

Review

Resilience of Agricultural Water Resource Systems in Yellow River Irrigation Districts

Jingwei Yao ¹ , Cheng Chen ^{2,3}, Xingye Han ¹, Peiqing Xiao ¹, Julio Berbel ⁴  and Wenyi Yao ^{1,*}

¹ Key Laboratory of Soil and Water Conservation on the Loess Plateau of the Ministry of Water Resources, Yellow River Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou 450003, China; solofromchina@163.com (J.Y.); thea_hanxy@163.com (X.H.)

² Yellow River Conservancy Technical University, Kaifeng 475003, China; 1997720123@yrctu.edu.cn

³ Henan Engineering Research Center of Eco-Hydraulics for Small Watersheds, Kaifeng 475003, China

⁴ Water, Environmental and Agricultural Resources Economics Research Group (WEARE), Universidad de Córdoba, Campus de Rabanales, 14014 Córdoba, Spain

* Correspondence: yaowenyi0512@163.com

Abstract

Yellow River irrigation districts must maintain food production under variable inflows, rigid diversion quotas, sedimentation, groundwater depletion, and soil salinization. This systematic review synthesized 79 journal articles from Web of Science and CNKI to clarify how resilience can be assessed and managed at the irrigation-district scale. The evidence indicates that resilience is a time-dependent combination of resistance, recovery, adaptability, and transformability within a coupled water source–canal–field–drainage–ecology–institution system. Although composite indices and hydrological–crop models have advanced, three gaps remain: operational thresholds rarely connect indicators to failure and recovery; farmer and institutional feedbacks are weakly represented; and assessments seldom translate into executable schedules. We, therefore, propose an irrigation-district-specific framework that couples water, sediment, salt, crops, ecology, and governance across basin–district–field scales without transferring risk between scales. Management priorities differ spatially: upstream districts require coordinated water–salt control; middle-reach well–canal systems require surface-water substitution and groundwater recovery; and downstream diversion districts require multi-source allocation and adaptive intake. A digital twin-based closed loop—continuous monitoring, forecasting, optimization, operational commands, and feedback correction—can translate diagnosis into canal rotation, recharge, drainage, and emergency actions. This review provides operational indicators and a decision-oriented research agenda for resilient irrigation modernization.

Keywords: agricultural water management; resilience assessment; social–ecological systems; Yellow River Basin; irrigation modernization; water–salt balance; digital twin; climate adaptation



Academic Editor: Junsheng Lu

Received: 4 July 2026

Revised: 2 August 2026

Accepted: 16 August 2026

Published: 18 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The Yellow River Basin is a major ecological security barrier and grain-producing region in China. National strategies for ecological protection and high-quality development, together with the Yellow River Protection Law, require coordinated control of water withdrawals, ecological protection, and socioeconomic development [1]. However, irrigation districts face chronic resource and engineering scarcity, aging infrastructure, inefficient distribution, and fragmented management. Climate extremes and increasingly rigid diversion

quotas can, therefore, propagate rapidly from basin inflow to canal supply, groundwater use, crop production, and ecological return flows [2]. Improving agricultural water resource system resilience has consequently become central to reconciling food security with ecological security.

Resilience theory offers a framework for understanding these interacting risks. Holling defined ecological resilience as the magnitude of disturbance a system can absorb before its structure and function change fundamentally [3]. The concept has since been adopted across multiple disciplines, including water resources, urban resilience, and health system research [4–6]. Subsequent work emphasized the capacity to maintain function, adapt, and transform within social–ecological systems [7,8]. In water resources research, the reliability–resiliency–vulnerability (R–R–V) framework established a quantitative basis for evaluating failure, recovery, and severity [9,10]. Climate adaptation, water security, and adaptive management have since broadened resilience research from recovery after a single disturbance to performance under persistent and compound change [11–13].

Research in China has progressed from conceptual discussion to composite assessment, process simulation, and regulation analysis. Recent studies have quantified exposure, sensitivity, recovery speed, adaptive capacity, and governance response [14–16]. Yellow River studies have also examined critical thresholds during extreme drought, the relationship between agricultural water use efficiency and recovery capacity, and the evolution of water–energy–food nexus resilience under policy and climate drivers [17–20]. These advances support water allocation planning, water-right design, and the transition from a static supply–demand balance toward dynamic safety boundary management.

However, most existing Yellow River assessments use basin- or provincial-scale indicators, while broader reviews emphasize urban infrastructure or integrated water systems [14–16,18]. They do not treat an irrigation district as an operational unit in which basin quotas, headworks, sediment, canal conveyance, field irrigation, drainage, salinity, farmer behavior, and ecological constraints interact. This review, therefore, contributes four elements: (i) an explicit six-component system boundary; (ii) operational definitions for resistance, recovery, adaptability, and transformability; (iii) a nested basin–district–field synthesis of water–sediment–salt–crop–ecology–institution feedbacks; and (iv) a diagnosis-to-scheduling pathway for executable regulation. Because study designs, outputs, and metrics are heterogeneous, the review uses bibliometric and thematic synthesis rather than statistical meta-analysis. Its objective is to identify robust mechanisms, evidence limitations, and priority actions for resilient Yellow River irrigation district modernization.

2. Methodology

2.1. Review Design and Research Questions

This review combined a systematic search, bibliometric description, design-sensitive critical appraisal, and thematic narrative synthesis. The protocol followed the reporting logic of PRISMA 2020 [21], while bibliometric procedures followed Donthu et al. [22]. Prior basin-scale research identified substantial spatial differences in resilience levels, barrier factors, and evolutionary pathways among provinces and autonomous regions along the Yellow River [23], supporting a more operational synthesis at the irrigation district scale. Three questions guided this review: (1) What system boundary and capacity dimensions are appropriate for Yellow River irrigation districts? (2) How well do current indicators, process models, and optimization methods represent drought, diversion quotas, groundwater fluctuation, sediment, and water–salt imbalance? (3) How can assessment results be converted into closed-loop operational decisions that protect food production, water supply, and ecological baselines?

2.2. Search Strategy and Eligibility Criteria

The Web of Science Core Collection and the CNKI core journal database were searched from 1 January 2000 to 1 May 2026 (Table 1). Both searches were finalized on 1 May 2026, before the initial manuscript submission; records indexed after that date were not eligible. Table 1 reports the full search strings, document type and language rules, exclusions, and the roles of the core and background corpora. The geographic terms intentionally delimit the bibliometric corpus to Yellow River and arid-region applications. Foundational international theories were retrieved separately through backward and forward citation tracing and were used only for conceptual interpretation, not for bibliometric counts or keyword network construction.

Table 1. Search strategy, eligibility criteria, corpus roles, and final record counts.

