Study on the Water-Sediment Regulation Degree of Reservoirs on Sediment-laden Rivers During the Flood Season

Authors: Zhang Jinliang, Hu Chunhong, Liu Jixiang, Luo Qiushi, Lu Jun

Date: 2021-09-01T00:00:00+00:00

Abstract

The flood season constitutes a critical period for water and sediment regulation in reservoirs on high-sediment rivers. Previous research and practice have primarily employed qualitative or broad indicators to characterize such regulation. Consequently, establishing precise or relatively accurate measurement index systems and investigating the degree of water and sediment regulation during flood seasons in these reservoirs is of significant importance for scientifically understanding reservoir regulation capacity and guiding reservoir design and operation. Based on water and sediment dispatch practices in the Yellow River, this study defines indices for runoff regulation degree and sediment regulation degree during flood seasons in reservoirs on high-sediment rivers, and provides corresponding calculation expressions. Utilizing water and sediment inflow data since 1986, we analyze the magnitude of flood-season water and sediment regulation degree for mainstream and tributary reservoirs in the middle reaches of the Yellow River. The findings reveal that existing constructed projects exhibit relatively low regulation degrees with insufficient regulation capacity, whereas planned and under-construction projects demonstrate relatively high regulation degrees. Furthermore, mathematical models are employed to conduct comparative analyses of the impacts of different reservoir operation modes on variations in flood-season water and sediment regulation degree. The results demonstrate that compared with the "storing clear water and discharging turbid water" operation, the "storing clear water and regulating turbid water" approach not only effectively reduces sediment deposition in the reservoir area across different periods, but also enables partial regeneration and reuse of sediment storage capacity, thereby enhancing the flood-season water and sediment regulation degree of reservoirs. These research findings can provide an important basis for constructing the Yellow River water and sediment regulation system and for the design and operation of reservoirs on high-sediment rivers.

Full Text

Study on Regulation Degree of Water and Sediment of Reservoirs from Sediment-laden Rivers in Flood Season

Zhang Jinliang1,2, **Hu Chunhong**3, **Liu Jixiang**1,2, **Luo Qiushi**1,2, **Lu Jun**1,2*

1 Yellow River Engineering Consulting Co., Ltd., Zhengzhou 450003, China
2 Key Laboratory of Water Management and Water Security for Yellow River Basin, Ministry of Water Resources (under construction), Zhengzhou 450003, China
3 China Institute of Water Resources and Hydropower Research, Beijing 100038, China

Abstract

The flood season represents a critical period for water and sediment regulation in reservoirs on sediment-laden rivers. Previous research and practice have primarily relied on qualitative or broad indicators to describe water-sediment regulation. Therefore, establishing precise or relatively accurate measurement indices and studying the water-sediment regulation degree of reservoirs on sediment-laden rivers during flood season is of great significance for scientifically understanding reservoir regulation capability and guiding reservoir design and operation. Based on water-sediment regulation practices in the Yellow River, this paper defines indices for runoff regulation degree and sediment regulation degree during flood season for sediment-laden river reservoirs and provides corresponding calculation expressions. Using inflow water and sediment volumes since 1986, we analyze the flood season water-sediment regulation degree of reservoirs in the middle reaches of the Yellow River. The results reveal that existing projects exhibit relatively small regulation degrees and insufficient regulation capacity, while projects under construction or planned demonstrate larger regulation degrees. Furthermore, mathematical modeling is employed to compare and analyze the impacts of different reservoir operation modes on the variation of flood season water-sediment regulation degree. The results demonstrate that compared with the "storing clear water and discharging muddy flow" approach, the "storing clear water and regulating muddy flow" operation can not only effectively reduce sediment deposition in the reservoir area across different periods but also enable the regeneration and reuse of part of the sediment storage capacity, thereby improving the flood season water-sediment regulation degree. The research findings can provide an important reference basis for the construction of the Yellow River water-sediment regulation system and the design and operation of reservoirs on sediment-laden rivers.

