Adjusting the water-sediment matching relationship to reduce sedimentation in the flow rate constraint reach of the Lower Yellow River, China

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Abstract. The bank-full discharge along the Dongbatou-Aishan river reach of the Lower Yellow River is significantly lower than that of the upper reach and is the flow rate constraint reach that dictates the flood safety of the Lower Yellow River. The water and sediment matching relationship is the important factor that affects the scurr and siltation along this reach. It is necessary to control the relationship between water and sediment by retaining a portion of sediments in the upper reach in order to increase the overflow capacity in this reach. We first analyse the relationship between the water and sediment processes of the Lower Yellow River and the scouring and siltation of the constraint reach and verify the water and sediment conditions that require sediment retention in the upper reach. By analysing the characteristics of the river, we determined the area of sediment retention to be the reach that stretches from Xiaolangdi to Huayuankou. The relationship between the incoming sediment coefficient at Huayuankou Station and the percentage of sediment discharged and deposited in the lower reach is analysed. The results showed that when the incoming sediment coefficient is more than 0.04 kg\cdot s/m\textsuperscript{6}, sediment should be retain in the Xiaolangdi-Huayuankou river reach to maintain non-siltation in the constraint reach. Using bank-full discharge in the river reach from Xiaolangdi to Huayuankou and the channel stability as constraints we propose that the sediment retention in this river reach should be less than 0.144 billion m\textsuperscript{3}.

1. Introduction
An extremely wide and shallow section, a longitudinal slope, and serious siltation are three major, basic problems associated with river bed evolution of the Lower Yellow River [1]. These problems are especially prominent in the Dongbatou-Aishan river reach, and they make the flood conveyance of this reach smaller than that of upstream and downstream areas. It becomes the constraint reach that restricts the transport of water sediment in the Lower Yellow River [2] and will be the key river reach for remediation after the Xiaolangdi Reservoir goes into operation. Qi et al [3] once proposed to shape narrow and deep river channels, transform the wide and shallow river channels above Aishan, and use the narrow and deep river channels to convey flood with relatively high sediment content into the sea. The research results of Xu [4] also indicate that the sediment transport efficiency of narrow and deep river reaches is higher than that of wide and shallow reaches. Therefore, it is worth studying how to
shape and maintain narrow and deep river channels and increase the sediment transport capacity in the Dongbatou-Aishan reach and fundamentally change the braided characteristics of this river reach. Chen et al [2] analysed the formation mechanism of this river reach based on the current situation and proposed a treatment method using mechanical and manual dredging, respectively. Then, the water and sediments are regulated and operated by means of the Xiaolangdi Reservoir, and the excavated river channel is maintained for the long-term. River morphology is mainly shaped by water and sediment, and therefore it is necessary to analyse the relationship between river morphology and flow-sediment transport process if a narrow and deep channel to be shaped and maintained. The uncoordinated matching of water and sediment is one of the main factors related to continuous deposition in the Lower Yellow River. Han [5] analysed siltation data for the Sanmenxia-lijin river reach from September 1960 to October 1996 and suggested that deposition by floods, which have high sediment contents, is the principal reason for deposition. If floods with high sediment contents are not considered, there is subtle scouring in this river reach. Lin et al [6] and Xu [4] analysed flood data for multiple episodes and suggested that the key factor of sedimentation in the Lower Yellow River is incoming sediment coefficient, which is defined as

\[ \phi = \frac{S}{Q} \]  

(1)

where \( \phi \) (kg·s/m³) is incoming sediment coefficient; \( S \) (kg/m³) is sediment concentration; \( Q \) (m³/s) is flow rate.

And they propose the critical incoming sediment coefficient that maintains non-siltation in the Lower Yellow River is 0.012 and 0.01 kg·s/m³, respectively. Through calculations, Yao et al [7] concluded that floods with a flow rate of 4000 m³/s and sediment concentration of 50 kg/m³ are most favourable for downstream sediment transport. For the braided river reach of the Lower Yellow River, to shape a stable and deep river course by scouring and increase the sediment transport capacity of the river course is an approach to fundamentally solve the problem of continuous siltation along the river course and change its braided behaviour. Therefore, we study the influence of the water and sediment matching relationship on the scouring and siltation in the river course and adopt measures to shape reasonable water and sediment processes that are significant for the remediation of the Lower Yellow River.

