

RESEARCH ON TECHNICAL MEASURES AND STRATEGIES FOR IRRIGATION AND DRAINAGE DEVELOPMENT IN THE YELLOW RIVER BASIN UNDER CLIMATE CHANGE

RECHERCHE SUR LES MESURES TECHNIQUES ET LES STRATÉGIES POUR LE DÉVELOPPEMENT DE L'IRRIGATION ET DU DRAINAGE DANS LE BASSIN VERSANT DE JAUNE FACE AU CHANGEMENT CLIMATIQUE

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ABSTRACT

The Yellow River Basin serves as a key grain-producing area and an ecological barrier in China. Its irrigation and drainage system has long faced structural weaknesses, including aging and dilapidated facilities and poor connectivity between main and on-farm networks. Under climate change, the basin has experienced abrupt drought–flood alternations and increasingly frequent and intense extreme water-related disasters, exposing the system's significant vulnerability and rendering the traditional approach of engineering expansion and extensive management unsustainable. Based on an analysis of temperature increases, precipitation variability, evapotranspiration changes, and recent drought and flood characteristics in the Yellow River Basin, this paper systematically identifies three major challenges: outdated irrigation and drainage infrastructure, disconnection between main and field-level systems, and insufficient capacity to cope with extreme climate events. To address these issues, technical measures and development strategies are proposed from two perspectives—engineering upgrading and digitalization, and institutional safeguards. The findings can provide systematic technical support for enhancing the climate resilience of the irrigation and drainage system in the Yellow River Basin, promoting efficient water resource utilization, and ensuring national food security.

Keywords: Yellow River Basin; climate change; irrigation and drainage; technical measures; standard system

RESUME

Le bassin versant de Jaune est une zone important clé de production céréalière et une barrière écologique en Chine. Son système d'irrigation et de drainage souffre depuis longtemps de faiblesses structurelles, notamment le vieillissement et la vétusté des installations, ainsi qu'une mauvaise connectivité entre les réseaux principaux et ceux de l'exploitation. Dans le contexte du changement climatique, le bassin a connu de brusques alternances de sécheresse–inondation et des catastrophes hydriques extrêmes de plus en plus fréquentes et intenses, exposant la vulnérabilité importante du système et rendant insoutenable l'approche traditionnelle de l'expansion technique et de la gestion extensive. Sur la base d'une analyse de la hausse de température, de la variabilité des précipitations,

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des changements d'évapotranspiration et des caractéristiques récentes de sécheresse et d'inondation dans le bassin versant de Jaune, cet article identifie systématiquement trois défis majeurs : la vétusté des infrastructures d'irrigation et de drainage, le manque de connexion entre les systèmes principaux et ceux des parcelles, et la capacité insuffisante de faire face aux événements climatiques extrêmes. Pour répondre à ces préoccupations, des mesures techniques et des stratégies de développement sont proposées sous deux angles : la modernisation technique et la numérisation, ainsi que les garanties institutionnelles. Les résultats peuvent fournir un soutien technique systématique pour renforcer la résistance climatique du système d'irrigation et de drainage dans le bassin versant de Jaune, promouvoir une utilisation efficace des ressources en eau et assurer la sécurité alimentaire nationale.

Mots-clés : Bassin versant de Jaune; Changement climatique; Irrigation et drainage; Mesures techniques; Système normal.

1. Background

The Yellow River Basin (YRB) is a vital grain-producing area and ecological barrier in China. Its irrigation and drainage (I&D) system has long faced structural weaknesses—aging facilities and poor connectivity between main and on-farm networks—leading to inefficient water delivery and intensifying upstream–downstream conflicts. Since the turn of the century, extreme climate events such as abrupt drought–flood alternations, prolonged droughts, and short-duration intense rainfall have become more frequent and severe (Zhuang et al 2023).

Existing I&D facilities suffer from low design standards, inadequate regulation and storage capacity, and sparse monitoring networks, making it difficult to achieve the basic goal of “irrigate when dry, drain when waterlogged” and seriously threatening the stability of grain production (Li et al., 2022). The traditional model of engineering expansion and extensive management is no longer viable. An urgent transition toward digital, smart, and resilient I&D systems is needed, driven by next-generation information technologies such as digital twins, precision sensing, and intelligent decision-making, along with the reconstruction of climate-adaptive I&D standards. This study explores systematic solutions from three perspectives—infrastructure upgrading, intelligent decision-making empowerment, and institutional and standardization safeguards—offering significant theoretical value and practical relevance for enhancing the climate resilience of basin agriculture, promoting sustainable water resource utilization, and ensuring national food security.

