Mechanism of sediment transport by flood and longitudinal peak discharge amplifications in the Yellow River

H H Qi¹, P Qi²,³, Z Y Sun² and S A Zhang²

¹Guy Carpenter, Philadelphia, PA, USA
²Yellow River Institute of Hydraulic Research, Zhengzhou, Henan, China
³Email: qipu2011@sina.cn

Abstract. As the general principle of river bed evolution during the fluvial process, the channel is formed by river flows, while the movement of river flows is contained by channels. When the hyperconcentrated flood propagates along the wandering reach of the Yellow River, the peak discharge of the flood can increase along the reach. Due to the recurrence of this phenomenon, attentions have been drawn from various stakeholders, since the amplifications of flood peak can jeopardize flood control works. By analyzing the field observed data, we present our research findings of “scour during rising” and “deposit during falling” of a flood event, as well as the sediment transport mechanism with constant discharge. The bedform affects the characteristics of sediment transport and the resistance force. When the bedform is in the dynamic equilibrium state, sediment transport characteristics can be described as “the more sediment input, the more sediment output”. When the shear stress created by flow acting on bed is increasing, scour is observed on the channel bed. On the contrary, when shear stress is decreasing, deposition is observed. When the shear stress remains the same, sediment transport is in the equilibrium state. After the operation of Xiaolangdi Reservoir, due to coarsen of the bed material, the bedform resistance increased. When the flow condition changes and the bed roughness decreased abruptly, the increasing flow velocity can result in the reduction of channel storage volume. This is the main reason for the longitudinal amplifications of peak discharge in the wandering reach of the Yellow River.

1. Introduction
A great amount of measured data from the main stem of Yellow River and its tributaries indicate that different combinations of incoming water and sediment can form different river channel patterns and develop different river types [1,2]. When there is too much silt with small discharge, it often forms a wandering river section, and the channel is shallow and wide, and it is impossible to control the channel regime change. The sediment transport capacity is also low. When the sediment is mainly transported by flood, a narrow and deep channel is developed, and many years of small discharge can develop a curved channel. The sediment in the Yellow River consists of the finest sand (0.05-0.15 mm) which is easier to incipient motion, regardless of the high and low sediment concentration (up to 900 kg/m³, down to 10 kg/m³); steep or mild of the bed slope (from the tenths of tenth thousand to 0.6 of ten thousand) [3-5], the riverbed is always scoured during the rising phase of the flood hydrograph, but silted vice versa. This phenomenon cannot be explained by applying the existing sediment transport theory and formula. In fact, when the channel is in upper-stage regime with high sediment transport rate, the characteristics of the channel can be described as “the more sediment input, the more output”. The current mathematical model does not consider the slower motion of the bed sediment than the flood wave, causing the change of sediment transport capacity to be lagged behind the water flow. The
effect, which caused the change of flood transport characteristics [6,7] and the river bed to rise and fall. After the operation of Xiaolangdi Reservoir, the downstream river channel is strongly scoured, and the riverbed composition becomes coarser; which generates abnormal phenomena of amplification of flow discharge [8,9]. It’s important to analyze this phenomenon so that we know how to operate the reservoir more reasonably and scientifically for different purposes. This paper will study the sediment transport mechanism in detail, and provide guidance on how to operate the reservoir.

2. General principle of bed evolution of the lower Yellow River channel

2.1. Different channel types along lower Yellow River

As it’s known to all, Yellow River is a heavily sediment-laden river in the world. Throughout ancient time, with long term natural evolution of the environment and human’s habitation, the 800 km lower Yellow River from upstream to downstream (Tiexie to Lijin) has developed different river regimes and channel types [10], as shown in Figure 1. Each reach has its own characteristics of channel evolution and sediment transport mechanism. The 300 km long reach from Tiexie to Gaocun, with bed slope ranging from 0.0027 to 0.0017, can be called as a typical “wide and shallow” and wandering section. The 165 km reach from Gaocun to Taochengpu has a transition channel type with a bed slope from 0.0017 to 0.0011. The 460 km reach from Taochengpu to Lijin (river mouth), where bed slope is only 0.001, the channel can be described as “deep and narrow” and meandering.

