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Review

Intelligent technology-driven synergistic governance of the water-energy-food-ecology nexus in the Yellow River Basin: A paradigm for resilient and sustainable resource management [version 1]

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ABSTRACT

The Yellow River Basin, a critical ecological and economic corridor in China, faces escalating pressures from competing demands for water, energy, and food, exacerbated by climate change and fragmented governance frameworks. This review presents an integrated governance paradigm that leverages intelligent technologies—such as digital twins, AI-driven analytics, IoT networks, and multi-source remote sensing—to address the nonlinear interdependencies within the water-energy-food-ecology (WEFE) nexus. By synthesizing spatiotemporal data from GF-1, Landsat-8, and UAV hyperspectral platforms with machine learning algorithms (e.g., Random Forest, Extra Trees), this study develops precision management strategies for soil moisture monitoring, irrigation optimization, and renewable energy integration. Key innovations include blockchain-enabled carbon trading mechanisms, predictive flood modeling with an accuracy of 92.3%, and adaptive resource allocation frameworks that enhance water use efficiency by 30% and renewable energy integration by 15%. The proposed governance model emphasizes cross-sectoral coordination, differentiated regional pathways (e.g., upstream soil conservation and midstream pollution control), and market-driven mechanisms such as green financing and ecological compensation. Findings demonstrate that AI-enhanced digital twins and IoT-based "perception-analysis-decision-execution" systems enable a dynamic equilibrium between ecological preservation and socioeconomic development. This paradigm not only addresses systemic trade-offs in the Yellow River Basin but also establishes a replicable blueprint for global river basin governance, advancing the transition toward ecological civilization through technology-driven resilience and multi-stakeholder collaboration.

KEYWORDS

Intelligent basin governance, digital twin systems, sustainable development, Yellow River Basin, ecological compensation..

1 Introduction

The Yellow River Basin emerges as a multifunctional geostrategic entity, serving as both a hierarchical ecological safeguard and an economic lifeline for China. This dual role emphasizes the intricate balance of national food security, energy provisioning, and ecological resilience. It underscores the necessity of adopting spatially differentiated, ecology-sensitive strategies to address the pronounced disparities in environmental vulnerability and socio-economic development pressures between upstream and downstream regions (Zhang et al., 2024). However, entrenched structural contradictions stemming from mismatches between ecological sensitivity gradients and governance scales have intensified systemic tensions between resource exploitation and ecological preservation in the basin (Daniell and Barreteau, 2014). These contradictions are further exacerbated by fragmented institutional frameworks that inadequately account for regional differentiation in ecological vulnerability assessments. This misalignment results in suboptimal coordination between spatially explicit conservation priorities and socioeconomic development pressures.

Escalating competition within the water-energy-food (WEF) Nexus has exerted profound pressures on ecological water provisioning in ecologically fragile regions such as Northern Shaanxi. Empirical analysis indicates that agricultural irrigation demands and energy production activities are engaged in intense competition for water resources, with the blue water footprint of energy production increasing from 3.25 Gm^3 in 1997 to 12.54 Gm^3 in 2016. This region exemplifies the classification of a "water pressure-dominated area" ($I_{WS} \geq 2$), where unsustainable water appropriation practices have reduced ecological water allocations by 19.36% over two decades, underscoring the urgent need for basin-scale coordination mechanisms (Hua et al., 2021). Substantial socioeconomic damages, estimated to be in the billions of yuan annually, result from ecological degradation caused by unsustainable land use practices in ecologically fragile regions. At the same time, entrenched high-carbon energy systems and fragmented governance frameworks intensify systemic barriers to green transitions, especially in alpine ecosystems, which are characterized by high sensitivity and low resilience (Ji et al., 2024b).

These systemic challenges stem from three fundamental governance deficits: 1) Management frameworks that are constrained by administrative boundaries, which overlook the integrity of watersheds; 2) Overlapping departmental mandates and data silos that contribute to inefficiencies in water resource management; and 3) Increased hydrological vulnerabilities that are exacerbated by the compounded effects of climate change and anthropogenic pressures.

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Contemporary governance paradigms face dual challenges. Theoretically, critical gaps persist in elucidating the nonlinear synergies within the water-energy-food-ecosystem (WEFE) nexuses, particularly concerning the bidirectional spatiotemporal feedback loops between geomorphic controls on check-dam sediment retention and gradients in photovoltaic efficiency. These knowledge deficits hinder the optimization of synergistic benefits across basin-scale sustainability frameworks, where the cascading effects of sediment trapping on terrestrial-aquatic productivity and renewable energy generation remain inadequately quantified (Rahmati et al., 2020). This is particularly evident in the areas of cross-scale feedback loops, spatially explicit thresholds for trade-offs and synergies, and the differential resilience of upstream and downstream socio-ecological systems. These theoretical lacunae are exemplified in the Tana-Beles Sub-basin, where the uneven distribution of ecological security patterns (19.36% protected upstream versus vulnerable lower reaches) and mismatched biomass energy demand-supply dynamics (with an 85% reliance on firewood exceeding the regional regenerative capacity) underscore the necessity for adaptive governance frameworks (Abera et al., 2024). Conventional operational frameworks demonstrate systemic inadequacies in integrating operational efficiency with ecological robustness, particularly under the compounded pressures of climatic stochasticity and anthropogenic perturbations. This is evidenced by their failure to incorporate nonlinear dynamics, cross-scale feedback mechanisms, and the adaptive governance principles that are characteristic of complex adaptive systems (Tampekis et al., 2024). Traditional management approaches, originally designed for static systems, are becoming increasingly inadequate for navigating the dynamic transformations of eco-economics. This inadequacy necessitates paradigm-shifting technological innovations.

