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Research on Water and Sediment Regulation of the Yellow River under New Situation

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Abstract: Water and sediment regulations are critical for the long-term safety of the Yellow River. The amount of water and sediments in the Yellow River continues to vary and is influenced by both natural factors and human activities, such as water and soil conservation. The amount of water resources decreased slightly and sediments decreased sharply. A scientific prediction of the amount of future sediment is crucial for formulating a strategy for water and sediment regulation of the Yellow River. In this study, the variation characteristics of the amount of water and sediments from 1919 to 2020 are analyzed, annual sediment transport of the Yellow River over the next 50 years is predicted, and the main problems regarding water and sediment regulation in the Yellow River Basin, such as river sedimentation atrophy in the upper reaches, incompatibility between river regulation strategies with high-quality development requirements in the lower reaches, and mismatched measures of soil and water loss control in the Loess Plateau, are systematically summarized. Three targeted strategies for water and sediment regulation under new conditions are proposed. The first is to perfect the water and sediment regulation engineering system with a focus on the development of the Heishanxia reach and the construction of the Guxian water conservancy project. The second is to manage regional floodplains in the lower reaches, renovate river channels, and release part of the floodplains. The third is to adjust soil and water conservation measures according to local nature and water conditions.

Keywords: Yellow River; new water and sediment conditions; water and sediment regulation; hydropower-complex project; regional management; ecological protection

1 Introduction

The Yellow River is the second largest river in China and the "Mother River of the Chinese Nation." The Yellow River Basin plays a vital role in guaranteeing national security in terms of grain, energy, and ecological goods and services. Indeed, the Yellow River accounts for 2.5% of the total water sources in China, feeds 12% of the Chinese population, irrigates 15% of cultivated land in China, and contributes to 14% of China's gross domestic product. In

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addition, the Yellow River Basin produces 12.3% and 55% of the national grain yield and coal resources, respectively.

The Yellow River Basin contains a higher proportion of sediment than the other river basins in China. Consequently, the Yellow River is prone to sediment deposition, river channel breach, and diversion. Historically, the Yellow River has breached twice every three years and has changed its course once every hundred years, with frequent flood events. Therefore, there is an urgent need to understand the water-sediment balance of the Yellow River to ensure the long-term prevention of disasters in the basin. Over the past few thousand years, the history of harnessing the Yellow River has provided lessons on water and sediment regulation. During the Eastern Han Dynasty, Wang Jing exploited river storage to regulate water and sediment. During the Ming Dynasty, Pan Jixun constructed an embankment to retain sand using water [1,2]. Measures were implemented during the 1960s to regulate water and sand in the river, including widening the river course, strengthening the embankment, retaining water and sand, and segmented drainage of the river [3]. Water and sediment regulation was conducted in Xiaolangdi Reservoir in 2002 [4]. The strategies for water and sediment regulation of the Yellow River during each period differed according to water and sediment conditions, engineering conditions, understanding of the processes under which water and sediment are transported, and past experience of harnessing the Yellow River. The *Comprehensive Planning of the Yellow River Basin (2012–2030)* issued in 2013 is the main reference for systematic layout and key engineering planning of water and sediment regulation of the Yellow River in China [5]. This approach is based on the predicted sediment entering the Yellow River at the Tongguan Hydrological Station Section in 2030 (9×10^8 to 1×10^9 t/a). In recent years, climate change and anthropogenic activities, such as water sediment reduction, soil conservation, and sediment detention in reservoirs, have resulted in reduced sediment input into the Yellow River. For instance, the measured annual sediment discharge at Tongguan Hydrological Station decreased from 3×10^8 t/a to 1.78×10^8 t/a from 2001–2010 to 2011–2020 [6]. In addition, there has been a general long-term decline in incoming sediments within the great rivers in China [7].

The regulation of water and sediment in the Yellow River depends greatly on the incoming quantities. Therefore, predicting the future inflow of water and sediment into the Yellow River is important for assessing the future water and sediment conditions and appropriate governance strategies. Current strategies for regulating water and sediment in the Yellow River Basin are inconsistent with predictions of future incoming quantities of sediment and water and fail to meet the high-quality development requirements of the river. The present study systematically analyzed the evolution of incoming water and sediment amounts in the Yellow River Basin at a century scale (1919–2020), and the quantities of sediment and water for the next 50 years were predicted. The present study also analyzed the main challenges facing the regulation of water and sediment in the Yellow River, and the main strategies under future changed conditions were proposed. This study can act as a reference for water and sediment regulation, ecological protection, and high-quality development of the Yellow River.

2 Evolution and future trends in quantities of sediment and water of the Yellow River at the century scale

2.1 Evolution of incoming water and sediment to the Yellow River

There were no significant changes in the natural annual runoff of the key sections of the mainstem of the Yellow River at the century scale (1919–2020) [8]. However, anthropogenic activities resulted in significant reductions ($P < 0.01$) in the measured annual runoff and sediment discharge of the main river sections [9]. The analysis showed abrupt changes in the annual quantities of incoming water and sediment in the main sections of the Yellow River. Among them, the natural annual runoff of the Toudaoguai section in the upper reaches showed drastic changes in 1933, 1990, and 2005, whereas the measured sediment discharge changed drastically in 1933, 1986, and 2005; the natural annual runoff in the Huayuankou section in the middle reaches showed drastic changes in 1933, 1990, and 2004, whereas annual sediment discharge in the Tongguan section showed drastic changes in 1933, 1980, and 1997.

