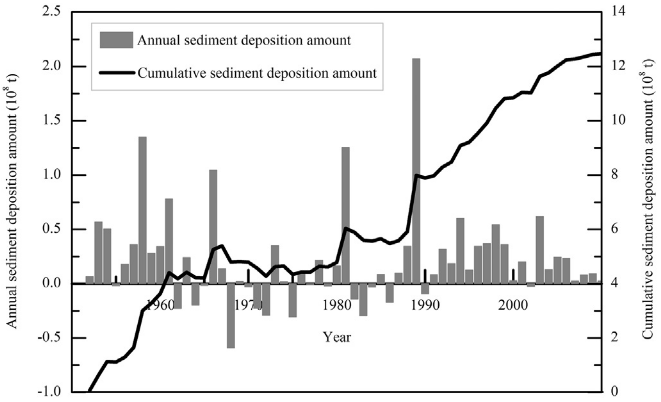

Fig. 6. The annual deposition changes and cumulative sediment deposition in the Sanhuhekou -Toudaoguai Reach (1952–2010).

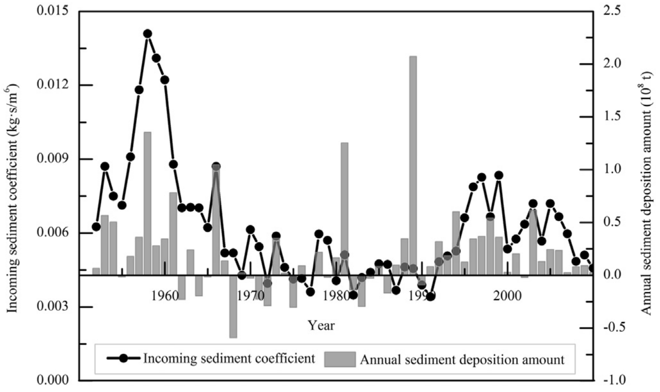

Fig. 7. Changes in the incoming sediment coefficient at the Sanhuhekou Cross-section and its relation with the sediment deposition amount in the Sanhuhekou-Toudaoguai Reach.

curve, in which the channel was notably filled before the 1970s, then slightly scoured during the 1970s and 1980s, and became filled again since the 1990s. It should be noted that the deposition since the 1990s is nearly as serious as that before 1970s, especially during the 1990s it almost increases linearly, and becomes slower in the 2000s.

The incoming sediment coefficient of the Sanhuhekou Cross-section is shown in Fig. 7, which ranges from 0.003 to 0.014 kg s/m^6 and shows remarkable annual variations. Except for some catastrophic flood years (e.g., 1968, 1981, and 1989), the coefficient values reflects the trend of sediment deposition in the reach, in which larger coefficient values also lead to heavier sediment deposition in the reach. Generally, larger values of the incoming sediment coefficient were found before 1968 with an average of 0.0085 kg s/m^6, and it sharply reduced to an average of 0.0047 kg s/m^6 between 1969 and 1985, and then slightly increased to an average of 0.0057 kg s/m^6 in the period after 1985. It is also noted from Fig. 7 that the horizontal axis intersects with the left vertical axis at the value of 0.0041 kg s/m^6 where zero deposition in the reach occurs, suggesting that it could be used as a critical value to roughly determine the scour and deposition status of the river reach.

The fitted equation according to Eq. (7) is as follows:

$$W_S = 0.60 - 0.0045Q_s + 0.3781W_{s,s} + 1.0271W_{s,k} \tag{9}$$

for which the correlation coefficient is $R^2 = 0.82$, indicating good agreement to the observed data (see Fig. 8). It can be seen that the annual runoff at the Sanhuhekou Crosssection has a negative effect on the annual deposition-scour amount of the study reach, suggesting that the increase of annual runoff can reduce the sediment deposition amount in the reach. In contrast, the annual sediment loads at the Sanhuhekou Crosssection and the Shidakongdui area have positive effects, in which the Shidakongdui area has a larger coefficient value (1.0271), and, thus, contributes more to the sediment deposition in the study reach.