Emerging smart technologies, particularly digital twin systems and AI-driven analytics, possess the potential to fundamentally transform the holistic governance of the Yellow River Basin (Sun et al., 2024). These technologies enable dynamic risk response mechanisms, promote cross-sector synergies, and enhance systemic resilience across ecological, economic, and societal dimensions. In contrast to the technology-driven monitoring frameworks of the Rhine Basin and the market-based water allocation mechanisms of the Colorado River, China is advancing a synergistic paradigm that integrates spatio-temporally explicit ecological sensitivity assessments with transboundary systemic governance. Drawing on localized innovations such as the ecosystem service-based ecological source identification in the Yellow River Basin, which covers 19.36% of its area, and minimum cumulative resistance (MCR) modeling for ecological corridor planning, this approach synergizes AI-enabled real-time monitoring with multi-stakeholder policy frameworks (Islam et al., 2024). This dual focus on data-driven precision and scale-sensitive integration positions China as a pioneer in operationalizing the IPCC's call for basin-level climate adaptation pathways.

Digital twin platforms facilitate comprehensive decision-making frameworks by creating high-fidelity digital replicas of river basins. These platforms enable simulations driven by graph neural networks, achieving over 90% spatiotemporal accuracy in flood propagation modeling and hazard trajectory forecasting (Roudbari et al., 2024). AI-driven optimization algorithms utilize big data analytics and predictive modeling to elucidate complex nonlinear interdependencies among hydrological, agronomic, and energy systems, resulting in a 30% to 40% improvement in the efficiency of pumped hydro storage scheduling and the matching of irrigation water resources (Abiri et al., 2023). Moreover, blockchain-enabled carbon sink platforms, supported by decentralized and transparent ecological asset markets as well as smart contract-driven tokenization mechanisms, facilitate the monetization of ecosystem service values while promoting verifiable cross-border carbon credit trading (Yadav et al., 2024).

These technological breakthroughs not only transition governance from reactive responses to predictive regulation but also facilitate the integration of global governance through cross-border data-sharing frameworks. This research addresses two pivotal scientific questions: 1) Quantifying dynamic WEFE interactions through material-energy flow analysis and threshold identification; 2) Developing an AI-enhanced adaptive management framework to balance system resilience under climate and human stressors. Our findings will provide theoretical foundations for resolving the "efficiency-equity-sustainability" trilemma in basin governance, while contributing intelligent solutions that blend Chinese characteristics with universal applicability. By establishing a resilience-oriented governance paradigm, the Yellow River Basin could achieve a historic transformation from ecological degradation to green prosperity, offering a replicable model for basin-scale sustainable development within the global ecological civilization framework.

2 The paradigm innovation of the five-dimensional collaborative governance of water-energy-food-ecosystem-intelligence

Water resources underpin the sustainability of both socioeconomic production systems and human livelihoods, forming an intricate web of interdependencies with energy generation processes and food security frameworks (Verma et al., 2024). The Yellow River Basin, a critical ecological safeguard and pivotal economic powerhouse in China, necessitates an integrated strategy that concurrently ensures water security, accelerates energy transition, stabilizes food production, and enhances ecological resilience. This approach fosters an innovative governance paradigm (Wang et al., 2025). The synergistic integration of AI-driven decision-making and digital twin-enabled system orchestration, supported by next-generation 6G networks, unlocks unprecedented opportunities for spatio-temporal optimization of the WEFE nexus (Sheraz et al., 2024). This convergence facilitates adaptive resource allocation, real-time anomaly detection, and cross-domain policy implementation, effectively addressing systemic trade-offs between resource scarcity, environmental sustainability, and socio-economic demands in hyper-connected urban-agrarian landscapes.

This research integrates multiple sources of remote sensing technologies, including GF-1, Landsat-8, and GF-4 imagery, to facilitate real-time monitoring of heterogeneous hydrological, meteorological, and pedological data (Figure 1). By employing advanced machine learning algorithms —specifically Extra Trees (ETr), Random Forest (RF), and Linear Regression (LR) —we construct robust models for soil moisture inversion tailored to agricultural contexts. These integrative approaches enable spatiotemporal analysis of soil moisture dynamics, support precision irrigation scheduling, and enhance regional water resource management strategies within the agro-pastoral ecotone of northern China (Liu et al., 2023a). These technologies facilitate the real-time integration of multispectral, thermal infrared, and ancillary datasets, utilizing automated machine learning frameworks to develop spatiotemporal

