

Comprehensive Management of the Above-Ground River in the Lower Yellow River Below Taohuayu Through Reservoir Capacity Zoning

Shuo Cui *

Dachang Happy School, Hebei, China

* Corresponding Author Email: dian63962952521514@outlook.com

Abstract. The river section below Taohuayu in the Yellow River is a typical above-ground suspended river. A prolonged imbalance between water and sediment, combined with ongoing sediment deposition, has led to a steady rise in the riverbed and a persistent decline in flood discharge and sediment transport capacity, posing a direct threat to flood-control safety and ecological health in the basin. Based on the formation mechanisms of the above-ground river in the lower Yellow River and relevant water-sediment data, this paper reviews the governance outcomes achieved through the application of reservoir capacity zoning in reservoir engineering projects. The findings indicate that reservoir capacity zoning can effectively curb riverbed aggradation, enlarge the cross-section of the main channel, and improve flood conveyance conditions in the lower reaches, thereby providing technical support for the long-term management of the above-ground river in the lower Yellow River and for achieving basin-wide safety, stability, and high-quality development.

Keywords: Lower Yellow River; River Channel Management; Water-sediment Regulation; Reservoir Capacity Zoning.

1. Introduction

Due to heavy sediment from the middle reaches, the lower Yellow River has become a typical above-ground suspended river. In most places, the riverbed stands 3 to 6 meters above the surrounding floodplains, and in some sections, the height difference reaches 10 meters. The channel is wide in the upper part and narrow in the lower part, and the main channel width varies along the way. Over the years, efforts to control soil erosion and operate water projects have helped slow down sediment buildup. But the natural setting is still tough—the riverbed slopes only a little, and the water just does not have enough force to move much sediment. So, the basic situation—riverbed rising and more pressure on the levees—has not really changed. A riverbed that sits high above the land brings big flood risks. When floods come, the river can easily break through its banks, putting towns and people in the lower reaches in danger. The high riverbed also alters how water moves through the region, leading to saline soil and ecosystem damage. All these problems increase management costs and make it hard for the region to develop sustainably [1,2]. The Xiaolangdi Reservoir was finished in 2002. Since then, running the reservoirs together has steadily made water and sediment conditions better in the lower reaches, and the riverbed has been rising more slowly. One important technique is reservoir capacity zoning. This approach lets managers control water and sediment more precisely, handle flood control and sediment reduction simultaneously, and balance the different ways the reservoir is used. Looking at how water and sediment vary over time and space in the Yellow River, and at what the project needs to do, the reservoir's total storage is split into four zones: dead storage, flood-control storage, water-sediment regulation storage, and beneficial storage. Each zone keeps water at a certain level, lets water out when needed, and works together with the others. By managing each zone for its own purpose, this setup traps coarse sediment in the reservoir for a long time, creates artificial flood peaks to flush sediment out, and provides a steady water supply. Now, with the national strategy for protecting the Yellow River's ecology and promoting high-quality development, the way this paper manages the river is changing significantly, moving away from a focus solely on flood control toward an integrated approach that combines flood control, ecological protection, and resource use. Many new methods and technologies need to be carefully examined and assessed with

an eye to the future [3]. So, this paper examines how the suspended river in this section is currently managed using reservoir capacity zoning at the Xiaolangdi Reservoir and summarises the achievements of comprehensive management techniques.