2. Characteristics of Climate Change in the Yellow River Basin

2.1 Temperature Changes

The temperature in the YRB has exhibited an upward trend amid normal interannual and interdecadal fluctuations, consistent with global warming. From 1961 to 2000, the mean annual temperature in the YRB increased by 0.6°C (Liu et al., 2010). The warming trend was highly pronounced in winter and weakest in summer. The climate in the YRB was relatively cool before the mid-1980s, after which it became predominantly warm. This warming became particularly persistent and significant from the mid-to-late 1990s onward, with the trend becoming even more marked since the beginning of the 21st century.

Due to geographical differences, the temperature responses to global warming vary across different regions of the basin. The source region has experienced the largest magnitude of change. Over the past 40 years, the average temperature in the upper reaches of the Yellow River (YR) has risen by 0.32°C. In the area above the Tangnaihai station, the mean annual temperatures in the 1990s were approximately 0.5°C higher than the long-term average. The most pronounced warming occurred in the Zeku region, where the average temperature increased by 0.58°C. Temperature changes in the YRB across different decades are presented in Table 1 (Xia et al., 2011).

Table 1. Decadal variation of annual mean temperature in the YRB

Reach	1956-1959 (°C)	1960-1969 (°C)	1970-1979 (°C)	1980-1989 (°C)	1990-1999 (°C)	2000-2003 (°C)
Entire Basin	7.3	7.4	7.5	7.5	8.1	8.4
Upstream of Longyangxia	0.8	0.9	1.1	1.1	1.4	1.8
Longyangxia to Lanzhou	3.8	3.8	3.9	4	4.5	4.9
Lanzhou to Hekouzhen	6.8	7	7	7.2	8.0	7.9
Hekouzhen to Longmen	8.2	8.3	8.3	8.2	8.9	9.3
Longmen to Sanmenxia	10.2	10.3	10.4	10.4	11.1	11.1
Sanmenxia to Huayuankou	12.8	12.9	12.9	12.6	13.1	13.4
Downstream of Huayuankou	11.6	12	12	12	12.6	12.6

2.2 Precipitation Changes

Compared with the mean precipitation of the 1956–2016 series for the YRB, the mean precipitation of the 1956–1979 series was 1.6% higher, during which all secondary subregions of the YRB experienced above-average precipitation except for the area above Longyangxia, which was 2.6% lower. The mean precipitation of the 1980–2000 series was 3.4% lower than that of the 1956–2016 series, during which all secondary subregions experienced below-average precipitation except for the area above Longyangxia, which was 0.7% higher. The mean precipitation of the 2001–2016 series was 2.1% higher than that of the 1956–2016 series, during which all secondary subregions experienced above-average precipitation except for the Lanzhou–Hekou Town reach, which was 1.1% lower, and the Sanmenxia–Huayuankou reach, which remained nearly the same. The interdecadal variation in annual precipitation in the YRB is shown in Table 2.

Table 2. Decadal variation of annual precipitation in the YRB

Reach	1956–1979		1980–2000年		2001–2016年		1956–2016 series precipitation (mm)
	Precipitation (mm)	1956–1979 series change from 1956–2016 series (%)	Precipitation (mm)	1980–2000 series change from 1956–2016 series (%)	Precipitation (mm)	2001–2016 series change from 1956–2016 series (%)	
Upstream of Longyangxia	477.9	-2.6	494.0	0.7	505.8	3.1	490.7
Longyangxia to Lanzhou	506.6	0.7	494.6	-1.7	509.8	1.3	503.3
Lanzhou to Hekouzhen	271.2	3.9	251.4	-3.7	258.2	-1.1	261
Hekouzhen to Longmen	455.0	2.1	407.5	-8.6	482.2	8.2	445.8
Longmen to Sanmenxia	555.2	2.5	521.7	-3.7	547.5	1.1	541.6
Sanmenxia to Huayuankou	668.9	2.6	634.4	-2.7	649.1	-0.4	651.8
Downstream of Huayuankou	669.4	4.3	610.0	-5.0	642.9	0.1	642
Inland River Area	291.7	4.2	261.4	-6.6	286.4	2.3	279.9
Entire Basin	459.3	1.6	436.8	-3.4	461.6	2.1	452.2

