“Storing Clear and Regulating Turbid” Operation Mode and Design Technology for Reservoirs in Sediment-Laden Rivers

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Abstract

This study systematically summarizes the development history of reservoir operation methods for sediment-laden rivers in China since the 1950s-1960s, elucidates the evolution of reservoir operation methods and their design technologies across different periods, and provides a detailed analysis of the “storing clear water and regulating turbid water” operation method and its design technology. In terms of design, it requires scientifically and rationally designing the sediment regulation storage capacity and the discharge capacity corresponding to the sediment flushing water level, considering different sedimentation states during the sediment regulation process, and conducting reservoir capacity allocation design according to the storage distribution rule of “deep channel for sediment regulation, middle channel for beneficial use, and high channel for flood control” ; for ultra-high sediment concentration rivers, emergency sediment flushing bottom outlets should be added below the normal sediment flushing outlets to form a “normal + emergency” dual sediment erosion base level; for extremely high sediment concentration rivers, the coordination between effective storage capacity maintenance and water supply regulation is difficult, requiring the adoption of a separated water and sediment development approach. In terms of operation, it should be flexibly determined based on reservoir development tasks and inflow water-sediment conditions, etc. Reservoirs in high sediment concentration rivers can adopt the operation mode of “retaining sediment during low flows, discharging sediment during high flows, creating peaks at appropriate times, and silting beaches while shaping channels” ; reservoirs in ultra-high sediment concentration rivers can employ unconventional sediment discharge scheduling methods combined with outlet arrangements; reservoirs in extremely high sediment concentration rivers can adopt the operation mode of “large mainstream reservoir for sediment regulation and small tributary reservoir for water supply regulation” in conjunction with separated water and sediment development. The “storing clear water and regulating turbid water” operation method can, on the basis of maintaining the reservoir' s effective storage capacity over the long term, further accommodate the needs of water and sediment regulation, effectively avoid sediment occupation of the reservoir' s effective storage capacity, and reduce the adverse impacts of forced sediment flushing on downstream water-sediment relationships. The research findings will provide guidance and reference for the design and operation of sediment-laden river reservoir projects in the current and future periods.

Full Text

Preamble

Application and Design Technology of "Storing Clear Water and Regulating Muddy Flow" for Reservoirs in Sediment-Laden Rivers

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Abstract

This paper systematically reviews the development of reservoir operation modes for sediment-laden rivers in China since the 1950s and 1960s, explaining the evolution of reservoir operation strategies and their design technologies across different periods, with detailed analysis of the "storing clear water and regulating muddy flow" approach and its design techniques. In terms of design, it requires scientifically and rationally designing sediment regulation storage capacity and discharge capacity corresponding to sediment-flushing water levels, considering different sedimentation states during the regulation process, and configuring reservoir capacity according to the distribution rule of "deep channel for sediment regulation, medium channel for beneficial use, and high channel for flood regulation." For ultra-high sediment concentration rivers, abnormal sediment discharge bottom outlets should be added below normal discharge orifices to form a "normal + abnormal" dual sediment erosion datum plane. For super-high sediment concentration rivers, coordination between effective storage capacity maintenance and water supply regulation is difficult, necessitating a water-sediment separation development approach. In terms of operation, strategies should be flexibly determined based on reservoir development tasks and inflow water-sediment conditions. High sediment concentration reservoirs can adopt the operation mode of "retaining sediment during low flows, discharging sediment during high flows, creating peaks at appropriate times, and depositing on beaches while shaping channels." Ultra-high sediment concentration reservoirs can employ unconventional sediment discharge scheduling combined with orifice layout, while super-high sediment concentration reservoirs can adopt a water-sediment separation operation mode of "large mainstream reservoir for sediment regulation and small tributary reservoir for water supply regulation.” The “storing clear water and regulating muddy flow” operation mode can maintain effective reservoir capacity over the long term while meeting water-sediment regulation needs, effectively preventing sediment deposition from occupying effective storage capacity and reducing adverse impacts of forced sediment discharge on downstream flow-sediment relationships. The research findings will provide guidance and reference for the design and operation of reservoir projects in sediment-laden rivers in the current and future periods.