During the formulation of the water diversion plan of the Yellow River "Eight/Seven water diversion plan" in the 1980s, the multi-year average natural runoff from 1919 to 1975 was used to calculate the incoming quantity of water (5.8×10^{10} m^3 and 5.59×10^{10} m^3 for the Lijing and Huayuankou sections, respectively), and the multi-year

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measured sediment discharge from 1919 to 1959 was used to calculate the incoming sediment (1.6 × 10^9 t for the Tongguan section).s

Based on the above analysis and the strong influences of anthropogenic activities, the present study divided the study period from 1919 to 2020 into four sub-periods to analyze the evolution of incoming water and sediment: (1) 1919–1959; (2) 1960–1989; (3) 1990–2004; and (4) 2005–2020. The first period was selected as the reference level, against which all other estimates of annual incoming water and sediment were compared.

2.1.1 Changes in incoming water and sediment of the upper reaches of the Yellow River

Figs. 1–4 show the natural annual runoff, measured annual runoff, and measured annual sediment discharge in the Toudaoguai section in the upper reaches of the Yellow River, as well as a comparison of statistical eigenvalues at different stages. The multi-year average natural runoff in the Toudaoguai section from 1919 to 1959 was 3.187 × 10^{10} m^3. The multi-year average measured runoff and sediment discharge were 2.505 × 10^{10} m^3 and 1.42 × 10^8 t, respectively (reference level). Compared to the reference level, the multi-year average natural runoff, measured runoff, and measured sediment discharge in the Toudaoguai section from 1960 to 1989 increased by 13.1%, decreased by 1.1%, and decreased by 7.4%, respectively. The multi-year average natural runoff, measured runoff, and measured sediment discharge in the Toudaoguai Section from 1990 to 2004 decreased by 14.6%, decreased by 41.8%, and increased by 74.8%, respectively. The multi-year average natural runoff, measured runoff, and measured sediment discharge in the Toudaoguai section from 2005 to 2020 increased by 7.2%, decreased by 17.5%, and decreased by 56.9%, respectively.

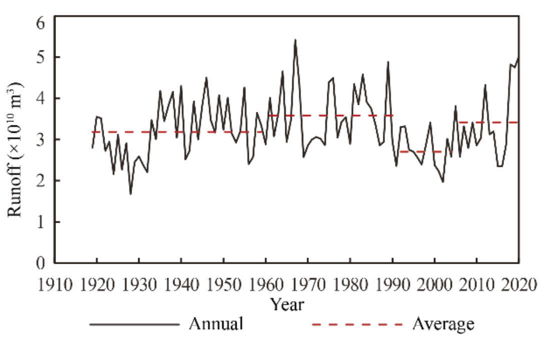

Fig. 1. Natural annual runoff at the Toudaoguai section of the Yellow River from 1919 to 2020.

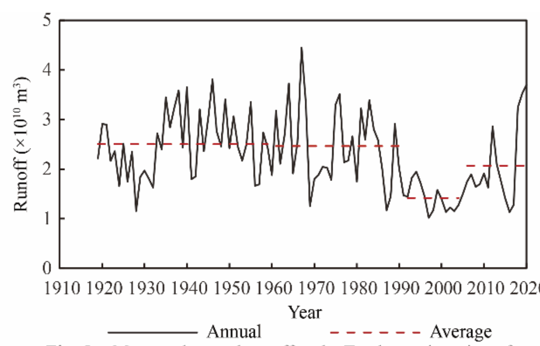

Fig. 2. Measured annual runoff at the Toudaoguai section of the Yellow River from 1919 to 2020.

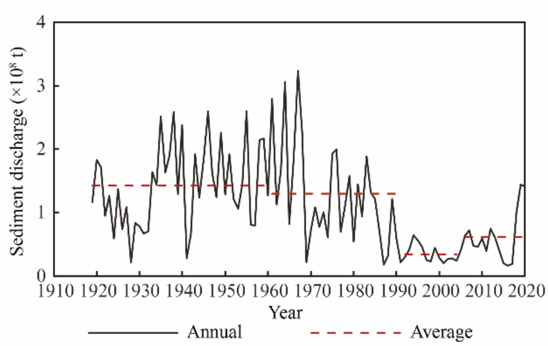

Fig. 3. Measured annual sediment discharge at the Toudaoguai section of the Yellow River from 1919 to 2020.