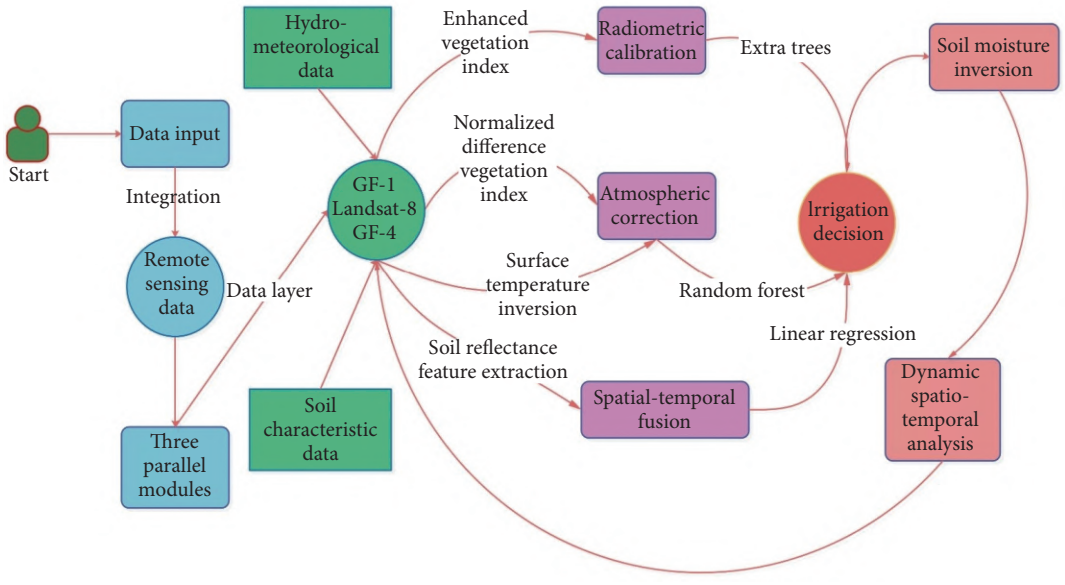


Fig. 1 Multi-source remote sensing and machine learning-driven spatiotemporal soil moisture analysis for precision irrigation in Northern China.

dynamic models for soil moisture estimation (Li et al., 2025). This integrated strategy enhances resource efficiency by optimizing water allocation, improves agricultural productivity through sustainable practices, accelerates the transition to clean energy systems, and preserves ecosystem integrity, thereby advancing China's multifaceted sustainability goals (Yang and Solangi, 2024). An intelligent basin management strategy has the potential to synergistically optimize water resource efficiency, ensure food security, promote sustainable energy transitions, and restore the ecological integrity of basins. This approach aims to achieve a harmonious coexistence of multi-dimensional objectives related to the food-energy-water nexus through integrated modeling and adaptive governance frameworks (Tian et al., 2018).

An intelligent basin management strategy has the potential to maximize water resource efficiency, ensure food security, promote adjustments to the energy structure, and restore the ecological health of the basin, thereby achieving a dynamic equilibrium among multiple objectives (Figure 2). Nonetheless, the development of such a sophisticated governance framework cannot be expedited hastily. Currently, the Yellow River Basin faces significant challenges in fostering cross-sectoral synergy, enhancing interregional data interoperability, and aligning institutional frameworks with policy instruments (Ji et al., 2024a). There is an urgent need to establish a synergistic mechanism that integrates institutional, technological, and market innovations. At the strategic level, a national development plan for smart basin management should be formulated, clearly delineating the responsibilities of local governments and establishing platforms for data aggregation and business collaboration. In terms of technological advancements, it is essential to increase investment in research and development focused on hydrological modeling, agricultural remote sensing, and ecological monitoring to address bottlenecks in sensing, analysis, and regulation. In relation to market-oriented operations, it is vital to encourage participation from social capital, innovate investment and financing models, and establish mechanisms for cost-sharing and benefit-sharing. Only through these measures can a robust foundation be established for intelligent basin governance, fostering a long-term mechanism characterized by multi-party participation and multi-dimensional synergy.

An intelligent, technology-driven approach to Yellow River Basin management offers transformative potential for coordinating WEFE governance. By integrating artificial intelligence (AI), Internet of Things (IoT), big data analytics, and remote sensing, this approach enables real-time resource monitoring and precision allocation across interconnected systems. This strategy enhances agricultural productivity through data-informed irrigation optimization, fertilizer management, and pest control while minimizing waste. It simultaneously advances the clean energy transition by smartly incorporating hydropower, solar, and wind resources into adaptive grid networks, complemented by intelligent storage solutions that reduce dependence on fossil fuels and emissions.

Ecological restoration is advanced through the integration of multiscale predictive modeling and precision hydrological optimization strategies. These approaches synergize habitat connectivity enhancement with erosion control, leveraging spatiotemporal land-use simulations, resistance surface construction, and ecological corridor planning to achieve a balance between biodiversity preservation and soil and water conservation (Liu et al., 2024). The system's adaptive capacity strengthens resilience against climate fluctuations and socioeconomic pressures by maintaining a dynamic equilibrium across competing priorities. As a global governance innovation, this integrated technological framework establishes a replicable model for harmonizing complex resource systems. The Yellow River initiative exemplifies how intelligent management can drive sustainable development while preserving ecosystem integrity, positioning it as an international benchmark for nexus-based environmental stewardship.

