Great Changes on Flood Control of Lower Yellow River after Operation of Xiaolangdi Reservoir

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Abstract. Representing the most important influence on the land-ocean sediment fluxes in the world, dams and reservoirs alter the continuity of sediment transport and decrease the supply of sediment to downstream reaches. After the operation of Xiaolangdi Reservoir, channel bed of the lower Yellow River has been strongly eroded, and the discharge capacity increased gradually. In recent decades, the trend of flow and sediment alters due to the massive harnessing projects on the upper and middle reaches. The amount of sediment entering the lower reach has been gradually reduced significantly, and there are no big flood events. There are no floods exceeding the warning water stage, thus the flood control situation of the downstream reach has changed dramatically. In addition, the volume of sediment which is transported to the estuary has also been greatly reduced, so as the siltation and extension at the river mouth, thus its impact on the upper reaches can be ignored. With the multi-year sediment regulation of Xiaolangdi Reservoir, we can take full advantage of sediment discharge by flood to further scour the riverbed of the lower reach. The current downstream reach becomes one of the most secure rivers in the world, which will inevitably affect the future prospects of governing the Yellow River basin. In order to prevent situations similar to the excessive river management in North China, we should maintain the healthy life of the river, and it is necessary to adjust the scale of harnessing projects on the upper and middle reaches, as well as to construct Taohuayu Project in the lower reach for better control of floods.

1. Introduction
As one of the most common natural hazards in the world, river flooding leads to all other natural disasters with respect to the number of people affected and in resultant economic losses [1]. River systems around globe have been increasingly changed by dam and reservoir construction for flood control, irrigation, water supply and energy generation needs [2]. Human’s activities simultaneously increased river sediment transport through soil erosion, and decreased it through sediment retention in reservoirs [3] [4]. Dams and reservoirs represent the most important influence to the land-ocean sediment fluxes in the world [5]. They altered the continuity of sediment transport and then reduce the supply of sediment to downstream reaches. Dams also caused sediment to accumulate within the reservoir itself, which impairs reservoir operation and decreasing storage, and deprives downstream reaches of sediments essential to maintain channel form and to support the riparian ecosystem [6].

Famous for its abounded sediment in the world, the Yellow River has most deposition in the lower reaches, which is the main reason of flooding. Historically, the river was rated as a river causing deep
sorrow. In the past, the Yellow River was closely connected with the disaster. When the Yellow River was mentioned, it was always thought about flooding and people have no way of making a living. In order to fundamentally govern the Yellow River, a comprehensive plan was developed by the principle of “storing water by multiple reservoirs and sediment retention by segment”, in an attempt to make the Yellow River clear, and fundamentally solve the downstream flood disaster. Because the plan did not meet the conditions of the society at that time, the Sanmenxia Reservoir was forced to undergo two reconstructions, and the operation rule of “impounding water and intercepting sediment” was forced to change to “detaining flood and discharge sediment”.

Lowering reservoirs impounding upstream sediment supply can trigger a series of channel evolution steps such as degradation, lateral erosion, and redeposition that can significantly change the reservoir landscape and decouple the relationship between stream power and sediment supply [7] [8]. For the Yellow River, it was estimated that 30% of the recent decrease in sediment flux can be explained by decreased precipitation throughout the river’s watershed, 40% by soil conservation practices and 30% by reservoir retention [9]. As a large number of water conservancy projects have been built on the main stem and tributaries of the Yellow River, the floods and sediments have been effectively controlled. Great changes have taken place for the incoming flow and sediment conditions as well as the downstream of the Yellow River. The amounts of water and sediments in the Yellow River have been decreased substantially. After Xiaolangdi Reservoir was operated, downstream river bed has been greatly eroded. The flood level has dropped sharply, and the flow capacity of the channel has increased rapidly. In response to the governance of Yellow River in the 21st century, the Ministry of Water Resources proposed the macro-governance goal, “no break of the embankment, no dry-up of the river course, no exceeding of water quality standard and no rising of the riverbed”, which has already been achieved. The lower Yellow River has already become one of the safest rivers in the world. The current design standards of flood are obviously too large, resulting in over-standard embankment projects in downstream and excessive management in middle reaches.