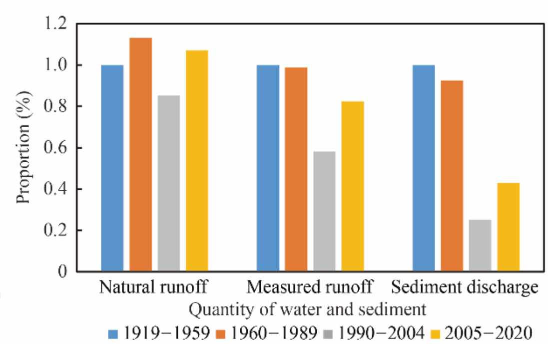

Fig. 4. Annual quantities of sediment and water at the Toudaoguai section of the Yellow River at different stages (as a ratio with the reference level).

2.1.2 Variation in incoming water and sediment in the middle reaches of the Yellow River

Figs. 5–8 show the statistical eigenvalues of different processes and stages of natural annual runoff, measured annual runoff, and measured annual sediment discharge at representative sections in the middle reaches of the Yellow River. From 1919 to 1959, the multi-year average natural runoff, multi-year average measured runoff, and multi-year average measured sediment discharge in representative sections in the middle reaches of the Yellow River (natural annual runoff in the Huayuankou section, measured annual runoff in the Tongguan section, and annual sediment discharge in the Tongguan section) were 5.433 × 10^{10} m^3, 4.258 × 10^{10} m^3, and 1.6 × 10^9 t (reference level), respectively. From 1960 to 1989, compared to the reference levels, the multi-year average natural annual runoff, measured runoff, and measured sediment discharge in representative sections of the middle reaches of the Yellow River increased by 11.2%, decreased by 8.1%, and decreased by 26.7%, respectively. From 1991 to 2004, the multi-year average natural runoff, measured runoff, and measured sediment discharge in representative sections of the middle reaches of the Yellow River decreased by 21%, decreased by 45.4%, and decreased by 59%, respectively. From 2005 to 2020, the multi-year average natural runoff, measured runoff, and multi-year average measured sediment discharge in representative sections of the middle reaches of the Yellow River decreased by 5.6%, decreased by 35.4%, and decreased by 88%, respectively.

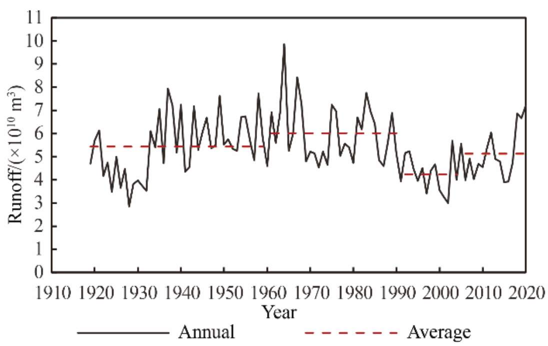

Fig. 5. Natural annual runoff at the Huayuankou section of the Yellow River from 1919 to 2020.

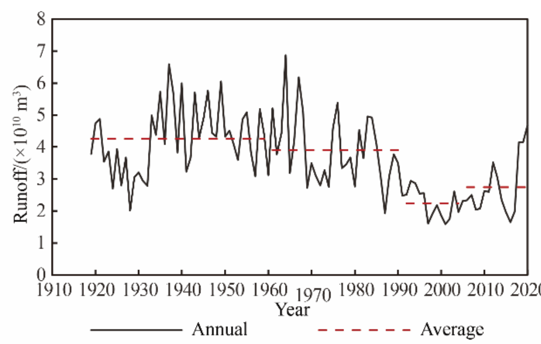

Fig. 6. Measured annual runoff at the Tongguan section of the Yellow River from 1919 to 2020.

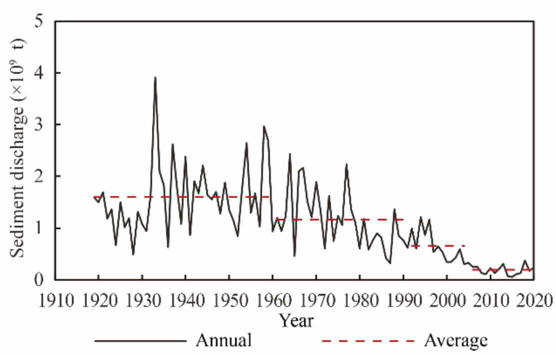

Fig. 7. Measured annual sediment discharge at the Tongguan section of the Yellow River from 1919 to 2020.

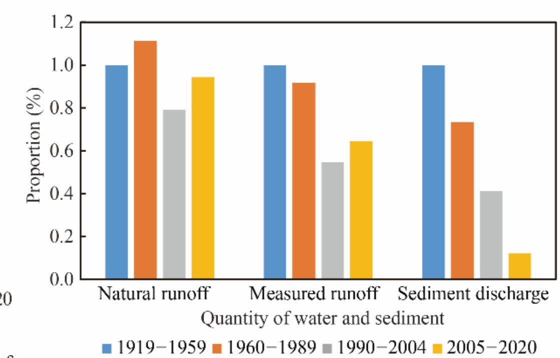

Fig. 8. Ratio between average annual quantity of sediment and the reference level in representative sections of the Yellow River during different periods.