Sediment retention is one of the approaches used to determine the matching relationship between water and sediment. Its general, the idea is to adjust the river reach through sediment retention within a time period (generally one year) and obtain the water and sediment conditions of the constraint reach, thereby obtaining a favourable water-sediment matching relationship. Meanwhile, a coordinated water and sediment relation is better for environment [8]. Then, sediments are transported into the sea, which maintains this river reach in a stable, non-siltation state. According sediment transport regime [9,10], after sediment retention, when the sediments encounter favourable water and sediment conditions, flows can remove some or all remaining sediments and therefore maintain a stable and non-siltation state for the entire course of the Lower Yellow River.

In this study, by analysing the relation between deposition amount and incoming sediment coefficient, and analysis of channel geometry of different reaches, we proposed the appropriate flow and sediment condition and the location for sediment retention. Finally the maximum amount of sediment retention is obtained by numerical model calculation under river pattern stable condition. This study can be helpful in sediment treatment and flood control in Lower Yellow River.

2. Relationship between water and sediment processes in the Lower Yellow River and scouring and siltation in the constraint reach

2.1. Influence of annual average water and sediment processes on sedimentation

We use daily average water and sediment data for the Yellow River at the downstream of Xiaolangdi, collected over a period of 39 years from 1965-2003, and statistically obtain the annual average incoming sediment coefficient at Huayuankou hydrologic station. The relationship between the
incoming sediment coefficient and sediment delivery ratio in Dongbatou-Aishan river reach is shown in figure 1. Sediment delivery ratio is defined as

\[ D_r = \frac{Q_{S_{\text{out}}}}{Q_{S_{\text{in}}}} \]  

(2)

where \( Q_{S_{\text{out}}} \) (kg) and \( Q_{S_{\text{in}}} \) (kg) is the amount of sediment transport at the outlet and inlet of the river reach respectively.

In this river reach, the percentage of sediment discharged decreases as the incoming sediment coefficient at Huayuankou Station increases. They generally exhibit an exponential relationship, for which the correlation coefficient is -0.80. When the ratio of sediment discharged is greater than 1, the amount of sediment discharged from the river course will be greater than the amount of sediment entering the river course. Under these conditions, the riverbed will be affected by scouring; otherwise, it will experience sedimentation. To obtain a balance between scouring and silting, the percentage of sediment discharged must be equal to 1. From the exponential relationship for the fitting between the incoming sediment coefficient at Huayuankou and the percentage of sediment discharged in the reach from Huayuankou to Aishan, we infer that when the percentage of sediment discharged is equal to 1, the incoming sediment coefficient is 0.01 kg·s/m\(^6\). That is, when the annual average incoming sediment coefficient at Huayuankou Station is less than 0.01 kg·s/m\(^6\), the constraint reach for the given rate of flow can maintain a non-siltation state.

There is also a relatively good relationship between the scour magnitude and siltation volume of the constraint reach and the incoming sediment coefficient of the upper reach; they exhibit obvious trends. Their correlation coefficient is 0.85, and they exhibit a positive correlation. Sediment deposition increases as the incoming sediment coefficient increases. From the fitting relationship, we can infer that when sediment deposition in this river reach is 0, the corresponding incoming sediment coefficient for the scouring and silting balance is 0.01 kg·s/m\(^6\).

Based on this analysis, it is apparent that from the perspective of either the percentage of sediment discharged or sediment deposition, if the incoming sediment coefficient of Huayuankou Station is smaller, it is more favourable for sediment transport through the lower reach and for reducing downstream sedimentation. The incoming sediment coefficient that maintains stability or the scouring and silting balance of the Dongbatou-Aishan river reach should be approximately 0.01 kg·s/m\(^6\).

2.2. Influence of water and sediment processes on sedimentation during the year

Changes in scouring and silting in the Lower Yellow River mainly occur during the flooding process in the flood season [6]. The process associated with incoming water and sediment during the flood
season is considerably different than that during the non-flood season; further, water and sediment are mainly concentrated in the flood season. The percentages of water and sediment for the whole year during the flood seasons of 1965-2003 at Huayuankou Station are shown in figure 2. It is apparent that the percentage of incoming sediment is obviously higher than the percentage of incoming water during the flood season. Since the water volume is less than the sediment volume, and water and sediment are not matched. Therefore, the incoming sediment coefficient during the flood season is much higher than the incoming sediment coefficient during the non-flood season. The incoming sediment coefficient during the flood season is generally above the critical incoming sediment coefficient, whereas the incoming sediment coefficient during the non-flood season is typically lower than the critical incoming sediment coefficient. Consequently, this shows that sediment deposition during the flood season is much greater than that during the non-flood season (figures 3 and 4).