CNKI Core-Journal Database/Common Rule	Web of Science Core Collection	Item
1 January 2000–1 May 2026; Chinese. Both searches finalized on 1 May 2026 before initial submission.	1 January 2000–1 May 2026; English	Coverage and language
Topic = (“water resources system” OR “irrigation district” OR “agricultural water”) AND Topic = (“resilience” OR “restorative capacity” OR “adaptive capacity” OR “vulnerability”) AND Topic = (“Yellow River” OR “arid region”)	TS = (“water resources system” OR “agricultural water” OR “irrigation district”) AND TS = (“resilience” OR “robustness” OR “adaptive capacity” OR “vulnerability”) AND TS = (“Yellow River” OR “arid region”)	Exact search string
Core-journal articles and reviews; peer-reviewed journal evidence relevant to water system resilience	Articles, reviews, and early-access articles	Eligible document types
Theses, doctoral dissertations, books, conference materials, editorials, news items, and off-topic records; no date extension	Conference materials, editorials, news items, books, dissertations, and off-topic records	Exclusions
Same role; n = 17. Final bilingual core corpus: n = 79	Bibliometric counts, keyword network, and thematic synthesis; n = 62	Core-corpus role and count
Interpretive use only; excluded from the 79-record bibliometric corpus	Backward/forward citation tracing of foundational international sources	Background/theory corpus

The core corpus was restricted to peer-reviewed journal articles and reviews in English or Chinese. Theses, dissertations, books, conference materials, editorials, news items, and other grey literature were excluded to maintain a common publication-quality threshold. This rule improves comparability but may omit locally detailed engineering and institutional evidence; the resulting scope is, therefore, treated explicitly as a limitation.

2.3. Screening and Corpus Construction

The database searches identified 99 records: 62 from Web of Science and 37 from CNKI. Title, DOI, and author–year checks found no complete duplicates. Document-type screening excluded 20 CNKI records (13 master’s theses, 4 doctoral dissertations, and 3 books). The remaining 79 journal articles underwent title/abstract and full-text eligibility assessment; no further exclusions were required. The final corpus, therefore, comprised 62 English-language and 17 Chinese-language articles (Figure 1).

The evidence base is modest and language-skewed: English articles account for 78.5% (62/79) and retained Chinese articles for 21.5% (17/79). Although 37 CNKI records were identified, only 17 met the journal-only rule. Excluding theses, dissertations, technical reports, and other grey literature may underrepresent field-level engineering experience, local governance innovations, and negative results. Accordingly, conclusions are framed as evidence-informed propositions that require local validation rather than as exhaustive estimates of all Yellow River irrigation district practice.

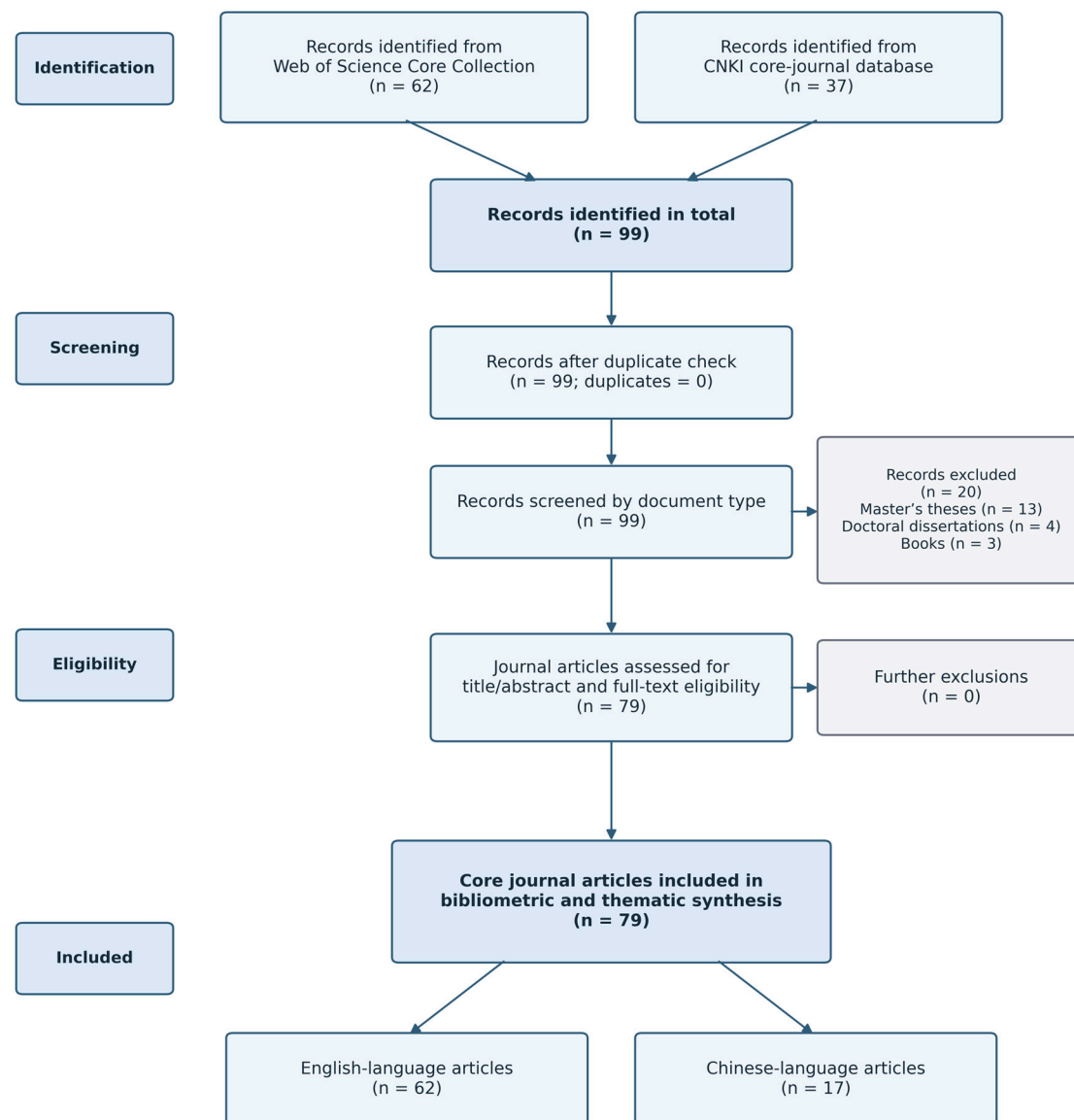


Figure 1. PRISMA-style flow diagram for identification, screening, eligibility assessment, and inclusion. Both databases were last searched on 1 May 2026, before the initial manuscript submission. No records were excluded after document-type screening.

2.4. Critical Appraisal and Evidence Weighting

Because the corpus includes conceptual papers, observational assessments, process model studies, optimization studies, and reviews, a single-effect study risk-of-bias tool would be inappropriate. We, therefore, used a design-sensitive appraisal informed by JBI critical appraisal principles [24]. Each study was examined for topical relevance, design and data transparency, calibration or external validation where applicable, uncertainty or sensitivity analysis, and reproducibility/transferability (Table 2). Evidence with transparent data and validated methods was given greater interpretive weight for operational claims. Conceptual studies and unvalidated case models were retained for theory development or hypothesis generation but were not treated as equivalent proof of intervention effectiveness. No pooled effect size was calculated because outcomes, scales, and designs were not commensurable.