The Yellow River showed a clear increase and decrease in water and sediment input at the century-scale, respectively. (1) The Yellow River experienced more and less input of water and sediment, respectively, from 1960 to 1989, compared with that from 1919 to 1959. The annual natural runoff in representative sections of the upper and middle reaches of the Yellow River increased by 13.1% and 11.2%, respectively, whereas the annual measured sediment discharge decreased by 7.4% and 26.7%, respectively. The reduction in sediment input to the Yellow River can mainly be attributed to the large-scale control of soil erosion in the Loess Plateau. (2) The Yellow River showed lower inputs of both water and sand from 1990 to 2004 than from 1960 to 1989. The annual natural runoff in representative sections of the upper and middle reaches of the Yellow River decreased by 24.5% and 29%, respectively, whereas the annual measured sediment discharge decreased by 72.8% and 43.6%, respectively. The drastic reduction in sediment discharge in the Toudaoguai section of the upper reaches of the Yellow River at this stage could mainly be attributed to impoundment by the Longyangxia Reservoir in 1986, in combination with the impacts of the Liujiaxia Reservoir. The operation of these reservoirs significantly changed the water sediment process of the river reaches in the Ningxia–Inner Mongolia region, resulting in decreased siltation. Statistics indicate that the river reaches in the Ningxia–Inner Mongolia region received a cumulative quantity of sediment of 1.42×10^9 t and an annual quantity of sediment of approximately 9.467×10^7 t from 1990 to 2004 [10]. The drastic decrease in sediment discharge in the Tongguan section in the middle reaches of the Yellow River can be attributed to the implementation of water and soil

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conservation measures, such as the comprehensive treatment of small basins in the Loess Plateau and the management of key ditch projects since the 1980s. (3) The Yellow River received more and less water and sand, respectively, from 2005 to 2020 than from 1990 to 2004. The annual natural runoff in representative sections of the upper and middle reaches of the Yellow River increased by 25.6% and 19.5%, respectively, whereas the annual sediment discharge in the Toudaoguai section in the upper reaches of the Yellow River increased by 79.6% (by 2.55×10^7 t), and the sediment discharges in controlling sections of the middle reaches of the Yellow River decreased by 70.5%. The increased measured sediment discharge in the Toudaoguai section in the upper reaches of the Yellow River during this stage can be attributed to the high sediment load of water from the upstream side of the Yellow River since 2005. The river reaches in the Ningxia–Inner Mongolia region acted to increase water flow, increase gully sediment transport, and decelerate the siltation of river reaches. Sediment originating from the upstream flowed into the Toudaoguai section. The statistics showed that the accumulated sediment deposition and annual siltation in the reaches of the Ningxia - Inner region from 2005 to 2020 were ~2.11×10^8 t and ~1.319×10^7 t, respectively [10], with the latter accounting for only 1/7 of the annual siltation from 1990 to 2004. The further decrease in sediment discharge at representative sections of the middle reaches of the Yellow River can be attributed to water and soil conservation measures, such as reforestation, implementation of silt arrester systems, and transformation of slopes in the Yellow River Basin into terraces since 1998.

2.2 Prediction of future trends in incoming water and sediment in the Yellow River

Incoming water and sediment in the Yellow River Basin are dynamic and uncertain and are affected by precipitation, climate, the underlying surface, artificial measures, and policy. Therefore, the prediction of the incoming water and sediment in the Yellow River is complex. The predicted annual incoming sediment in the Yellow River since 2000 was 3×10^8 to 8×10^8 t/a, which is significantly different from the observations. This discrepancy can be attributed to the hydrological and water conservation prediction methods used, which do not consider all the influencing factors. The differences in predictions among different studies can also be attributed to differences in the selected indicators, statistical sources, statistical methods, study periods, and boundary conditions. The underlying surface conditions on which the predictions are based are also subject to constant changes. Since 2010, there have been significant increases in the quantity and quality of forest and grass coverage, terraces, and silt arrests. This has contributed to significant discrepancies in modelling studies that base the water-sediment relationship on historical underlying surfaces [11].

The present study applied nine different methods to predict the quantities of sediment and water in the Yellow River for the next 50 years, including a distributed water cycle model, basin hydrodynamic model, and big data neural network model. These models were applied to the unified future climate and surface scenarios. The results showed that runoff and sediment discharge in the Tongguan section in the middle reaches of the Yellow River for the next 50 years will be 2.4×10^{10} m^3 and 2.45×10^8 t, respectively, with 90% confidence intervals of $[1.64, 3.28] \times 10^{10}$ m^3 and $[0.79, 5.12] \times 10^8$ t, respectively [12]. The results of the predictions indicate that, under the current underlying surface conditions, despite excessively heavy rainfall periods such as that in 1933, sediment entering the Yellow River in the Tongguan section will be ~5×10^8 t, 3.41×10^9 t lower than that measured in 1933, with a decrease of 87% [12]. In addition, the predictions of the future incoming water and sediment to the Yellow River in the Tongguan section, in combination with those of previous studies, provide a range of 2.47×10^{10} to 2.49×10^{10} m^3 and 3×10^8 to $3. 1 \times 10^8$ t, respectively [13,14]. In summary, the annual runoff and annual sediment discharge in the Tongguan section of the Yellow River for the next 50 years are predicted to be 2.5×10^{10} m^3 and 3×10^8 t, respectively.