Figure 2. Percentage of water and sediment in the flood season.

Figure 3. Incoming sediment coefficient in the flood and non-flood seasons.

Figure 4. Sediment deposition along Dongbatou-Aishan reach in the flood and non-flood seasons.

Figure 4 shows sediment deposition along the constraint reach during the flood and non-flood seasons. Sedimentation is mainly concentrated in the flood season, whereas the non-flood season is dominated by scouring. Volumetrically, sediment deposition during the flood season is much greater than the magnitude of erosion during the non-flood season. For instance, in 1977, the incoming sediment coefficient during the flood season was 0.049 kg·s/m$^6$, and sediment deposition reached 405 million t, whereas during the non-flood season of the same year, the incoming sediment coefficient was 0.009 kg·s/m$^6$ and sediment deposition was -90 million t; i.e., there was scouring. Siltation occurs during the flood season, and scouring occurs during the non-flood season; their absolute values are nearly more than 40-times different. Therefore, the Lower Yellow River perennially hosts sedimentation. The river bed continues to rise, and flooding is not consistent.
2.3. Water and sediment conditions that cause sediment retention

By comparing the distribution of incoming sediment coefficients and sediment deposition, we can see that during either the flood season or the non-flood season, sediment deposition is proportional to the incoming sediment coefficient. Moreover, when the incoming sediment coefficient is near 0.01 kg·s/m², the river course is essentially at an equilibrium state between scouring and silting. The distribution of incoming sediment coefficients is essentially consistent with the distribution of sediment deposition. When the incoming sediment coefficients for the flood and non-flood seasons are close, the amounts of scouring and siltation are also consistent. When the difference between the incoming sediment coefficients for the flood and non-flood seasons is relatively large, sediment deposition during the flood season and the non-flood season is also considerably different. Therefore, the incoming sediment coefficient is not only related to sediment deposition on an annual mean significance. Over short time periods, such as flood season and non-flood season, it is closely related to sediment deposition. For both the flood season and non-flood season, when the incoming sediment coefficient is less than 0.01 kg·s/m², the river course remains non-siltation, and this critical coefficient of water and sediment can also maintain the scouring and silting balance for the entire Lower Yellow River [11]. We can see from the results of the above analysis, that the maintenance of year-round non-siltation in the lower reach should satisfy the following constraint condition:

\[
\begin{align*}
S_T / (Q_f b) & \leq 0.01 \\
S_f (1-a)/[Q_f(1-b)] / t_f & \leq 0.01 \\
S_T / Q_f / ((t_r + t_f) & = \phi_s
\end{align*}
\]

where \( S_T \) (kg) and \( Q_T \) (m³) are the total annual amounts of incoming sediment and incoming water, respectively; \( a \) and \( b \) are the respective proportions of water and sediment during the flood season; \( t_r \) (s) and \( t_f \) (s) are the respective temporal lengths of the flood and non-flood seasons; and \( \phi_s \) (kg·s/m²) is the annual average incoming sediment coefficient. When the temporal lengths of the flood season and non-flood season are determined, the proportions of water and sediment during the flood season, \( a \) and \( b \), will change with the annual average incoming sediment coefficient \( \phi_s \). When \( \phi \) is greater than 0.04 kg·s/m², we solve the equation (3) and the obtained proportions of water and sediment during the flood season fall outside the range \([0, 1]\). This indicates that when the annual average incoming sediment coefficient exceeds 0.04 kg·s/m², in order to avoid siltation along the constraint reach, we must reduce the amount of sediment that enters the reach. Sediment retention in the upper reach is an effective approach.