Intelligent water governance is a gradual process that necessitates phased implementation across various regions and scales. In practical applications, it is crucial to tailor governance priorities and pathways according to the resource endowments and socio-economic conditions of each basin segment. In the ecologically vulnerable upstream zones of the Yellow River basin, priority should be given to enhancing watershed ecological security through integrated soil and water conservation practices (Rong et al., 2024). Additionally, differentiated restrictions on water-intensive industries should be imposed based on virtual water trade mechanisms and pathways for

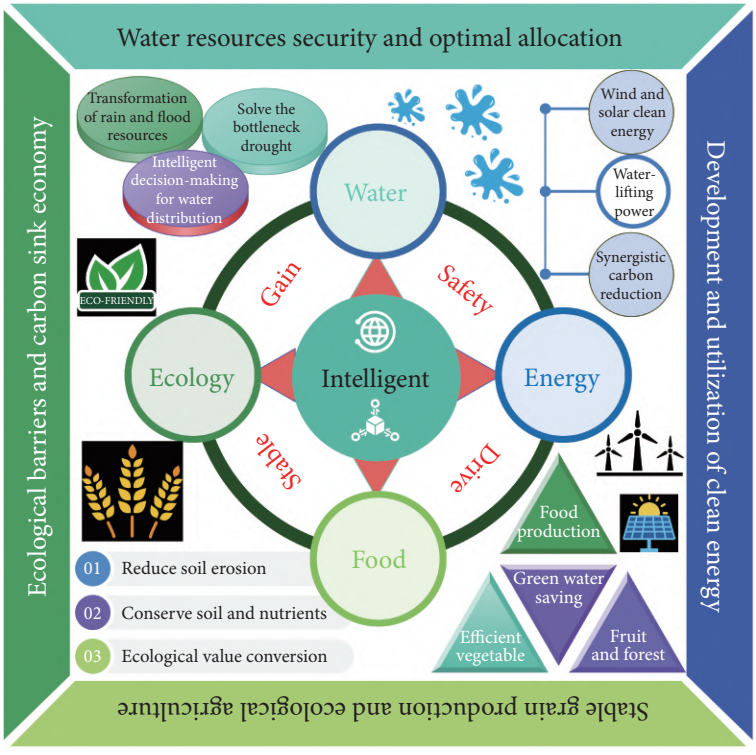


Fig. 2 Water resources security and multi-system coordinated development: an integrated strategy of water, energy, grain and ecology driven by intelligence.

optimizing industrial structure. In the ecologically fragile middle reaches of the Loess Plateau, it is imperative to prioritize the establishment of a synergistic development paradigm that integrates water-saving irrigation systems, drought-resilient dryland farming practices, and initiatives for an ecological circular economy (Jia et al., 2024). This approach should be supported by multi-scale critical zone monitoring, the optimized allocation of water-soil resources, and the implementation of climate-smart agricultural technologies to achieve sustainability within the water-energy-food nexus.

Intelligent basin governance represents a complex systems engineering endeavor that requires not only technological innovation but also conceptual and modal shifts. As climate change intensifies, economic and social transformations accelerate, and technological iterations quicken, the Yellow River Basin will encounter an increasingly complex and volatile external environment, thereby placing higher demands on the adaptability and resilience of its governance system. Consequently, it is imperative to adopt a global perspective by strengthening benchmarking exchanges with internationally advanced river basins and learning from successful experiences in smart water governance abroad. Active participation in global water resource and sustainable development agendas, contributing Chinese solutions and wisdom, and promoting the construction of a community with a shared future for mankind are essential. It is foreseeable that with the further integration of intelligent technologies and basin governance, the Yellow River Basin has the potential to become a global exemplar in integrated river basin management, thus contributing more Chinese wisdom to the sustainable development of human society. Through the implementation of AI and digital twin technologies to achieve "forecast-warning-simulation-plan" intelligent regulation, the four-dimensional synergy of water, energy, food, and ecology can be finely tuned and resiliently enhanced, thereby supporting the realization of a sustainable and harmonious coexistence between humanity and nature.

3 The design of an innovation chain from data perception to decision empowerment

As the cradle of Chinese civilization and a global geostrategic asset, the Yellow River Basin plays a crucial role in safeguarding national ecological security, enhancing the resilience of energy systems, ensuring food sovereignty, and promoting high-quality development. The complex hydrological-ecological-economic nexus of the basin underpins China's sustainability agenda, necessitating integrated governance to balance resource exploitation with ecosystem preservation (Zhu et al., 2024). This extensive region serves as both a vital ecological barrier and an economic powerhouse, currently facing multifaceted challenges: intensifying imbalances in water resources, the dual pressures of energy transition and the deployment of clean energy, conflicting demands between the preservation of cropland and agricultural modernization, as well as urgent needs for ecosystem restoration and biodiversity conservation. In this context, breakthroughs in intelligent technologies are transforming basin governance through an integrated "perception-analysis-decision-execution" framework, thereby redefining developmental paradigms across the basin (Figure 3).