2. Operation of Xiaolangdi Reservoir Leads to Great Changes on Flood Control in Lower Reach

2.1 Strong Erosion of the Channel
After the Sanmenxia Reservoir was reconstructed, the deposition reduction effect of the “store the mud water and release the clear water” has made the river above Huayuankou basically not silt. Xiaolangdi Reservoir has been operated for 16 years since 2000, and the downstream river has been scoured for 2 billion m³ [10]. The depth of erosion is 2-3 m, and the flood discharge capacity of the channel has been increased rapidly. The channel in the Henan section scoured for more than 2 m (Figure 1), increasing the bankfull flow to 7,200-6,100 m³/s (Table 1), and the channel flow capacity above Gaocun reached 6,100 m³/s. If considering flood protection effect of the 1.5m high production dikes, the river channel inside the dike above the Huayuankou can discharge more than 22,000 m³/s, and the section above the Gaocun can pass more than 15,000 m³/s.

2.2 One of the Safest Rivers in the World Has Been Developed
The managing and monitoring of natural and artificial river levees are crucial in order to reduce the flood risk [11]. The embankment of the lower Yellow River was designed according to the 100-year flood before 2000. The peak discharge at Huayuankou Station was 22,000 m³/s, and the height of the embankment from Huayuankou to Gaocun was built at 3 m higher than the designed flood level. The width of the embankment base was 100 m. After Xiaolangdi Reservoir was built, the design standard becomes 1 in 1,000-years. After Caiji Breaching Crisis in 2003, the production dike in the lower reaches of the Yellow River was greatly enhanced. It has formed a relatively complete flood control system that is 2-3.5 m above the floodplain, and 4 to 8 m at the top of the embankment [12].
In the river reach below Gaocun, the levee top elevation was designed to exceed the designed flood level by 2.5 m. After the operation of Xiaolangdi Reservoir, the river bed was washed more than 1.5 m (Figure 1). The channels inside the production dike could discharge 6,800 to 8,000 m³/s. The top of the lower Yellow River's embankment was already 5 to 7 m above the floodplain (Table 1). The analysis shows that there is no possibility that flooding can get onto the floodplain in the future. The role of flood detention and sediment deposition proposed in the Yellow River Plan cannot be achieved, and policy compensation will also be lost.

### Table 1. Bankfull Discharge and Flow Capacity after Operations of Xiaolangdi Reservoir

| Hydrologic Station | Huayuankou | Jiahetan | Gaocun | Sunkou | Aishan | Luokou | Lijin |
|--------------------|------------|----------|--------|--------|--------|--------|-------|
| Measured Bankfull Discharge |            |          |        |        |        |        |       |
| Year 1999 (m³/s) | 3,650 | 3,400 | 2,700 | 2,800 | 3,100 | 3,200 | 3,200 |
| Year 2015 (m³/s) | 7,200 | 6,800 | 6,100 | 4,350 | 4,250 | 4,600 | 4,650 |
| Increased Bankfull Discharge (m³/s) | 3,550 | 3,400 | 3,400 | 1,550 | 1,150 | 1,400 | 1,450 |
| Flood Elevation (Alert Flood Level) (Dagu) | 93.85 | 76.85 | 63.20 | 48.65 | 41.65 | 31.40 | 14.24 |
| At 3,000 m³/s Water Level Drop (m) | 2.40 | 2.66 | 2.35 | 1.60 | 1.53 | 1.76 | 1.29 |
| Effect of Production Dike | Water Elevation after Adding 1.5m (Dagu) | 95.35 | 78.35 | 64.70 | 50.15 | 43.15 | 32.9 | 15.74 |
| Flood Discharge Capability (m³/s) | 22,000 | 15,000 | 15,000 | 9,000 | 7,000 | 6,800 | 8,000 |
| Bankfull Discharge of Dike (m³/s) | 22,000 | 21,500 | 20,000 | 17,500 | 11,000 | 11,000 | 11,000 |
| Top Elevation of North Dike (Dagu) | 99.48 | 83.56 | 68.62 | 55.52 | 49.22 | 38.47 | 19.15 |
| Top Elevation of South Dike (Dagu) | 99.51 | 82.56 | 69.04 | 54.92 | - | 38.03 | 19.56 |
| Elevation Difference between Dike and Flood Elevation (m) | 5.3 | 5.7 | 5.4 | 6.3 | 7.6 | 6.6 | 5.0 |