2.3 Evapotranspiration Changes

Numerous observations and studies have shown that pan evaporation in the YRB has exhibited a declining trend over the past 40 years, with the most pronounced decreases occurring in spring and summer (Xu et al., 2005; YE et al., 2022). The climate change trends in local areas of the YRB are not entirely synchronous with those of the basin as a whole: pan evaporation shows a decreasing trend in the upper and lower reaches, while it remains nearly stable with a slight increasing trend in the middle reaches (Jin et al., 2024). The decline in pan evaporation is mainly attributed to the decrease in global radiation in recent years.

In contrast to pan evaporation, actual evapotranspiration in the YRB has been increasing year by year (Yu et al., 2024). Increases in sunshine duration, temperature, and saturation deficit in the upper reaches have led to higher evapotranspiration from grasslands. Although solar radiation has weakened to some extent, in relatively arid areas, irrigation water use has increased, and water supply conditions have become the dominant factor determining land surface evaporation.

3. Total Water Resources and Variation Trends in the Yellow River Basin

According to the Third National Water Resources Survey and Assessment and the China Water Resources Bulletin, the mean annual total water resources of the YRB for the 1956–2024 series is 71.64 billion m³, of which surface water resources amount to 59.71 billion m³, groundwater resources amount to 38.43 billion m³, and the non-overlapping amount between groundwater and surface water is 11.93 billion m³. Over recent decades, both the total water resources and surface water resources in the YRB have generally exhibited a decreasing trend. Compared with the 1956–2000 series, the total water resources and surface water resources in the 2001–2024 series are both about 2% lower. The annual variations in surface water resources and total water resources in the YRB from 1956 to 2024 are illustrated in Figure 1.

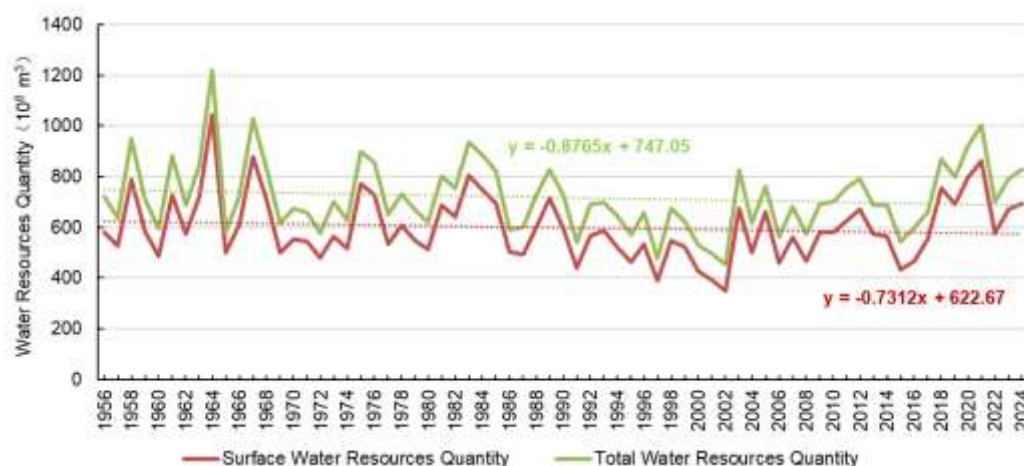


Figure 1. Trends in surface water resources and total water resources in the YRB, 1956–2024