The convergence of the IoT and geospatial technologies has resulted in the creation of a comprehensive "digital nervous system" across the basin. Shore-based hydrological monitoring stations, equipped with multi-parameter sensors, continuously capture real-time hydrological parameters, including water level, flow velocity, and sediment concentration. These stations achieve an exceptional data availability rate of 95% through IoT-enabled telemetry systems (Quaranta et al., 2023). Additionally, high-frequency groundwater level monitoring networks, which consist of 223 multi-layered observation wells distributed across four aquifers, meticulously track subsurface



Fig. 3 Architecture diagram of the closed-loop governance system for smart river basins - the collaborative development path of ecological economy based on the framework of "Perception - Analysis - Decision-Making – Execution".

hydrological dynamics with sub-centimeter precision (±3 cm). These efforts are further enhanced by automated data processing workflows and time-series analysis, which together facilitate the identification of aquifer compaction patterns (Hung et al., 2024). Fleets of drones equipped with hyperspectral cameras perform routine patrols, working in synergy with satellite remote sensing to establish an omnidirectional ecological monitoring network. Enhanced by advanced AI-driven surveillance systems, this integrated platform utilizes deep learning-based object detection algorithms to identify illicit sand mining activities and unauthorized pollutant discharges in real time. Coupled with multispectral satellite imagery and UAV-based monitoring, it leverages vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), which has been validated to achieve a precision of ±0.02 through rigorous ground-truthing, to quantitatively evaluate ecological restoration outcomes (Aili et al., 2024). The integration of atmospheric, hydrological, pedological, and biological monitoring enables minute-level response capabilities, thereby establishing an unprecedented data foundation for evidence-based governance.

Deep learning-driven hydrological forecasting systems, utilizing 70 years of spatiotemporal meteorological and runoff datasets, achieve an NSE accuracy of 92.3% in 72-hour flood forecasting (Zhao et al., 2024). This success is attributed to advanced spatiotemporal feature extraction architectures and ensemble learning frameworks, as evidenced by recent studies. In the energy sector, a digital twin platform utilizing the Teaching-Learning-Based Optimization (TLBO) algorithm effectively predicts renewable energy output through the Gated Recurrent Unit (GRU) deep learning model. When integrated with the dynamic scheduling strategy of the energy storage system (SBU), this approach has resulted in a 15% enhancement in renewable energy integration capability in the pilot area of Qinghai (Bo and Yi, 2024). Integrating soil moisture sensors and AI-driven crop growth models into Agricultural IoT systems has demonstrated significant improvements in irrigation efficiency in agricultural regions such as Henan and Shandong. Case studies indicate that these advancements have resulted in water savings of up to 30% through optimized scheduling and real-time monitoring of soil conditions (Tang et al., 2024). These innovations surpass traditional governance limitations by replacing empirical judgments with data-driven and quantified management protocols.

The Central Valley of California, a crucial agricultural region characterized by arid climates, has made significant advancements in sustainable water management through the implementation of the UNet-ConvLSTM model (Ye et al., 2024). This model integrates high-resolution remote sensing imagery with temporal AI-driven analytics to optimize irrigation scheduling and improve the resilience of crop yields. This initiative has resulted in a 30% improvement in irrigation efficiency, achieved through dynamic scheduling and variable-rate irrigation (VRI) technology, as evidenced by regional case studies (Ahmed et al., 2023). In midstream river reaches, integrated air-ground monitoring systems that combine UAV-based hyperspectral imaging with AI-driven early-warning platforms effectively detected and mitigated 23 water pollution incidents in 2023 (Song et al., 2024). This demonstrates their capability to identify algal blooms, nutrient overloads, and industrial effluents in real-time. Regionally, digital twin-integrated water replenishment initiatives are designed to harmonize fluvial dynamics, urban water resilience, and ecological equilibrium across watersheds. These initiatives leverage real-time data assimilation and physics-informed modeling to optimize resource allocation (Yang et al., 2024). This comprehensive strategy aligns the

utilization of water resources with the principle of the *Four Waters* and *Four Determinants*, which asserts that the availability of water dictates urban planning, land allocation, industrial capacity, and agricultural development priorities (Figure 4).

In the renewable energy hubs of Inner Mongolia, smart grids have achieved a renewable energy forecasting accuracy exceeding 95% through the integration of edge computing and advanced grid-side energy storage systems (Zhang et al., 2023). Meanwhile, virtual power plants have successfully aggregated distributed resources into systems that respond effectively to grid demands. Digital twin-powered energy management platforms have achieved an 18% reduction in energy intensity at the Yulin Chemical Park, demonstrating significant efficiency gains through optimized resource allocation and process control (Chong et al., 2025). Advanced occupant-centric control systems, integrated with machine learning techniques such as reinforcement learning, have achieved energy savings of up to 23.8% in building operations while ensuring thermal comfort (Liu et al., 2023c). This underscores the rapid advancement of smart, energy-efficient solutions that are driving the green transition across various industries.