3. Sediment retention location

3.1. Riverbed slope

The Lower Yellow River is commonly divided into three parts according to river pattern, including upstream which is called transitional reach between mountain and plain (Xiaolangdi-Huayuankou), middle reach which is known as braided river reach (Huayuankou-Aishan) and downstream which is meandering reach (Aishan-Lijin). Riverbed slope of the Lower Yellow River generally decreases from the upstream areas to the estuary (figure 5). The average slope from Xiaolangdi to Huayuankou is approximately 2.0/10000, and from Huayuankou to Aishan, the riverbed slope gradually decreases from 2.0/10000 to approximately 1.0/10000. From Aishan to Lijin, the riverbed slope is essentially stable and is slightly greater than 1.0/10000. The riverbed slope is the major factor influencing flood conveyance [12], and a large slope is beneficial to water and sediment transport. Therefore, we can see
that the Xiaolangdi-Huayuankou reach has a relatively large potential for sediment transport.

![Figure 5. Riverbed slope of each reach in the Lower Yellow River.](image)

After the construction of the Xiaolangdi Reservoir, large volumes of sediment were deposited in the reservoir. Along with the transfer of water and sediment in recent years, there has been scouring of relatively large magnitude in the reach extending from Xiaolangdi to Huayuankou. After construction of the Xiaolangdi Reservoir, from 1999 to 2008, the total cumulative scouring in the river reach from Xiaolangdi to Huayuankou reached 0.376 billion m$^3$. Considering that the dry bulk density after the siltation of sediment stabilizes is 1.50 t/m$^3$ [13], the volume of scoured sediment from this river reach was 0.564 billion t.

The scouring slightly reduces the average riverbed slop which decreases from 2.14/10000 to 2.08/10000. However, the riverbed slop in different river reaches could increase or decrease compared to before scouring. The slope increases from Tiexie to Peiyu, and the slope decreases from Peiyu to Huayuankou. The longitudinal profile of Xiaolangdi to Huayuankou reach is shown in figure 6. Due to impoundment of Xiaolangdi reservoir in 1999, this reach was eroded significantly. The maximum depth of scour occurred in the middle of the reach (from 30 to 80 km distance to Xiaolangdi reservoir), while scour depth at both ends of the reach was relatively low. Thus, the riverbed slop of the upstream of the reach got steeper and that of the down stream became gentle. In recent years, scouring and cutting has not caused a large change in the bottom slope of this river reach, and this river reach still has relatively strong sediment transport capability.

![Figure 6. Changes in channel longitudinal profiles of the Xiaolangdi-Huayuankou Reach.](image)
3.2. Cross-section morphology

The cross-section of the Lower Yellow River is mostly a typical, compound cross-section, usually composed of river troughs and bottomlands. The elevation between the bottomland and trough is one of the important parameters that reflect the morphology of the section and its stability. If the relief between the bottomland and trough is relatively low, there is a higher likelihood of bottomland flooding, and the stability of the section is relatively poor. Figure 7 shows the variation in relief between bottomland and troughs on typical large sections of the Lower Yellow River.

**Figure 7.** Relief between bottomlands and troughs along the Lower Yellow River.

It is apparent that from the perspective of spatial distribution, the relief between bottomland and troughs generally decreases from upstream to downstream. The relief between the bottomland and trough at the Huayuan Town section is consistently approximately 4 m. Until the Huayuankou section at the inlet of the braided river reach, the relief between the bottomland and trough decreases to approximately 2 m, and the relief between the bottomland and trough in the river reach from Huayuankou to Gaocun remains at this level. The multi-year average relief between the bottomland and trough in the Aishan section increases to 3 m, and the relief between the bottomland and trough at the section of the lower reach gradually decreases. By comparing figures 5 and 7, we find that at the reach with a low riverbed slope, its corresponding elevation between thalweg and beach along that section is relatively high. The riverbed slope and elevation between thalweg and beach in the constraint reach are both obviously smaller than those of the adjacent river reaches on the upper and lower reaches.

Before construction of the Xiaolangdi Reservoir (1992-1998), the relief between the bottomlands and troughs for the entire Lower Yellow River exhibited a decreasing trend, whereas after construction of the Xiaolangdi Reservoir (1998-2003), the elevation between bottomlands and troughs obviously increased. Over the 11 years between 1998 and 2008, the Xiaolangdi-Huayuankou River course generally exhibited scouring, for which the average scour area was 2602 m$^2$. The elevation of the river bottom generally decreased after scouring, and for the entire river reach, the average elevation of the river bottom in 2008 decreased by 0.434 m compared to that in 1998, with the place of maximum reduction in the Huayuankou section. The cumulative scouring depth on the river bottom was 0.928 m, and the measured water level under the same discharge also greatly decreased.