4. Flood and Drought Disasters in the Yellow River Basin

4.1 Major Flood Disasters in Recent Years

In recent years, flood disasters in the YRB have exhibited a trend of frequent and severe occurrences, particularly characterized by high-intensity and long-duration autumn floods. In 2020, six numbered flood events occurred on the YR, the highest number since the introduction of the numbering system. Among them, the Tongguan station recorded a maximum discharge of 6,300 m³/s, the largest since 1998, and the Huaxian station on the Wei River recorded its largest discharge since 2011. In 2021, the middle and

lower reaches of the YR experienced the largest autumn flood since 1949, with three numbered flood events occurring on the main stream. The tributaries Fen River, North Luo River, and Yiluo River experienced their largest floods since 1964, 1999, and 1982, respectively. Major flood processes also occurred on tributaries such as the Jing, Wei, Yiluo, and Qin Rivers, and the Tongguan station recorded a maximum discharge of 8,360 m³/s (the largest since 1979). In 2022, the ice flood situation on the YR remained stable, the main stream experienced one numbered flood, the Jing River recorded its highest water level since 1965, and 13 tributaries, including the Tarim River in Xinjiang, experienced floods exceeding the guaranteed level. In 2023, the ice flood situation remained stable, one numbered flood occurred on the main stream, 36 rivers experienced floods exceeding the warning level, and 4 rivers, including the Bielezi River in Xinjiang, exceeded the guaranteed level. In 2024, one numbered flood occurred on the main stream, 80 rivers exceeded the warning level—of which 21 rivers, including the Tarim River in Xinjiang, the North Luo River in Shaanxi, and the Suyukou Gully in Ningxia, exceeded the guaranteed level—and 7 rivers, including the Irtysh River in Xinjiang and the Gan River, a tributary of the Wei River in Shaanxi, exceeded historical observed records.

In recent years, the nine provinces along the YR have experienced a pattern of periodic high incidence of flood disasters, characterized by “outbreaks in extreme years and relative calm in normal years.” The years 2021 and 2023 stood out as two prominent peaks, with an overall upward trend in economic losses and affected areas. The flood-affected situations in the nine provinces along the YR in recent years are shown in Table 3. The year 2021 was the most severe, with peak values in affected population (31.281 million), dead and missing persons (515), direct economic losses (177.95 billion yuan), crop-affected area (2,518.2 thousand hectares), crop failure area (482.5 thousand hectares), and collapsed houses (130,000). In 2022, all indicators reached their minimum (e.g., an affected population of 5.642 million and direct economic losses of 21.82 billion yuan), representing the mildest disaster year. In 2023, the affected population and affected area rebounded sharply, but the numbers of dead and missing persons and collapsed houses were significantly lower than those in 2021. The 2024 data shared some identical indicators with 2023 (e.g., an affected area of 2,655.9 thousand hectares and a crop failure area of 112.7 thousand hectares). Overall, the figures indicate sharp annual fluctuations, with prominent losses in extreme years.

Table 3. Flood disaster impacts in the 9 provinces along the YR in recent years

Year	Affected Population (10 ⁴ person-times)	Dead/Missing Persons (persons)	Direct Economic Loss (100 million yuan)	Affected Cropland Area (10 ³ hectares)	Cropland Area with Total Crop Failure (hectares)	Collapsed Houses (10 ⁴ units)
2019	1190.8	225.0	660.3	1165.9	202.9	3.6
2020	2264.6	119.0	727.2	1402.7	160.3	3.9
2021	3128.1	515.0	1779.5	2518.2	482.5	13.0
2022	564.2	75.0	218.2	976.0	125.9	0.7
2023	2977.9	67.0	293.9	2655.9	112.7	0.3
2024	1994.9	153.0	727.9	2655.9	112.7	0.3

4.2 Major Drought Disasters in Recent Years

Drought disasters in the YRB in recent years have been dominated by spring–summer continuous droughts and summer–autumn droughts, with severe conditions in localized areas. In 2020, the overall drought situation in the basin was relatively mild, but drought persisted in localized areas such as Inner Mongolia. In 2021, summer drought occurred in parts of northern and southwestern China. July to August coincided with the critical growth period for crops such as maize, cotton, and mid-season rice. The drought-affected cropland area in the four provinces/regions of Inner Mongolia, Shaanxi, Gansu, and Ningxia accounted for more than 90% of the national total, and drought conditions were not relieved in most of the affected areas until the end of September. In 2022, a spring–summer continuous drought occurred in the Huang–Huai–Hai and Northwest regions. From April to mid-June, precipitation was