2. Reservoir Capacity Zoning and the Formation Mechanism of the Above-Ground River Below Taohuayu

2.1. Reservoir Capacity Zoning

Reservoir capacity zoning means dividing up the space for storing water based on several things: how the water flows, where and how sediment settles, the local geology, and what the reservoir needs to do—control floods, supply water, protect the environment, and so on. The boundaries of these zones are derived from typical water levels, sediment deposit shapes, geological limits, and control thresholds [4]. Take reservoirs that handle a lot of sediment. Their zones are set up based on how sediment accumulates and where the erosion base level sits. The capacity gets split into sediment regulation storage, beneficial storage, and flood regulation storage. That way, the reservoir can reduce sedimentation while maintaining its storage capacity, use the water, and handle floods when they come. For reservoirs focused on ecology, they use multi-level water-supply control lines to delineate different zones: ecological storage, domestic storage, agricultural storage, and flood-control storage. This ensures sufficient flow to support the river's ecology and meet various water needs. Groundwater reservoirs follow geological and water level boundaries. They are divided into dead storage, regulation storage, and empty storage zones. That helps keep the groundwater system stable and smooth out the ups and downs of the water supply over time. Also, some reservoirs use flexible capacity ratios and control based on set thresholds to make the different zones work together. This brings together flood control, efficient water use, sediment management, and ecological protection, improving the reservoir's reliability and increasing its overall benefits.

2.2. How the Above-Ground River Forms Below Taohuayu

The Yellow River from Taohuayu down to the mouth runs 785.6 km. Over that distance, the water drops only 93.6 m, so the average slope is just 0.12‰. That makes it a typical alluvial river that sits above the surrounding ground. Why did it form this way? Two factors are at work: the natural mismatch between water and sediment, and human activities. The core problem is that for a long time, more sediment has come in than the river can carry away, so sediment builds up faster than it gets washed out. Looking at nature first. At Sanmenxia Station in the middle Yellow River, the average yearly sediment load over many years was 1.6 billion tons, with an average concentration of 35 kg/m³. About 83% of that sediment came down during the flood season. Below Taohuayu, the river loses energy quickly. As a result, about 389 million tons of sediment settle into the riverbed every year on average.

2.3. Formation Mechanism of the Above-Ground River Below Taohuayu

The Yellow River section from Taohuayu to the estuary stretches 785.6 km, with a total drop of 93.6 m and an average channel gradient of only 0.12 ‰, forming a typical alluvial above-ground suspended river [5]. Its formation results from the coupled effects of natural water-sediment imbalance and human intervention, with the core issue being that sediment inflow has long exceeded the river's sediment transport capacity, and the sedimentation rate has consistently outpaced the erosion rate. In terms of natural factors, the multi-year average sediment load at Sanmenxia Station in the middle Yellow River is 1.6 billion tons, with an average sediment concentration of 35 kg/m³, and sediment delivered during the flood season accounts for approximately 83%. Downstream of Taohuayu, flow energy declines sharply, leading to an average annual sediment deposition of about 389 million tons in the riverbed. From 1950 to 2002, the riverbed in the lower reaches aggraded at an average rate of 0.08m per year, generally rising 4.2 m above the surrounding ground surface, with the

highest section reaching 10 m. The natural spatial-temporal mismatch between water and sediment—where non-flood-season flows are unable to flush out sediment deposited during the flood season—results in continuous, cumulative aggradation. In terms of human factors, levees on both banks have narrowed the river channel. Between 1985 and 1997, the proportion of sediment deposited in the main channel increased from 23.1% to 70.6%. The average annual water diversion from the Yellow River in the lower reaches amounted to 8.84 billion m³, causing the bankfull discharge to drop to 1,780 m³/s and significantly reducing sediment transport capacity. From Dongbatou to Taochengpu, the floodplain transverse slope reached 1.5‰ forming a secondary perched river that further intensified channel aggradation and increased flood-control risks [6].

3. Comprehensive Management Measures and Effects

3.1. Management Measures

3.1.1. Core Management Measure: Functional Design and Regulation

The Xiaolangdi Reservoir sits at the lower end of the Yellow River's main stream and is the last major control project there. Its capacity zone was designed specifically to address what causes the above-ground river. The total storage capacity is 12.65 billion m³, split into four main functional zones based on the river's management needs. These zones work together to achieve sediment retention, water regulation, flood control, and beneficial use simultaneously. That aligns well with the key factors driving the development of the above-ground river [7].

Dead storage for sediment retention (about 7.55 billion m³): The Yellow River carries a lot of coarse sediment (particles larger than 0.05 mm), and this kind of sediment tends to settle easily in the main channel of the lower reaches [8,9]. To deal with that, this zone follows a catch the coarse sediment first rule. By keeping the water level below 205 m, it traps coarse particles for extended periods, preventing them from moving further down and making the main channel even shallower [10,11]. How well this zone holds back sediment depends closely on the size makeup of the incoming sediment. If coarse particles account for more than 30% of the incoming material, the retention rate can exceed 65%.