6. Discussion

6.1. *Effect of construction and operation of upstream reservoirs*

The construction and operation of large-scale reservoirs have multiple impacts on the runoff and sediment transport in the downstream channel, one of which is on the direct storage and regulation capacity (Zahar et al., 2008). Compared to the Longyangxia Reservoir, the Liujiaxia Reservoir has much smaller storage and regulation capacity. Therefore, the construction and

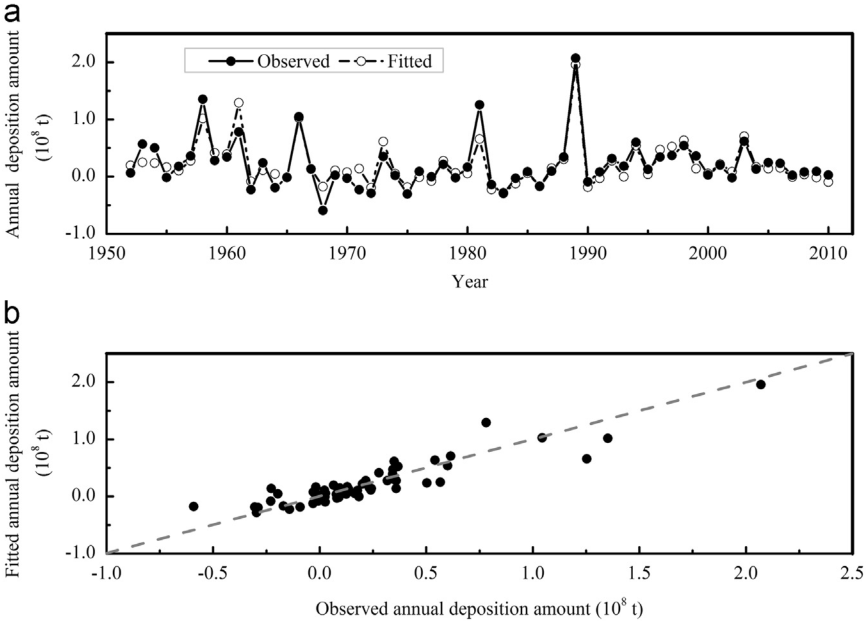

Fig. 8. Multiple linear regression fitting to the estimated annual deposition in the study reach.

operation of the Liujiaxia Reservoir didn't cause a serious reduction in the channel flow of the study reach. That is, a decrease of only less than 10% in the average annual runoff was found at the Sanhuhekou Crosssection in the second period between 1969 and 1985 (see Fig. 2). In contrast, after the construction of the Longyangxia Reservoir and the joint operation of the two reservoirs since 1986 (the third period), a reduction of about 40% in the average annual runoff was found compared to the first time period, indicating that the operation of the Longyangxia Reservoir seems to be a major factor leading to the reduction of annual runoff of the study reach, which can be seen from the Mann-Kendall trend and jump point tests (Fig. 3).

The situation of the sediment load is different, in which about 50% and 70% reductions were found in the second and third periods compared to the first period (see Fig. 2), respectively, suggesting that the Liujiaxia Reservoir makes more contribution to the reduction of the annual sediment load at the Sanhuhekou Crosssection than the Longyangxia Reservoir does. These differences can be explained by the fact that the runoff of the upper Yellow River mainly comes from the drainage area above the Longyangxia Dam, which has a drainage area of 131,420 km^2 comprising of 18% of the Yellow River's total drainage area. Therefore, the interception of water can significantly reduce the runoff to the downstream channel considering its huge storage capacity. Meanwhile, its drainage area is located in the Qinghai Plateau where soil erosion is relatively low, with only an average annual suspended sediment load of 0.11×10^8 t, which is much smaller than that of the Liujiaxia Reservoir (1.03×10^8 t). Additionally, the Liujiaxia Reservoir is located downstream of the Longyangxia Reservoir, and, thus, can have more impact on the direct interception of suspended sediment.

In addition to reducing the annual runoff and sediment load, the upstream reservoirs also alter the flood characteristics of the downstream river, in which the most notable change is the significant reductions of runoff and sediment load in the summer flood season, especially after the joint operation of the two reservoirs in which almost all the flood peaks larger than 1000 m^3/s were eliminated (see Fig. 5) and as a result the scouring capabilities of the floods were also remarkably reduced.