3. The Amount of Water and Sediment of Rivers in North China Decreased Significantly

#### 3.1 Great Changes of Rivers in North China

The characteristics of river basins in North China are similar to those in the Yellow River basin. After the operations of the tributary reservoirs, there have been no major floods for several decades. With the further harnessing of the upper reaches of the Yellow River, the flood peaks in the lower reaches will gradually decrease. Take the reservoir on upper Fen River as an example; there are 69 small type-1 and above reservoirs with a total capacity of 1.33 billion m³ constructed in the basin, which exceeds the annual amount of water (annual runoff of 970 million m³). The flood at Hejin Station has basically disappeared. Because of the governance of the Hai River basin, the rivers in the North China Plain have
gradually become dry rivers, only with occasional floods. According to the investigation by the Ministry of Environmental Protection, 2/3 of the northern rivers in North China have become dry rivers (ratio of dry rivers: 227/333). There are 141 large and medium-sized reservoirs in the Hai River Basin, with 123 reservoirs having a total capacity of 24.7 billion m$^3$, and a normal storage capacity of 7 to 8 billion m$^3$.

The major tributaries of Yongding River, Juma River, Hutuo River, Zhang River, and the main stem of Fen River have been cut off for a long period of time. Governance of the Yellow River must avoid this kind of situation. For the tributaries of the Hai River in North China, the annual runoff and total storage capacity ratio of the Yongding River is (14/21), the Hutuo River (22/29), and the Zhang River (Yuecheng Reservoir capacity 13). There have been no major floods in decades [13].

3.2 Flood of the Yellow River Is Significantly Reduced

Impact of reservoirs on global streamflow has become considerable over the 20th century [14]. According to statistics from 1994, there are 30 reservoirs on the main stem of the Yellow River with a total capacity of 62.6 billion m$^3$. There are more than 600 large-, medium- and small-scale water control facilities on the tributaries [15], with a total storage capacity of 11 billion m$^3$. The total storage capacity of the reservoirs on the main stem of Yellow River reaches more than 60 billion m$^3$, resulting in a total storage capacity of more than 70 billion m$^3$. This exceeds the Yellow River's annual water volume of 60 billion m$^3$. Only the four reservoirs, Longyangxia, Liujiaxia, Sanmenxia and Xiaolangdi have reached a flood protection capacity of 15.62 billion m$^3$ (which is equivalent to the 12-day total of a 1,000-year original design flood). Many large-scale reservoirs are also built on the main tributaries below the Xiaolangdi Reservoir, such as the Luhun Reservoir on Yi River, and Guxian Reservoir on Luo River. The flood control storage capacity is 677 million m$^3$ and 698 million m$^3$ respectively, and the Hekoucun Reservoir on Qin River has the capacity is 330 million m$^3$. The peak flow of a 100-year flood was reduced from 29,200 m$^3$/s to 15,700 m$^3$/s. If there was a flood of 22,300 m$^3$/s in 1958, the peak discharge at Huayuankou Station would be reduced to 9,620 m$^3$/s.