Water-sediment regulation storage (about 1.05 billion m³): There is a well-known timing and space problem: the flood season brings in a lot of sediment at once, but in the dry season, flows drop below 1,000 m³/s, and the river cannot carry much sediment. To fix that, this zone uses a three-step schedule: lower the water before the flood season, hold back water during the flood season, and release it afterwards. Before the floods come, the water level is dropped to 225 m to free up space. During the flood season, water is let out in stages (with flows controlled between 2,600 and 4,000 m³/s) to create an artificial flood wave. That gives the flow enough power to scour the main channel. After the flood season, the base flow is kept at or above 1,500 m³/s to prevent sediment from settling back during the dry months [12].

Flood control storage (about 4.05 billion m³): The lower Yellow River experiences high flood peaks and lacks sufficient storage capacity to pass them safely. This zone is built to store and regulate floodwater and, at the same time, help manage sediment in stages during floods. By releasing floodwater gradually, the sediment that comes down during floods is spread out along the lower channel. That stops too much sediment from piling up in one place and shrinking the main channel. It also keeps the downstream levees safe, so flood control and sediment reduction work together.

As shown in fig1, beneficial regulation of storage: People draw water from the Yellow River for many uses, which has reduced base flow and greatly weakened the river's ability to carry sediment. To address this, the beneficial storage zone regulates water use during the dry season. It ensures that the lower channel receives sufficient flow to support the ecology and at least the minimum flow needed to move sediment. That prevents sediment from settling in the dry season when flows would otherwise be too low. At the same time, it meets the water needs for supply and irrigation in the lower reaches. In this way, river management and regional development go hand in hand.

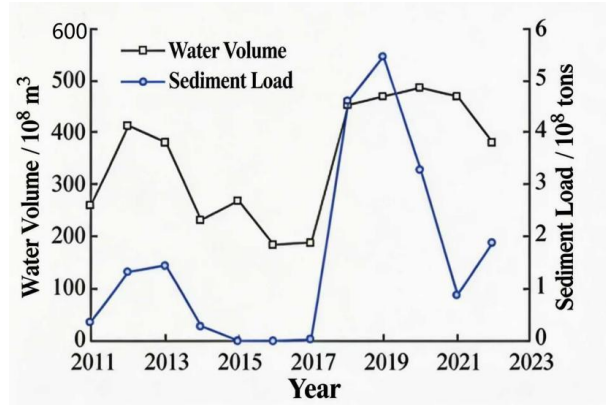


Fig.1 Annual water discharge and sediment load in the lower Yellow River from 2011 to 2022 [7].

3.2. Management Effects

The comprehensive management system centred on reservoir capacity zoning regulation has achieved a historic breakthrough in managing the above-ground river below Taohuayu on the Yellow River. From the perspectives of total sediment control, river channel morphology reshaping, and flood conveyance capacity enhancement, it has reversed the trend of continuous deterioration of the above-ground river.

3.2.1. Sediment Control

The sediment management system, centred on the sediment retention function of reservoir capacity zoning, has achieved a significant reduction in total sediment entering the Yellow River and a fundamental reversal of the sedimentation trend in the lower reaches. On one hand, relying on the long-term sediment retention effect of the dead storage zone at the Xiaolangdi Reservoir, combined with the source reduction effects of soil and water conservation projects on the Loess Plateau in the upper reaches, the annual average sediment load entering the Yellow River has dropped sharply from approximately 1.6 billion tons in the second half of the last century to around 300 million tons in recent years, a reduction of over 80%. This has fundamentally eliminated the material source basis for sedimentation in the lower river channel. On the other hand, through coordinated regulation of water-sediment storage and flood-control storage, the rational transport of sediment in the lower reaches has been achieved. Since the first water-sediment regulation operation in 2002, the cumulative scour volume in the main channel downstream of Taohuayu has exceeded 3 billion m^3 , completely reversing the natural trend of continuous sedimentation and aggradation in the lower reaches, thereby providing core support for the systematic management of the above-ground river.