Keywords: Reservoirs from sediment-laden rivers; Regulation degree of water and sediment in flood season; Yellow River; Storing clear water and regulating muddy flow

Introduction

Water and sediment inflow to sediment-laden rivers is primarily concentrated in the flood season, which constitutes the key period for water-sediment regulation. Reservoirs generally utilize the storage capacity below the flood control level to regulate incoming water and sediment through rational control of water levels and discharge rates. The magnitude of regulation capacity during flood season is not only related to incoming water-sediment conditions and the size of regulation storage but is also influenced by reservoir operation modes. How can we measure the water-sediment regulation capacity of reservoirs on sediment-laden rivers? Establishing scientifically sound metrics to define and quantify reservoir water-sediment regulation capacity during flood season is crucial for guiding the construction of the Yellow River water-sediment regulation system and enabling scientific reservoir operation.

Since the 1950s, design and operation technologies for reservoirs on sediment-laden rivers in China have continuously evolved, progressing through two stages — "storing water and blocking sediment" and "storing clear water and discharging muddy flow" —and more recently advancing to the new stage of "storing clear water and regulating muddy flow." Different stages entail varying concepts and magnitudes of water-sediment regulation. Previous research has primarily focused on reservoir operation methods, scheduling indices, scheduling models, and scheduling effectiveness. For instance, Qian Ning pointed out that in managing sediment-laden rivers, human initiative should be fully exercised to rationally regulate water-sediment processes using upstream reservoirs, employing measures such as artificial flood peaks and increased flood discharge to scour downstream river channels. Lian Jijian et al. simulated and optimized the scheduling process for artificially created density currents through a cascade reservoir joint operation model. Yao Wenyi et al. analyzed the regulatory effects of reservoir operation on runoff-sediment processes and their impacts on downstream river boundary conditions based on river dynamics principles. Hu Chunhong systematically analyzed the role of the "storing clear water and discharging muddy flow" operation mode in water-sediment regulation and proposed optimization suggestions for the operation of multi-purpose reservoirs on sediment-laden rivers such as the Yellow River Xiaolangdi Reservoir. Zhang Jinliang et al. studied the "storing clear water and regulating muddy flow" operation mode and its design technology for sediment-laden river reservoirs, highlighting the importance of "regulating muddy flow" in reservoir operation. However, previous studies have lacked research on the water-sediment regulation capacity of sediment-laden river reservoirs during flood season. Currently, there are no scientific indicators to reasonably measure this capacity, making it difficult to quantitatively calculate the regulation degree across different periods or compare regulation capabilities under different operation modes.

Based on years of research and Yellow River water-sediment scheduling prac-

tice, this paper analyzes the specific meaning of flood season water-sediment regulation degree for sediment-laden river reservoirs and provides calculation expressions. Taking the Yellow River basin as the study area, we analyze the flood season water-sediment regulation capacity of existing and planned reservoirs in the middle Yellow River. Using mathematical modeling, we compare and analyze the variation of water-sediment regulation degree under two typical operation modes: "storing clear water and discharging muddy flow" and "storing clear water and regulating muddy flow." The research findings can provide important references for the design and operation of sediment-laden river reservoirs and serve as a basis for constructing the Yellow River water-sediment regulation system.

2.1 Study Area Overview

The Yellow River is the second largest river in China, originating from the Yueguzonglie Basin on the Qinghai-Tibet Plateau and flowing through nine provinces (autonomous regions) including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong before emptying into the Bohai Sea at Kenli County, Shandong Province. The main stream extends 5,464 km with a drainage area of 795,000 km^2 [Figure 1: see original paper]. The Yellow River traverses multiple distinct natural geographic units with considerable variations in topography, landforms, and climate. Runoff primarily originates from the area above Hekou Town in the upper reaches, accounting for 62% of the total river flow, while sediment mainly comes from the reach between Hekou Town and Tongguan in the middle reaches, representing approximately 90% of the total sediment load. During the period of minimal human impact from 1919–1959, the Tongguan Station recorded a mean annual runoff of 42.61 billion m^3 and a sediment load of 1.592 billion tons (see Table 1), with an average sediment concentration of 37.36 kg/m^3. Sediment discharge is heavily concentrated in the flood season, with flood season sediment accounting for over 80% of the annual total.

