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Thoughts on Improving the Flood Control Engineering System in the Yellow River Basin

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Abstract

This study presents a comprehensive analysis and systematic exposition of the current flood control engineering system construction and flood control capacity in the Yellow River Basin, and objectively analyzes the main problems existing in the current flood control engineering system. The new situation confronting flood control in the Yellow River Basin during the new development stage is analyzed from three perspectives: changes in river-reservoir storage-discharge relationships, new requirements for flood control arising from economic and social development, and new challenges posed by extreme weather events. Based on these analyses, improvement measures for the basin flood control engineering system are proposed, including enhancing “upper storage” projects, consolidating “lower discharge” projects, advancing safety construction in detention basins, and implementing comprehensive improvement and management projects for river channels and floodplains, with the aim of providing technical support for promoting high-quality water conservancy development in the new stage in China.

Full Text

Preamble

Thoughts on Measures for Improving the Flood Control Engineering System of the Yellow River Basin

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Abstract

This paper provides a comprehensive analysis and systematic exposition of the current construction status and flood control capacity of the flood control engineering system in the Yellow River Basin, while objectively analyzing its main existing problems. The new situation facing Yellow River flood control in the new development stage is examined from three perspectives: changes in river-reservoir storage-discharge relationships, heightened flood control requirements driven by economic and social development, and new challenges posed by extreme weather events. Based on this analysis, the paper proposes measures to improve the basin's flood control engineering system, including enhancing "upper storage" projects, consolidating "lower discharge" projects, advancing safety construction of flood storage and detention areas, and implementing comprehensive improvement projects for river channels and floodplains. These initiatives aim to provide technical support for promoting high-quality water conservancy development in the new stage of China's modernization.

Keywords: Improving flood control engineering system; Flood control situation; Storage-discharge relationship; Engineering layout; Yellow River Basin

2.1 Flood Control Engineering System Construction and Capacity

The Yellow River flood control engineering system is constructed through the coordinated integration of multiple components across the entire basin, with backbone reservoirs on the main and tributary streams as the core, river levees as the foundation, flood storage and detention projects as the safeguard, and supplemented by river training works. The basin's flood control regulation concept operates as follows: backbone control reservoirs on the main and tributary streams serve as the primary regulation means to intercept floods and reduce peak flows, thereby alleviating flood control pressure in the lower reaches; levees function as the foundation, leveraging the storage capacity of river channels and floodplains; and when reservoirs' storage capacity proves insufficient during extraordinary floods or when levees approach or reach their design water levels, flood storage and detention areas are activated to accommodate excess floodwater, ensuring flood safety in key regions.

The flood control engineering systems in the upper, middle, and lower reaches of the Yellow River Basin are described below:

(1) Lower Reaches. The lower Yellow River represents the most critical section for basin flood control. Control reservoirs including Sanmenxia, Xiaolangdi, Luhun, Guxian, and Hekoucun have been constructed on the main and tributary streams. Concurrently, the Yellow River levees on both banks have been raised and reinforced four times, standardized levee projects have been completed, river training works have been implemented, and the Dongping Lake

flood storage area project has been finished. The Beijin dike flood storage area has been designated as a reserved detention area. These efforts have essentially established a “upper storage and lower discharge, with bilateral detention” flood control engineering system for the lower reaches. The total flood control storage capacity of the five reservoirs (Sanmenxia, Xiaolangdi, Luhun, Guxian, and Hekoucun) is 14.73 billion m^3 . During the normal operation period of the Xiaolangdi Reservoir, the total flood control storage capacity is approximately 10.6 billion m^3 . Through joint operation of these five reservoirs, the 100-year flood peak at Huayuankou can be reduced from 29,200 m^3/s to 15,700 m^3/s , and the 1,000-year flood peak from 42,300 m^3/s to 22,600 m^3/s , approaching the design flow capacity of the levees at the Huayuankou section. The standardized levees in the lower reaches have been essentially completed, with a total length of 1,371.1 km, bringing the flood control standard of the reach above Aishan to nearly 1,000-year level. The levees include 147 dangerous works sections totaling 334.3 km and 234 flow-guiding and beach-protection projects extending 494.9 km, which have brought most river regimes under basic control. Two flood storage areas exist in the lower reaches: Dongping Lake, a key storage area capable of storing 1.75 billion m^3 of Yellow River floodwater, and Beijin dike, a reserved storage area capable of storing 2.0 billion m^3 .