Keywords: Yellow River; reservoir sediment; water storage and sediment interception; storing clear water and discharging muddy flow; storing clear water and regulating muddy flow; operation mode

Classification Number: TV145

1 Introduction

In sediment-laden rivers of severe soil erosion areas in northern China, characterized by low water discharge, high sediment load, large sediment transport volumes, and high sediment concentrations, reservoir construction often leads to massive sediment deposition [1]. Extensive engineering practice demonstrates that improper sediment management affects projects comprehensively [2-3]. Inadequate sediment management at reservoir tails causes continuous upstream extension of deposition, expanding reservoir sedimentation and inundation ranges and creating resettlement and social issues. Poor sediment handling in reservoir areas leads to continuous loss of effective storage capacity, making development objectives difficult to achieve. Improper sediment management near dams causes clogging of discharge structures and changes in dam stress conditions, resulting in frequent safety operation accidents. Inadequate sediment prevention and avoidance measures in discharge orifices lead to severe abrasion of turbines or discharge structures. Numerous reservoirs, including the Sanmenxia, Yanguoxia, and Qingtongxia reservoirs on the Yellow River mainstream, the Bajiazu Reservoir on the Puhe River, and the Wangyao Reservoir on the Yanhe River, have been forced to undergo reconstruction due to sediment deposition [4-7].

To control reservoir sedimentation, maintain effective storage capacity over the long term, and achieve reservoir development objectives, Chinese water conservancy professionals have conducted long-term exploration and practice. Building upon early “water storage and sediment retention”operations, they gradually developed the “storing clear water and discharging muddy flow” approach [1], which provides a guarantee for long-term storage capacity preservation and effectively supports reservoir planning, design, and operation practices in China’ s sediment-laden rivers [8-13]. The successful construction and operation of the Xiaolangdi Water Control Project represents a key milestone in the maturation of the “storing clear water and discharging muddy flow” operation mode and its design technology for sediment-laden rivers [14-23]. Following Xiaolangdi, relying on the planning and design of multiple sediment-laden river water control projects such as the Guxian Project on the Yellow River, Dongzhuang Project on the Jinghe River, and Malian River Project in Gansu, China’ s reservoir operation modes and design technologies for sediment-laden rivers have gradually evolved from “storing clear water and discharging muddy flow” to “storing clear water and regulating muddy flow.” This evolution has effectively addressed world-class technical challenges in deposition morphology design, capacity allocation, and restoration of lost capacity for major water projects on high (annual average 10–100 kg/m^3), ultra-high (annual average 100–200 kg/m^3), and super-high (annual average >200 kg/m^3) sediment concentration rivers, making the construction of water control projects on ultra-high and super-high sediment concentration rivers increasingly feasible.

Based on reviewing the development of reservoir operation modes for sediment-laden rivers in China since the 1950s and 1960s, this paper elaborates on the proposal of the “storing clear water and regulating muddy flow” operation mode and its design technology, systematically analyzes key theoretical and technical aspects, and presents specific practical cases.

2 Proposal of “Storing Clear Water and Regulating Muddy Flow”

Sediment issues are the key and core problem throughout the entire design process of reservoirs on sediment-laden rivers [24]. During design, it is necessary to thoroughly evaluate inflow water-sediment conditions, operation scheduling methods, sediment deposition morphology, effective storage capacity distribution, backwater inundation range, and sediment prevention and protection measures for the hub. This includes identifying potential sediment problems after project completion, analyzing their impacts, and proposing solutions to ensure reliable design of storage capacity scale, characteristic water levels, and discharge and sediment flushing facilities. During operation, appropriate reservoir operation modes must be studied based on design operation methods while considering changes in inflow water-sediment conditions, sedimentation status, and comprehensive utilization requirements. The following sections explain the background and characteristics of the “storing clear water and regulating muddy flow” operation mode and its design technology according to the development process of reservoir operation modes and design technologies for sediment-laden rivers.

2.1 “Water Storage and Sediment Retention”

Large-scale reservoir construction in China began in the 1950s and 1960s. Due to limited understanding of sediment issues, reservoirs on sediment-laden rivers during this period mostly followed the design of clear-water rivers and adopted the “water storage and sediment retention” operation mode. These reservoirs did not have dedicated sediment flushing periods and operated with year-round water storage, with sediment deposition primarily considered to accumulate within dead storage capacity [27]. By reserving a certain scale of sediment storage capacity to trade space for time, reservoirs could maintain sufficient regulation capacity to generate benefits for a certain period. In design, few reservoirs were equipped with dedicated sediment discharge facilities, and some small and medium-sized reservoirs had no sediment discharge facilities at all. Reservoirs designed during this period had limited service lives: sediment would first fill the dead storage capacity, then begin to occupy effective storage capacity until the reservoir lost its original design function. The reservoir' s lifespan was essentially the number of years required to fill the dead storage capacity (or reserved sediment storage capacity) [28]. At that time, measures such as enhancing soil and water conservation and constructing sediment interception dams in upstream watersheds were proposed to reduce sediment inflow and slow reservoir sedimentation, but the sediment management philosophy remained confined to "retention," without proposing design concepts or requirements for long-term effective storage capacity maintenance.