The Yellow River is characterized by low water discharge and high sediment load, resulting in an uncoordinated water-sediment relationship. This has caused the lower reaches to become a "suspended river" above the surrounding floodplain and the Ningxia-Inner Mongolia reach to form a "new suspended river." Decades of Yellow River management practice have demonstrated that water-sediment regulation through reservoirs plays a crucial role in coordinating the water-sediment relationship. Since the founding of the People' s Republic of China, reservoir construction has been continuously strengthened. The Sanmenxia Reservoir, the first large-scale multi-purpose water control project built on the middle Yellow River mainstream with primary functions of flood control and additional benefits of ice jam prevention, irrigation, power generation, and water supply, serves as one of the controlling 骨干 reservoirs in the Yellow River basin. Subsequently, multiple large-scale key water control projects including Liujiaxia, Longyangxia, and Xiaolangdi were constructed, along with numerous

cascade reservoirs for power generation. Currently, 30 cascade reservoirs have been built along the Yellow River mainstream below Longyangxia, including six existing reservoirs in the middle reaches: Wanjiazhai, Longkou, Tianqiao, Sanmenxia, Xiaolangdi, and Xixiayuan. Additionally, numerous reservoirs have been constructed on Yellow River tributaries.

Design and operation technologies for sediment-laden river reservoirs have continuously evolved, advancing from the "storing clear water and discharging muddy flow" stage to the new "storing clear water and regulating muddy flow" stage. During the "storing clear water and discharging muddy flow" period, reservoirs stored water for beneficial use during non-flood seasons and lowered water levels to discharge sediment during flood seasons. While this approach could maintain effective storage capacity to some extent, reservoirs still faced challenges during normal operation periods, including minimal runoff regulation, insufficient sediment regulation capacity, and forced sediment discharge during flood seasons. The "storing clear water and regulating muddy flow" approach represents an innovative development beyond the previous method. It involves comprehensively considering the water-sediment matching relationships of individual flood events and inter-annual variations (wet, normal, and dry years) based on reservoir development objectives. By coordinating the impacts of sediment regulation on reservoir deposition patterns and effective storage capacity, with the core goal of improving water-sediment relationship coordination in downstream reaches, appropriate sediment storage and water-sediment regulation capacities are established. Through comprehensive "blocking, regulating, and discharging" coordination, long-term maintenance of effective storage capacity and regeneration of part of the sediment storage capacity can be achieved, enabling integrated use of sediment storage and water-sediment regulation capacities. This allows partial interchange between "water storage capacity" and "sediment storage capacity"within certain time periods, fully leveraging the reservoir' s "internal" regulation of sediment. Under favorable water-sediment conditions, annual runoff regulation can be achieved, and through cascade reservoir operation combined with natural flood-sediment processes, better coordination of water-sediment relationships entering downstream reaches can be realized to maximize comprehensive reservoir benefits. Currently, the "storing clear water and regulating muddy flow" operation and its design technology have been applied to the existing Xiaolangdi Reservoir and planned reservoirs such as Dongzhuang and Guxian on the Yellow River.

2.2 Definition and Expression of Water-Sediment Regulation Degree in Flood Season

Reservoirs on sediment-laden rivers generally require designated sediment storage capacity and water-sediment regulation capacity. Reservoir operation is divided into sediment blocking stage and normal operation stage. During the sediment blocking stage, sediment accumulates in the reservoir but the designed sediment storage capacity has not yet been filled, allowing water-sediment reg-

ulation using the capacity below the flood control level after deducting the deposited volume. During the normal operation stage, when the designed sediment storage capacity is filled, regulation can only utilize the capacity between the designed flood control level and dead water level, plus regenerated sediment storage capacity [Figure 2: see original paper]. As incoming water-sediment conditions and reservoir sedimentation boundary conditions change, the water-sediment regulation capacity during flood season also varies continuously.