(2) Upper Reaches. Twenty-four cascade reservoirs including Longyangxia, Liujiaxia, and Haibowan have been constructed. Levees extending 895 km have been built in the Qinghai-Gansu reach, while the Ningxia-Inner Mongolia reach features 1,417 km of levees and 255 km of river training works, establishing a preliminary “upper control, middle distribution, lower discharge” flood control and ice jam prevention system for the upper reaches. The combined flood control storage capacity of Longyangxia and Liujiaxia reservoirs below their design water levels is 4.16 billion m^3 . After joint flood control operation of these two reservoirs, the flood control standard for the Lanzhou urban reach reaches 100-year level, while levees in the Ningxia-Inner Mongolia reach achieve 20–50-year standards, playing a crucial role in ensuring flood and ice jam safety for important cities and regions including Lanzhou and the Ningxia-Inner Mongolia Plain.

(3) Middle Reaches and Major Tributaries. In the middle reach between Yukoumen and Sanmenxia Dam, 256 km of bank protection and flow-guiding works have been constructed. The lower Qinhe River has 164 km of levees meeting 25–100-year flood standards. The Yiluo River has 389.3 km of levees and bank protection works with 20–100-year standards. The lower Weihe River features 265.42 km of flood control levees with 50–300-year standards. These improvements have enhanced flood resistance in the middle reaches of the Yellow River Basin and reduced flood disasters.

2.2 Main Problems in the Flood Control Engineering System

After 70 years of continuous construction, the Yellow River flood control engineering system has achieved tremendous progress. However, the fundamental characteristics of the Yellow River—scarce water, abundant sediment, and uncoordinated water-sediment relationships—remain unchanged, and flood risk continues to pose the greatest threat to the basin. Current flood control capacity still exhibits prominent weaknesses, requiring constant vigilance to ensure Yellow River security.

(1) Incomplete “Upper Storage” Projects. Although Haibowan and Hekoucun reservoirs have been completed and put into operation, and Dongzhuang Reservoir is under construction, three of the seven planned major control projects on the Yellow River main stream—Heishanxia, Guxian, and Qikou—remain unbuilt. In the upper reaches, Longyangxia and Liujiaxia reservoirs are far from the Ningxia-Inner Mongolia reach, providing insufficient regulation capacity for ice floods. As a multi-year regulating reservoir, Longyangxia bears the important task of regulating basin water resources, making it difficult to release floodwater during normal or dry years. This prevents coordination of water-sediment relationships in the Ningxia-Inner Mongolia reach, curbing the development of new perched rivers and restoring/maintaining main channel flow capacity. In the middle and lower reaches, 18,000 km² of the Xiaohua interval remains uncontrolled by projects, producing a 100-year flood peak of 12,000 m³/s with high peak flows and only 8 hours of forecast lead time, posing a serious threat to lower reach flood safety. The existing Wanjiashai Reservoir has small storage capacity, and Sanmenxia Reservoir operates at low water levels, lacking control projects to share flood storage capacity for major floods. Xiaolangdi Reservoir’s subsequent water-sediment regulation capacity is insufficient, preventing full utilization of the integrated water-sediment regulation system and making it difficult to reduce the Tongguan elevation or alleviate sedimentation in the lower Weihe River. Additionally, 113,000 residents live below Sanmenxia Reservoir’s flood control operation level of 333.65 m, 102,000 residents below Lulun Reservoir’s design level of 327.5 m, and 15,700 residents below Guxian Reservoir’s design level of 548.55 m, significantly affecting reservoir operation during major floods.