Scouring of the river course mainly occurs in the main channel, and similar changes in the bottomlands are relatively small. The scoured areas of different sections are essentially the added area of the main channel. Table 1 is a statistical analysis of the area of the main river channel in 1998 and 2008. It is apparent that after the construction of the Xiaolangdi Reservoir was completed, there was relatively large variation in the main channel area of the Xiaohua reach. The relative added value of
The area for the Peiyu section was the largest. The area of the main channel in 2008 was 3.78 times that in 1998, and it is the maximum for the various sections. The area of Xiagujie, with the smallest change, was 1.05 times that before scouring occurred. Scouring and cutting of the river channel in this river reach over recent years has provided accommodation for sediment retention.

**Table 1. Variation in main channel due to erosion.**

| Section name    | Area in 2008 (m²) | Area in 1998 (m²) | Amplification factor of cross-sectional area |
|-----------------|-------------------|-------------------|---------------------------------------------|
| Tiexie          | 4756.3            | 3692.3            | 1.29                                        |
| Xiagujie        | 5093.5            | 4848.0            | 1.05                                        |
| Huayuan Town    | 5341.6            | 3524.2            | 1.59                                        |
| Mayugou         | 4193.3            | 1530.9            | 2.74                                        |
| Peiyu           | 4905.0            | 1298.6            | 3.78                                        |
| Yiluo Estuary   | 4217.4            | 3260.6            | 1.29                                        |
| Gubaizui        | 5327.4            | 2744.2            | 1.94                                        |
| Luocunpo        | 3626.2            | 1909.3            | 1.90                                        |
| Guanzhuangyu    | 4288.5            | 2179.0            | 1.97                                        |
| Qin chang       | 3850.2            | 2091.7            | 1.84                                        |
| Huayuankou      | 11467.4           | 4024.5            | 2.85                                        |

Note: In this table, the bank-full discharge is calculated according to the Chez formula. The Huayuankou section is the braided river reach, and the main channel is not stable; the area of the main channel in the statistical analysis is the sum of the areas of the two river channels.

Recently, the Xiaolangdi-Huayuankou reach was scoured. The main channel generally undercut the banks and expanded, and flood areas increased. Except for the Huayuankou section, the main channel of various sections is relatively stable on the plane, and there is no violent switching phenomenon. This indicates that this reach is relatively stable, which is favourable for sediment retention.

Channel in Xiaolangdi-Huayuankou reach is relatively narrow and deep with relatively strong flow and sediment conveyance capacity. Moreover, because the Xiaolangdi Reservoir is located at the inlet of this river reach, it can be used as the water and sediment control node of the inlet. Therefore, this river reach is a relatively ideal region for sediment retention.

**4. Theoretical sediment retention amount**

**4.1. Bank-full discharge**

We adopt a one-dimensional mathematical model [14], which is divided into multiple orders of magnitude, such as 500 and 1000, and calculate the water levels of different sections. From this, we can obtain the relationship between water level and discharge for different sections and then determine the bottomland elevation of various sections on the section map. Based on the relationship between water level and discharge, we can obtain the bank-full discharge of different sections. This method has been verified, and it has relatively high computation accuracy for bank-full discharge of the Lower Yellow River [15]. In this paper, we perform the calculations based on the terrain in 1998 and 2008 to obtain the bank-full discharge of different sections on these two terrains (table 2). The bank-full discharge for different sections increased due to impoundment of Xiaolangdi reservoir, and the increase in the middle river reach is particularly obvious. For instance, the bank-full discharge of the Peiyu section increases from 2400 m³/s to 11000 m³/s, and the flow capacity of the main channel increases by 8600 m³/s, which is equivalent to 4 times the original overflow capacity. While the flow capacity of the main channel increases, the bank-full discharge of various sections also tends to be consistent, and the ratio between the maximum and minimum bank-full discharge decreases from 7:1 in 1998 to 4:1 in 2008. This indicates that the flow capacity of original constraint reach gradually increases, and the flow of the entire river reach is smoother. Based on the bank-full discharge of different sections, we use the separation distance of the section as the weight, and adopt the weighted average method to calculate the overflow capacity in the main channel for the entire river reach. The
bank-full discharge of the entire river reach after scouring of the river reach increased from 4446 m$^3$/s in 1998 to 9563 m$^3$/s in 2008.