Based on Yellow River water-sediment scheduling practice, "water-sediment regulation degree" measures a reservoir' s capacity to regulate incoming water-sediment processes. When measuring primarily "water" regulation capacity, it is termed "runoff regulation degree" ; when measuring primarily "sediment" regulation capacity, it is termed "sediment regulation degree." For sediment-laden river reservoirs during flood season, runoff regulation degree and sediment regulation degree are defined separately. Runoff regulation degree refers to the average water storage below flood control level divided by the multi-year average incoming runoff during flood season. Sediment regulation degree refers to the regulation capacity below flood control level plus regenerated capacity divided by the multi-year average incoming sediment during flood season. The specific formulas are as follows:

Runoff regulation degree:

$$R_{fw} = \frac{V_{fw}}{W_f}$$

Sediment regulation degree:

$$R_{fs} = \frac{V_r + V_h}{W_{fs}}$$

where R_{fw} is the flood season runoff regulation degree; R_{fs} is the flood season sediment regulation degree; W_f is the multi-year average incoming runoff during flood season; W_{fs} is the multi-year average incoming sediment load during flood season; V_{fw} is the average water storage below flood control level during flood season; V_r is the regulation capacity below flood control level; and V_h is the regenerated capacity.

These formulas demonstrate that during the sediment blocking period, as sediment accumulates in the reservoir, the flood season water-sediment regulation degree continuously decreases until sedimentation reaches the designed sediment storage capacity, after which it stabilizes. A larger flood season water-sediment regulation degree indicates greater reservoir capacity for water-sediment regulation, and vice versa.

3 Analysis of Flood Season Water-Sediment Regulation Degree for Middle Yellow River Reservoirs

To deepen understanding of flood season water-sediment regulation degree for sediment-laden river reservoirs, this study examines the regulation degree magnitude of important Yellow River reservoirs. We selected existing and planned reservoirs in the middle Yellow River, including Wanjiazhai, Longkou, Tianqiao, Dongzhuang, Sanmenxia, Xiaolangdi, and Xixiayuan, as well as planned Guxian and Qikou reservoirs. Using post-1986 flood season water-sediment inflow at dam sites and regulation capacity sizes after entering normal operation period, we calculated each reservoir' s flood season water-sediment regulation degree. The calculation results are presented in Table 2 .

Table 2 Basic information on flood season water-sediment regulation degree of major reservoirs in the middle Yellow River

Note: Reservoir capacity and water volume units are billion m^3; sediment volume units are billion tons.

Under post-1986 inflow conditions, existing reservoirs in the middle Yellow River exhibit relatively small runoff regulation degrees. The primary reason is that, except for Xiaolangdi, existing reservoirs have small flood season regulation capacities, making it difficult to substantially regulate flood season water-sediment processes. This also constitutes one of the main reasons for the insufficient subsequent driving force for Xiaolangdi' s water-sediment regulation. Among reservoirs under construction or planned for the middle and lower Yellow River, the Dongzhuang Reservoir on the Jinghe tributary has a relatively small multi-year average flood season inflow but a large runoff regulation degree. The planned Guxian and Qikou reservoirs on the main stream feature large designed flood season regulation capacities and consequently possess large runoff regulation degrees. This indicates that planned reservoirs in the middle Yellow River have substantial runoff regulation capacity and represent key projects in the backbone engineering system.