3 Major issues facing the regulation of water and sediment in the Yellow River

An effective water and sediment regulation system was developed in the 1960s for the Yellow River Basin. Specifically, large-scale soil erosion control was implemented in the Loess Plateau, and a series of water and sediment regulation projects, including the Longyangxia, Liujiaxia, Wanjiazhai, Xiaolangdi, Luhun, and Guxian reservoirs were constructed on the mainstem and tributaries of the Yellow River. Consequently, forest and grass coverage of the Loess Plateau increased from 6% in 1949 to 65% in 2020, and the quantity of sediment entering the Yellow River decreased from 1.6×10^9 t/a in 1919–1959 to 1.93×10^8 t/a in 2005–2020. The Xiaolangdi Reservoir water and sediment regulation project continued for 20 years, and there was an initial strict regulation of the continual siltation-induced shrinkage of the mainstem in the lower reaches of the Yellow River. Consequently, the minimum discharge capacity of the main channel increased from 1800 m^3/s before the flood period in 2002 to 4500 m^3/s after the flood period in 2020. The lower reaches of the Yellow River underwent accumulated sediment scouring of ~2.98 $\times 10^9$ t, and the depth of the mainstem of the lower reach was reduced by an average of 2.6 m. Despite the considerable achievements in water and sediment regulation of the Yellow River Basin, the changes in the quantities of sediment and water, and particularly the significant reduction in sediment, have resulted in measures taken to regulate water and sediment being inconsistent with the observed incoming sediment. Therefore, various urgent issues affecting water and sediment regulation in the Yellow River need to be addressed.

3.1 Sedimentation-induced shrinkage in the upper reaches of the Yellow River and the emerging "suspended river" problems

The river reaches in the Ningxia–Inner Mongolia region comprise canyon and plain river channels, with the section between Bayangaole and Toudaoguaihe (denoted as the Inner Mongolia Reach) as a typical plain alluvial reach. Sedimentation and shrinkage of the main alluvial river sections since 1980 have increased the height of the riverbed by 4–6 m compared to the backwater surface. The flow capacity of the main channel of the Inner Mongolia Reach sharply decreased, resulting in six and one occurrences of riverbank bursts during the ice flood and flood periods, respectively, with flood control over the former period remaining serious.

Regulating reservoirs, such as the Longyangxia and Liujiaxia reservoirs (both operated after the flood period of 1968), were constructed in the upper reaches of the Yellow River to supply water resources for the Yellow River Basin. These reservoirs store and replenish water during flood and dry periods. However, this operation also changed the water-sediment process of the upper reaches of the Yellow River and resulted in a decline in the frequency of large flow processes conducive to sediment transport. Before the operation and storage of the Liujiaxia Reservoir in 1968, the flood volume to dry season volume ratio of the Lanzhou section in the upper reaches of the Yellow River was 6:4. The operation of Longyangxia Reservoir in 1986 resulted in a change in this ratio to 4:6. The number of days in which the Lanzhou section demonstrated a large annual flow process (> 2000 m3/s) decreased from 29.5 before 1985 to 3.7 during 1986–1999 and almost zero during 2000–2017. The decrease in the frequency of large flow events into the reaches in the Ningxia–Inner Mongolia region resulted in a reduction in the sediment-carrying capacity of the flow, which in turn led to sedimentation-induced shrinkage of the Inner Mongolia Reach. Fig. 9 shows the sediment scouring and silting processes in the Inner Mongolia Reach. The results showed that the Inner Mongolia Reach experienced balanced sediment scouring and silting before the impoundment of the Longyangxia Reservoir in 1986. Since 1987, Inner Mongolia Reach has experienced continuous sediment-induced shrinkage. The accumulated sediment in the Yellow River in the Inner Mongolia Reach between 1987 and 2020 was ~1.75 $\times 10^9$ t, whereas the annual sediment was ~0.51 $\times 10^8$ t. Correspondingly, the bankfull discharge of the Sanhu Estuary section decreased from 4400 m^3/s in 1986 to 1600 m^3/s in 2020. Fig. 10 shows the changes in bankfull discharge in the Sanhu Estuary section.

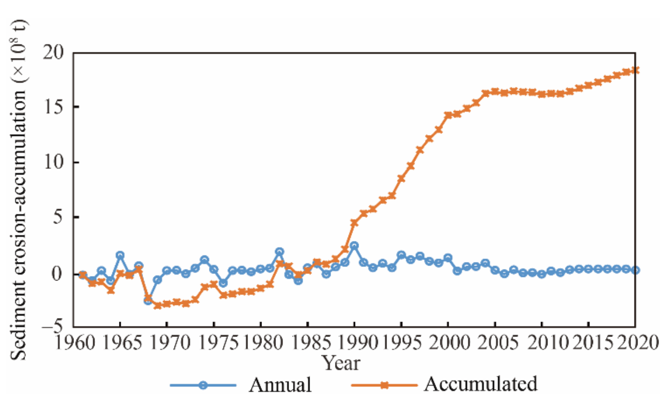

Fig. 9. Trends of sediment scouring and siltation in the Inner Mongolia Reach of the Yellow River.