![Figure 1. Longitudinal Profile and Typical Sections of Lower Yellow River.](image)

2.2. Sediment transport capacities of the lower reach channel

Using the analysis of field observations at different reaches along Lower Yellow River, as well as the major tributaries of Wei River and Beiluo River, wandering reach will be developed when small discharge carries large amount of sediment. The hyperconcentrated flow in natural channels is always fully turbulent. The flow holds the same friction characteristics as clear water, so resistance force can still be computed by using Manning’s equations. The grain size of sediment in Yellow River is so small with \( d_{50} = 0.03-0.10 \) mm. As sediment concentration is increasing, the particle fall velocity decreases significantly. The sediment distribution becomes more even along the vertical line. From the analysis of velocity distribution along vertical direction and the effect of sediment on flow, when the sediment concentration is around 200 kg/m\(^3\), it is most difficult for sediment transport [2,10]. With increase of the viscosity, even coarse sediment particle can be transported easily. Sediment transport rate can reach up to 900 kg/m\(^3\), which illustrates the high sediment transport efficiency of the hyperconcentrated flow. Downstream of Aishan in the lower reach, the observed maximum sediment concentration is around 200 kg/m\(^3\). Because of the great sediment conveyance capacity of the
hyperconcentrated flow, a concentration as high as 800 kg/m$^3$ can be easily transported through the river channel into the ocean when discharge is ranging from 2,000 m$^3$/s to 3,000 m$^3$/s. The key requirement is to transform the existing shallow and wide channel to a narrow, deep and stable one.

In Table 1, the river channel characteristics of the Wei River, Beiluo River and the lower Yellow River are shown. The observed data shows all three rivers have great sediment transport capacity.

| River          | Reach          | Length (km) | Channel Width (m) | Width over Depth (B/h) | Slope (10$^{-4}$) | Bankfull Discharge (m$^3$/s) |
|----------------|----------------|-------------|-------------------|------------------------|------------------|-------------------------------|
| Yellow River   | Aishan - Lijin | 282         | 400 - 600         | 3 - 6                  | 1.0              | 3,000 - 6,000                 |
| Tributary:     | Beiluo River   | Luo 17# - Chaoyi | 87               | 60 - 100               | 2.3              | 300 - 1,000                   |
| Tributary:     | Wei River      | Lintong - Tongguan | 165             | 80 - 300               | 3 - 6            | 1,000 - 5,000                 |

Figure 2 shows at five key hydrologic stations, the longitudinal variations of sediment concentration along the lower Yellow River for major flood events with maximum sediment concentrations. The sediment concentration declined significantly from 220 - 320 to 80 - 150 kg/m$^3$ along the “wide and shallow” type of channel. But in the 300 km “deep and narrow” channel with a mild slope, the average sediment concentration still has some amplification. This phenomenon demonstrates the influential sediment transport capacity of the hyperconcentrated flow.

![Figure 2. Sediment Concentration (kg/m$^3$) of Five Hyperconcentrated Floods along Lower Yellow River.](image)

3. **Resistance force and development of alluvial channel in the lower reach**

As the general principle of fluvial river bed evolution process, the channel is developed by flows, while the motion of flows is restricted by channels. The hydraulic geometry of the channel is a comprehensive reflection of the flow pattern and the channel characteristics, as well as the resistance characteristics of the moving bed. The river bed erosion and siltation is not only dependent on flow conditions, but also due to the hydraulic characteristics of the bed sediment and the movement characteristics of the bottom sand. The hydraulic geometry of the channel variations with the flow
characteristics, determines the scouring and depositing state of the riverbed. The relative movement of the flood and the sediment determines the scouring and silting process. The in-depth analysis of these problems will help to understand the rush of the alluvial channel and the mechanism of silt characteristics and sediment transport characteristics.