Under post-1986 sediment inflow conditions, among existing reservoirs in the middle Yellow River, Wanjiazhai and Xiaolangdi have relatively large sediment regulation degrees, while other existing reservoirs have relatively small degrees. Currently, regulating sediment in the middle Yellow River during flood season requires joint operation of multiple reservoirs to achieve meaningful effects. However, although Wanjiazhai Reservoir has a large sediment regulation degree, its actual role in sediment regulation remains limited due to relatively small sediment inflow at its dam site. Under current engineering conditions, Yellow River water-sediment regulation primarily relies on Xiaolangdi Reservoir. Among reservoirs under construction or planned, Guxian and Qikou have large flood season regulation capacities and high sediment regulation degrees, indicating strong sediment regulation capabilities. The Dongzhuang Reservoir under construction on the Jinghe River, in addition to having certain flood season regulation capacity, employs "storing clear water and regulating muddy

flow" design technology in its planning, enabling partial regeneration and reuse of sediment storage capacity for sediment regulation, thus also achieving a large sediment regulation degree.

In summary, existing reservoirs in the middle Yellow River have relatively small water-sediment regulation degrees and insufficient regulation capacity. Current Yellow River water-sediment regulation mainly depends on Xiaolangdi Reservoir, which faces insufficient subsequent driving force for water-sediment regulation and limited regulation capacity after entering normal operation. Reservoirs under construction and planned all possess substantial water-sediment regulation capacity, and their commissioning will significantly enhance the water-sediment regulation capability of the middle Yellow River reservoir group.

The Guxian Reservoir is located in the lower section of the Jin-Shaan Canyon, controlling 80% of the Yellow River' s water volume, 60% of its sediment, and 80% of its coarse sediment. Under post-1986 water-sediment conditions, this reservoir achieves a flood season runoff regulation degree of 0.23 and a sediment regulation degree of 20.44. Compared with Xiaolangdi Reservoir, its runoff regulation degree and sediment regulation degree are 2.5 times and 6.8 times larger, respectively, demonstrating Guxian' s unparalleled superiority and irreplaceability in both geographic location and sediment regulation capacity, making it the core project of the Yellow River water-sediment regulation system.

4 Impact of Different Operation Modes on Water-Sediment Regulation Degree

As analyzed above, reservoir regulation capacity size and flood season water-sediment inflow are direct factors affecting flood season water-sediment regulation degree. Meanwhile, different reservoir operation modes influence reservoir sediment erosion and deposition patterns and regulation capacity changes, thereby affecting water-sediment regulation capacity. Based on the water-sediment regulation degree index and combined with the RSS one-dimensional water-sediment mathematical model, this study calculates the inter-annual variation of water-sediment regulation degree under two operation modes— "storing clear water and discharging muddy flow" and "storing clear water and regulating muddy flow" —to further investigate the impact of operation modes on regulation capacity.

Using Dongzhuang and Xiaolangdi reservoirs as examples, we employed the mathematical model to calculate reservoir sedimentation volumes and water-sediment regulation degree variations under the two operation modes during different periods, based on reservoir design operation data and relevant scheduling regulations. Dongzhuang Reservoir is currently under construction, with the calculation period beginning at its commissioning, while Xiaolangdi Reservoir is already in operation and currently in the first stage of post-sediment-blocking period, with calculations starting from 2017. Based on the results, we plotted annual variations of reservoir sedimentation volume and flood season

water-sediment regulation degree, shown in Figures 3–6 [Figure 3: see original paper][Figure 4: see original paper][Figure 5: see original paper][Figure 6: see original paper].

Overall, the variation trends of flood season runoff regulation degree and sediment regulation degree are basically consistent for both reservoirs, gradually decreasing in the early stage and then stabilizing. This trend occurs because sediment-laden river reservoirs operate through sediment blocking and normal operation periods. During the sediment blocking period, reservoirs continuously trap incoming sediment, gradually increasing sedimentation volume and decreasing regulation capacity, which weakens water-sediment regulation degree. During normal operation, reservoirs experience both erosion and deposition, basically maintaining sediment balance with minimal changes in regulation capacity and water-sediment regulation degree.