(2) Imperfect “Lower Discharge” Projects. In the lower reaches, river training works remain incomplete, with river regimes in 299 km of wandering channels above Gaocun not fully controlled. The beach lips in the lower river are generally 3 m higher than the levee-adjacent ground, reaching 4–5 m at maximum, creating a severe “secondary perched river” condition prone to transverse, oblique, and rolling flows that endanger levee safety. Floodplain management challenges are urgent: after implementation of resident relocation plans in Henan and Shandong, nearly one million people still live in flood-threatened areas, creating acute conflicts between floodplain operation and economic development. Some water diversion sluices and flood diversion gates through levees

pose safety hazards, affecting overall levee integrity. Flood control works in the estuary area remain incomplete, with the Diaokouhe alternative flow path severely 萎缩 (shrinking) and encroached. In the upper and middle reaches, levee projects in sections such as Yongjing County in Gansu still fail to meet standards. River training works in the Ningxia-Inner Mongolia reach remain incomplete, and levees have not been tested by major floods, potentially harboring flood risks. Over 10,000 people in the Inner Mongolia reach floodplains remain threatened by floods. Training works in the middle reach between Yukoumen and Sanmenxia Dam are incomplete, with frequent beach and bank collapses endangering residents. The lower Weihe River suffers severe sedimentation, with the Tongguan elevation remaining high. Tributaries including the Heihe, Baihe, Dahehe, Wudinghe, Yiluohe, and Qinhe rivers all have incomplete flood control projects.

(3) Lagging “Storage and Detention” Area Construction Affecting Flood Diversion. Dongping Lake flood storage area contains 329,800 residents (109,600 in the old lake area and 220,300 in the new lake area), with severely lagging safety facilities construction affecting flood diversion operation. Beijin dike flood storage area contains 1,728,900 residents (1,713,200 in Henan Province and 15,700 in Shandong Province). Originally designed as a flood retention area with 2.0 billion m^3 diversion capacity, joint operation with five reservoirs including Xiaolangdi reduces diversion volumes to approximately 100 million m^3 for 1,000-year floods and 700 million m^3 for 10,000-year floods. Following the 2008 ice flood breach in the Inner Mongolia reach, six emergency ice diversion areas were constructed on both banks, but only two larger areas (Ulan Buh, Hetao Irrigation District, and Wuliangsuhai) can be normally activated, while four smaller areas remain incomplete or fail to meet original design diversion capacity.

(4) Other Weak Links. Accelerated urban development along the Yellow River has expanded city boundaries, yet some cities lack adequate flood control and drainage projects or meet insufficient standards, failing to satisfy urban development and ecological river management needs. Reinforcement of dangerous reservoirs and silt dams and management of medium-small rivers remain incomplete, with mountain flood and debris flow disasters still occurring.

3.1 Changes in River-Reservoir Storage-Discharge Relationships Under Combined Natural and Human Influences

(1) Water-Sediment Regime Changes. Due to climate change, human impacts on underlying surfaces, and substantially increased water consumption for economic and social development, water and sediment inflow to the Yellow River has gradually decreased, with significant changes since the mid-1980s and even greater reductions since 2000. However, the fundamental problem of scarce water, abundant sediment, and uncoordinated water-sediment relationships persists. Since 2000, the sediment concentration at Tongguan Station during flood season remains approximately 20 kg/m^3 , the highest among major world rivers,

confirming the Yellow River as a heavily sediment-laden river. After Xiaolangdi Reservoir's sediment retention period, sedimentation will continue, and without sufficient external water sources, the riverbed may continue to aggrade, causing main channel sedimentation and reduced flow capacity. Consequently, comprehensive measures for flood control and sediment management remain necessary.

(2) Human Activity Impacts. Extensive water conservancy and soil conservation projects, rubber dams, and levee construction along tributaries such as the Yiluo and Qinhe rivers have altered watershed runoff generation and concentration patterns and river flow evolution. Since 2010, major floods occurred in the upper reaches in 2012, 2018, 2019, and 2020, with reservoir flood releases during these events slightly restoring main channel capacity in the Ningxia-Inner Mongolia reach. In the middle and lower reaches, Xiaolangdi and other reservoirs have continuously conducted water-sediment regulation based on different water-sediment conditions, increasing the minimum flow capacity of the lower Yellow River main channel to 5,000 m³/s. While clear water releases over a period caused significant riverbed scouring—beneficially increasing flow capacity and channel storage while reducing flood levels—these releases also intensified river channel adjustments, accelerating beach and bank collapses that potentially endanger levee safety and shoreline stability.