Table 2. Design-sensitive critical appraisal domains and evidence-weighting rules used in the synthesis.

Limitation Signal and Use in Synthesis	Higher-Certainty Evidence	What Was Examined	Appraisal Domain
Ambiguous object or resilience equated with efficiency; used only as contextual evidence	Explicit irrigation/water system boundary and disturbance–function link	System object, disturbance, valued function, and management objective	Relevance and boundary
Opaque data, unexplained weighting, or selective reporting weakens descriptive and causal claims	Traceable data, justified indicators, and clear temporal/spatial scale	Sampling, indicators, data sources, scale, and analytical steps	Design and data transparency
No validation or in-sample fit only; not used alone for strong operational recommendations	Calibration plus independent, temporal, spatial, or cross-case validation	Testing against observations or independent evidence	Calibration and validation
Single deterministic result; thresholds and projected benefits treated cautiously	Sensitivity/uncertainty analysis with alternative scenarios	Parameter, scenario, structural, and stakeholder uncertainty	Uncertainty and sensitivity
Insufficient detail or unqualified generalization; case-specific insight only	Methods reproducible and boundary conditions specified	Availability of equations/parameters and transfer conditions	Reproducibility and transferability
Higher: operational synthesis; moderate: contextual inference; lower/contextual: hypothesis generation	Multiple domains satisfied, including validation for model-based claims	Evidentiary role assigned across the five domains	Overall weighting rule

2.5. Bibliometric and Thematic Synthesis

CiteSpace (version 7.0.0), VOSviewer (version 1.6.21), and the R bibliometrix/Biblioshiny (version 5.4.1) toolkit were used to standardize record fields, inspect duplicates, merge synonymous keywords, and summarize annual publication patterns. Terms such as “water resources resilience,” “WRSR,” and “water resource system resilience” were consolidated. Thematic synthesis then compared mechanisms, indicators, models, thresholds, and governance recommendations across the appraised evidence. Only the 79-record core corpus contributed to the quantitative and keyword analyses; the background corpus supported interpretation.

The annual distribution shows three stages: inception (2000–2005), fluctuating growth (2006–2017), and rapid growth (2018–2026). Table 3 adds representative studies and emphases to the verified publication counts.

Table 3. Annual publication volume, sample share, research emphasis, and representative studies in the core corpus.

Representative Studies	Research Emphasis	Core-Sample Share	Period and Publication Count	Development Stage
[25,26]	R–R–V concepts, allocation, and water management reform	1.27%	2000–2005; n = 1; 0.17 article/year	Inception
[13,27–31]	Climate adaptation, water security, governance, and social–ecological resilience	18.99%	2006–2017; n = 15; 1.25 articles/year	Fluctuating growth
[17–20,32–38]	Nexus resilience, extreme drought regulation, water–salt coupling, digitalization, and dynamic assessment	79.75%	2018–2026; n = 63; 7.00 articles/year	Rapid growth

objective is not only higher water productivity; it is the capacity to sustain or restore food production and ecological baselines under drought, flood, infrastructure failure, salinity, and institutional change [43–45].

In this review, an agricultural water resource system comprises six coupled components: water source supply, canal conveyance and distribution, field-level use, drainage and salt removal, ecological feedback, and institutional regulation. Sediment is treated as a cross-cutting process that affects intake reliability, canal capacity, drainage, and maintenance. Resilience is the time-dependent capacity of this system to absorb compound disturbances, maintain minimum food and ecological functions, restore damaged services, adapt operations and behavior, and transform structures or institutions when the existing pathway becomes untenable.

The framework distinguishes four capacities. Resistance is the ability to limit performance loss during a disturbance. Recovery is the rate and completeness with which critical functions return to an acceptable state. Adaptability is the ability to adjust operating rules, technologies, crop choices, and institutions while retaining the system’s core identity. Transformability is the ability to reconfigure infrastructure, resource portfolios, or governance when incremental adaptation can no longer maintain a safe operating space [10,17,27,32,46–49]. These capacities are related but not interchangeable; a district may resist a short drought yet remain unable to adapt to persistent quota tightening.

Table 4 translates the four capacities into measurable indicators. The indicators are a harmonization framework, not a universally validated composite index. Their thresholds, directions, and weights must be calibrated to crop calendars, infrastructure standards, groundwater conditions, salinity risks, and stakeholder priorities in each district.

Table 4. Illustrative operational indicators for the four resilience capacities in Yellow River irrigation districts.

Yellow River Application Example	Illustrative Indicators, Units, and Data	Operational Definition	Capacity
Adaptive intake and multi-source allocation in lower-reach diversion districts during low flow	Supply reliability (% satisfied periods); critical-stage deficit (%); canal/drain availability (% functional hours); and ecological flow compliance (% days). Data: gate/SCADA records, crop demand, inspections, and flow gauges.	Limits functional loss while a disturbance is active	Resistance
Canal desilting and repair, emergency recharge, and leaching after drought or failure	Time to restore supply (days); recovery slope (performance points/day); repair completion (%); and days for groundwater or root-zone salinity to return to target. Data: maintenance, water level, salinity, and remote-sensing records.	Restores critical functions after damage	Recovery
Surface water substitution and elastic groundwater use in middle-reach well–canal systems	Flexible allocation share (%); metered area (%); crop pattern change (% area); surface water substitution (%); and rule updates/year. Data: allocation plans, meters, crop maps, well records, and institutional documents.	Adjusts operations, technology, behavior, and rules under persistent change	Adaptability
Integrated water saving, drainage, salt control, and digital twin modernization in Hetao/Qingtongxia	Reconfigured infrastructure (% capacity); non-conventional water share (%); digital control coverage (% nodes); institutional redesign; and threshold exceedance frequency. Data: project, water account, platform, and policy records.	Reconfigures structure or governance when the previous pathway is unsustainable	Transformability

The system is nested across basin, irrigation district, and field scales [50]. Basin inflow, reservoir operation, ecological flow requirements, and allocation quotas define the district's external water boundary [51,52]. District-scale canal capacity, gate and pump control, drainage condition, metering, and water-right implementation determine distribution reliability and equity [53,54]. Field-scale soil water and salt, evapotranspiration, irrigation equipment, crop choice, and farmer decisions determine yield, consumptive use, and return-flow quality [55,56]. Physical flows, sediment and salt transport, policy transmission, and behavioral responses connect these scales; performance at one scale must, therefore, not be improved by transferring risk to another.

4. Research Methods for Irrigation District Water Resource System Resilience

4.1. Theoretical Methods

Theoretical approaches are moving from single-discipline analysis toward coupled-system explanations. Complex network theory identifies nodes, weighted links, critical pathways, and cascading failure risks among headworks, canals, drains, groundwater, crop stages, and institutions [28,33,57]. It also supports analysis of multi-actor governance among irrigation managers, farmers, water user associations, local governments, and ecological regulators, whose decisions affect water pricing, pumping, crop choice, and return flows [25,58,59]. Foundational sources used in this interpretation were retrieved through citation tracing and are not counted in the 79-record bibliometric corpus.