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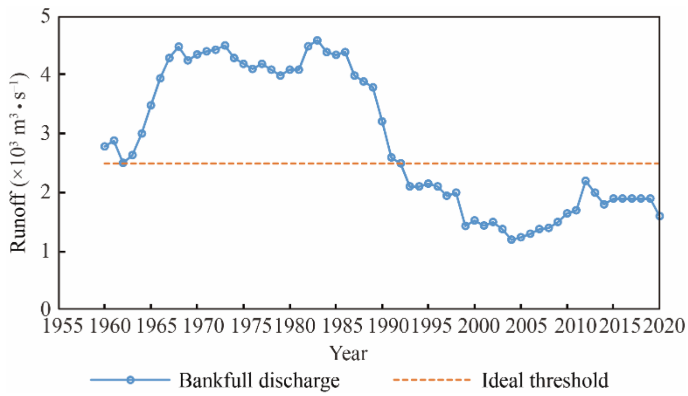

Fig. 10. Trend of bankfull discharge at the Sanhu Estuary section of the Yellow River.

3.2 Inconsistencies in management strategies of the beach area in the lower reaches of the Yellow River

Long-term sedimentation and embankment construction resulted in a beach area of 3154 km^2 between the levees on both banks of the lower reaches of the Yellow River. This beach area experiences flood discharge, water retention, and sedimentation during the flood period and is also important for the socioeconomic development of 1.9 million residents. The current management strategy for the Yellow River beach area is to relocate and resettle residents living along the beach area. However, this process has been hindered by constraints in capital and policy, and by resistance from residents. Thus, local residents will continue to be exposed to flood risk in the long term.

Flood control and beach area management of the lower reaches of the Yellow River constitute important tasks in the governance and management of the Yellow River. Currently, two different approaches for flood control and beach area management of the lower reach have been proposed: (1) widening and strengthening the dyke and (2) narrowing and strengthening the dyke [15]. The main source of uncertainty is the quantity of sediment predicted to enter the lower reaches of the Yellow River in the future. The *Comprehensive Planning of the Yellow River Basin* [5] issued in 2013 reported that, by 2030, water and soil conservation measures will be able to reduce the amount of sediment entering the Yellow River by 6×10^8–6.5×10^8 t per year, with 9×10^8–1×10^9 t of sediment still entering the Yellow River; consequently, the strategy to manage the beach area of the lower reach was to widen and strengthen the dyke, and the gradual demolition of dykes was proposed.

The prediction of incoming sediment in the Tongguan section for 50 years was 3×10^8 t, 1/3 of that in the *Comprehensive planning of the Yellow River Basin (2012–2030)*. The management of the widening and strengthening of dykes in the lower reaches of the Yellow River would be inconsistent with future predicted inputs of sediment. Meanwhile, the demolition of production dykes in the beach area would face a series of issues, including the safety and implementation of a compensation policy. The inability to ensure the safety of the beach area can result in poor flood storage and water retention, thereby posing a long-term risk of flooding in the beach area and seriously constraining its development.

3.3 Regional imbalance of soil erosion control in the Loess Plateau

Over the past 70 years, considerable advances have been made in soil erosion control in the Loess Plateau. However, the large-scale control of soil erosion has highlighted certain drawbacks that have led to emerging issues.

3.3.1 Artificial vegetation coverage in some areas has exceeded the regional water carrying capacity threshold, resulting in soil aridification

Tree-planting and afforestation are the main soil erosion control measures implemented in the Loess Plateau. The Loess Plateau falls in a semi-humid and semi-arid transitional climate zone, and soil water is the direct source of water for vegetation growth. If exceedance of artificial vegetation coverage over a certain threshold value results in long-term vegetation, soil water consumption will exceed water supplies from precipitation, resulting in drought soil and large-scale recession [16]. The overall vegetation restoration potential (coverage) of Loess Plateau has been reported as 70% [17,18]. In 2020, vegetation covered approximately 65% of the Loess Plateau, whereas that in the southeast Loess Plateau (Ziwuling and Huanglongshan forest zones) exceeded 90%, which is close to or even surpasses the recovery potential of this area. Because precipitation is the major factor restricting the restoration of vegetation in the Loess Plateau, vegetation restoration in the Loess Plateau should be in accordance with local water conditions. Nevertheless, vegetation restoration measures in some areas are not in agreement with local precipitation conditions. For example, zones in which closure measures should be imposed are areas where there has been extensive tree planting and afforestation. The phenomenon in which afforested areas perform poorly because of local conditions should be avoided.

3.3.2 There is an urgent need to optimize the current uneven spatial governance pattern of the Loess Plateau

The Loess Plateau can be categorized into nine types according to regional natural characteristics and erosion environment, including the loess hilly and gully, Loess Plateau gully, and wind-sand regions. Although different regions require different soil erosion control measures, the goals and implementation measures of soil erosion control in the Loess Plateau currently lack regional classification and overall planning. Trees should be removed from areas in which irrigated grassland is more appropriate, the area of terraced farmland should be increased in regions in which grain production is important, silt arrester engineering should be implemented in basins in which sediment retention and erosion reduction are insufficient, the area of terraces should be increased in highly urbanized land, and the number of diches and dams should be reduced in areas that require improved ecological conditions. These challenges can result in an unbalanced regional governance [19].