Integrating crop phenotyping systems with real-time multispectral sensors, such as NDVI monitoring, and AI-driven decision algorithms has resulted in a 20% reduction in fertilizer inputs while simultaneously achieving a 15% increase in yield (Shi et al., 2020). This was accomplished through site-specific nutrient management tailored to intrafield variability. Utilizing the RZWQM2 model to optimize deficit irrigation strategies, researchers in Southern Xinjiang achieved a 40.54% increase in irrigation water productivity by strategically applying irrigation at 90% of field capacity during critical flowering stages (Kuang et al., 2024). This approach not only enhanced water productivity but also maintained superior cotton fiber quality when compared to traditional flood irrigation methods. By precisely regulating the leaching amount (ranging from 75 to 300 mm) and timing (utilizing combinations of the seedling stage, bud stage, and flowering and boll-setting stage), and by adopting the W3T2 mode (which involves 225 mm of fractional leaching) optimized through the TOPSIS method, the remediation cycle of saline-alkali land can be reduced by 50% (Liu et al., 2023b). This approach can increase cotton yield by up to 139% while effectively lowering the concentration of harmful ions such as Na^+ and Cl^- in the soil. This demonstrates the significant multiplier effect of scientific management measures on salinity control. These advancements represent critical breakthroughs in securing national food security, particularly in water-scarce environments.

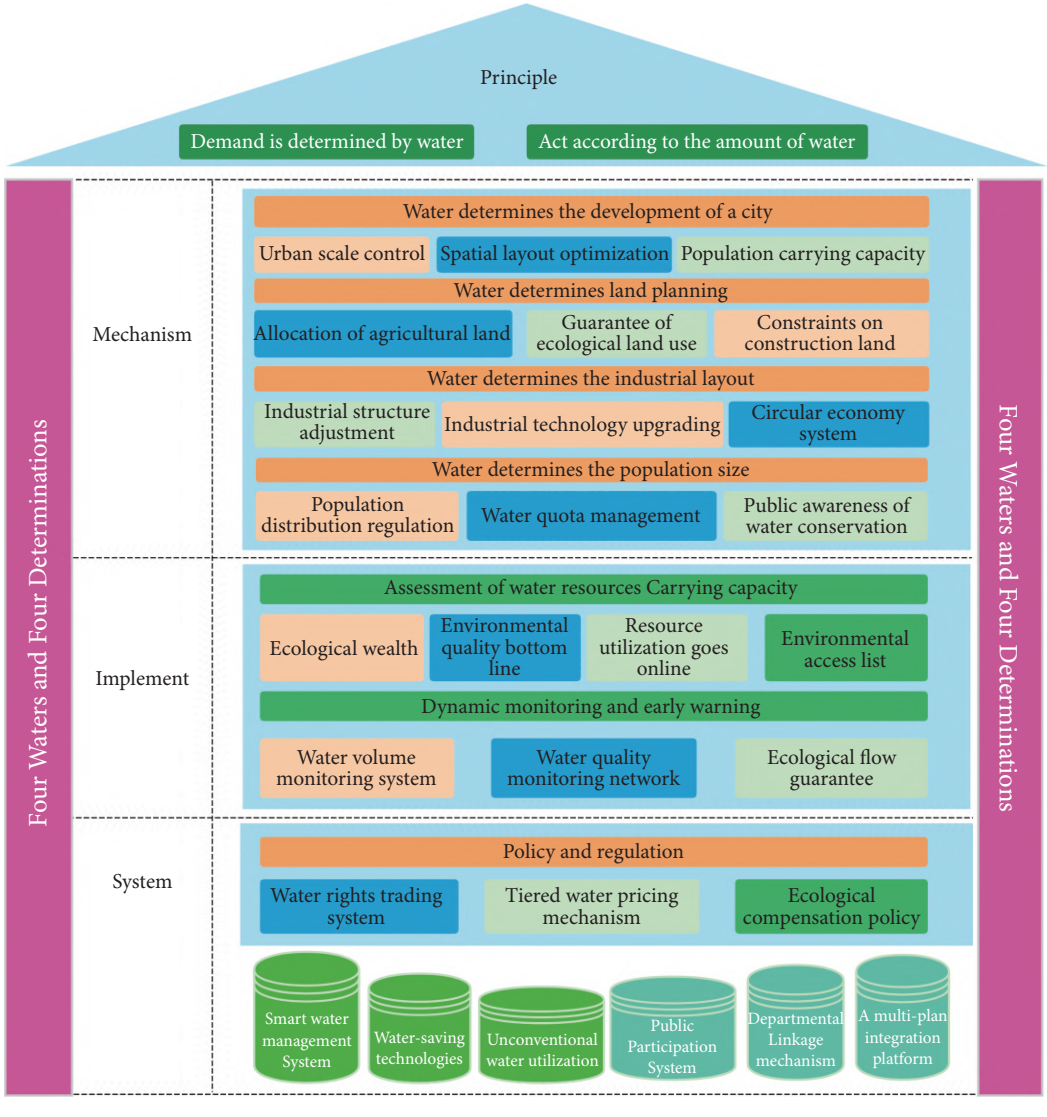


Fig. 4 Four waters and four determinations: a management framework for urban sustainable development based on water resources carrying capacity.