3.2 Higher Requirements for Flood Control from Economic and Social Development

On one hand, sustained economic and social development, optimized industrial patterns, and concentrated populations have significantly increased both population and social wealth, amplifying flood disaster risks and raising flood control costs. Flood safety requirements continue to escalate, with Ningxia and Inner Mongolia provinces repeatedly requesting higher design standards for some levee sections. In the lower reaches, nearly one million people and extensive farmland remain in floodplains, creating acute conflicts between floodplain operation and economic development. Dongping Lake and Beijin dike storage areas also contain large populations with incomplete safety facilities and lack well-established risk-sharing and compensation mechanisms. Increased levee standards in historical floodplains such as the Yiluo River inter-beach area have eliminated the river's original storage functions, increasing flood volumes entering the lower reaches.

On the other hand, societal tolerance for flood losses has decreased while expectations for water project performance exceed design standards. Since Xiaolangdi Reservoir's completion, its large sediment retention period storage capacity and strong flood control capability have led to “beach protection” operations during floods, exceeding the reservoir's original design functions and increasing sedimentation risk while preventing effective functioning of the floodplains' natural storage and sedimentation roles. Industrial development in historical floodplains such as the Yiluo River inter-beach area has encroached upon flood channels, with local authorities showing insufficient understanding of flood diversion and

reduced willingness to implement levee breaching for flood release. These factors have transferred flood control pressure primarily to backbone control projects like Xiaolangdi Reservoir, making spatial flood distribution extremely difficult during extraordinary floods and necessitating strategic and tactical adjustments to meet new situation demands.

3.3 New Challenges from Extreme Weather Events

Since 2000, although no basin-wide major floods have occurred in the Yellow River, localized extreme flood events have happened frequently. After 2010, upper reach inflows were generally abundant, with numbered floods occurring in 2012, 2018, 2019, and 2020. The 2012 flood lasted long, with July-August runoff at Tangnaihai Station reaching 13.03 billion m^3 , 106% above the multi-year average and the highest since station establishment in 1956. Since 2000, some middle reach tributaries have experienced historically heavy rainstorm floods. The Qingjian River in July 2002 and the Fenchuan River in July 2013 experienced record floods since station establishment. The Dongwan Station on the upper Yiluo River experienced its second-largest flood in 2010. The Yan River in July 2013 saw the largest monthly rainfall since 1952 measurements began. In July 2017, the Wuding River rainstorm flood produced a record peak discharge of 4,480 m^3/s and maximum sediment concentration of 873 kg/m^3 at Baijiachuan Station, affecting 255,300 people in Suide County.

Consequently, global climate change and intensified human activities have increased the risk of extreme and sudden hydrological events, further exacerbating flood threats across the basin. There is an urgent need to enhance flood control and disaster reduction capabilities of water infrastructure under complex conditions, guard against potential above-standard floods in local areas or even the entire basin under extreme climate conditions, and minimize water security risks' impact on basin economic and social development.

4 Measures for Improving the Basin Flood Control Engineering System

Based on new changes in basin flood control situations and new requirements from economic and social development, with full consideration of coordination with overall territorial spatial planning and following flood control and disaster reduction strategies for the new development stage, this study proposes engineering measures for storage, detention, and discharge to improve the basin flood control engineering system.

4.1 Improving “Upper Storage” Projects to Enhance Reservoir Regulation Capacity

The Guxian Water Conservancy Project should be commenced as soon as possible for joint operation with Xiaolangdi Reservoir to regulate middle reach

flood sediment, reduce sedimentation in Sanmenxia Reservoir, and maintain its long-term flood control storage capacity. This will lower the Tongguan elevation, reduce sedimentation in the lower Yellow and Weihe Rivers, and maintain long-term main channel flow capacity.

Preliminary work on the Heishanxia Water Conservancy Project should be advanced to improve the upper reach flood control and ice jam prevention system with Longyangxia, Liujiaxia, and Heishanxia reservoirs as backbone projects. Implementing upper reach water-sediment regulation will coordinate water-sediment relationships, curb suspended river development in the Ningxia-Inner Mongolia reach, and maintain main channel flow capacity.