For sediment-laden rivers, sediment inflow is virtually unlimited while storage capacity is finite. Due to limited understanding of sediment issues during this period, the design and operation philosophy primarily focused on "retention," passively using sediment storage capacity to "block" sediment in exchange for reservoir service life. This approach failed to adequately address sediment deposition problems, resulting in severe sedimentation issues in reservoirs built during this era and forcing numerous projects to undergo reconstruction. According to survey data from the 1970s [29], among 192 reservoirs in Shaanxi Province with a total capacity of 1.5 billion m^3, poor consideration of sediment discharge in planning and design led to a loss of 473 million m^3 of storage capacity by the end of 1973, accounting for 31.4% of total capacity, with an average annual loss of 30 million m^3. Twenty-two percent of these reservoirs were completely filled or rendered useless by sediment. In Shanxi Province, 43 large and medium-sized reservoirs with a total capacity of 2.23 billion m^3 lost 700 million m^3 of capacity by the end of 1974, representing 31.5% of total capacity, with an average annual loss of 50 million m^3. This severely reduced reservoir lifespans and caused complete or partial loss of original development functions. Typical examples include the Guanting Reservoir on the Yongding River, the Sanmenxia Reservoir on the Yellow River mainstream, and the Bajiazu Reservoir on the Puhe River [37].

The Guanting Reservoir, the first large backbone reservoir built on the Yongding River in China, was designed for flood control, water supply, power generation, and irrigation. The design reserved 900 million m^3 as sediment storage capacity, 300 million m^3 as beneficial storage, and 1.07 billion m^3 for flood control, with plans to implement watershed soil and water conservation to reduce sediment inflow. Construction began in 1953, and the reservoir commenced operation in 1955 using water storage and sediment retention. Severe sedimentation occurred, with total sediment accumulation reaching 586 million m^3 by May 1980, including 399 million m^3 in dead storage, 117 million m^3 in beneficial storage, and 70 million m^3 in flood control storage. Sediment deposition caused a series of problems including reduced flood control standards, unreliable water supply, expanded inundation losses around the reservoir, and impacts on discharge structure safety and power generation/water supply quality, forcing reconstruction in 1985.

The Sanmenxia Reservoir, the first large water control project built on the middle Yellow River mainstream with primary functions of flood control and comprehensive benefits including ice prevention, irrigation, power generation, and water supply, was originally designed with a maximum flood level of 360 m, total storage capacity of 64.6 billion m^3, and flood control capacity of 10 billion m^3. The original design recognized that reservoir sedimentation would critically impact service life and benefits, assuming 20% sediment reduction by 1967 and 50% reduction after 50 years through upstream watershed management. To ensure the reservoir would not become ineffective within 50-100 years, 33.6 billion m^3 of sediment storage capacity was reserved considering 50 years of sedimentation [30]. Construction began in April 1957, and the reservoir commenced operation in September 1960. Initial "water storage and sediment retention" operation caused severe sedimentation. To address this, from March 1962, the reservoir operated with fully opened gates during flood seasons, retaining only the task of defending against extraordinary floods. However, due to insufficient discharge capacity, the reservoir still experienced "retarding flood and discharging sediment" with massive sediment deposition during large floods, forcing two phases of reconstruction and expansion of flood discharge and sediment flushing facilities from 1965-1969 and 1969-1973.

The sedimentation problems at Sanmenxia included: (1) upstream extension of deposition causing a 4.5 m rise in the Tongguan elevation, seriously threatening flood safety in the Guanzhong Plain and even Xi'an; and (2) severe capacity loss, with 44% loss of storage capacity below elevation 355 m by the post-flood season of 1964, severely impacting designed flood control and beneficial functions. Consequently, the reservoir underwent two reconstructions.

2.2 "Storing Clear Water and Discharging Muddy Flow"