6.2. Effect of sediment load from the Shidakongdui area

The soil erosion in the Shidakongdui area is serious. Most of the rivers in the area are seasonal rivers, and the annual precipitation is less than 250 mm in the west, and increases to 350 mm in the east. A typical characteristic of the sediment load from the Shidakongdui area is that a huge amount of sediment discharges within a short period of time induced by rainstorms in the summer flood season, and the sediment load is largely dependent on the frequency and intensity of the rainstorms (Xu, 2014). According to Lin et al. (2014), the estimated average suspended sediment load from the Shidakongdui area during the years between 1952 and 2010 was about 0.19×10^8 t/yr, with very significant annual variations. The average sediment load in the 1950s was about 0.12×10^8 t/yr. It increased to 0.23×10^8 t/yr in the 1960s, and reduced to 0.19×10^8 t/yr in the 1970s, and then reached the maximum of 0.37×10^8 t/yr in the 1980s. Since the 1990s, the sediment load started to decrease, especially in the 2000s in which it significantly reduced to about 0.066×10^8 t/yr. This reduction is mainly due to the result of a series of water-soil conservation measures taken in the area in the past several decades, including the Three-North Shelter Forest Programme (TNSFP), conversion of degraded farm land into forest, and afforestation. These conservation measures mainly started around the year of 2000, and reached the total area of about 222.8, 552.2, and 1600.2 km^2 in the year 2010, respectively (Zhao, 2015).

An improvement of vegetation coverage can be found by the Normalized Difference Vegetation Index (NDVI) values calculated from Moderate Resolution Imaging Spectroradiometer (MODIS) images (MODIS13Q1 from the U.S. National Aeronautics and Space Administration (NASA), with spatial resolution of 250 m. The time period of the images ranged from 2000 to 2010, for which the data between July and September were chosen). The vegetation coverage almost linearly increased from 0.26 to 0.33 in the 2000s. Liu et al. (2016) also reported that the vegetation cover of the area has improved since 1998 (compared to 1980) due to a series of conservation measures, in which the land use changes suggested that unused land was converted to low and middle coverage grassland, low coverage grassland to middle and high coverage grassland, and middle coverage grassland to high coverage grassland. The conversion areas were mainly distributed in the upper and middle basin of the ten tributaries where the sediment yield was highest. Zhao et al. (2010) reported a similar result. In addition, the changes in the relation between discharge and sediment concentration of the Xiliugou River, one typical river of the Shidakongdui, also indicate a downward trend in sediment load since the 1990s, in which the concentration of suspended sediment under the same flow discharge notably reduced according to the monitoring data.

However, the decrease in sediment load from the Shidakongdui area didn't reduce the sediment deposition in the study reach. Instead, the situation became even more serious since the late 1980s than the period of 1969–1985 (see Fig. 6). This is mainly due to the fact that almost 99% of the suspended sediment load from the Shidakongdui area is discharged in the flood season (from June to September) (Lin et al., 2014; Xu, 2014), but the corresponding flow discharge from the upstream channel has been significantly reduced especially by the joint operation of the Longyangxia Reservoir and the Liujiaxia Reservoir since 1986 (see Fig. 5). Therefore, there's a serious lack of transport capacity for the sediment load in the flood season, especially for coarse sand, as the Shidakongdui area is the major source of coarse sand in the upper Yellow River basin.

6.3. Effect of major tributaries in the upstream

There is a notable decrease in the runoff and suspended sediment yield of the Qingshui River in the 1960s and 1970s as the result of a series of reservoirs constructed since the late 1950s. These reservoirs took effect since the early 1960s and reached their best regulation capacities in the 1970s and 1980s, intercepting about 1/3 of the runoff and more than 1/2 of the sediment load, which was one important contributor to the notable reduction of suspended sediment at the Sanhuhekou Crosssection in the period of 1969–1986. However, most of the reservoirs lost their regulation capacities as a result of sediment deposition since the 1990s, and the runoff and sediment load of the river have increased accordingly, but they were still lower than those in the 1950s (Wang et al., 2010).