Table 2. Bank-full discharge calculated by the numerical model.

| Section name     | Tiexie | Xiagujie | Huayuan Town | Mayugou | Peiyu | Yiluo Estuary |
|------------------|--------|----------|--------------|---------|-------|---------------|
| Bank-full discharge/m$^3$/s | 1998 | 6 000 | 6 800 | 4 750 | 2 400 | 2 400 | 3 500 |
|                  | 2008 | 11 200 | 11 000 | 10 800 | 9 400 | 11 000 | 8 000 |

Due to flood control safety for the river reach dedicated to sediment retention, after sediment retention, the flow capacity of the main channel in the river reach should maintain a certain level. By analysing the multi-year measurement data and the operational mode of the Xiaolangdi Reservoir, we refer to the standard for a healthy main channel of the Lower Yellow River [16] and consider the basic functions of flood discharge and sediment transport for the Lower Yellow River [17] and the existing flow capacity of the main channel along this river reach. Under the premise of ensuring flood control safety, the bank-full discharge in this river reach after sediment retention should not be less than 5000 m$^3$/s. For various sections, we use a bank-full discharge of 5000 m$^3$/s as the constraint condition, and existing river channels can retain some sediments. The deposition area of different sections and the sediment deposition for the entire river reach are shown in table 3, under the premise that the average flow rates in the sections before and after the sediment retention section essentially do not change. At present, the river channel of the Xiaolangdi-Huayuankou reach is narrow and deep, and the width of the main channel ranges from 1000 to 2000 m. The area of the river channel ranges from 4000 to 5000 m$^2$, and the slope of the river-bottom is approximately 2.1/10000. The flow velocity is relatively high, and therefore, a relatively large volume of flow can pass through. At the current overflow condition of the river course, in order to ensure that the main channel for different sections can pass the flow volume of 5000 m$^3$/s without using the flood plain, the maximum sediment detention in the main channel is 0.160 billion m$^3$, which is smaller than the cumulative scour amount of this river reach after the construction of the Xiaolangdi Reservoir.

Table 3. Theoretical sediment retention amount.

| Section name     | Area of sediment detention (m$^2$) | Available sediment detention between sections ($\times 10^4$ m$^3$) | Cumulative available sediment retention ($\times 10^8$ m$^3$) |
|------------------|----------------------------------|---------------------------------------------------------------|------------------------------------------------------------|
| Tiexie           | 3330.0                           | -----                                                        | 0                                                          |
| Xiagujie         | 2568.0                           | 1253.3                                                      | 0.13                                                       |
| Huayuan Town     | 3227.1                           | 2541.2                                                      | 0.38                                                       |
| Mayugou          | 1428.1                           | 2932.8                                                      | 0.67                                                       |
| Peiyu            | 2311.1                           | 1162.9                                                      | 0.79                                                       |
| Yiluo Estuary    | 801.8                            | 1923.8                                                      | 0.98                                                       |
| Gubaizui         | 1767.2                           | 2026.9                                                      | 1.18                                                       |
| Luocunpo         | 935.3                            | 1582.3                                                      | 1.34                                                       |
| Guanzhuangyu     | 1890.9                           | 378.7                                                       | 1.38                                                       |
| Qinchang         | 568.3                            | 1545.6                                                      | 1.53                                                       |
| Huayuankou       | 140.6                            | 635.9                                                       | 1.60                                                       |

4.2. Channel regime coefficient

Sediment detention in the main channel will cause a reduction in the discharge area of the main
channel. In the situation that the width of the water surface does not change, it inevitably causes a reduction in the average water depth under bank-full discharge, and therefore, it will cause an increase in the channel regime coefficient [18]. The channel regime coefficient is closely related to the sediment transport capacity of the river course and the river pattern, and therefore, sediment retention likely causes changes in the river pattern. Table 4 lists the changes in channel regime coefficients for different sections by adopting the maximum possible amount of sediment detention.