In response to numerous reservoir sediment problems emerging in the 1950s and 1960s, Chinese water conservancy professionals gradually recognized that the design and operation philosophy focusing primarily on "retention" and passively using sediment blocking to 赋予水库一定的寿命 was not feasible [31], necessitating approaches for long-term effective storage capacity maintenance. As early as 1964, Tang Richang and Lin Yishan proposed concepts for long-term effective storage capacity maintenance based on the successful experiences of the Naodehai and Heisonglin reservoirs [32]. Before Sanmenxia' s reconstruction, they predicted that reconstruction could achieve long-term storage capacity maintenance and recommended that reservoirs under design or construction on the Yellow River or similar rivers be designed or modified according to long-term use principles. Han Qiwei further elaborated the theoretical principles and basis for long-term reservoir use and provided methods for determining preserved capacity [6]. Simultaneously, to reduce reservoir sedimentation, maintain effective storage capacity for long-term use, and fully realize comprehensive benefits, Chinese water conservancy professionals conducted long-term exploration and practice. Addressing Sanmenxia's severe sedimentation problems through reconstruction and operation adjustments, they innovatively proposed the "storing clear water and discharging muddy flow" operation mode, successfully solving Sanmenxia' s sedimentation issues. Control of sedimentation at Qingtongxia [33-34] and Sanshenggong reservoirs further demonstrated the feasibility of long-term effective storage capacity maintenance through "storing clear water and discharging muddy flow" operation for large comprehensive reservoirs, gradually forming consensus [24] and exploring the final equilibrium deposition morphology and calculation methods [35]. Subsequent planning and design work further explored the "storing clear water and discharging muddy flow" operation mode and its design technical requirements, with significant contributions from Tu Qihua [36], Li Shiying [26], Liu Jixiang [25], and Cao Ruxuan [36], culminating in successful application at the Xiaolangdi Project and marking the basic maturity of "storing clear water and discharging muddy flow" operation and design technology for sediment-laden rivers.

The "storing clear water and discharging muddy flow" operation mode aims for long-term effective storage capacity maintenance, requiring large discharge capacity at dead water levels and dedicated sediment discharge periods. Storage capacity allocation and backwater calculations are based on sedimentation equilibrium morphology, with effective storage capacity corresponding to this equilibrium state. The development of this operation mode and design technology is illustrated through Sanmenxia' s reconstruction and Xiaolangdi' s design.

Sanmenxia operated in "retarding flood and discharging sediment" mode from March 1962. Due to insufficient discharge capacity, sedimentation remained severe, prompting reconstruction to increase discharge capacity. The first-phase reconstruction of discharge structures was completed in 1968, adding "two tunnels and four pipes," increasing discharge capacity below elevation 315 m from 3,804 m^3/s to 6,102 m^3/s. The second-phase reconstruction was completed in 1971, opening original construction diversion bottom outlets #1-#8, further increasing discharge capacity below 315 m to 9,059 m^3/s. These two reconstructions significantly increased discharge capacity. Based on this, flood season operation water levels were further reduced. From the post-flood season of 1973, Sanmenxia began "storing clear water and discharging muddy flow" operation, controlling water level at 305 m during normal flow periods for power generation and fully opening gates for sediment discharge during large floods.

The period from November 1973 to October 1986 was characterized by abundant water and moderate sediment, with favorable water-sediment conditions. Sedimentation below Tongguan was only 70 million m^3, with an average annual deposition of 5.4 million m^3, and the Tongguan elevation remained basically stable. After 1986, due to consistently low water inflow and fewer large flow events entering the reservoir, the reservoir area showed a sedimentation trend.

By 2002, cumulative sedimentation below Tongguan reached 243 million m^3, with the Tongguan elevation continuously rising from 327 m to approximately 328.5 m. After 2002, operation water levels were further reduced to enhance sediment discharge, with full gate opening when inflow exceeded 1,500 m^3/s during flood seasons. Due to significantly reduced sediment inflow and increased water inflow in the Yellow River, favorable water-sediment conditions combined with optimized reservoir operation enabled erosion below Tongguan, with cumulative sediment erosion of 182 million m^3, curbing the continuous rise of the Tongguan elevation and maintaining it around 328 m [1]. After two reconstructions and adoption of "storing clear water and discharging muddy flow" operation, Sanmenxia gradually reached a sedimentation equilibrium state. Regarding deposition morphology, within 80 km from the dam, the average riverbed elevation experienced significant erosion and deposition changes. The reservoir deposition slope decreased sequentially from the tail section to the dam section, forming multiple slopes (see [Figure 1: see original paper]). The average deposition slope in the dam section was 1.60/000 over 40.8 km; the second section averaged 2.10/000 over 40 km; and the third section was 2.50/000 over 44.8 km, yielding an overall slope of 2.10/000 across the 125.6 km reach.

Through "storing clear water and discharging muddy flow" operation and increased discharge capacity via reconstruction, Sanmenxia achieved effective sedimentation control, forming a "high beach deep channel" equilibrium morphology and realizing long-term effective storage capacity maintenance, providing valuable experience for sediment-laden river reservoir planning and design. Guided by this concept, Xiaolangdi' s design set 7.55 billion m^3 of storage capacity below the "high beach deep channel" equilibrium morphology as sediment retention capacity, with 5.1 billion m^3 of effective storage capacity above this morphology. This included 1.05 billion m^3 of water-sediment regulation capacity between dead water level and flood season limit level, and 4.05 billion m^3 of flood control capacity between flood season limit level and design flood level, with beneficial storage capacity shared with water-sediment regulation and flood control capacities. To achieve long-term effective storage capacity maintenance, the reservoir was designed with a discharge capacity of 8,000 m^3/s at dead water level, preventing retarding flood sedimentation under moderate flood conditions.

