Theory and Practice of water and sediment regulation in flood season of Yellow River in 2018

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Abstract. In recent years, the water and sediment pattern of the Yellow River has changed significantly, and a preliminary water and sediment regulation system was constructed. Based on a summary of the regulation principles of water and sediment in the Middle Yellow River, this paper proposes three key technologies to determine the water and sediment control thresholds, the artificial creation of a long-distance density current, and an engineering regulation for water and sediment control of the Yellow River. Taking the actual flood and sedimentation regulation of the Yellow River Basin in 2018 as an example, the practical applications of these relevant technologies are analyzed. This study provides an important theoretical and practical reference for the flood and sediment regulation of sediment-laden rivers in arid and semi-arid areas during flood season.

1 Introduction

The Yellow River passes through the Loess Plateau which is the largest c in the world. The basin is dry, and water resources are scarce. Storm floods mainly originate from the upstream and middle reaches, and occur mostly from June to October. The floods in the Upper Yellow River mainly come from Lanzhou and have the characteristics of long duration, low flood peak, and large flood volume [1]. The storm floods in the Middle Yellow River mainly come from the sections of Hekou Town to Longmen, Longmen to Sanmenxia, and Sanmenxia to Huayuankou. During the flood season, the rainstorms are frequent, strong, and short in duration, and the floods are characterized by high peaks, short durations, and rapid rises and recessions. According to the temporal and spatial distribution of floods, the floods from the river water of Helongjian and Longsanjian upstream of Sanmenxia are called “upper heavy floods.” They are characterized by high peaks, large volumes, and large sediment content, which pose a serious threat to flood protection in the Lower Yellow River. The floods from the river water of the main stream between Sanmenxia and Huayuankou and the tributaries of the Yiluo River and Qin River are called “lower heavy floods.” They have the characteristics of high flood peaks, strong rises, concentrated flooding, small sediment content, and short foresight periods, which makes them the most serious threat to flood protection in the Lower Yellow River.

The sediment in the Yellow River mainly comes from the middle reaches of the Hekou Town to the Sanmenxia section. The incoming sediment content has changed significantly during recent years, as shown in Fig. 1 [2]. The distribution during the year is also extremely uneven, as the amount of sediment influx from July to October in the flood season accounts for about 90% of the annual amount of influx, especially in the storm floods during the flood season [3].
The serious discontinuity between the temporal and spatial distribution of the Yellow River’s water and sediment has resulted in severe disasters to the Yellow River Basin historically. Since the founding of the People’s Republic of China, the state has taken various measures to ensure flood control safety in the basin. Among them, the construction of a water and sediment regulation system is an important part among multiple measures for the flood control of the Yellow River.

The regulation of water and sediment utilizes reservoirs built on the Yellow River to scientifically regulate the process of naturally incoming flood and sediment. Sediment discharge from the reservoir and the downstream rivers is achieved through the timely storage or discharge of water and sediment and by reshaping the naturally uncoordinated water-sediment relationship into a coordinated water-sediment one.

A complete Yellow River water and sediment regulation engineering system should include the Yellow River’s seven major backbone reservoirs at Longyangxia, Liujiaxia, Heishanxia, Qikou, Gu County, Sanmenxia, and Xiaolangdi (see Fig. 2), as well as the tributary reservoirs at Jinghe Dongzhuang, Qinhe Hekou Town, Iluo River Luhuan, and Gu County [4]. At present, the Yellow River water and sediment regulation engineering system is composed of backbone reservoirs located at Longyangxia, Liujiaxia, Sanmenxia, Xiaolangdi, etc., supplementary reservoirs located at Haibowan and Wanjiazhai, and controlling reservoirs located at the tributaries at Luhun, Gu County, Hekou Town, etc.

Together with the water and sediment regulation non-engineering system, which consists of water and sediment monitoring, water and sediment forecasting, and reservoir regulation decision support, a preliminary water and sediment regulation system for the Yellow River has been constructed. This plays a vital role in the flood and ice flood prevention safety and unified regulation of water volume, among other aspects [5].