Further comparative analysis of sedimentation volumes and flood season water-sediment regulation degrees under the two operation modes reveals differences primarily in two aspects. First, during the sediment blocking period, both reservoirs exhibit smaller sedimentation volumes and larger flood season water-sediment regulation degrees under the "storing clear water and regulating muddy flow" mode. For example, in year 11 of the calculation period, Xiaolangdi Reservoir sedimented 7.413 billion m^3 under "storing clear water and discharging muddy flow," with runoff and sediment regulation degrees of 0.1 and 1.7, respectively. Under "storing clear water and regulating muddy flow," sedimentation was only 6.050 billion m^3, with regulation degrees of 0.2 and 3.6—nearly double the values. This difference arises because "storing clear water and discharging muddy flow" only considers lowering reservoir operation levels for sediment discharge during flood season, while "storing clear water and regulating muddy flow" fully considers water-sediment matching relationships of individual flood events, enabling coordinated "blocking, regulating, and discharging"to rationally regulate sediment discharge over longer timescales and slow reservoir sedimentation. Second, during normal operation, Dongzhuang Reservoir shows larger inter-annual variations in sedimentation volume and stronger flood season water-sediment regulation degrees under "storing clear water and regulating muddy flow." This results from Dongzhuang' s application of dual sediment erosion base level technology and consideration of extraordinary sediment discharge scheduling, which can effectively restore partial sediment storage capacity regeneration during favorable wet years, thereby enhancing flood season water-sediment regulation degree. For instance, in year 66 of the calculation period, Dongzhuang Reservoir sedimented 2.244 billion m^3 under "storing clear water and discharging muddy flow," with regulation degrees of 0.2 and 0.43. Under "storing clear water and regulating muddy flow," sedimentation was 2.069 billion m^3 with regulation degrees of 0.4 and 0.98. In the following year, sedimentation increased to 2.323 billion m^3 under the former mode, decreasing runoff regulation degree to 0.1 and sediment regulation degree to 0.18, while under the latter mode, sedimentation decreased to 1.975 billion m^3, increasing runoff regulation degree to 0.5 and sediment regulation degree to 1.27.

Comparative analysis of reservoir flood season water-sediment regulation degrees under different operation modes demonstrates that "storing clear water and regulating muddy flow" exhibits higher flood season water-sediment regulation degrees across different operation periods compared with "storing clear water and discharging muddy flow,"thereby effectively improving water-sediment process regulation effectiveness for sediment-laden river reservoirs.

Conclusions

(1) To accurately or relatively accurately characterize the flood season water-sediment regulation capacity of sediment-laden river reservoirs, this paper establishes definitions for flood season water-sediment regulation degree and provides calculation expressions. Taking middle Yellow River reservoirs as the study object, we investigate reservoir flood season water-sediment regulation capacity using the regulation degree concept, revealing that existing reservoirs in the middle Yellow River have insufficient flood season water-sediment regulation capacity, while reservoirs under construction and planned possess substantial regulation capacity.

(2) Based on the definition of flood season water-sediment regulation degree for sediment-laden river reservoirs and combined with water-sediment mathematical modeling, we calculate and analyze the inter-annual variation of water-sediment regulation degree for Dongzhuang and Xiaolangdi reservoirs under both "storing clear water and discharging muddy flow" and "storing clear water and regulating muddy flow" operation modes. The results indicate that the "storing clear water and regulating muddy flow" design technology and operation mode enable reservoirs to maintain certain runoff regulation capacity during flood season, effectively reduce sedimentation volumes in different periods, prolong sediment storage capacity service life, and substantially improve flood season water-sediment regulation degree.