Employing UAV LiDAR and hyperspectral remote sensing technologies, researchers mapped the spatial distribution of mangrove species in the Maowei Sea estuary with centimeter-level resolution, achieving a species classification accuracy of 86.77% using CART decision-tree classification (Tian et al., 2023). In the Loess Plateau, UAV-based Structure-from-Motion photogrammetry and machine learning algorithms are synergistically applied to optimize gully stabilization strategies (Medeiros et al., 2025). This approach results in a significant improvement in the precision of erosion monitoring and the effectiveness of vegetation regrowth, achieved through high-resolution topographic mapping and predictive modeling. An integrated ecological security framework was developed for basin-scale environmental governance by synthesizing multi-source geospatial datasets, including hydrological, pedological, atmospheric, and biological metrics (Zhang and Xu, 2017). This was achieved through spatial normalization and aggregation techniques to identify critical ecological stressors and inform sustainable management strategies.

4 Differentiated governance paths in typical regions

The Yellow River Basin serves as a crucial ecological bulwark and a cornerstone for promoting sustainable socioeconomic progress in China through integrated high-quality development strategies (Yang et al., 2023). Strategic Environmental Assessment (SEA) serves as a multidimensional and adaptive framework that integrates environmental stewardship into policy, planning, and governance (Noble and Nwanekezie, 2017). It leverages systematic analysis and institutional innovation to facilitate sustainability transitions across various decision-making hierarchies. Given the diverse environmental challenges across various regions of the basin, it is essential to develop tailored governance strategies that address the unique needs of each area. This document outlines a comprehensive plan for ecological governance in the Yellow River Basin, emphasizing region-specific strategies, collaborative governance models, continuous monitoring and assessment, as well as the importance of capacity building and institutional innovation.

The northern reaches of the Yellow River Basin exhibit pronounced ecological fragility, driven by arid climatic conditions, rugged topography, and intensified anthropogenic pressures (Zhang et al., 2022). However, recent ecological restoration initiatives, particularly afforestation programs, have demonstrated measurable improvements in resilience within these vulnerable landscapes. Therefore, ecological protection and restoration efforts should prioritize intact habitats in the northwestern and northeastern mountainous regions, while enhancing corridor connectivity to ensure regional ecological stability and biodiversity conservation (Li et al., 2022). Conservation initiatives must prioritize the safeguarding of intact ecosystems, the rehabilitation of degraded landscapes through natural regeneration and the restoration of native species, as well as the fostering of community-led efforts to enhance biodiversity and adaptive livelihoods (Di Sacco et al., 2021). Advancing sustainable tourism initiatives, such as certified organic cultivation and regenerative livestock management, not only promotes economic growth but also preserves ecological balance (Xiao et al., 2025). Developing nature-centric tourism initiatives, such as protected ecosystems and wildlife corridors, can enhance visitor engagement and stimulate local economies while ensuring environmental preservation through strategic government policies and stakeholder collaboration (Baloch et al., 2023).

The midstream regions of the Yellow River Basin face significant challenges regarding water quality deterioration. This decline is marked by elevated concentrations of total nitrogen, arsenic, lead, and chromium, all of which surpass national standards. Additionally, there are considerable health risks associated with carcinogenic contaminants, primarily driven by intensive agricultural practices and the discharge of industrial wastewater (Chen et al., 2020). To address these issues, strategies should focus on soil and water conservation as well as pollution control. The implementation of advanced agricultural techniques, such as precision farming and the utilization of drought-resistant crops, can enhance soil fertility and mitigate erosion. Promoting water-saving irrigation systems, such as drip and sprinkler irrigation, can optimize water usage and minimize waste. Additionally, establishing buffer zones along riverbanks and investing in modern wastewater treatment facilities are crucial steps in mitigating pollution and preserving water quality.

Downstream regions are critical for ensuring the sustainable use of water resources and controlling pollution. Strategies in these areas should focus on enhancing water use efficiency and implementing stringent pollution management practices. This includes upgrading existing water infrastructure to reduce losses, promoting the use of recycled water in industrial and agricultural processes, and enforcing strict regulations on industrial emissions. Additionally, facilitating the transformation and upgrading of traditional industries to more sustainable and less polluting alternatives can significantly improve environmental outcomes. Encouraging the development of strategic emerging industries, such as renewable energy and high-tech manufacturing, can drive economic growth while minimizing ecological impact.

Addressing the complexities of ecological governance in the Yellow River Basin requires the implementation of regional collaborative governance models through pilot demonstrations. By selecting representative and diverse regions for these pilots, customized governance plans can be developed that consider local environmental conditions and socio-economic factors. These pilot projects should function as testing grounds for innovative governance approaches, facilitating continuous refinement and the establishment of best practices that can be replicated and scaled throughout the entire basin.