Overall, "storing clear water and discharging muddy flow" adopts a "retention + discharge" sediment management philosophy, fundamentally solving rapid storage capacity loss problems at reservoirs like Sanmenxia and further developing applications at Xiaolangdi, satisfactorily addressing design challenges for rivers with sediment concentrations below 100 kg/m^3. This represents a major advancement in China' s reservoir operation and design technology following the "water storage and sediment retention" approach. However, several issues require further research. Using Xiaolangdi as an example, first, reservoir capacity distribution and backwater design are based on sedimentation equilibrium morphology. However, after reaching equilibrium, reservoirs operate for water-sediment regulation during main flood seasons and water storage during non-flood seasons. With variations in water-sediment conditions between wet, normal, and dry years, the reservoir area experiences both erosion and deposition, creating risks of short-term sediment deposition occupying flood control capacity. The design inadequately considers impacts of "sediment regulation" during normal operation periods. Second, the designed water-sediment regulation capacity is relatively small. Currently in the sediment retention period, the reservoir has large regulation capacity and can effectively deliver water-sediment regulation benefits. However, after entering normal operation, sediment deposition during water-sediment regulation will inevitably occupy regulation capacity. Under unfavorable water-sediment conditions or severe sedimentation, forced sediment discharge is required to ensure adequate effective storage capacity, inevitably causing phenomena like "small water carrying large sediment" and resulting in extremely uncoordinated downstream flow-sediment relationships. This creates a contradiction between maintaining effective storage capacity and coordinating downstream flow-sediment relationships, affecting long-term sediment reduction benefits. Additionally, some reservoirs on ultra-high and super-high sediment concentration rivers struggle to maintain effective storage capacity even with "storing clear water and discharging muddy flow" operation. For example, the Bajiazu Reservoir has an average annual sediment concentration of 220 kg/m^3 and, despite three heightening reconstructions, continues to experience annual storage capacity loss, making coordination between long-term effective capacity maintenance and water supply regulation difficult [37].

2.3 "Storing Clear Water and Regulating Muddy Flow"

From the late 1960s to 1970s, evolving Yellow River management practices gradually recognized that "more sediment than water and unbalanced water-sediment relationship" significantly impacted downstream channel sedimentation, leading to proposals for using large reservoirs for "water-sediment regulation" to reduce downstream sedimentation [38]. During the 1980s–1990s, Xiaolangdi' s design adopted "storing clear water and discharging muddy flow" operation and design technology, considering water-sediment regulation in its design. In the late 1990s, Zhang Jinliang et al. [39], based on Sanmenxia' s operation practices, proposed that sediment-laden river reservoirs should not only maintain effective storage capacity through water-sediment regulation but also optimize outflow water-sediment combinations to benefit downstream channel sediment reduction. During this period, reservoir operation research was evolving from "storing clear water and discharging muddy flow" to "storing clear water and regulating muddy flow." Subsequently, research focusing on Xiaolangdi's water-sediment regulation and operation optimization, building upon "retention + discharge" sediment management, deeply investigated reservoir group artificial density current sediment discharge technology [40], joint water-sediment regulation scheduling modes for reservoir groups, simultaneous beach-channel shaping in sediment-laden rivers, and regeneration and diversified utilization of sediment retention capacity, gradually forming the "storing clear water and regulating muddy flow" technology centered on maximizing long-term improvement of downstream flow-sediment relationship coordination.

At the planning and design level for sediment-laden river reservoirs, new design challenges emerged following Xiaolangdi. For instance, the Guxian Water Control Project on the Yellow River faces an average annual sediment concentration of 28 kg/m^3 and, as an ultra-long reservoir with lateral sediment inflow on a high sediment concentration river, presents unprecedented challenges in lateral sedimentation morphology and capacity distribution design [41-46]. The Dongzhuang Project on the Jinghe River, with an average annual sediment concentration of 140 kg/m^3, confronts world-class challenges in sediment transport through meandering channels, effective storage capacity maintenance, and capacity regeneration for ultra-high sediment concentration rivers [47-51]. The Malian River Project in Gansu, with an average annual sediment concentration of 280 kg/m^3, faces severe contradictions between effective storage capacity maintenance and water supply regulation for super-high sediment concentration river water supply reservoirs, where traditional development models cannot achieve development objectives. Building upon design and research practices at Sanmenxia, Xiaolangdi, and other sediment-laden river reservoirs, Zhang Jinliang et al. [52] gradually improved the reservoir sediment design index system and methodology through long-term research, solving world-class technical challenges in deposition morphology design, capacity allocation, and restoration of lost capacity for major water projects on high (10–100 kg/m^3), ultra-high (100–200 kg/m^3), and super-high (>200 kg/m^3) sediment concentration rivers. Thus, the “storing clear water and regulating muddy flow” operation mode and its design technology for sediment-laden river reservoirs have gradually taken shape.