Water and soil conservation measures, such as terraces and silt dams, were also installed beginning in the 1960s in the catchment of the Zuli River, and the runoff and sediment load of the river began to decrease gradually since then. As more conservation measures were applied after 2000, the average annual runoff and suspended sediment load in the 2000s significantly decreased from 1.14×10^8 m^3 and 0.47×10^8 t within the period of 1960s–1990s to 0.65×10^8 m^3 and 0.17×10^8 t, composing reductions of about 40% and 60%, respectively. This is another important factor that leads to the decrease of the sediment load at the Sanhuhekou Crosssection especially after 2000.

It should also be noted that the effect of these tributaries on the runoff at the Sanhuhekou Crosssection can be neglected, as the total annual runoff of the two tributaries only composes about 1% of that of the Sanhuhekou Crosssection. However, their total sediment load is as high as or even larger than that of the Sanhuhekou Crosssection. This phenomenon is very interesting, suggesting that the channel flow and suspended sediment of the Sanhuhekou Crosssection are from different sources, i.e. the runoff is mainly from the upper Yellow River, which is heavily regulated by large reservoirs such as Longyangxia and Liujiaxia as previously described, while the sediment primarily comes from the nearby tributaries, such as the Qingshui River and the Zuli River. Almost more than 90% of the suspended sediment load from these tributaries is yielded during the summer flood season, but the corresponding runoff is remarkably reduced by the upstream reservoirs, leading to a severe lack of capacity to carry these sediments. This is one of the most important reasons that cause the cumulative deposition in the study reach in recent decades.

6.4. *Meaning of incoming sediment coefficient*

The incoming sediment coefficient is an important indicator of runoff-sediment relation and has been widely used in previous studies on the Yellow River (Wu et al., 2015; Xu, 2014; Zhang et al., 2008). For the whole Ningxia-Inner Mongolia Reach of the Yellow River, the values of 0.0034 and 0.0017 kg s/m^6 were suggested by Zhang et al. (2008) when the channel reaches a balance between scour and deposition in the flood and non-flood seasons, respectively. Wu et al. (2015) suggested a value of 0.00506 and 0.00401 kg s/m^6 for the Bayangaole-Sanhuhekou and Sanhuhekou-Toudaoguai Reaches, respectively, in which the interval sediment yield within the reach was considered and a regression method was used to determine the coefficient. In this study, a good relation was found between the deposition amount and the incoming sediment coefficient value and a value of 0.0041 kg s/m^6 was determined for the study reach, which is consistent with Wu et al. (2015). This value is meaningful and could be used as a critical value to determine whether the study reach channel experiences scour or deposition.

7. Conclusions

The annual changes of deposition-scour in the Sanhuhekou-Toudaoguai Reach during the past 60 years were investigated based on runoff and suspended sediment observations from the Sanhuhekou and Toudaoguai hydrological stations and multiple influencing factors, such as reservoirs and tributaries in the upstream, as well as discharge from the Shidakongdui area were analyzed. The main conclusions are as follows:

(1) Even though the major sources of suspended sediment load, the Shidakongdui area and the upstream tributaries, such as the Qingshui River and the Zuli River, were obviously reduced (especially since the 2000s), the study reach was still in a status of cumulative aggradation, indicating a close relation to the characteristics of upstream runoff and sediment loads.

(2) The results from the Mann-Kendall trend test suggested that the joint operation of the Liujiaxia Reservoir and the Longyangxia Reservoir has important effects on the study reach. This joint operation not only significantly reduced the annual runoff and sediment load at the Sanhuhekou Crosssection, but also sharply decreased the sediment transport capacity of flow in the summer flood season when more than about 90% of the sediment loads are delivered to the study reach. The altered relation between water and sediment is a major contributor to the cumulative sediment deposition in recent decades.

(3) The water-sediment relation plays a critical role for sediment deposition-scour for the riverbed in the study reach. The estimated incoming sediment coefficient of the Sanhuhekou Crosssection ranged from 0.003 to 0.014 kg s/m^6, for which 0.004 kg s/m^6 can be used as a rough critical value to determine the scour or deposition status for sediment in the study reach. Increase of runoff from the upstream channel, especially in the summer flood season, and/or reduction of sediment load from the Shidakongdui area are important ways to reduce the sediment deposition in the study reach.

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