30%–70% below normal, and temperatures were 1–3°C above normal. The crop area affected by drought reached 4,358.67 thousand hectares, and 160,000 people and 1.46 million head of large livestock faced drinking water difficulties. Strong rainfall occurred in the drought-affected areas from late June to early July, and drought conditions were gradually relieved in most areas, but drought in western Inner Mongolia persisted until October. In 2023, precipitation in the YRB was slightly above normal, and drought conditions were generally mild. However, summer–autumn drought occurred in the eastern and northern parts of Northwest China, with the Hexi Corridor in Gansu experiencing a drought with a return period of 60 years. Water supply was strained in several cities and towns, and drought conditions in central and western Inner Mongolia persisted for nearly five months. In 2024, precipitation in the YRB was below normal after August, and inflows to the main stream and tributaries of the YR were 10%–60% lower than the average for the same period. Summer drought occurred in the North China, Northwest China, and Huang–Huai regions, with up to 5,484 thousand hectares of cropland affected in eight provinces at one point, impacting the timely sowing and growth of crops such as maize and soybeans.

In recent years, drought losses in the nine provinces along the YR have generally shown a downward trend, particularly in 2024, when all indicators decreased substantially, reflecting improvements in water source engineering and emergency regulation capacity within the basin. However, the numbers of people and large livestock facing drinking water difficulties remained relatively high in 2022, indicating that drought risk persists. The drought-affected situations in the nine provinces/regions along the YR in recent years are shown in Table 4. In 2024, all indicators in the nine provinces/regions along the YR dropped sharply to their lowest levels: the crop affected area was only 738.1 thousand hectares, the crop failure area was 97.4 thousand hectares, the population with drinking water difficulties due to drought was 118,000, and large livestock affected were 623,000 head—representing decreases of approximately 73%, 65%, 88%, and 70%, respectively, compared to the previous five-year averages. The most severe years in terms of drought-affected area in the nine provinces/regions along the YR were 2019 (with an affected area of 3,195.4 thousand hectares) and 2021 (with a crop failure area of 442.9 thousand hectares). The peak in population with drinking water difficulties occurred in 2022 (1.801 million people), and the peak in affected large livestock occurred in 2019 (2.349 million head).

Table 4. Drought disaster impacts in the 9 provinces along the YR in recent years

Year	Affected Crop Area (10 ³ hectares)	Crop Failure Area (10 ³ hectares)	Population with Drinking Water Scarcity Due to Drought (10 ⁴ persons)	Large Livestock with Drinking Water Scarcity Due to Drought (10 ⁴ heads)
2019	1190.8	225.0	660.3	1165.9
2020	2264.6	119.0	727.2	1402.7
2021	3128.1	515.0	1779.5	2518.2
2022	564.2	75.0	218.2	976.0
2023	2977.9	67.0	293.9	2655.9
2024	1994.9	153.0	727.9	2655.9

5. Problems in the Irrigation and Drainage System

5.1 Aging and Dilapidated I&D Facilities

Most backbone I&D works in the YRB were constructed between the 1950s and 1970s with low standards, incomplete supporting structures, and chronic underinvestment, resulting in severe aging. Main and branch canals suffer from low lining rates, leakage, and structural damage (carbonation, cracks, reinforcement corrosion) in aqueducts, inverted siphons, and sluices. Electromechanical wells and pumping units are mostly overaged, inefficient, and often operate in a faulty state. On-farm systems are clogged, gates inoperable, and drainage ditches collapsing, with engineering integrity far below standards. This systemic decay causes low canal water use efficiency, reduced irrigation reliability, poor

flood-season drainage, and high groundwater levels, exacerbating secondary salinization and failing to meet the demands of ecological protection and high-quality development.

5.2 *Disconnection between Main and On-Farm Systems*

Despite modernization of trunk and branch canals, the “last kilometer” field ditches and drains remain incomplete, substandard, and unmanaged, creating a bottleneck where backbone water cannot reach plots efficiently. Most field canals are unlined earth channels subject to sedimentation and weed obstruction, lacking measurement and control facilities. Consequently, water is wasted upstream while downstream suffers drought, driving unregulated groundwater extraction and inefficient use. Field drainage connections are equally obstructed, leading to waterlogging, rising groundwater, and renewed salinization risk. This structural disconnection—functional network but blocked terminals—limits water’s role in drought and flood mitigation and yield security.