3.3.3 Insufficient supporting measures and systems to implement the “Two Mountains Theory” and the need to improve the quality and efficiency of soil erosion control.

Recent comprehensive control of the Loess Plateau, based on small basin units, has achieved remarkable results, thereby reducing the quantity of sediment entering the Yellow River. Simultaneously, certain challenges have persisted, including insufficient consideration of local ecological goods and services, grazing in mountainous areas, returning farmland to forests, and consolidating the achievements of water and soil conservation. This highlights the shortcomings of the traditional soil erosion control model, in which the main goal is to reduce soil erosion and increase grain supply capacity, including insufficient integration with socioeconomic development, a lower contribution of soil erosion control to increasing the incomes of farmers, and the gap between soil erosion control and requirements for high-quality development of the Yellow River Basin. There is an urgent requirement to explore the path required to realize high-quality development in the Yellow River Basin.

4 Key strategy for water and sediment regulation of the Yellow River under new water and sediment conditions

Recently, significant changes have occurred in the process and flux of incoming water and sediment to the Yellow River. In particular, the drastic decrease in the quantity of sediment entering the Yellow River has resulted in changes to the movement of water and sediment, as well as to the evolution of the river course. These changes are definite and show a certain trend, which directly affects the formulation of water and sediment regulation strategies for the Yellow River [20]. Therefore, the present study proposes the following key control strategies in view of the main challenges facing water and sediment regulation in the Yellow River.

4.1 Improvement of the water and sediment regulation system for the Yellow River

The volumes of water and sediment and their drivers can be controlled through the construction of a water and sediment regulation system, thus ensuring the continuity of the basic course of water and sand transport in the mainstem of the Yellow River. Strategies for the regulation of sediment and water inputs in the Yellow River should focus on regulating reservoirs. Currently, there is a lack of control reservoirs along the 1440-km stream segment from the Liujiaxia Reservoir to the Toudaoguai section. The total sedimentation of Xiaolangdi Reservoir by the end of the 2020 flood season accounted for 42.8% of the designed sediment containment capacity of the reservoir. Therefore, this reservoir has an insufficient capacity for future water and sediment regulation, and further improvement of the water and sediment regulation engineering system is required.

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4.1.1 Strengthening the preliminary demonstration of the Heishanxia reach governance project

The Heishanxia Reach is near the border between Gansu Province and the Ningxia Autonomous Region in the upper reaches of the Yellow River. This area has been identified as suitable for reservoir construction. After the completion of water conservancy projects in the Heishanxia Reach, water and sediment regulation can be conducted in conjunction with the Liujiaxia and Liujiaxia reservoirs in the upper reaches of the Yellow River. This approach can be beneficial to sediment transport within the Ningxia–Inner Mongolia Reach and can facilitate the recovery and maintenance of long-term bankfull discharge of the Inner Mongolia Reach at 2000–2500 m^3/s. Therefore, this approach can effectively alleviate sedimentation-induced shrinkage of the "suspended river" in the Ningxia–Inner Mongolia Reach and reduce the risk of floods and ice floods. Meanwhile, this approach can provide the hydrodynamic conditions required for water and sediment regulation and recovery of the effective storage capacity of key reservoirs in the middle reaches. This approach can also achieve connectivity in the upper, middle, and lower reaches of the Yellow River. Although the discussion of the Heishanxia Reach control project has continued for several decades, there has been minimal progress in the discussion of its function and construction scheme. This study suggests combining the western route of the South-to-North Water Diversion Project with water and sediment regulation of the Yellow River to accelerate the preliminary demonstration of the Heishanxia Reach project.

4.1.2 Optimize the development goal and construction scale of the Guxian Water Conservancy Project in the middle reaches of the Yellow River and initiate its construction as soon as possible

The Xiaolangdi Reservoir is the only water control hub in the middle and lower reaches of the Yellow River that can comprehensively regulate and utilize water and sediment. The capacity of the Xiaolangdi Reservoir plays an important role in flood control, ecology, and water supply security in the lower reaches of the Yellow River. There is a need to construct a regulating reservoir in the mainstem of the middle reaches of the Yellow River before the sediment storage capacity of the Xiaolangdi Reservoir can be reached. Joint water and sediment regulation between this new reservoir and Xiaolangdi Reservoir is required. The site of the planned Guxian Water Conservancy Project in the middle reaches of the Yellow River offers good construction conditions, and the project has been under discussion for nearly 70 years. The project has a designed multi-year average incoming sediment quantity, total storage capacity, and sediment storage capacity of 7.73×10^8 t, 1.29×10^{10} m^3, and 9.342×10^9 m^3, respectively [21]. Upon completion, this project will completely change the continuous sedimentation of the Xiaobeiganliu segment of the Yellow River and help reduce the elevation of the Tongguan section. Meanwhile, the joint operation of the Guxian and Xiaolangdi reservoirs will overcome the challenge of insufficient follow-up power in the regulation of water and sediment by the Xiaolangdi Reservoir. The project will allow the flood discharge and sediment transport function of the river course of the lower reaches to be maintained in the long term and will alleviate the "secondary suspended river" condition.