The Taohuayu Reservoir scheme should be studied to control floods in the Xiaohua interval and enhance flood defense capabilities in the lower Yellow River and floodplains. Preliminary work on the Qikou Water Conservancy Project should be promoted to establish an “upper storage” system with main stream backbone projects (Qikou, Guxian, Sanmenxia, Xiaolangdi) coordinated with large tributary flood control reservoirs. This system will intercept sediment, regulate floods, extend Xiaolangdi’s sediment retention period, reduce lower reach sedimentation, maintain long-term main channel flow capacity, and improve large flood defense capabilities in the middle and lower reaches.

Safety construction below flood control operation levels should be implemented for Luhun, Guxian, and Sanmenxia reservoirs to address resettlement issues during flood operations. Optimizing operation modes for Xiaolangdi and other reservoirs through deepening “store clear water and regulate muddy water” operations will improve comprehensive utilization benefits. Research should explore technologies for restoring reservoir sediment-occupied capacity, conducting sediment removal pilots at main and tributary reservoirs including Sanmenxia, Xiaolangdi, Haibowan, Bapanxia, Bajiazui, and Fenhe to restore effective flood control storage.

4.2 Consolidating “Lower Discharge” Projects to Enhance River Channel Capacity

Comprehensive lower reach river channel management should be implemented, utilizing and improving standardized levees on both banks to constrain large and extraordinary floods and ensure no levee breaches. Complete reconstruction and reinforcement of all dangerous works to improve levee anti-risk capacity. Focus on river training above Gaocun, implementing extension and reinforcement of flow-guiding projects to further streamline river regimes and gradually shape a relatively narrow, deep, and stable main channel to restore and maintain flow capacity. Below Gaocun, address local river regime issues. Implement “secondary perched river” treatment in the Dongbatou-Taochengpu reach, initially advancing silt filling of seven low-beach dike-river areas including Lankao, Dongming, and Xicheng beaches to basically eliminate flood hazards along key reach dikes. Select pilot reaches for channel dredging and beach surface filling to elim-

inate transverse slopes, effectively preventing transverse and oblique flows, with gradual comprehensive promotion. Implement estuary reach management, completing levee reinforcement and flow-guiding project construction to basically solve estuary flood problems, while studying dual-flow-path schemes to extend estuary flow path service life.

Comprehensively advance flood control management of the Sichuan reach of the Yellow River main stream, improving levees, flow-guiding, and bank protection works in Qinghai and Gansu reaches to meet design standards. Strengthen river training construction in the Ningxia-Inner Mongolia reach to further improve the river defense system. Conduct comprehensive management including levee standardization, river training, floodplain management, and waterway improvement in the upper reaches. Continue river management in the main stream reaches from Yukoumen to Tongguan and Tongguan to Sanmenxia Dam, improving flow-guiding and bank protection works to stabilize river regimes, reduce beach and bank collapses, protect residents and resettled migrants, and advance management of the greater north main stream while strengthening shoreline protection and control.

Govern key reaches of major tributaries including the Huangshui, Taohe, Huangfuchuan, Wudinghe, Kuyehe, Weihe, Yiluohe, and Qinhe rivers to ensure flood safety in critical sections.

4.3 Advancing Flood Storage and Detention Area Safety Construction to Ensure Detention Functions

Implement comprehensive Dongping Lake flood storage area management to improve flood risk avoidance capacity west of Jinshan Dam, construct flood diversion channels, raise and reinforce the secondary lake dike and Jinshan Dam, and implement old lake dredging and capacity expansion. Improve safety construction measures including relocation settlement, local flood shelter, and evacuation routes. Construct south and north discharge projects, reconstruct dangerous sluices, and achieve “divert in, store securely, discharge out” capability while comprehensively addressing production, living, and poverty alleviation issues for storage area residents. Optimize Beijin dike flood storage area zoning operation schemes, proposing partitioned storage and operation layouts. Further advance and improve upper reach emergency flood and ice diversion projects. Study impacts of levee construction in the Yiluo River inter-beach storage area on Huayuankou floods and flood diversion operation issues in the Qinbei natural storage area to advance safety construction and ensure detention functions.