Adaptive cycle and panarchy theories describe nonlinear phases of exploitation, conservation, release, and reorganization and help identify when a district may cross a threshold into structural change [29,30]. They are especially relevant where biophysical processes and governance feedbacks create multiple stable states. However, ecological theory alone does not specify irrigation operating rules, engineering constraints, or farmer responses, so it must be connected to process models and institutional analysis.

A purpose-built irrigation district resilience theory should include the following: (i) an explicit six-component boundary and disturbance typology; (ii) the four time-dependent capacities; (iii) nested basin–district–field interactions; (iv) coupled water–sediment–salt–crop–ecology processes; (v) multi-actor behavioral and institutional feedbacks; (vi) thresholds, safe operating spaces, and regime shifts; (vii) food, equity, and ecological constraints; and (viii) a direct link from diagnosis to executable control. In this review, “multi-scale resilience symbiosis” means coordinated resilience across nested scales without transferring risk; for example, meeting a basin withdrawal quota must not be achieved by causing field-scale salt accumulation, aquifer depletion, or unacceptable yield loss. This definition converts a broad ecological metaphor into a testable cross-scale requirement.

4.2. Model Methods

Models provide complementary representations of hydrology, engineering, crops, and institutions (Table 5). WEAP is suited to demand-driven allocation, scenario comparison, and scheduling priorities [26]. Coupling WEAP with MODFLOW can represent how surface water allocation affects groundwater heads and storage, while climate scenarios should test temperature, precipitation, drought duration, and evapotranspiration uncertainty [60]. Model selection must follow the decision question and spatial–temporal scale rather than assuming that one model captures all resilience capacities.

AquaCrop simulates crop biomass and yield responses to water supply and stress at the field scale [61]. SWAT represents rainfall–runoff, land use, and basin hydrological processes [62]. MODFLOW is a groundwater-flow model for aquifer heads, storage, pumping, and surface water–groundwater interaction [63]; it does not simulate grain yield by

itself. The study cited in reference [64] estimated irrigation demand and grain yield with AquaCrop-OS, not MODFLOW. Yield or food security assessment, therefore, requires a crop, statistical, or agro-economic model coupled to groundwater outputs.

Positive mathematical programming (PMP) calibrates production behavior and can test how water prices, rights, quotas, and subsidies affect crop choice [65]. Multi-objective optimization can then balance water, land, farm income, energy, food, and ecological constraints [66,67]. These economic tools should be coupled with hydrological and crop models when policy responses alter pumping, canal demand, or return flows.

Table 5. Principal models for irrigation district resilience assessment, appropriate outputs, and coupling requirements.

Model	Type and Principal Outputs	Appropriate Resilience Use/Limitation	Refs.
WEAP	Allocation/planning: multi-source supply–demand balance, priorities, and scenarios	Basin/district planning and drought scheduling; coupling is needed for groundwater heads and crop yield	[26,34]
MODFLOW	Groundwater flow: heads, storage, pumping effects, and surface water–groundwater exchange	Conjunctive use and over-extraction analysis; does not simulate crop yield independently	[34,63]
SWAT	Distributed hydrology: rainfall–runoff, sediment, land-use, and basin response	Provides catchment/large-district boundary conditions; limited field and institutional detail without coupling	[62]
AquaCrop/AquaCrop-OS	Crop water productivity: biomass, yield, evapotranspiration, and water stress	Field irrigation and food security analysis; requires hydrological inputs for groundwater feedbacks	[61,64]
PMP	Economic behavior: calibrated crop choice, production, and policy response	Tests water price, rights, quotas, and subsidies; requires biophysical constraints	[65]
Multi-objective optimization	Trade-off solutions for water, land, food, income, energy, and ecology	Decision support under multiple constraints; sensitive to objectives, weights, and uncertainty	[66,67]

The main methodological gap is not a lack of models but weak coupling, validation, and uncertainty propagation. Future model chains should follow a mechanism–parameter–validation sequence; represent basin, district, and field feedbacks; and report how parameter, scenario, structural, and behavioral uncertainty affects resistance, recovery, adaptation, and transformation estimates. Artificial intelligence and digital twins can support emulation and real-time updating, but they should not replace physical constraints or independent validation.

5. Resilience Assessment of Water Resource Systems in Yellow River Irrigation Districts

Irrigation district assessment has moved from pressure–state–response (PSR) and driver–pressure–state–impact–response (DPSIR) structures toward capacity-based and social–ecological–engineering frameworks [31,68–71]. PSR/DPSIR organizes causal chains; DEA–Malmquist identifies changes in production efficiency and technology [69]; and capacity frameworks describe performance during and after disturbance. Neither is sufficient by itself. A district-scale assessment should include intake reliability, canal sedimentation, safe

groundwater depth, drainage and salt removal efficiency, root-zone salinity, return-flow quality, water-right flexibility, metering, and farmer response.

Three broad indicator families are evident in the literature:

- (1) PSR/DPSIR systems link socioeconomic drivers, water-use pressure, hydrological and ecological state, functional impacts, and policy responses [2,31]. Their strength is causal organization; their limitation is that annual composite scores may conceal failure timing and recovery dynamics.
- (2) Capacity-based systems extend R–R–V concepts to resistance, recovery, adaptability, and transformability [10,33]. Their strength is explicit disturbance performance; their limitation is inconsistent operational definitions and thresholds across studies. Table 4 provides a harmonized starting point.
- (3) Social–ecological–engineering systems integrate water, economy, ecology, institutions, and infrastructure [70,71]. They improve boundary completeness but can become highly aggregated, weight-sensitive, and difficult to translate into operational commands.

Most assessments still use annual statistics, combined subjective–objective weights, multi-criteria analysis, or barrier models. These methods support regional comparison but do not identify when to trigger emergency allocation, how much minimum irrigation or leaching water is required, or when pumping must stop [72]. Dynamic assessment should, therefore, define observable thresholds for minimum crop-stage supply, root-zone salinity, safe groundwater depth, drainage discharge, canal conveyance capacity, ecological flow, and sediment deposition. Thresholds should be tested in compound events and linked to predefined actions.

Dominant risks vary both among and within Yellow River reaches. Table 6 is, therefore, an illustrative typology based on representative cases, not an exhaustive classification. Each risk chain and intervention requires local data, stakeholder review, and threshold calibration before implementation.

Table 6. Illustrative resilience risk typology, transmission chains, and differentiated governance options for representative Yellow River irrigation districts.