It should be considered that because the future incoming sediment to the Bazhi section of the Guxian Water Conservancy Project will be markedly smaller than that accounted for in the plan, the sediment storage capacity of the reservoir is too large. Given the possible future water and sediment conditions of the Yellow River, it is suggested that further optimization of the development goal and construction scale of the Guxian Water Conservancy Project be conducted, and that the project should be initiated as soon as possible.

4.2 Zoning governance and management of the beach area of the lower reaches of the Yellow River

There will be a further decline in sediment entering the lower reaches of the Yellow River; the peak discharge will show a sharp reduction, and the probability of flood inundation will be extremely low owing to the construction and operation of controlling reservoirs, such as the Guxian and Dongzhuang reservoirs in the middle reaches of the Yellow River. Therefore, zoning, governance, management, and restoration of the beach area of the lower reaches of the Yellow River are required.

4.2.1 Zoning management of pilot beach areas according to local conditions

The beach area zoning governance pilot should be executed in appropriate river segments to maintain the status quo of the Yellow River levee and ensure its safety. Existing production dykes and other flood control projects in natural beach areas should be fully utilized, and certain flood control sub-embankments need to be constructed to form a closed flood storage detention area. Flood diversion and recession facilities should be established in appropriate areas, such as flood control sub-embankments and their upper and lower reaches. Water retention and sediment deposition should be selectively conducted according to flood control requirements and real-time flood conditions. Apart from flood diversion and storage areas, beach areas should be used only by residents for resettlement.

4.2.2 Modification of the river course of the lower reaches to free some beach areas

Pilot-zoning management of the beach area should be gradually expanded based on further observations and evaluations of the lower reaches of the Yellow River under future water and sediment conditions. Finally, two leading dykes should be constructed in the beach area of the Yellow River by using existing production dykes and river control works. This will result in a reduction in the width of the river course of the lower reaches of the Yellow River by 3 to 5 km, with a flow capacity of 8000–10 000 m^3/s. A flood detention area should be constructed in the beach area between the leading dykes and the Yellow River levee by utilizing embankments and roads to divide the flow exceeding 10 000 m3/s. The beach areas, besides the newly built flood detention areas, should be returned and converted into a permanent safe zone, thereby removing the conflict between the flood control role of the beach area in the lower reaches of the Yellow River and the requirements for high-quality development.

4.3 Governance and management of the Loess Plateau and coordinated promotion of ecological protection and rural vitalization

Water and soil conservation in the Loess Plateau should firmly adhere to the policies of returning farmland to forests and grasslands and the construction of silt arresters in the long term. However, some challenges persist, including emphasizing unsustainable tree and grass planting in certain regions, mismatched regional measures, unbalanced governance, emphasis on engineering measures over management, and insufficient driving force behind governance objectives and modes of rural vitalization. Therefore, the following suggestions were made.

4.3.1 Propose a rational soil erosion control approach for the Loess Plateau and adjust water and soil conservation measures to local conditions

Within soil erosion control and ecological development in the Loess Plateau, measures such as forest and grass vegetation, terraces, and silt arresters show critical limits to their impacts on sediment reduction [22]. Soil erosion control in the Loess Plateau is unlikely to completely remove sediment; however, measures such as forest and grass vegetation, terraces, and silt arresters should have implementation thresholds, above which the marginal benefit of water and soil conservation will be minor. The reduction of sediment entering the middle reaches of the Yellow River owing to water and soil conservation measures to a largely clear water state will introduce several further challenges, including severe scouring and abnormal river bend development, thereby introducing risks to flood control. In addition, a reduction in sediment can introduce the challenges of coastal erosion and seawater intrusion into the Yellow River estuary, thereby posing considerable risks to the ecological environment and stability of the estuary. Therefore, there should be a critical threshold for soil erosion control in the Loess Plateau to achieve a balance between basin sediment yield and river sediment transport. The present study suggests the need for rational clarification of the degree of soil erosion control required for each zone according to the local conditions of the nine areas in the Loess Plateau and the critical effects of water and soil conservation. Full consideration of the current water and soil conservation conditions in each zone is required, and the strategy of governance and management of the Loess Plateau should be adjusted according to specific conditions.

4.3.2 Integrated development between innovative ecological governance and rural vitalization

Future studies are needed to further explore the establishment of a multichannel and diversified investment mechanism for soil erosion control. There should be the integration of water and soil conservation ecological development funds along with increasing the central investment in the public finance framework of local governments at all levels, and different organizations should be encouraged to participate in water and soil conservation projects in various forms, such as through contracts, leases, and joint-stock cooperation. Private capital should be introduced into soil erosion control to improve governance efficiency. These measures can promote industrial development, improve living environments, and ultimately provide benefits to people.

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