The “storing clear water and regulating muddy flow” operation mode, based on reservoir development task requirements, fully considers variations in water-sediment processes for high, ultra-high, and super-high sediment concentration rivers, including event-scale floods and interannual wet/normal/dry variations. It coordinates the impacts of sediment regulation on reservoir deposition morphology and effective storage capacity, focusing on maximizing downstream flow-sediment relationship coordination. By establishing appropriate sediment retention and water-sediment regulation capacities, it achieves long-term effective storage capacity maintenance, partial regeneration of sediment retention capacity, and integrated utilization of sediment retention and water-sediment regulation capacities through comprehensive coordinated control of “retention, regulation, and discharge,” thereby better realizing comprehensive reservoir benefits. Compared with “storing clear water and discharging muddy flow,” the “storing clear water and regulating muddy flow” approach not only considers “retention”and “discharge”but emphasizes “regulation,”requiring flexible scheduling based on development tasks and inflow water-sediment conditions. High sediment concentration reservoirs can adopt “retaining sediment during low flows, discharging sediment during high flows, creating peaks at appropriate times, and depositing on beaches while shaping channels.” Ultra-high sediment concentration reservoirs should combine orifice layout with unconventional sediment discharge scheduling, while super-high sediment concentration reservoirs can adopt water-sediment separation development with “large mainstream reservoir for sediment regulation and small tributary reservoir for water supply regulation."

To better meet "regulation" requirements, "storing clear water and regulating muddy flow" also imposes different design requirements. First, reservoirs must have adequate water-sediment regulation capacity, including both water regulation capacity (for shaping large flow processes) and sediment regulation capacity (for managing interannual and intra-annual sediment variations due to wet/normal/dry water-sediment conditions and uncoordinated flow-sediment relationships). Second, capacity distribution design must consider dynamic changes in deposition morphology during "regulation" operations. During normal operation, sediment erosion and deposition exhibit characteristics of stable beaches and active channels, presenting three sedimentation states: "high beach deep channel," "high beach medium channel," and "high beach high channel." The distribution design of sediment retention capacity, water-sediment regulation capacity, beneficial storage capacity, flood control capacity, and ecological storage capacity must consider coupling with deposition morphology changes, following the rule of "deep channel for sediment regulation, medium channel for beneficial use, high channel for flood regulation" to reduce risks of forced sediment discharge caused by dynamic sediment regulation occupying effective storage capacity during normal operation. Third, for ultra-high sediment concentration rivers, "normal + abnormal" dual sediment erosion datum planes and unconventional sediment discharge technology should be employed by adding abnormal sediment discharge bottom outlets below normal discharge orifices. Combined with unconventional sediment discharge scheduling, this can regenerate partially "dead" sediment retention capacity and achieve perpetual integrated utilization with water-sediment regulation capacity while maintaining long-term effective storage capacity. Fourth, for super-high sediment concentration rivers where coordination between effective storage capacity maintenance and water supply regulation is difficult, water-sediment separation development should be adopted. A comparison of operation modes and design technologies between "storing clear water and discharging muddy flow" and "storing clear water and regulating muddy flow" is presented in .

3 Application and Design Practice of "Storing Clear Water and Regulating Muddy Flow"

(1) During Xiaolangdi Reservoir' s initial operation period, outflow discharge was regulated in stages during flood seasons to create a bipolar distribution while opportunistically generating sustained large flows to discharge sediment using high flows, conducting water-sediment regulation prototype tests. As sediment deposition progressed and Xiaolangdi entered the late sediment retention period, research proposed the "retaining sediment during low flows, discharging sediment during high flows, creating peaks at appropriate times, and depositing on beaches while shaping channels" technology for simultaneous beach-channel shaping. Compared with the

design operation mode, this technology changed the design' s sediment retention pattern of only deposition without erosion during the sediment retention period, achieving reservoir sediment management of "regulating while retaining and retaining while regulating." This avoided the adverse situation of "high beach high channel" during large floods when entering normal operation and the negative downstream impacts of concentrated sediment discharge during "high beach deep channel" formation. This technology was applied during flood seasons from 2018-2020. By April 2020, Xiaolangdi had accumulated 3.286 billion m^3 of sediment, accounting for 43.5% of designed sediment retention capacity. Mainstream deposition totaled 2.549 billion m^3 (77.6% of total deposition), while tributary deposition was 737 million m^3 (22.4%). Deposition morphology in the Xiaolangdi mainstream area primarily formed a delta shape, with delta front slopes ranging from 1.210/000 to 2.910/000. As deposition continued, the delta vertex gradually advanced toward the dam, from 69.4 km from the dam in 2000 to 7.7 km in 2020 (see [Figure 3: see original paper]), essentially eliminating the tributary mouth bar formed during the initial sediment retention period and maintaining good control of deposition morphology.