![Figure 2. Variations of Field Observed Peak Discharges at Huayuankou Station](image)

3.3 The Amount of Sediment Has Decreased Significantly

The water and sediment in the Yellow River are mainly from the upper and middle reaches of the river. The Tongguan station in the middle reach controls 91% of the drainage area, 90% of runoff, and nearly 100% of sediment [14]. The analysis of water and sediment changes at various times at Tongguan hydrological station reveals that the water and sediment of the Yellow River have changed since the 1960s, due to the influence of water and soil conservation projects. Based on the comprehensive conservancy measures for soil and water conservation in the entire basin, utilization of reservoirs on main stem, and the cumulative annual flow volume and sediment transport changes at Tongguan station,
three key periods of the water and sediment changes in the Yellow River have been analysed in more than 20 years. Figure 3 shows the changes in the measured annual sediment transport volume at the Tongguan Station (1919-2015) [16]:

![Figure 3. Variations of Annual Sediment Transport Amount at Tongguan Station](image)

Before 1960s, the water and sediment in the Yellow River were less affected by conservation measures. The measured sediment discharge can basically represent the natural conditions before the implementation of water and soil conservation projects. From 1919 to 1959, the average annual runoff measured at Tongguan Hydrologic Station was 42.61 billion m$^3$. The sediment transport amount was 1.592 billion tons, and the average sediment concentration was 37.4 kg/m$^3$.

Since mid-1980s, the use of reservoirs for regulating the Yellow River, Yanguoxia, Qingtongxia, Liujiaxia, and Longyangxia, and water and soil loss control in the Loess Plateau have been further strengthened. Especially with the implementation of projects, the Yellow River's runoff and sediment discharge have been significantly reduced. During the relatively short time period from 2000 to 2012, compared with the 26-year series since 1987, the runoff and sediment discharge at the Tongguan Station was even smaller, and the sediment concentration was further reduced. The runoff and sediment discharge amounted to 23.12 billion m$^3$ and 276 million tons respectively, with the average sediment concentration of 12.0 kg/m$^3$.

### 3.4 Trend of Changes in Sediment Volume of the Yellow River in Estuary

According to 50 years’ statistics from 1950 to 1999 at Lijin Hydrological Station, the annual average runoff was 34.33 billion m$^3$, and the average annual sediment load was 868 million tons. Obviously, the sediment of the Yellow River is the main driving force for rapid land development in the Yellow River Delta. Figure 4 shows that the characteristics of flow and sediment over the past years at the Lijin Station of the Yellow River Basin indicate that the amount of incoming flow and sediment is decreasing year by year, showing a general trend of changes of the Yellow River entering into ocean.
4. Problems in Harnessing the Yellow River

4.1 Changes in Water and Sediment Lead to Adjustment of Operational Mode of Xiaolangdi Reservoir

In the future, after the Xiaolangdi Reservoir is full of silt, it can still be utilized for discharging sediment by the flood, resulting in more floods, more incoming sediment, but the reservoir will have more opportunities for sediment removal. The floodwater will transport more sediment into the sea, and the river’s bankfull flow will increase, as long as the lower reaches of the Yellow River form a narrow and high-efficiency flood and sediment discharge channel through two-banks training strategy. It is possible that the river bed will not rise, and the amount of water used for sediment transport can also be greatly saved [17].

The initial total storage capacity of the Xiaolangdi Reservoir is 12.6 billion m$^3$. After 15 years, the storage capacity of the 7 billion m$^3$ below the 254 m elevation will be full according to the design of this reservoir. In fact, up to now, the reservoir has only 3.2 billion m$^3$ of silt and sediment, and the available storage capacity is 9.4 billion m$^3$. The reduction of flood flow and the reduction of required flood storage capacity can make Xiaolangdi Reservoir play a greater benefit. After the Yellow River has been undergoing several decades of governance, the phenomenon of “big flood bringing large sediment” is no longer present. In the past, the Yellow River's incoming sediment was mainly carried by floods. Before 1986, sediment was mainly carried by large floods, and the year with large amount of water was also the year with large sediment. This feature was obvious. But it was not obvious from 1986 to 1999 [17]. Therefore, Xiaolangdi Reservoir should be used for multi-years sediment regulation, fully utilize the flood water to transport sediment into the sea, and the adjustment capacity will also increase. It is also necessary to adjust the control parameters of water level.