District Type and Representative Cases	Core Risk and Illustrative Transmission Chain	Differentiated Governance Options	Refs.
Upper-reach arid/semi-arid: Hetao and Qingtongxia	Rigid diversion constraint → insufficient leaching/groundwater change → root-zone salinity → yield and wetland impacts	Coordinate irrigation, drainage, and salt control; protect minimum leaching and ecological water; and combine precision irrigation with suitable drainage	[35,47,53–56,73]
Middle-reach conjunctive well–canal: Guanzhong/Jinghuiqu and Fen–Wei systems	Surface-water shortage → chronic emergency pumping → aquifer decline → energy-cost and ecological-flow losses	Substitute surface water; use safe-threshold flexible pumping; recharge in wet periods; adjust crops; and jointly schedule wells and canals	[17,19,34,41,72]
Lower-reach diversion: Henan and Shandong districts	Low flow, quota restriction, or sedimentation → intake/allocation shortfall → reduced irrigation reliability → food production risk	Use adaptive headworks intake, multi-source allocation, sediment management, rotational scheduling, and suitable reclaimed/local water	[17,36,45,46,51,52]

Note: The cases and strategies synthesize representative evidence. Risk intensity and intervention effectiveness vary within each reach; the table should not substitute for district-specific hydrogeological, salinity, infrastructure, economic, or governance assessment.

6. Strategies for Enhancing Water Resource System Resilience in Yellow River Irrigation Districts

6.1. Coordinated Regulation Strategies for Engineering and Management

Enhancing resilience requires coordinated engineering, operational, and institutional measures. Single-purpose water-saving projects may create new risks if they reduce leaching, increase energy use, or shift shortages to vulnerable farmers. The following strategies, therefore, pair physical interventions with operating rules, monitoring, incentives, and safeguards.

- (1) Coordinate irrigation, drainage, and water–salt control. In arid upper and middle reaches, excessive diversion reduction can lower leaching and trigger secondary salinization. Water saving should, therefore, be evaluated jointly with drainage performance, soil salinity, crop returns, and ecological requirements [35,73]. Priority actions include maintaining backbone drains, using subsurface drainage where appropriate, monitoring root-zone salinity and groundwater depth, and defining a minimum leaching requirement. Irrigation quotas should protect long-term soil productivity rather than maximize short-term diversion reduction.
- (2) Combine multi-source substitution with flexible groundwater use. Where seasonal drought coexists with groundwater depletion, a permanent pumping ban can reduce short-term resistance, whereas unrestricted pumping destroys long-term resilience. Districts should improve surface-water conveyance and storage, capture suitable wet-season water for recharge, and incorporate Yellow River water, local surface water, reclaimed water, and groundwater into one allocation plan. Emergency pumping should be allowed only within monitored safe-depth and recovery thresholds, so groundwater functions as a drought reserve rather than a routine supply [36].
- (3) Link infrastructure modernization to precision operation. Canal lining, sediment management, gate and pump automation, drainage rehabilitation, and reliable volumetric metering improve resistance and recovery only when matched by maintenance and scheduling. IoT and SCADA data should support crop-demand-based rotational irrigation, transparent volumetric charging, and contingency plans. Engineering upgrades and operating rules should be evaluated together to avoid creating unused digital or hydraulic capacity.

6.2. Governance Strategies Combining Rigid Constraints and Flexible Regulation

Governance should combine rigid safeguards with flexible incentives. Water-right confirmation, total-use control, quota limits, ecological-flow requirements, and metering establish non-negotiable boundaries. Tiered agricultural water pricing, local water-right exchange, benefit sharing, disaster insurance, and participatory scheduling provide room to adapt within those boundaries. Institutional trust and risk sharing are important for climate resilience [74]. A collaborative network among government, district managers, water-user associations, farmers, and ecological regulators is, therefore, preferable to water-saving mandates alone.

6.3. Closed-Loop Regulation Strategies Supported by Digital Twin Technology

“Digital twin-based closed-loop regulation” is defined here as a continuously updated virtual representation that links monitoring, state estimation, forecasting, optimization, operational commands, and feedback correction. It should move management from post-event assessment to an iterative cycle of early warning, online diagnosis, scheduling, execution, and performance verification. The engineering foundation includes reliable canals, pumps, gates, meters, and drains [37,38]. The information layer integrates satellite and UAV observations, soil moisture and salinity sensors, groundwater monitoring, and

pump-and-gate SCADA. Physical models and optimization algorithms then generate constrained actions for multi-source allocation, canal rotation, recharge, drainage, salt removal, and gate control. Human authorization, fallback rules, cyber/data quality checks, and post-action evaluation remain essential.

7. Conclusions and Prospects

7.1. Conclusions

- (1) Yellow River irrigation districts are nested basin–district–field systems. Their resilience depends on a six-component boundary—water source supply, canal conveyance and distribution, field-level use, drainage and salt removal, ecological feedback, and institutional regulation—and on cross-cutting sediment, groundwater, crop, and behavioral processes. Resilience should, therefore, be distinguished from static efficiency or supply–demand balance.
- (2) Existing research provides useful complex-network, adaptive-cycle, index, hydrological, crop, economic, and optimization methods. However, operational definitions, validation, uncertainty analysis, and cross-scale coupling remain inconsistent. MODFLOW should be used for groundwater dynamics, while yield and food-security outputs require crop or agro-economic models.
- (3) Four capacities—resistance, recovery, adaptability, and transformability—should be measured separately and linked to disturbance-specific thresholds. The illustrative indicators in Table 4 provide a basis for comparing performance while preserving local calibration.
- (4) Management priorities are geographically differentiated. Upstream districts require coordinated water–salt–ecology control; middle-reach well–canal systems require surface-water substitution and groundwater recovery; and lower-reach diversion districts require multi-source allocation, adaptive intake, and sediment management. Across all reaches, assessment must be translated into executable schedules and feedback.

7.2. Prospects

This review identifies four persistent research gaps:

- (1) Conceptual ambiguity: efficiency, carrying capacity, and supply–demand balance are sometimes treated as resilience, even when water saving reduces leaching and increases salinity risk.
- (2) Indicator homogenization: provincial or urban indicators often omit intake reliability, sediment, safe groundwater depth, drainage, root-zone salinity, return-flow quality, water-right flexibility, and farmer response.
- (3) Static diagnosis: annual indices rarely identify disturbance-specific failure thresholds, recovery trajectories, cascading mechanisms, or uncertainty.
- (4) Implementation gap: resilience scores and barrier rankings are seldom translated into canal rotation plans, pumping limits, recharge programs, leaching requirements, sediment operations, water-right rules, or emergency actions.

This review also has important limitations. The 79-record core corpus is small, recent, and language-skewed; the geographic search terms exclude broader international applications from the bibliometric counts; and the journal-only rule omits theses, reports, and other grey literature that may contain detailed Chinese engineering and institutional evidence. Heterogeneous outcomes precluded meta-analysis, and incomplete harmonization of affiliation fields precluded reproducible country or institution rankings. The proposed indicators, typology, and evidence-weighting framework should, therefore, be tested with district-level data and stakeholder input. Future reviews should expand multilingual

databases, include a separately appraised grey-literature stream, preregister extraction and appraisal procedures, and preserve article-level quality and affiliation metadata.