3.2.2. Main Channel Conveyance Capacity

Relying on the regular artificial flood peaks generated by the water-sediment regulation storage zone, combined with the reinforcement of river channel training works in the lower reaches, the flood conveyance and sediment transport capacity of the main channel downstream of Taohuayu has been fundamentally restored and enhanced. Monitoring data indicate that the minimum conveyance capacity of the main channel in the lower reaches has recovered from less than $2,000 \text{ m}^3/\text{s}$ at the beginning of this century to a stable level exceeding $4,000 \text{ m}^3/\text{s}$, representing a doubling of conveyance capacity. This effect has directly driven a significant optimization of the river channel morphology in the lower reaches: the main channel cross-section has continued to expand, the elevation difference between the main channel and the floodplain has steadily increased, completely reversing the adverse situation of continuous main channel shrinkage and a wide, shallow, and disordered channel pattern that existed at the end of the last century. At the same time, the risk of overbank flooding and the pressure on flood control in the floodplain areas have been greatly reduced, and the probability of adverse flow patterns, such as transverse and oblique flows, has decreased, further consolidating the sedimentation-reduction effects of the main channel. This has formed a virtuous cycle of scour expansion—conveyance capacity enhancement—sediment transport capacity

strengthening—continuous scour, laying a foundation for the long-term stable management of the above-ground river.

4. Conclusion

This study focuses on the developmental characteristics and formation mechanisms of the typical above-ground river section downstream of Taohuayu on the Yellow River, systematically analysing the mechanisms and implementation effects of the comprehensive management system centred on reservoir capacity zoning regulation at Xiaolangdi Reservoir. The main conclusions are as follows.

First, the core causes of the above-ground river downstream of Taohuayu lie in the inherent water-sediment contradiction of abundant sediment with limited water and spatial-temporal mismatches, compounded by human activities that have narrowed the river channel, reduced base flow, and diminished sediment transport capacity, ultimately leading to the formation of a secondary perched river with continuous aggradation. The management system centered on reservoir capacity zoning regulation at the Xiaolangdi Reservoir, through the functional division and coordinated operation of dead storage for sediment retention, dedicated water-sediment regulation storage, flood control storage, and beneficial regulation storage, precisely addresses the core contradictions driving the development of the above-ground river, representing the key mechanism for achieving the historic transition from continuous sedimentation to full-scale scour in the lower reaches.

Second, the management system that relies mainly on reservoir-capacity zoning has yielded historic results. On the one hand, the dead storage zone traps sediment at the source, and upstream soil and water conservation work also helps. Together, they have cut sediment entering the Yellow River by more than 80%, greatly easing the problem of channel aggradation. On the other hand, regular artificial flood peaks created through the water-sediment regulation storage zone have scoured the lower main channel. The total scour volume so far has exceeded 3 billion m³, and the minimum flow the main channel can handle has increased from under 2,000 m³/s in the early 2000s to over 4,000 m³/s now—a doubling of capacity. This has completely reversed the earlier trend of main-channel shrinkage and ongoing channel aggradation and has greatly improved flood-control resilience in the lower reaches.

Third, the current management system still has some weak points. For one thing, sediment continues to accumulate in the dead storage zone of the Xiaolangdi Reservoir, so its ability to hold sediment over the long term is slowly declining. The operating rules for water-sediment regulation are not always well suited to changes in upstream water and sediment conditions, and there is room to improve how the different storage zones work together. For another, current management does not pay enough attention to making sure that reservoir capacity zoning works in tandem with supporting measures in the lower reaches. Some local river training projects have not fully taken advantage of the sedimentation reduction brought by reservoir regulation. Also, there is too much focus on short-term results, while long-term ecological sustainability gets neglected. In some river sections, this has even created ecological risks. The overall situation—riverbed rising and levee pressure increasing—has not yet been fundamentally turned around.

Fourth, future management of the above-ground river downstream of Taohuayu should keep reservoir capacity zoning as the main approach, while also pushing for a better, more optimised way to manage the river.

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