The river channel hydraulic geometry is usually described by a set of equations shown below:

\[ B = K_1 Q^{\beta_1} \]  
\[ h = K_2 Q^{\beta_2} \]  
\[ V = K_3 Q^{\beta_3} \]

The K-value represents the initial state of the variables at the reference discharge, and \( \beta \)-value shows the rate of changes in the hydraulic geometry with discharge. From the continuity equation \( Q = \beta hV \), we know \( K_1 K_2 K_3 = 1 \) and \( \beta_1 + \beta_2 + \beta_3 = 1 \). From a rigid rectangular channel B is a constant, \( \beta_1 = 0, \beta_2 = 0.6 \) and \( \beta_3 = 0.4 \). For a natural channel with complex geometry, the situation becomes more complicated. Using observed data at Aishan, Luokou and Lijin stations, the characteristics of channel hydraulic geometry were studied. The curve is approximately composed of two straight lines intersecting at \( Q = 1,500 \) m\(^3\)/s. For this discharge, K-values and B-values are listed for all three stations in Table 1. Evidently both K and \( \beta \) differ greatly when discharge is greater or smaller than 1,500 m\(^3\)/s. So far as flow characteristics and movable bed resistance are more concerned, with variation of \( \beta \) explained in Table 2.

| Discharge | Station | \( K_1 \) | \( K_2 \) | \( K_3 \) | \( \beta_1 \) | \( \beta_2 \) | \( \beta_3 \) |
|-----------|--------|--------|--------|--------|--------|--------|--------|
| <1,500 m\(^3\)/s | Aishan | 110    | 0.303  | 0.030  | 0.178  | 0.258  | 0.564  |
|           | Luokou | 48.2   | 0.96   | 0.0216 | 0.242  | 0.145  | 0.613  |
|           | Lijin  | 87.2   | 0.500  | 0.0230 | 0.237  | 0.192  | 0.571  |
| >1,500 m\(^3\)/s | Aishan | 300    | 0.018  | 0.186  | 0.032  | 0.645  | 0.323  |
|           | Luokou | 215    | 0.0124 | 0.376  | 0.032  | 0.742  | 0.226  |
|           | Lijin  | 208    | 0.0218 | 0.220  | 0.104  | 0.613  | 0.283  |

All these characteristics have profound influence on the behavior of the alluvial reach. It is of special interest to concerning the demarcation discharge of 1,500 m\(^3\)/s, because since long it has been recognized as the demarcation of two different patterns of “more sediment can be transported if more sediment being supplied” and “more sediment will be transported and partially deposited if more sediment being supplied”. It’s meaningful to think of some internal links between channel hydraulic geometry, variation of movable bed resistance and the specific condition of sediment transport in this reach.

4. Unsteady nature of flood determines “scour during rising and deposit during falling of hydrograph”

4.1. Basic physical nature
In flood events, unsteady nature of flow has a vital effect on flow field structure as well as the motion of sediment particles, therefore influencing the sediment transport and bed morphology [11]. When the channel bed is in dynamic equilibrium state with high sediment transport rate, scouring or deposition of the river bed is directly determined by the variation of sediment transport intensity of bedload. The existing research shows that bedload sediment intensity is determined by the shear stress \( \tau = \gamma h \nu \) or shear power \( \Phi = \gamma h \nu V \), as shown in Figure 3. When the shear stress or power is gradually increased on the bed surface, the river bed will be scoured when the sediment transport intensity of the bottom sand is gradually increased, otherwise riverbed will be deposited. That is: when \( \Phi_1 < \Phi_2 \), the riverbed is scouring, when \( \Phi_1 = \Phi_2 \), riverbed is in the equilibrium state of sediment transport, and when \( \Phi_1 > \Phi_2 \), riverbed is silted.
4.2. Variations of discharge, flow depth, velocity and energy slope during flood

The theoretical calculation of the unsteady flow evolution show that [6], in the case of fixed bed, the additional gradient drops to a positive value when the flood rises, and it drops to a negative value when the flood falls, so the maximum flow velocity appears before the maximum flood peak. Previously, the maximum water depth appeared after flood reaching its peak, and the water level vs. flow discharge relationship can be described as counterclockwise rope. When the river bed can be quickly scoured during the flood, the water level vs. discharge relationship can be described as a clockwise rope. The generalization of the variation of discharge, velocity, water depth and additional gradient during flooding is shown in Figure 4 \((J = J_0 + \nabla J, \ \nabla J = \nabla Z/\nabla t/V_m)\).