### Table 4. Variation in channel regime coefficient due to sediment retention.

| Section name       | Tiexie Before sediment detention | Xiaguji | Huayuan Town | Mayugu | Peiyu | Yiluhekou |
|--------------------|----------------------------------|---------|--------------|--------|-------|-----------|
| Channel regime coefficient $\zeta$ Before sediment detention | 5.37 | 5.61 | 4.34 | 7.43 | 6.61 | 5.78 |
| After sediment detention | 17.90 | 11.32 | 10.96 | 11.26 | 12.49 | 7.14 |

| Section name       | Guabazui Before sediment detention | Luocunpo | Guanzhangu | Qinchaung | Huayuankou | Gubaizui |
|--------------------|-----------------------------------|----------|------------|------------|------------|----------|
| Channel regime coefficient $\zeta$ Before sediment detention | 7.70 | 9.61 | 13.56 | 10.46 | 31.68 | |
| After sediment detention | 11.52 | 12.96 | 24.26 | 12.27 | 33.07 | |

For the same river course, in general, the channel regime coefficient is small, and the morphology is narrow and deep, which is favourable for water transport and sediment transport and maintaining a stable river course. Table 4 shows that from Tiexie to Huayuankou, the channel regime coefficient generally increases, and the channel regime coefficient of the Huayuankou section reaches 31.68. The channel regime coefficient of the braided river reach in the Lower Yellow River is $\zeta>19$ [18], and therefore, the Huayuankou section is a typical braided channel section. Since the Yellow River has a bed composed of relatively fine sediments, when $\zeta<5.5$, it is a mountain river [18]. It is apparent that the upper part of this river reach is essentially a mountainous reach before sediment retention, and the middle part is a transitional reach. Both are relatively stable. After sediment retention, the channel regime coefficient of different sections obviously increases. Except for the Guanzhangu and Huayuankou sections, it is still smaller than the lower critical value of the channel regime coefficient in the braided river course of the Lower Yellow River. Therefore, the river course remains relatively stable. For the Guanzhangu and Huayuankou sections, the channel regime coefficient was relatively high before sediment retention, and the stability of the river course was relatively poor. Sediment retention is not favourable for the stability of the river along this reach, and eliminating sediment retention may increase stability. The maximum possible volume of sediment retained in this reach is 0.144 billion m$^3$.

### 5. Conclusions

By analysing the measured water and sediment data, from the perspectives of water and sediment conditions for sediment detention, range of sediment detention, and theoretical amount of sediment detention, we studied the remediation of the Dongbatou-Aishan river reach by adopting the idea of sediment retention in the Lower Yellow River. In this river reach, the percentage of sediment discharged and sediment deposition are both related to the incoming sediment coefficient of the Lower Yellow River. The lower the incoming sediment coefficient is, the higher the percentage of sediment discharged in the downstream river course. The critical incoming sediment coefficient of the lower reach river course that is necessary to maintain a non-siltation flow rate in the constraint reach is 0.01 kg·s/m$^6$. The incoming sediment coefficient during the flood season is greater than the critical value, and that during the non-flood season is less than the critical value. The water and sediment conditions that require sediment retention are when the incoming sediment coefficient is greater than 0.04 kg·s/m$^6$. The location of sediment retention should be selected along the Xiaolangdi-Huayuankou river.
reach because the river slope of the Xiaolangdi-Huayuankou reach is greater than that downstream, providing it with a relatively strong sediment transport capacity and a relatively low risk of sediment retention, and the relief between the bottomland and the trough of the river along the Xiaolangdi-Huayuankou reach is relatively high, and it has a relatively large flood area. Moreover, the river course itself is relatively stable, providing space for sediment retention. Finally, by comprehensively considering the basic functions of flood discharge and sediment transport for the Lower Yellow River, with a minimum bank-full discharge no less than 5000 m$^3$/s as a constraint, as well as assuming stability of this river reach after sediment retention, we determine that the theoretically available amount of sediment retention in the Xiaohua reach is 0.144 billion m$^3$.

All the data used in this study is based on the persistance of flow and sediment condition in the 20th century, but in the recent decades, especially after 2000, because of water and soil conservation in China, sediment discharge in many rivers decreased dramatically [19,20]. Further study on sedimentation in Lower Yellow River is necessary under the condition of water and sediment change.

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