(3) Under the "storing clear water and regulating muddy flow" design technology and operation mode, comparing the runoff and sediment regulation degrees of key reservoirs in the Yellow River water-sediment regulation system and considering their control over runoff, sediment, and particularly coarse sediment, the Guxian Reservoir—located in the lower Jin-Shaan Canyon controlling 80% of the Yellow River' s water volume, 60% of its sediment, and 80% of its coarse sediment—achieves a flood season runoff regulation degree of 0.23 and sediment regulation degree of 20.44 under post-1986 water-sediment conditions. Compared with Xiaolangdi Reservoir, its runoff and sediment regulation degrees are 2.5 times and 6.8 times larger, respectively, demonstrating Guxian' s unparalleled superiority and irreplaceability in both geographic location and sediment regulation capacity, making it the core project of the Yellow River water-sediment regulation system.

References

[1] Hu Chunhong. Study on water and sediment variation and regulation strategies of the Yellow River[J]. Journal of Hydroelectric Engineering, 2016, 35(10): 1-11.
[2] Zhang Jinliang. Practice of water and sediment regulation in the Yellow River[J]. Journal of Tianjin University, 2008(09): 1046-1051.
[3] Zhang Jinliang, Hu Chunhong, Liu Jixiang. "Storing clear water and regulating muddy flow" operation mode and design technology for sediment-laden river reservoirs[J]. Journal of Hydraulic Engineering, 2021, 52(S): 1-10.
[4] Li Guoying. Water and sediment regulation in the Yellow River[J]. China Water Resources, 2002(11): 34-38+10.
[5] Han Qiwei. Study on initial operation of Xiaolangdi Reservoir and water-sediment regulation of the Yellow River[J]. Journal of Sediment Research, 2008, 000(003): 1-18.
[6] Luo Qiushi. Study on numerical simulation technology for 2D and 3D water-sediment operation based on unstructured grids[D]. Wuhan University, 2009.
[7] Chen Cuixia, An Cuihua, Luo Qiushi, et al. Current status and effectiveness of water-sediment regulation in the Yellow River[J]. Journal of Sediment Research, 2019, 44(02): 69-74.
[8] Qian Ning, Zhang Ren, Zhao Ye' an, et al. Discussion on water-sediment regulation issues in river management from the perspective of riverbed evolution laws in the lower Yellow River[J]. Acta Geographica Sinica, 1978(01): 13-24.
[9] Lian Jijian, Wan Yi, Zhang Jinliang. Study on optimal operation of cascade reservoirs for density current processes[J]. Journal of Hydroelectric Engineering, 2008(01): 18-23.
[10] Yao Wenyi, Hou Suzhen, Ding Yun. Regulation mechanism of Longyangxia and Liujiaxia reservoirs on water-sediment relationship in the upper Yellow River[J]. Advances in Water Science, 2017, 28(1): 1-13.
[11] Hu Chunhong. Development and practice of "storing clear water and discharging muddy flow" operation mode for sediment-laden river reservoirs in China[J]. Journal of Hydraulic Engineering, 2016, 47(03): 283-291.
[12] An Cuihua, Lu Jun, Wu Moxi, et al. Study on sediment transport threshold for balanced sediment transport in the lower Yellow River[J]. Journal of Hydraulic Engineering, 2020, 51(4): 402-409.
[13] Lu Jun, An Cuihua, Wu Xiaoyang. Study on characteristics and causes of water-sediment variation in the Ningxia-Inner Mongolia reach of the Yellow River[J]. Journal of Sediment Research, 2018, 43(6): 40-46.
[14] Zhang Jinliang, Lian Jijian, Zhang Yuansheng, et al. Coordination degree of water-sediment relationship in the Yellow River and regulation role of key reservoirs[J]. Journal of Hydraulic Engineering, 2020, 51(08): 897-905.

Corresponding Author: Lu Jun, E-mail: 393956425@qq.com

Author Contributions Statement:

Zhang Jinliang: Conceived research ideas and designed research methodology;

Zhang Jinliang: Conducted experiments;
Zhang Jinliang: Collected, cleaned, and analyzed data;
Zhang Jinliang: Drafted the manuscript;
Zhang Jinliang: Revised the final version of the paper.

Note: Figure translations are in progress. See original paper for figures.