(2) The Guxian Water Control Project on the Yellow River is located 72.5 km upstream of the Longmen hydrological station, controlling a drainage area of 489,948 km^2 (71% of Sanmenxia' s control area) and 80% of the Yellow River' s coarse sediment, with an average annual sediment concentration of 28 kg/m^3. Major sediment design challenges include: first, the Guxian reservoir area extends over 200 km, with six major tributaries (Wudinghe, Qingjianhe, Yanhe, Sanchuanhe, Quchanhe, and Qiushuihe) joining along both banks, creating difficulties in designing sediment deposition morphology and capacity allocation under complex main-tributary water-sediment interactions; and second, reservoir tail deposition affects resettlement water level determination, influencing resettlement scale and impacts. Analysis indicates that discharge capacity at design dead water level is 8,206 m^3/s. Considering sediment erosion and deposition variations during "storing clear water and regulating muddy flow" operation, a coupled design of deposition morphology and capacity distribution was proposed. During normal operation, channel erosion and deposition morphology considers three states: "high beach deep channel," "high beach medium channel," and "high beach high channel." The "deep channel" morphology has a dead water level of 588 m, beach surface elevation of 625.5 m at the dam, with three reaches of 60 km, 60 km, and 81 km, and channel deposition slopes of 1.70/000, 2.10/000, and 3.00/000, respectively. The beach slopes for the first two reaches are 1.00/000 and 1.20/000, with the deposition tail located 1.6 km downstream of the Houqiao section at the lower end of Wubao County, not affecting Wubao during flood seasons. The "high channel" morphology represents the most unfavorable sedimentation state under severe water-sediment regulation capacity sedimentation, also located 1.6 km downstream of the Houqiao section. Based on these

three channel morphologies, reservoir capacity allocation follows the “deep channel for sediment regulation, medium channel for beneficial use, high channel for flood regulation” rule (see [Figure 3: see original paper]), with designed sediment retention capacity of 9.342 billion m^3, water-sediment regulation capacity of 2.0 billion m^3, beneficial storage capacity of 1.5 billion m^3, and flood regulation capacity of approximately 1.777 billion m^3. Backwater calculations using the “high beach high channel” boundary conditions enabled rational resettlement water level design, avoiding Wubao County relocation.

(3) The Dongzhuang Water Control Project on the Jinghe River is an important tributary reservoir in the Yellow River water-sediment regulation system and the only flood control and sediment reduction backbone project in the Weihe River Basin. With total storage capacity of 3.276 billion m^3, average annual sediment concentration of 140 kg/m^3, and dam height of 230 m, it is the world’ s highest double-curvature arch dam on an ultra-high sediment concentration river. Preliminary work began in the 1950s, facing three major challenges: functional positioning, sediment deposition, and karst leakage, with two related to sediment issues that constrained project development. Applying “storing clear water and regulating muddy flow” concepts and ultra-high sediment concentration river sediment retention capacity regeneration design, the project includes four flood discharge and sediment flushing deep outlets and two abnormal sediment discharge bottom outlets. The bottom elevation of the two abnormal sediment discharge bottom outlets is 15 m lower than both the dead water level and the flood discharge and sediment flushing deep outlets, with discharge capacity reaching 1,000 m^3/s. Considering Dongzhuang’ s inflow flood characteristics of rapid rise and fall, high peaks, and small volumes with high sediment concentrations, during the sediment retention period (sediment retention volume $<$2.053 billion m^3), when the deposition surface elevation at the dam is between 693 m (abnormal sediment discharge bottom outlet inlet elevation) and 708 m (flood discharge and sediment flushing deep outlet inlet elevation) and reservoir water level is below 780 m, abnormal sediment discharge bottom outlets are opened for sediment discharge when inflow exceeds 600 m^3/s. During normal operation (sediment retention volume $>$2.053 billion m^3), abnormal sediment discharge bottom outlets are opened when suitable flood conditions occur to enhance sediment discharge capacity, restore reservoir capacity, and achieve repeated utilization of sediment retention capacity, maximizing comprehensive benefits. The abnormal sediment discharge bottom outlets play important roles in enhancing sediment discharge capacity, extending sediment retention service life, and restoring sediment retention capacity. Research shows that installing abnormal sediment discharge bottom outlets can advance sediment discharge by three years, extend sediment retention capacity service life by three years, and restore a cumulative 445 million m^3 of sediment retention capacity within 50 years (see [Figure 4: see original paper]),

accounting for 21.7% of designed sediment retention capacity.