4.2 Governance of the Yellow River on Main Stem and Tributaries Is still Developing

The continuous management of the main stem and its tributaries of the Yellow River in recent decades resulted in dramatic changes in the Yellow River Basin. According to the main stem of the Yellow River Basin Planning, there are 6 reservoirs to be built, with a total storage capacity of 42.2 billion m$^3$. In the future, the total reservoir capacity of the Yellow River tributaries will be greater than 115.8 billion m$^3$. On the tributaries of the Yellow River, there are currently large reservoirs under construction. For example, in downstream Hekoucun Reservoir and Dongzhuang Reservoir on the Jing River are under construction. The construction of the reservoirs on the main stem and tributaries, due to flood control and utilization of reservoirs, has led to great reduction in peak floods into the downstream. The flood is mainly released in the form of basic flows, in order to meet the demand for power generation and river
diversion for irrigation. The change pattern of floods in the Yellow River Basin is similar to that of the Hai River flood. The difference is that the Yellow River is a large river with a large amount of water coming from above Lanzhou with a wide drainage basin. This change is restricted by more factors and the decay rate is slower, but the trend cannot be altered.

4.3 Current Design Flood of Yellow River Is Significantly Higher

Before the Xiaolangdi Reservoir was built, the downstream embankments were designed for a 100-year flood, and the peak discharge at the Huayuankou Station was 22,000 m$^3$/s. After it was operated, this value was upgraded to a 1,000-year flood. Currently, the flood control standard for the lower Yellow River is the highest in the world, and obviously unreasonable. In 2010 Professor Academician Pan Jiazheng explicitly proposed that the design flood standards for the Yellow River should be re-verified [17]: “Historically floods in the lower reaches of the Yellow River have been very serious, but in recent decades, they have not occurred due to various reasons. How can we reasonably determine future standards for flood protection in the lower Yellow River? These issues must have clear conclusions, and be approved by government, as a goal and basis for harnessing the Yellow River.”

4.4 Problems to Be Solved in the Future Downstream River Management

From the above analysis of the flood changes in the Yellow River, it is known that there will be no inundation in the floodplain for the future floods with the current capacity of the lower reaches of the Yellow River. The proposed floodplain and sedimentation site in the Yellow River Plan has become a historical thing. The objective conditions for freeing the floodplains in the lower Yellow River have been matured. At present, the main problem in the lower reaches of the Yellow River is that the mainstream of wandering channel is still oscillating and scouring in shallow channels, which is not good for stabilizing the mainstream, diverting water and flood control. It should be controlled through effective engineering measures, such as the formation of narrow and deep stable flood channels through two-bank strategy to form an efficient flood discharge channel.

5. Conclusions and Future Prospects of Managing the Yellow River

Rivers drain water from land to oceans and thus become the main path for transporting the products of continental weathering. Human-related activities, such as river impoundment and changes in land use, alter the sediment load in rivers [18]. After the operation of Xiaolangdi Reservoir, the lower reaches of the river are intensively scoured. The discharge capacity of the channel is rapidly increasing, and the flood control situation has undergone tremendous changes. “No rising of the riverbed” has been achieved. However, the main stem of wandering channels still oscillates in the wide and shallow river, which is not good for stabilizing the mainstream and diverting water and flood control. It should be controlled through effective engineering measures.

Harnessing the main stem and tributaries of the Yellow River, as well as the watershed management will greatly reduce the Yellow River flood discharge and sediment volume, and it will have a major impact on the Yellow River's future management prospects. Xiaolangdi Reservoir can provide greater benefits such as better flood control, use of flood to discharge sediment, and water supply. In the future, the reduction in the amount of flow and sediment entering the sea will make the impact of deposition rate on downstream river continue to weaken, and may even be ignored. The design standards of flood and protection of Yellow River should be verified as soon as possible, including reasonable flood control standards and design values of peak flood. The large reservoirs in the Yellow River basin should be properly controlled to prevent the long-term no-flow situation of rivers in North China, as well as the deterioration of the river basin environment. It is also necessary to construct Taohuayu Project in the lower reach for better control of floods.

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