4.3. Process of Shear Stress or Power Change on Riverbed and Change of Riverbed Erosion and Siltation during Flood

From the generalized diagram of the shear stress or power change on the bed surface in the flood process given in Figure 5, it can be seen that during the flooding rising period from \(t_i\) to \(t_{i+1}\) period, the flow discharge increases sharply with time, making the corresponding adjustment of water depth, flow rate, bed slope occurs, which causes the shear stress or power to increase on the bed surface; on the contrary, it is continuously weakened during the falling period of flood, resulting in weakening of the bed sediment transport intensity. Therefore, during the flooding period, the riverbed is inevitably washed; in the falling water period, the riverbed is bound to be silted; when the flow rate is stable, the shear stress or power on the bed is basically the same, and the riverbed is in an equilibrium state of sediment balance.
Figure 6 shows in 2002 during Regulation of Water and Sediment Operation of the Xiaolangdi Reservoir, the measured flood discharge and the riverbed elevation at Aishan Station of the lower Yellow River. The riverbed is rapidly deepening during the rising period of flood hydrograph; the mean bed elevation basically remained unchanged during the steady flow period; while the river bed elevation is rapidly increased during the flood falling period.

![Figure 6. Field Measured Flood Discharge and Bed Elevation Changes at Aishan Station.](image)

### 5. Analysis of longitudinal discharge amplifications along lower Yellow River

5.1. *Flood peak discharge increase after Xiaolangdi Reservoir’s operation*

The increase of flood peak discharge always occurred after the water regulation to create artificial flood peak [12]. The duration of sediment discharge using gravity flow was short, and the sediment volume was small. In the early stage, the flow in river channel was large, the riverbed was strongly scoured, and the riverbed was coarsened (Table 3). The riverbed has large resistance. When the flood peak suddenly increases, the sudden decrease of the riverbed resistance will also cause the flow to suddenly increase. The main reason is that the form resistance of the bed surface is reduced, thus the flow velocity is increased, and the channel storage capacity is reduced.

| Discharge between Xiaolangdi and Huayuankou before Flood (m$^3$/s) | “Aug 2004” Flood | “Jul 2005” Flood | “Aug 2006” Flood | “Jul 2010” Flood | “Jul 2011” Flood |
|---------------------------------------------------------------|------------------|------------------|------------------|------------------|------------------|
| Peak Discharge Amplification (%)                             | 43               | 53               | 44               | 83               | 44               |
| Discharge between Xiaolangdi and Huayuankou before Flood (m$^3$/s) | 810              | 700              | 1,500            | 2,450            | 1,450            |

The hyperconcentrated flood that occurred in the lower Yellow River in late August 2004 has the greatest sediment concentration flood since the Xiaolangdi Reservoir was operated, and it was also the largest flood with the largest amount of sediment; the flood had little flow but high concentration of sediment. The composition of the sediment is rather very fine. It is very important to analyse the characteristics of “Aug 2004” flood in the lower reaches for controlling the sediment retention period of Xiaolangdi Reservoir. Figure 7 (left) shows the “Aug 2004” flood Xiaolangdi Reservoir outflow water-sediment process and Figure 7 (right) shows the Huayuankou station flow and sediment concentration process. It can be seen that the flood peak flow increases significantly after flooding to the Huayuankou.
5.2. Great reduction in resistance force leads to amplifications of peak discharge

The main reason for the increase of the peak discharge of “Aug 2004” flood is that the outflow of the Xiaolangdi Reservoir suddenly increases, and the shear force acting on the bed surface is enhanced, so that the shape of the riverbed becomes smooth from sand dune formed by less flow with a high resistance (Table 4). The resistance force is greatly reduced, so the flow velocity suddenly intensifies, and the channel storage capacity drops, resulting in amplification of the peak flow. As the peak flood is controlled by the discharge capacity of the bankfull flow, there is no increase of discharge in the hydrologic stations below Huayuankou. The mechanism of the formation of the false tide phenomenon caused by the change of the resistance force under the Gaocun station is the same, which is initiated by the change of the moving bed resistance.