Future research should pursue three connected directions. First, it should test a purpose-built theory of multi-scale resilience symbiosis—coordinated basin–district–field performance without transferring risk across scales—using explicit food, equity, ecological, and safe-groundwater constraints. Second, it should couple WEAP, MODFLOW, AquaCrop, SWAT, PMP, and agent-based models only where their boundaries and data support the decision problem, with calibration, independent validation, and uncertainty propagation. Third, it should develop digital twin closed loops that connect monitoring and forecasts to authorized operational commands and feedback correction. The practical test of progress is whether research can reliably convert thresholds and scenarios into canal rotation, recharge, drainage, salt-control, sediment-management, water-right, and emergency plans under compound climate and policy uncertainty.

Author Contributions: J.Y.: data collection and processing, visualization, and writing—original draft. W.Y.: review and editing, funding acquisition, and project administration. C.C., X.H., P.X. and J.B.: review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Basic R&D Special Fund of Central Government for Non-profit Research Institutes (Grant No. HKY-JBYW-2026-21) and the Innovation Scientists and Technicians Troop Construction Projects of Henan Province (Grant No. 244400510011).

Data Availability Statement: The bibliographic sources analyzed in this review are cited in this article. The search strings, eligibility criteria, screening counts, and appraisal domains required to reproduce the review logic are reported in Section 2 and Tables 1–3. Further record-level information may be requested from the corresponding author.

Acknowledgments: We acknowledge the support granted to Jingwei Yao by the China Scholarship Council (CSC No. 202303340011).

Conflicts of Interest: All the authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Central Committee of the Communist Party of China; State Council. Outline of the Plan for Ecological Protection and High-Quality Development of the Yellow River Basin. 8 October 2021. Available online: https://www.gov.cn/zhengce/2021-10/08/content_5641438.htm (accessed on 2 August 2026).
2. Wang, H.; Li, N.; Liu, Y.; Liu, Y. Dynamic coupling and hierarchical obstacle analysis of water resources and ecological resilience in the Yellow River Basin. *Arid. Land Geogr.* **2026**, *49*, 569–580. [CrossRef]
3. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]
4. Zhao, Z.; Wang, H.; Zhang, L.; Liu, X.; Zhao, Y. Construction and application of resilience evaluation model of water resources–water environment–social economy complex system in the Yangtze River Economic Belt. *Adv. Water Sci.* **2022**, *33*, 705–717. Available online: <http://skxjz.nhri.cn/cn/article/id/33d7eabe-de76-415b-9f02-8f898a850f76> (accessed on 2 August 2026).
5. Meerow, S.; Newell, J.P.; Stults, M. Defining Urban Resilience: A Review. *Landsc. Urban Plan.* **2016**, *147*, 38–49. [CrossRef]
6. Biddle, L.; Wahedi, K.; Bozorgmehr, K. Health System Resilience: A Literature Review of Empirical Research. *Health Policy Plan.* **2020**, *35*, 1084–1109. [CrossRef]
7. Folke, C. Resilience: The Emergence of a Perspective for Social–Ecological Systems Analyses. *Glob. Environ. Change* **2006**, *16*, 253–267. [CrossRef]
8. Walker, B.; Holling, C.S.; Carpenter, S.; Kinzig, A. Resilience, Adaptability and Transformability in Social–Ecological Systems. *Ecol. Soc.* **2004**, *9*, art5. [CrossRef]
9. Wang, C.; Blackmore, J.M. Resilience Concepts for Water Resource Systems. *J. Water Resour. Plan.* **2009**, *135*, 528–536. [CrossRef]
10. Hashimoto, T.; Stedinger, J.R.; Loucks, D.P. Reliability, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation. *Water Resour. Res.* **1982**, *18*, 14–20. [CrossRef]
11. Kahn, M.E. *Climatopolis: How Our Cities Will Thrive in the Hotter Future*; Basic Books: New York, NY, USA, 2010.