(4) The Malian River Water Control Project in Gansu is located on the Malian River in Qingyang City, with average annual sediment concentration of 280 kg/m^3. As a large water project to break water resource bottlenecks in the old revolutionary base area, it has total storage capacity of 479 million m^3 and dam height of 71 m, representing a homogeneous earth dam on the world' s highest sediment concentration river. The contradiction between effective storage capacity maintenance and water supply regulation is extremely prominent for super-high sediment concentration (>200 kg/m^3) river reservoirs, where a single reservoir cannot simultaneously achieve long-term effective storage capacity maintenance and water supply tasks. Applying "storing clear water and regulating muddy flow" concepts, research concluded that super-high sediment concentration river reservoirs should adopt water-sediment separation development, constructing large and small reservoirs in parallel with a "large mainstream reservoir for sediment regulation and small tributary reservoir for water supply regulation" operation mode. The Jiazui Reservoir on the mainstream plus the Yanwachuan regulating reservoir on a tributary form a parallel development scheme. During the main flood season from July 1 to August 31, when Jiazui Reservoir inflow exceeds 20 m^3/s, it is designated as the sediment discharge period; other periods are non-sediment discharge periods. During sediment discharge periods, Jiazui Reservoir does not regulate runoff, with water supply provided by the Yanwachuan regulating reservoir. During non-sediment discharge periods, Jiazui Reservoir regulates runoff, recharges the Yanwachuan regulating reservoir, and supplies water to users after Yanwachuan' s regulation. This water-sediment separation development approach increased industrial water supply reliability from 56.6% to 96.1% and agricultural water supply from impossible to 86%. While meeting water supply tasks, the reservoir experiences both erosion and deposition during normal operation, maintaining effective storage capacity long-term (see [Figure 5: see original paper]).

4 Main Findings and Recommendations

This paper systematically reviews the development of reservoir operation modes for sediment-laden rivers in China, analyzing the formation and practice of "storing clear water and regulating muddy flow" operation and design technology based on summaries of "water storage and sediment retention" and "storing clear water and discharging muddy flow" operations. The main findings are as follows:

(1) Sediment issues must be fully considered when constructing reservoirs on sediment-laden rivers. "Water storage and sediment retention" adopts a "retention" strategy with year-round water storage during flood seasons and no sediment discharge periods, causing rapid loss of effective storage capacity. "Storing clear water and discharging muddy flow" adopts a

"retention + discharge" strategy, retaining relatively clear water and discharging sediment-laden water with distinct sediment discharge periods, largely achieving effective storage capacity maintenance and representing a major advancement in reservoir sediment management technology. "Storing clear water and regulating muddy flow" emphasizes "regulation," evolving from the "retention + discharge" approach of "storing clear water and discharging muddy flow" to comprehensive coordinated "retention, regulation, and discharge."

(2) "Storing clear water and regulating muddy flow" operation inherits from and develops upon "storing clear water and discharging muddy flow." In design, sediment-laden river reservoirs must scientifically and rationally design sediment regulation capacity and discharge capacity corresponding to sediment-flushing water levels, consider different sedimentation states during regulation processes, and configure reservoir capacity according to the "deep channel for sediment regulation, medium channel for beneficial use, high channel for flood regulation" distribution rule. Ultra-high sediment concentration rivers should add abnormal sediment discharge bottom outlets below normal discharge orifices to form "normal + abnormal" dual sediment erosion datum planes. Super-high sediment concentration river reservoirs, where coordination between effective storage capacity maintenance and water supply regulation is difficult, should adopt water-sediment separation development. In operation, sediment-laden river reservoir operation modes should be flexibly determined based on development tasks and inflow water-sediment conditions. High sediment concentration reservoirs can adopt "retaining sediment during low flows, discharging sediment during high flows, creating peaks at appropriate times, and depositing on beaches while shaping channels." Ultra-high sediment concentration reservoirs should further combine orifice layout with unconventional sediment discharge scheduling, while super-high sediment concentration reservoirs can adopt water-sediment separation operation of "large mainstream reservoir for sediment regulation and small tributary reservoir for water supply regulation."

(3) The "storing clear water and regulating muddy flow" operation mode and design technology have been applied at Xiaolangdi and other reservoirs, providing technical support for major water control projects including the Yellow River' s Guxian, Jinghe River' s Dongzhuang, and Gansu' s Malian River. Future work should further verify and refine the theory and design technology of "storing clear water and regulating muddy flow" through project construction and operation.

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

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