| Year    | Reach Above Huayuankou | Jiahetan | Gaocun - Sunkou | Aishan - Yuekou | Yuekou - Lijin |
|---------|------------------------|----------|----------------|----------------|----------------|
| 1999-2003 | 0.06-0.18               | 0.065-0.075 | 0.06-0.06 | 0.05-0.07 | 0.06-0.08 | 0.06-0.08 |
| 2015-2018 | 0.23                   | 0.17     | 0.12           | 0.10          | 0.09       | 0.08       | 0.075       |

6. Main conclusions of the research

Different combinations of incoming water and sediment can form different river channel patterns and develop different river types. When the sediment is mainly transported by hyperconcentrated flood, a narrow and deep river channel is developed and meandering reach is formed. When there is too much silt with small discharge, it often forms a wandering reach, with channel of wide and shallow width.

The change of shear force in riverbed is the cause of scour and siltation of the channel. During the rising period of flood hydrograph, the shearing force on the bed surface is increasing, causing the riverbed to continuously being scoured; the shearing force acting on the bed surface is decreasing during the falling period of flood hydrograph. The intensity of sediment transport is continuously weakened, and the river channel is continuously silted up. The balance of sediment transport in the constant discharge period basically remains unchanged.

Clear water released from Xiaolangdi Reservoir cause the scour of downstream river bed. The bed sediment coarsened and resistance value n increased from 0.01 to 0.03–0.04. When there is a sudden increase of discharge, the shear force exerting on the bed surface is intensified, so that the shape of the riverbed can be smoothed out from dune. The resistance force is greatly reduced; leading to a sudden increase in the flow velocity. The channel storage capacity is reduced, resulting in an amplification of the peak flow. As the peak flood is determined by the discharge capacity of bankfull flow, the increase of the peak flow only develops in the river reach until Huayuankou.
References

[1] Qian Y Y, Yang W H and Zhao W L 1985 Basic characteristics of hypercentrated flood and uniform flow International Symposium on Hypercontrated Flow (Beijing, China)

[2] Qi P and Li W X, 1996 Evolutiional characteristics of hyper-concentrated flow in braided channel of the Yellow River Int. J. Sediment Res. 11 49-57

[3] Qi P 1997 Effect of perennial sediment regulation in Xiaolangdi Reservoir on reduction of deposition in the lower Yellow River Int. J. Sediment Res. 12 58-67

[4] Qi P, Liang G T, Sun Z Y and Qi H H 2002 The forming conditions of Alluvial River channel patterns, Int. J. Sediment Res. 17 83-8

[5] Qi, P, 1982 Sediment transport characteristics of hyperconcentrated flow and formation of riverbed J. Hydraul. Res. 8 34-43

[6] Qi P and Sun Z Y 2013 Discussions on the reason for the longitudinal amplifications of flood peak discharges (Discussion with Professor Zhong Deyu) J. Hydraul. Res. 44 1002-7

[7] Qi P, Sun Z Y, Hou Q X and Peng H 2005 Influence of unsteady floods on sediment transport and riverbed evolution in Yellow River J. Hydraul. Res. 35 637-43

[8] Qi P and Han Q L 1991 Characteristics of flow resistance and calculation of hyperconcentrated flow in the Yellow River People’s Yellow River 1991(3) 16-24

[9] Graf W and Altinakar M S 1998 Fluvial Hydraulics: Flow and Transport Processes in Channels of Simple Geometry (New York, USA: John Wiley & Sons, Inc.) ISBN: 978-0-471-97714-8

[10] Qi P, Sun Z Y, and Qi H H 2010 Flood Discharge and Sediment Transport Potentials of the Lower Yellow River and Development of an Efficient Flood Discharge Channel (Zhengzhou, China: Yellow River Conservancy Press) ISBN: 978-7-807-34946-4

[11] Qi P, Peng H, and Qi H H 2017 Influence of regulation by two banks on the wandering reach of lower Yellow River based on scouring and deposition during flood process J. Sediment Res. 2017(2) 67-73

[12] Qi P, Li P, Chen L., and Li R, 2013 Cause of the increase of the flood peak discharge in the lower yellow river After the Operation of Xiaolangdi Reservoir People’s Yellow River 35 4-5