12. Partnerships and Cooperation for Water | UN World Water Development Report. 2023. Available online: <https://www.unesco.org/reports/wwdr/2023/en> (accessed on 2 June 2026).
13. Pahl-Wostl, C. Transitions towards Adaptive Management of Water Facing Climate and Global Change. *Water Resour. Manag.* **2006**, *21*, 49–62. [\[CrossRef\]](#)
14. Asghari, F.; Piadeh, F.; Egyir, D.; Yousefi, H.; Rizzuto, J.P.; Campos, L.C.; Behzadian, K. Resilience Assessment in Urban Water Infrastructure: A Critical Review of Approaches, Strategies and Applications. *Sustainability* **2023**, *15*, 11151. [\[CrossRef\]](#)
15. Liu, L.; Mijic, A. Performance-Based Resilience Assessment in Integrated Water Systems: Challenges and Opportunities. *J. Hydrol.* **2025**, *662*, 134042. [\[CrossRef\]](#)
16. Wang, Y.; Wan, F.; Peng, S.; Zheng, X.; Han, W.; Yan, D.; Wang, W.; Zhang, D. Resilience Level Assessment of Regional Water Resources System Based on Multi-Link. *Ecol. Indic.* **2024**, *160*, 111943. [\[CrossRef\]](#)
17. Wang, Y.; Zheng, X.; Lv, H.; Peng, S.; Zhou, X.; Shang, W.; Zhang, D. Research on resilience regulation of water resource systems in the Yellow River basin during extreme drought years. *Adv. Water Sci.* **2025**, *36*, 359–371. [\[CrossRef\]](#)
18. Lu, C.; Ji, W.; Hou, M.; Ma, T.; Mao, J. Evaluation of Efficiency and Resilience of Agricultural Water Resources System in the Yellow River Basin, China. *Agric. Water Manag.* **2022**, *266*, 107605. [\[CrossRef\]](#)
19. Niu, X.; He, Z.; Chen, Y.; Liu, Y. Decrypting Water–Energy–Food Nexus Resilience in the Yellow River Basin: Spatiotemporal Evolution, Internal Obstacles, and External Drivers. *J. Clean. Prod.* **2026**, *542*, 147527. [\[CrossRef\]](#)
20. Tian, G.; Li, J.; Wu, Z.; Zhao, Q.; Xia, Q.; Zhang, J.; Niu, X. Unveiling the Resilience of the Water-Energy-Food Nexus: A Context-Specific Framework and Evolutionary Insights for the Yellow River Basin. *Agric. Water Manag.* **2025**, *315*, 109514. [\[CrossRef\]](#)
21. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [\[CrossRef\]](#)
23. Wan, F.; Kang, Y.; Wang, Y.; Wang, W.; Guo, H.; Zhao, P.; Zhao, J.; Zhou, Z.; Li, M. Resilience Assessment and Spatiotemporal Evolution Analysis of Water Resources System in the Provinces along the Yellow River. *Sci. Rep.* **2025**, *16*, 1904. [\[CrossRef\]](#) [\[PubMed\]](#)
24. JBI. Critical Appraisal Tools. Available online: <https://jbi.global/critical-appraisal-tools> (accessed on 2 August 2026).
25. Wang, J.; Xu, Z.; Huang, J.; Rozelle, S. Incentives in Water Management Reform: Assessing the Effect on Water Use, Production, and Poverty in the Yellow River Basin. *Environ. Dev. Econ.* **2005**, *10*, 769–799. [\[CrossRef\]](#)
26. Yates, D.; Sieber, J.; Purkey, D.; Huber-Lee, A. WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 1: Model Characteristics. *Water Int.* **2005**, *30*, 487–500. [\[CrossRef\]](#)
27. Béné, C.; Doyen, L. From Resistance to Transformation: A Generic Metric of Resilience through Viability. *Earth's Future* **2018**, *6*, 979–996. [\[CrossRef\]](#)
28. Gao, J.; Barzel, B.; Barabási, A.-L. Universal Resilience Patterns in Complex Networks. *Nature* **2016**, *530*, 307–312. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Gunderson, L.; Cosens, B.A.; Chaffin, B.C.; Arnold, C.A.; Fremier, A.K.; Garmestani, A.S.; Craig, R.K.; Gosnell, H.; Birge, H.E.; Allen, C.R.; et al. Regime Shifts and Panarchies in Regional Scale Social–Ecological Water Systems. *Ecol. Soc.* **2017**, *22*, 31. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Allen, C.R.; Angeler, D.G.; Garmestani, A.S.; Gunderson, L.H.; Holling, C.S. Panarchy: Theory and Application. *Ecosystems* **2014**, *17*, 578–589. [\[CrossRef\]](#)
31. Sun, S.; Wang, Y.; Liu, J.; Cai, H.; Wu, P.; Geng, Q.; Xu, L. Sustainability Assessment of Regional Water Resources under the DPSIR Framework. *J. Hydrol.* **2016**, *532*, 140–148. [\[CrossRef\]](#)
32. Zhang, Y.; Bian, X.; Zhang, H.; Li, N.; Gao, Q.; Zhang, B. Research on the Application Prospect of Digital Twin in Large Irrigation Area. *J. Irrig. Drain.* **2022**, *41*, 71. [\[CrossRef\]](#)
33. Wang, Y.; Wan, F.; Wang, W.; Han, W.; Zheng, X.; Zhang, D.; Lv, H. Complex network characteristics and resilience-driving mechanisms of water resource systems in river basin. *Adv. Water Sci.* **2025**, *36*, 190–203. [\[CrossRef\]](#)
34. Li, X.; Jiang, Y. Resilience Assessment of Water Resources System in Jinghuiqu Irrigation District Based on a WEAP–MODFLOW Coupled Model. *J. Drain. Irrig. Mach. Eng.* **2026**, *44*, 48–57. [\[CrossRef\]](#)
35. Feng, Z.; Miao, Q.; Shi, H.; Gonçalves, J.M.; Li, R. Water Saving and Environmental Issues in the Hetao Irrigation District, the Yellow River Basin: Development Perspective Analysis. *Agronomy* **2025**, *15*, 1654. [\[CrossRef\]](#)
36. Wan, F.; Shen, X.; Shanguan, Q.; Lv, H.; Li, M.; Yang, Y.; Shang, W.; Zhou, Z.; Xiao, L. Spatio-Temporal Evolution of Water Resource System Resilience in the Yellow River Water Supply Area in Henan. *J. Hydrol. Reg. Stud.* **2026**, *65*, 103390. [\[CrossRef\]](#)
37. Wei, S.; Zhai, L.; Liu, C.; Wang, K.; Li, J. Resilience Assessment of Irrigation District Infrastructure: Indicators, Modeling, and Empirical Application. *Water* **2025**, *17*, 1214. [\[CrossRef\]](#)