1.1 Key technologies for water and sediment regulation in Middle and Lower Yellow River

The water and sediment control technologies for the middle and lower reaches are described in detail with regard to the “determination of water and sediment regulation threshold based on highly efficient sediment transport and stable main channel,” the “artificial creation of long-distance density current in the reservoir,” and “the engineering control theory for water and sediment regulation.”

1.2 Determination of water and sediment regulation threshold based on highly efficient sediment transport and stable main channel

The watershed geomorphology and climatic characteristics of the Yellow River determine the characteristics of the Yellow River’s sediment transport and bed forming as one “high” and three “strong.” The “high” refers to the high sediment content (the Yellow River has the world’s largest sediment content and sediment transport volume). The three “strong” refer to “strongly unbalanced” (the Yellow River has an unbalanced water-sediment relationship with less water and more sediment, and a large variation in sedimentation along the river), “strongly unstable” (the Yellow River’s highly sediment-laden stream is unstable, causing the river channel to migrate and change), and “strongly accumulating” (historically, the Yellow River has experienced multiple sedimentations, river migrations, and dyke breaches; the riverbed rises at 10 cm/year on...

![Fig. 2. Schematic diagram of seven major backbone reservoirs of Yellow River water and sediment regulation system.](image-url)
average, forming first-class/second-class ground-
suspended rivers).

Based on the Lower Yellow River’s unevenly distributed flood-bearing capacity where the upstream has a larger capacity and the downstream has a smaller capacity, after in-depth research and analysis, scholars established a sediment transport capacity equation to characterize the erosion and sedimentation regulation relationship of the downstream rivers [6]:

\[ Q_S = kQ^2 S_{above} \left( \frac{\sqrt{B}}{h} \right)^{m1} j^{m2} \gamma^{m3} \left( \sum P_i d_i \right)^{m4} \]  

(1)

1.3 Artificial creation of long-distance density current in reservoir

Utilizing the density current to discharge sediment from the reservoir is an important method of sediment discharge and sedimentation reduction during the reservoir’s sediment-retaining period. After 19 water and sediment regulation experiments, a highly sediment-laden density current that continuously advances to the dam was created to discharge the sediment. During this process, the scientific research workers accumulated profound firsthand data and made significant progress in research of the evolution pattern and the simulation method of different density currents in the reservoir.

When the density current advances toward the dam, stable power that is sufficient to overcome the resistance along the path, i.e., continuous supplementary density current, is required. Therefore, the important factors affecting the formation of the density current and the increase in the sediment discharge ratio in the Xiaolangdi Reservoir include the water and sediment input power, formation time of density current, and the topographic condition of the reservoir area.

In order to successfully create a density current in the reservoir, researchers systematically summarized five expressions for the density current transport of the Xiaolangdi Reservoir, the sedimentation process of the muddy water reservoir, and a quantitative description of the density current transport process in the reservoir:

(1) Expression to calculate the resistance coefficient of the density current interface [8]:

(2) Considering the comprehensive requirements for reservoir safety, downstream flood control safety, beach area disaster prevention, water resource security, etc., regulation indicators that can maintain a full-line erosion in the Lower Yellow River are proposed and listed in Table 1.

### Table 1. Regulation indicators for maintaining full-line erosion in Lower Yellow River. Sediment content: kg/m³. Flow Rate: m³/s.

| Sediment content of Huayuankou hydrologic station (kg/m³) | Flow of Huayuankou hydrologic station (kg/m³) | Flow of Aishan hydrologic station (m³/s) | Uninterrupted time (Day) |
|----------------------------------------------------------|---------------------------------------------|-----------------------------------------|--------------------------|
| S≤20                                                     | Q≥2600                                      | Q≥2300                                  | T ≥9                     |
| S≤40                                                     | Q≥3000                                      | Q≥2700                                  | T ≥8                     |

(Note: d < 0.025 mm of fine sediment content accounts for more than 90% of total sediment.)

\[ \lambda_i = \frac{8g h J}{(0.86(1 + m)V)^2} \]  