5.3 *Insufficient Capacity to Cope with Extreme Climate Events*

Extreme events—rainstorms, prolonged droughts, drought–flood alternations—are increasing in frequency and intensity, yet I&D facilities have low design standards and limited resilience. Most drainage channels are designed for 3–5 year return periods and are heavily clogged, causing prolonged waterlogging and crop failure. During extreme droughts, overreliance on river inflow leaves districts helpless when upstream flow ceases, while lack of emergency water sources forces excessive groundwater abstraction, risking land subsidence and ecological degradation. Regulation structures between irrigation and drainage systems are mostly non-automated, unable to rapidly switch functions when drought suddenly turns to flood. Sparse monitoring networks and the absence of intelligent forecasting platforms leave emergency responses lagging and reactive.

6. **Technical Measures for Irrigation and Drainage Development**

6.1 *Upgrading Irrigation Districts to Enhance Climate Resilience*

Aiming to withstand extreme events, modernization of large, medium, and small districts should prioritize structural reinforcement of hazardous structures and renewal of overaged pumps, comprehensive canal lining or pipeline conveyance, and raising design standards. Emergency storage ponds and backup water sources should be added at key nodes to form a flexible storage–diversion–lifting–drainage network. Simultaneously, automatic monitoring of rainfall, water, and soil moisture should be deployed, and a digital control platform built to enable remote gate and pump coordination, ensuring rapid functional switching during extreme fluctuations.

6.2 *Integrating with High-Standard Farmland to Open On-Farm “Capillaries”*

To resolve the disconnection, backbone rehabilitation must be deeply coupled with high-standard farmland construction in planning and standards. The focus is on completing field ditches and drains, eliminating unlined canals, installing measurement gates, and promoting efficient irrigation (drip, sprinkler, pipe). This ensures precise water delivery and eliminates waste. On the drainage side, field drains must connect smoothly to the backbone system with small structures (culverts, gates), enabling rapid discharge of excess stormwater and building genuine “irrigate when dry, drain when waterlogged” farmland, thus strengthening buffer capacity against drought and sudden rainstorms.

6.3 *Improving Drainage and Strengthening Coordinated Flood–Salt–Alkali Control*

Given high groundwater, salinization risks, and frequent extreme storms, regional drainage system remediation centered on waterlogging reduction and salt control is essential. Dredging backbone and field drains restores conveyance capacity for rapid discharge. In shallow-groundwater or low-lying areas, subsurface pipe or mole drainage should be installed to lower the water table below critical depths, breaking the waterlogging–salinization chain. Control gates and mobile pumping stations at key

drainage nodes boost forced drainage; ecological ditches and swales can retain part of stormwater for irrigation supplementation, achieving multi-objective synergy among drainage, salinity management, and rainwater reuse.

7. Development Strategies

To address aging, disconnection, and insufficient climate resilience amid increasing drought–flood alternations, digital and smart technologies should drive the following strategies:

- (1) Accelerate digital twin irrigation districts: Integrate satellite remote sensing, UAV inspection, and ground sensor networks to densely monitor soil moisture, water level, and conductivity. Digitally map backbone canals and control nodes, aggregating flow, water, soil moisture, situation, and engineering data to eliminate sensing blind spots and provide a real-time foundation for precise decision-making.
- (2) Establish a distributed hydrology–crop–salinity coupled model: Incorporate weather and inflow forecasts to automatically determine optimal irrigation timing and quotas, generating precise water distribution plans. Link the decision platform with gates, pumps, and field valves for remote, timely supply. Promote integrated water–fertilizer variable-rate irrigation, embedding dual control of total volume and quota and drought–flood pre-simulation to enable data-driven regulation and enhance buffering capacity.
- (3) Revise standards and institutional safeguards: Raise design assurance and waterlogging control standards by including extreme rainfall and prolonged drought as verification conditions. Develop guidelines for digital twin construction, operation, and maintenance, covering sensing deployment, model calibration, and control response. Implement intelligent monitoring and early warning for aging structures and promote preventive maintenance. Establish a climate adaptation indicator system—canal water use efficiency, drainage effectiveness, groundwater level, salinity dynamics, water outage duration—to drive full-chain upgrading of planning, design, construction, and management.

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