38. Esteves, R.; Calejo, M.J.; Rolim, J.; Teixeira, J.L.; Cameira, M.R. Framework for Assessing Collective Irrigation Systems Resilience to Climate Change—The Maiorga Case Study. *Agronomy* **2023**, *13*, 661. [\[CrossRef\]](#)
39. Fernald, A.; Guldán, S.; Boykin, K.; Cibils, A.; Gonzales, M.; Hurd, B.; Lopez, S.; Ochoa, C.; Ortiz, M.; Rivera, J.; et al. Linked Hydrologic and Social Systems That Support Resilience of Traditional Irrigation Communities. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 293–307. [\[CrossRef\]](#)
40. Cox, M. Applying a Social-Ecological System Framework to the Study of the Taos Valley Irrigation System. *Hum. Ecol.* **2014**, *42*, 311–324. [\[CrossRef\]](#)
41. Zheng, X.; Wang, Y.; Zhang, D.; Ma, C.; Wang, H. Driving factors and regulation strategies for resilience of water resources system in the Yellow River Basin. *J. Hydraul. Eng.* **2025**, *56*, 1253–1266. [\[CrossRef\]](#)
42. Rodina, L. Defining “Water Resilience”: Debates, Concepts, Approaches, and Gaps. *WIREs Water* **2019**, *6*, e1334. [\[CrossRef\]](#)
43. Sikka, A.K.; Alam, M.F.; Mandave, V. Agricultural Water Management Practices to Improve the Climate Resilience of Irrigated Agriculture in India. *Irrig. Drain.* **2022**, *71*, 7–26. [\[CrossRef\]](#)
44. Zhang, Y.; Yang, P.; Liu, J.; Zhang, X.; Zhao, Y.; Zhang, Q.; Li, L. Sustainable Agricultural Water Management in the Yellow River Basin, China. *Agric. Water Manag.* **2023**, *288*, 108473. [\[CrossRef\]](#)
45. Zhang, W.; Liang, W.; Gao, X.; Gao, X.; Li, S.; Zhao, X. Integrated Strategies for Water Sustainability in the Yellow River Basin: Roles of Water Transfer, Reclaimed Water, and Irrigation Efficiency. *Agric. Water Manag.* **2025**, *318*, 109694. [\[CrossRef\]](#)
46. Wang, Y.; Zheng, X.; Peng, S.; Zhang, D.; Lü, H.; Shang, W. Research and Prospect of Water Resources Allocation in the Yellow River Basin. *Yellow River* **2024**, *46*, 18–24. [\[CrossRef\]](#)
47. Du, X.; Yan, B.; Xu, K.; Wang, S.; Gao, Z.; Ren, X.; Hu, S.; Yun, W. Research Progress on Water–Salt Transport Theories and Models in Saline–Alkali Soils. *Chin. J. Soil Sci.* **2021**, *52*, 713–721. [\[CrossRef\]](#)
48. Qin, T.; Tong, J.; Zhi, Y. Influence and effect of water rights trading mechanism on agricultural water use efficiency. *J. Nat. Resour.* **2022**, *37*, 3282–3296. [\[CrossRef\]](#)
49. Ma, Y. Accelerating Modernization and Water-Saving Technology Application in Irrigation Districts to Promote Ecological Protection and High-Quality Development in the Yellow River Basin—An Interview with Academician Kang Shaozong of the Chinese Academy of Engineering. *China Water Resources*, 22 October 2021; pp. 4–7. Available online: <https://www.waterconserving.cn/talks/detail/2630> (accessed on 2 August 2026).
50. Zhang, N.; Su, X.; Zhou, Y.; Niu, J. Water resources carrying capacity evaluation of the Yellow River Basin based on EFAST weight algorithm. *J. Nat. Resour.* **2019**, *34*, 1759–1770. [\[CrossRef\]](#)
51. Qiao, X. Review and Prospect of Integrated Water Regulation of the Yellow River. *Yellow River* **2019**, *41*, 1–5. [\[CrossRef\]](#)
52. Wang, Y.; Peng, S.; Zheng, X. Key scientific issues of water allocation plan optimization and comprehensive operation for Yellow River basin. *Adv. Water Sci.* **2018**, *29*, 614–624. [\[CrossRef\]](#)
53. Shi, H.; Yang, S.; Li, R.; Li, X.; Li, W.; Yan, J.; Miao, Q.; Li, Z. Soil Water and Salt Movement and Soil Salinization Control in Hetao Irrigation District: Current State and Future Prospect. *J. Irrig. Drain.* **2020**, *39*, 1–17. [\[CrossRef\]](#)
54. Meng, H.; Zhan, C.; Hu, S.; Lin, Z. Research progress on simulation of soil water-salt transport in large-scale irrigation districts. *Arid. Land Geogr.* **2024**, *47*, 1566–1576. [\[CrossRef\]](#)
55. Wang, Y.; Gao, M.; Chen, H.; Fu, X.; Wang, L.; Wang, R. Soil Moisture and Salinity Dynamics of Drip Irrigation in Saline-Alkali Soil of the Yellow River Basin. *Front. Environ. Sci.* **2023**, *11*, 1130455. [\[CrossRef\]](#)
56. He, K.; Zhang, Q.; Ai, Z.; Xu, N.; Qiao, Y.; Tian, C.; Leng, P.; Cheng, H.; Chen, G.; Li, F. Characteristics and Influence Factors of Soil Water and Salt Movement in the Yellow River Irrigation District. *Agronomy* **2024**, *14*, 92. [\[CrossRef\]](#)
57. Diao, K.; Sweetapple, C.; Farmani, R.; Fu, G.; Ward, S.; Butler, D. Global Resilience Analysis of Water Distribution Systems. *Water Res.* **2016**, *106*, 383–393. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Hu, Z.; Wang, Y. Farmers’ evaluation, cause analysis and improvement suggestions on groundwater over-exploited comprehensive governance. *China Popul. Resour. Environ.* **2018**, *28*, 161–168. Available online: http://wanfangdata.com.cn/details/detail.do?_type=perio&id=zgrkzyyhj201810019 (accessed on 2 August 2026).
59. Luo, W.; Zhao, D.; Wang, J. Decision-making behavior of stakeholders in irrigation water rights trading based on evolutionary game theory. *J. Econ. Water Resour.* **2025**, *43*, 13–19. Available online: <https://jour.hhu.edu.cn/sljj/article/abstract/20250303> (accessed on 2 August 2026).
60. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022—Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2023; ISBN 978-1-009-32584-4.
61. Steduto, P.; Hsiao, T.C.; Raes, D.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts Underlying Principles. *Agron. J.* **2009**, *101*, 426–437. [\[CrossRef\]](#)
62. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large Area Hydrologic Modeling and Assessment Part I: Model Development. *JAWRA J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [\[CrossRef\]](#)

63. Harbaugh, A.W. MODFLOW-2005: The U.S. Geological Survey Modular Ground-Water Model—The Ground-Water Flow Process; U.S. Geological Survey Techniques and Methods 6-A16, 2005. Available online: <https://pubs.usgs.gov/publication/tm6A16> (accessed on 2 August 2026). [[CrossRef](#)]
64. Niu, C.; Qi, Y.; Guo, A.; Chang, J. Grain Yield and Food Security Evaluation in the Yellow River Basin under Climate Change and Water Resources Constraints. *Front. Water* **2022**, *4*, 908945. [[CrossRef](#)]
65. Howitt, R.E. Positive Mathematical Programming. *Am. J. Agric. Econ.* **1995**, *77*, 329–342. [[CrossRef](#)] [[PubMed](#)]
66. Li, M.; Cao, X.; Liu, D.; Fu, Q.; Li, T.; Shang, R. Sustainable Management of Agricultural Water and Land Resources under Changing Climate and Socio-Economic Conditions: A Multi-Dimensional Optimization Approach. *Agric. Water Manag.* **2022**, *259*, 107235. [[CrossRef](#)]
67. Zhang, Y.; Wang, Y. Water–Energy–Food Nexus in the Yellow River Basin of China under the Influence of Multiple Policies. *Land* **2024**, *13*, 1356. [[CrossRef](#)]
68. Tian, G.; Sun, Z.; Jing, X.; Yang, Y. Research on strategies for enhancing the resilience of the “Water–Energy–Food–Carbon” system in the Yellow River Basin under the background of high quality development. *China Rural Water Hydropower* **2024**, 1–11. [[CrossRef](#)]
69. Cheng, X.; Bian, J.; He, D.; Tang, D. An Analysis of Agricultural Production Efficiency of Yellow River Basin Based on a Three-Stage DEA Malmquist Model. *Humanit. Soc. Sci. Commun.* **2025**, *12*, 1343. [[CrossRef](#)]
70. Wang, Y.; Chen, Y.; Wang, H.; Lv, Y.; Hao, Y.; Cui, X.; Wang, Y.; Hu, R.; Xue, K.; Fu, B. Ecosystem Change and Its Ecohydrological Effect in the Yellow River Basin. *Bull. Natl. Nat. Sci. Found. China* **2021**, *35*, 521–528. [[CrossRef](#)]
71. Liu, L.; Wang, Y. Spatiotemporal Evolution and Influencing Factors Analysis of the Resilience of the Water-society-economy System in the Yellow River Basin. *Environ. Sci.* **2026**, *47*, 2673–2687. [[CrossRef](#)] [[PubMed](#)]
72. Wan, F.; Wang, Y.; Wang, W.; Zheng, X.; Han, W.; Yan, D.; Zhang, D. Influences of water network construction on water resources system resilience evolution in the Fenhe River Basin. *Water Resour. Prot.* **2025**, *41*, 19–26. [[CrossRef](#)]
73. Cao, Z.; Zhu, T.; Cai, X. Hydro-Agro-Economic Optimization for Irrigated Farming in an Arid Region: The Hetao Irrigation District, Inner Mongolia. *Agric. Water Manag.* **2023**, *277*, 108095. [[CrossRef](#)]
74. Hurlbert, M.; Mussetta, P. Creating Resilient Water Governance for Irrigated Producers in Mendoza, Argentina. *Environ. Sci. Policy* **2016**, *58*, 83–94. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.