(3)

\[ u = V_m e^{-0.55-0.68(z/h)^2} \]  

(4)

\[ u = (1 + m)V_{cp} (z/h)^m \]  

(5)

\[ u_e = \frac{\Delta V}{A\Delta} - \varphi u_0 + \varphi u_0 S_0 \]  

(6)

\[ S = ke^{-0.025p} - 0.12Q \]  

(7)

Fig. 3 shows a flowchart of the joint water and sediment regulation of Wanjiazhai, Sammenxia, and Xiaolangdi in 2014 [11].
During implementation, the researchers and engineering technicians investigated and determined the duration and process of the output of the Wanjiazhai Reservoir and the connecting water level of the Wanjiazhai discharge stream to the Sanmenxia. The researchers also determined the best timing of the sediment discharge, the sediment content of the output, the flow process, and the connecting water level of the Sanmenxia Reservoir to the Xiaolangdi Reservoir, as well as the best timing for restarting the sorting of the delta face and the apex sediment. Therefore, successful artificial creation of the density current was guaranteed.

1.4 Engineering control theory for water and sediment regulation

The Yellow River water and sediment regulation engineering control system has three major characteristics: high dimensionality, nonlinearity, and hysteresis. The high dimensionality refers to the larger number of sections/parameters describing the water and sediment transport system. The nonlinearity reflects the nonlinear mechanical relationship between water and sediment transport. The hysteresis refers to the time lag in reservoir regulation, water and sediment transport, and riverbed evolution. The Yellow River water and sediment regulation engineering control system involves thousands of kilometers of reservoir-river channel-river mouth water and sediment transport systems.

Among them, the meaning of engineering control refers to the realization of the joint regulation of reservoirs located at both the main stream and the tributaries (i.e., the water and sediment spatial connection). An engineering control concept map and its corresponding summary basis are shown in Fig. 4.

The main goal of water and sediment regulation is to extend the life of the reservoir and achieve micro-deposition/erosion of the entire channel. The control points include the Huayuankou section 100 km downstream of the Xiaolangdi Reservoir, the Sunkou section 420 km downstream, and the Lijin section and the Yellow River mouth 750 km downstream. The control parameters include the flow rate and the sediment content. The goal of water and sediment regulation is to limit the control targets of the control points within an allowable range through joint regulation of the reservoir group.

Therefore, according to the engineering control concept of water and sediment regulation, combined with the corresponding reservoir engineering parameters of the Yellow River Basin, a basic model for the water and sediment regulation of the Yellow River based on single-reservoir operation of the Xiaolangdi Reservoir, the connection of water and sediment processes from different source areas, and the joint regulation of multiple reservoirs at the main stream was established[12]. The model can effectively control the water and sediment process and the river channel sediment transport process (as shown in Fig. 5).
2 Reservoir group regulation practice in Middle and Lower Yellow River in 2018

This section describes the practical application of the water and sediment control technology in the Yellow River reservoir regulation as mainly based on the actual water and sediment control during the flood season in 2018. This section is divided into three parts: the water and sediment conditions of the Middle Yellow River during the flood season in 2018, the regulation process during the flood season in 2018, and the evaluation of the regulation effect.

2.1 Water and sediment conditions in middle reaches of Yellow River during flood season in 2018

Owing to strong rainfall between July 1 and 4, some branches of the Wei River tributary had a raised water level. The flood peak flow rate recorded at the Lin River hydrological station on the Wei River at 4:48 a.m. on the 5th was 2600 m³/s, and that at the Hua County hydrological station at 7:18 a.m. on the 6th was 2200 m³/s. After the flood merged into the Yellow River’s main stream, a flooding process with a flow rate of 2500 m³/s was formed at the Tongguan hydrological station on the Yellow River. The total flood yield at the Hua County hydrological station was 688 million cubic meters.