4.4 Innovating Downstream Governance Strategies: Implementing Comprehensive River Channel and Floodplain Improvement Projects

Under the premise of wide river channels and solid levees with completed standardized levee construction, ensuring Yellow River flood safety while considering floodplain residents' safety and economic development, implement a new ecological governance strategy for lower reach floodplains featuring "graded flood defense, partitioned sediment deposition, and zoned floodplain management." Tailor measures to specific floodplain conditions to construct ecological corridors. In the near term, implement the Fengqiu backflow area safety construction project to fundamentally solve flood safety and development issues for 431,000 people. Study and implement the Wenmeng beach flood improvement project to address flood safety for 106,000 residents. Evaluate schemes for connecting flow-guiding projects in wide-beach reaches of the lower river to enhance channel flow and sediment transport capacity, preventing flooding of medium and small floods. Study ecological governance schemes for lower river channels, building high platforms on the river side of levees for intensive construction of beautiful villages and characteristic towns to create lower reach ecological corridors, fundamentally solving flood safety issues for floodplain residents and achieving high-quality development.

4.5 Improving Urban Flood Control and Drainage Capacity

Focus on standardizing flood control and drainage projects in key cities including Lanzhou, Hohhot, Baotou, Taiyuan, Yan' an, and Luoyang to enhance central urban flood control capacity. Accelerate river management in urban sections of major tributaries and medium-small rivers, increase reconstruction of urban drainage pipe networks, and improve urban flood control and drainage capacity. Relying on the flood control engineering system and integrating sponge city construction, consider river-lake connectivity for storage regulation. Urban development should allocate land for low-impact development facilities, implementing rainwater infiltration, storage, and harvesting to improve flood control and drainage capacity.

4.6 Strengthening Dangerous Reservoir Reinforcement and Mountain Flood Disaster Prevention

Continue implementing reinforcement of dangerous reservoirs and silt dams, reinforcement of large and medium dangerous sluices, and accelerate management of weak links including medium-small rivers and mountain flood disaster prevention.

5 Conclusion

Engineering measures constitute the core of basin flood control and disaster reduction. Through systematic review of the current flood control engineering system's status and problems, it is evident that weaknesses remain. The current Yellow River Basin faces new changes in flood-sediment regimes, underlying surfaces, and engineering conditions, while new development concepts from the Party Central Committee pose new requirements for basin management. Consequently, improving the basin flood control engineering system faces new situations, challenges, and tasks.

This paper comprehensively analyzes and systematically expounds the current construction status and flood control capacity of the Yellow River Basin's flood control engineering system, objectively analyzing its main existing problems. It examines the new situation facing Yellow River flood control in the new development stage from three aspects: changes in river-reservoir storage-discharge relationships, heightened requirements from economic and social development, and new challenges from extreme weather events. Based on this analysis, improving the Yellow River Basin flood control engineering system in the new era should involve revising flood control plans according to new situations, comprehensively reviewing current flood control capacity and standards in key basin areas, further optimizing flood control engineering layouts, promoting construction of backbone reservoir projects, enhancing reservoir regulation capacity, strengthening levee and river training construction, and advancing flood storage area development to establish a flood control engineering system with appropriate standards.

In the new period, flood control engineering system improvement must deeply integrate ecological civilization concepts. Systematic governance schemes should be studied combining flood safety and ecological construction, preserving flood flow paths to the greatest extent possible, adopting ecological slope and bank protection structures, protecting river ecological functions, and protecting and rationally utilizing river shoreline resources. Simultaneously, integration with non-engineering measures is essential to jointly build a flood defense system, applying modern advanced technologies to rainstorm-flood monitoring and forecasting, flood dispatching, flood control decision-making, and flood control project management.

Further research is needed to optimize reservoir group dispatching, deepen "store clear water and regulate muddy water" operations, and correctly handle relationships between flood control and comprehensive water resources utilization. Issues regarding flood control and development in floodplains, storage areas, and flood-prone areas must be coordinated, establishing flood risk management systems that effectively balance human-nature relationships based on socio-economic spatial layouts and flood risk distributions. Public education efforts should be increased to guide media discourse and enhance society-wide flood control awareness.

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Author Contribution Statement:

Zhang Jinliang: Conceived research ideas and designed study methodology;

Zhang Jinliang: Collected and organized data and literature;

Zhang Jinliang: Drafted the manuscript;

Zhang Jinliang: Revised the final manuscript.

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

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