Affected by heavy rainfall from July 10 to 11, the water levels of the main tributaries of the Jing River and Wei River Basin generally rose. At 14:30 p.m. on the 11th, the Linjia Village hydropower station on the Wei River had a flood peak flow rate of 2390 m³/s. Meanwhile, some tributaries of the upper Jing River also experienced an increased water level. At 12:54 p.m. on the 12th, Zhangjiashan Station on the Jing River observed a flood peak flow rate of 1170 m³/s. When the floods of the Jing River and the Wei River merged, the flood peak flow at the Lintong hydrological station at 23:18 p.m. on the 12th was recorded at 4,500 m³/s.

After slowing down by the floodplain, the flood peak flow at the Huaxian hydrological station was 2400 m³/s at 2:00 a.m. on the 14th. Once the flood of the Wei River merged with the northern main stream and the North Luo River, the Yellow River Tongguan hydrological station observed a flood peak flow rate of 4620 m³/s at 17:00 p.m. on the 14th. This was the largest flood recorded at the Middle Yellow River during the flood season.

2.2 Water regulation principle during flood season in 2018

The regulation during this flood season was to plan multiple aspects together, utilize both storage and discharge, regulate the system scientifically, dedicate research fully to flood prevention and control, and ensure safety in order as to preserve more flood prevention capacity to cope with floods that could occur during the critical “July down August up” flood prevention season. This was conducted under the premises of ensuring the safety of downstream flood control, properly regulating the outflow of the reservoir, and using the water from the Wei River in the Middle Yellow River to minimize the reservoir water level while discharging the deposited sediment in the reservoir and adjusting the sedimentation pattern of the reservoir area. In the later stage, the water level of the reservoir was gradually raised according to the weather forecast, and the Xiaolangdi Reservoir was operated at a water level of less than 230 m. In addition, the flood-bearing safety of the river channels in the Qinghai and Gansu sections was ensured, the flood-bearing conditions of the Ningmen section and the Middle Xiaobei River section were improved, and the downstream water channels were shaped and maintained.

According to the flood forecast for the middle reaches, before the flood rose, the Sanmenxia Reservoir was operated at a balanced input and output. When the large-flow process from the Tongguan Station was about to enter the reservoir and the water level of the Xiaolangdi Reservoir reached approximately 222 m, the Sanmenxia Reservoir then started to substantially discharge the large-flow process until the flood was fully discharged. The goal was to make full use of its open discharge flow and the subsequent flood flow to prepare for the creation of a density current in the Xiaolangdi Reservoir area. This can then discharge the sediment, thereby improving the effect of sediment and erosion discharge at the Sanmenxia and the Xiaolangdi Reservoirs. Maintaining a long-term effective storage capacity at the Xiaolangdi Reservoir is one of the important tasks of flood control.

2.3 Regulation measures

Throughout July, the Xiaolangdi regulation plan was adjusted a total of five times (the Xiaolangdi Reservoir regulation information during the adjustment is shown in Fig. 6 and 7). The initial plan was to minimize the reservoir water level to below 222 m (the apex elevation...
of the sedimentation delta) before the arrival of the midstream flood in order to create a favorable condition for the density current discharge. After connecting with the large-flow process of the Sanmenxia Reservoir, the Xiaolangdi Reservoir was operated using the density current to discharge the sediment.

During this period, the amount of discharge was reduced in time to prevent the flood peak of the downstream river from increasing. After the density current sediment discharge was basically completed, the reservoir regulation was terminated, and the Xiaolangdi Reservoir was then operated at a balanced input and output at a water level of 220 m or less, which was beneficial for future flood regulation. During flooding, the Xixiayuan Reservoir was in principle operated at a balanced input and output.

First adjustment: On July 10, based on an analysis of the Shaoguan incoming water forecast, the Xiaolangdi Reservoir was proposed to discharge at a flow rate of 2,600 m$^3$/s. On July 13, when the water level dropped to a minimum of 211.77 m, the reservoir was operated at a balanced input and output.

Second adjustment: Owing to a decreased reservoir water level and water supply from upstream with continuous and stable sediment discharge, at 10:00 a.m. on July 14, the measured sediment content at the Xiaolangdi hydrological station suddenly increased to 369 kg/m$^3$ and continued to rise. This indicated that mud was discharged (with a higher content of coarse sediment), causing the sediment deposited in the reservoir over many years to be transported from the bottom of the reservoir to the Lower Yellow River. Subsequent hydrodynamics were not sufficient to transport the sediment into the sea. At 12:00 p.m., after discussion, the flood prevention office issued an order to close the previously opened orifice tunnel, and instead opened one free flow tunnel and three sediment discharge tunnels together with three to four assembly units operating, in order to keep the discharge flow rate unchanged to reduce the amount of sediment discharged.
Third adjustment: On July 22, in order to prevent the flood peak from increasing in the Lower Yellow River, the discharge flow rate was reduced from 3000 m$^3$/s, which lasted for 6 days, to 2300 m$^3$/s. 

Fourth adjustment: By July 25, the discharge flow was further reduced, and the water level dropped to 213.66 m. When the discharge flow dropped to about 1500 m$^3$/s, the reservoir began to store water and restored the water level to 224 m at the end of July.

The regulation processes of the Longyangxia Reservoir, Liujiaxia Reservoir, Sanmenxia Reservoir, and Xiaolangdi Reservoir during the four adjustments are shown in Fig. 8. The Longliu Reservoir, especially the Longyangxia Reservoir, played a significant role in reducing the flood peaks and retaining the flood. Alternatively, to ensure safety in flood control, more considerations were put toward the individual sediment discharge requirements of the Sanmenxia Reservoir and the Xiaolangdi Reservoir, thereby placing more refined requirements on the regulation.
2.4 Evaluation of regulation effect

According to the corresponding water conditions in the five adjustments of the Xiaolangdi Reservoir in July 2018, the effect of the regulation was evaluated. The results are as follows:

(1) Proper flood discharge to ensure flood prevention safety

As the Xiaolangdi Reservoir discharged nearly 300 million tons of sediment downstream, the river channel above the Huayuankou was heavily silted. Although the water level in the local river section was uplifted, there was no significant flooding that reached the beach or threatened a project in the Lower Yellow River. Therefore, the regulation ensured safe flood prevention in the Lower Yellow River.

(2) Highly efficient sediment discharge to restore effective reservoir capacity

During the No. 1 and No. 2 floods, the Sanmenxia Reservoir continued to discharge highly sediment-laden flow downstream, causing the reservoir area to be fully eroded. Meanwhile, the Xiaolangdi Reservoir maintained a continuous low-water-level operation and a large-flow discharge process, causing the Xiaolangdi Reservoir area to also be completely eroded, as shown in Fig. 9. By the end of July, the Sanmenxia Reservoir area had discharged 110 million tons of sediment, and the Xiaolangdi Reservoir area had discharged 208 million tons, with more than 300 million tons of sediment entering downstream. The sedimentation patterns of the...
Xiaolangdi Reservoir and Sanmenxia Reservoir therefore underwent major changes, and the overall reservoir area was eroded.

![Diagram of water and sediment input and output processes of Xiaolangdi Reservoir.](image)

**Fig. 9.** Water and sediment input and output processes of Xiaolangdi Reservoir.

### 3 Conclusion

During the No. 1 and No. 2 floods in the Middle Yellow River during 2018, the Xiaolangdi Reservoir successfully reduced the water level to below 220 m by discharging the continuous large-flow process downstream. Therefore, the long-term low-connection water level of the Xiaolangdi Reservoir was ensured, and a long-term density-flow sediment discharge process of the Xiaolangdi Reservoir was successfully implemented. Throughout July, the total amount of discharged sediment in the Xiaolangdi reached more than 300 million tons, of which the Sanmenxia reservoir area discharged 110 million tons of sediment and the Xiaolangdi reservoir area discharged 208 million tons. This effectively restored the storage capacity of the Sanmenxia and Xiaolangdi Reservoirs and achieved an ideal reservoir erosion effect.

The water and sediment transport process has helped to accumulate rich experience for studying the erosion patterns of reservoirs under a low-connection water level condition. The results also provide an important theoretical and practical reference for the flood and sediment control of sediment-laden rivers in arid and semi-arid regions.

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