During the pilot phase, it is essential to leverage the coordinating role of basin management institutions to ensure seamless collaboration among upstream and downstream areas, as well as between different riverbanks and tributaries. Establishing robust cross-regional coordination mechanisms facilitates the sharing of resources, information, and expertise, thereby enhancing the overall effectiveness of governance efforts (Figure 5). Furthermore, aligning these initiatives with national and local development plans ensures coherence and reinforces the collective commitment to ecological sustainability.

Effective ecological governance necessitates the establishment of a comprehensive and basin-wide environmental monitoring network. This network should encompass all regions of the Yellow River Basin, providing real-time data on critical ecological indicators such as water quality, soil health, and biodiversity levels. Regular monitoring facilitates the timely identification of environmental changes and emerging threats, thereby enabling proactive management responses. Periodic evaluations of governance initiatives are crucial for assessing their impact and effectiveness. These evaluations should systematically analyze the successes and shortcomings of implemented measures,

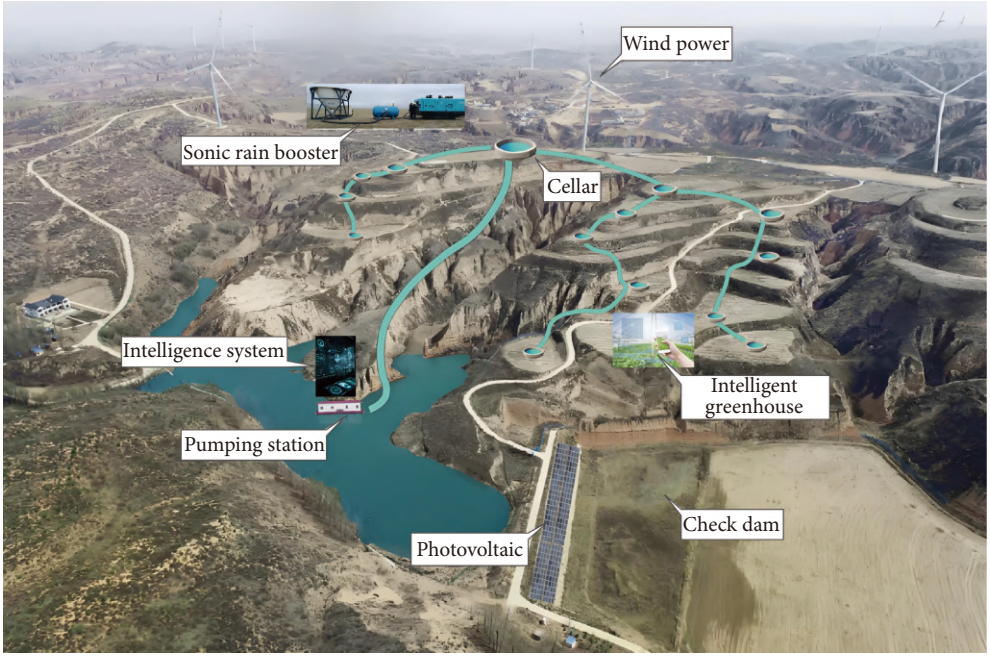


Fig. 5 A cross-regional water resources and energy collaborative management system based on intelligent interconnection: A comprehensive solution for the sustainable development of the Yellow River Basin. Note: This paper proposes the development of a digital twin platform that integrates the interconnections between water, energy, grain, and ecology. It aims to collect real-time data, including dam displacement, soil moisture, and photovoltaic output, through IoT sensors. The platform will optimize the dispatching strategy of pumped storage units by employing artificial intelligence (AI) algorithms. Furthermore, it will deploy an intelligent irrigation central system that integrates meteorological satellite forecasts, runoff models, and soil sensor data, achieving millimeter-level precision in controlling the concealed pipe alkali drainage network and drip irrigation valves.

identifying areas for improvement or adjustment. Incorporating feedback from various stakeholders, including local communities, businesses, and environmental organizations, ensures that governance strategies remain relevant and responsive to real-world conditions.

Moreover, adopting a dynamic approach to governance—where strategies are continuously refined based on monitoring and evaluation outcomes—promotes resilience and adaptability. Sharing successful practices and lessons learned from various regions fosters a culture of continuous improvement and collective learning, ultimately strengthening the basin-wide ecological management framework. Sustainable ecological governance in the Yellow River Basin relies heavily on the capacity of management institutions and the availability of skilled professionals. To this end, investing in the development of a competent and dedicated workforce is paramount. This involves providing training and educational opportunities for environmental specialists, policymakers, and local government officials to enhance their technical expertise and managerial capabilities.

Establishing robust ecological compensation mechanisms is a critical aspect of capacity building. By ensuring that regions with significant ecological functions receive adequate financial support through transfer payments, local governments are incentivized to prioritize environmental protection and sustainable practices. This financial support can offset the costs associated with implementing green initiatives and encourage broader participation from various sectors of society. Institutional innovation plays a vital role in creating an enabling environment for effective governance. Developing and enforcing basin-wide regulations clarifies the roles and responsibilities of different stakeholders, ensuring accountability and fostering collaboration. Additionally, creating centralized information-sharing platforms facilitates the seamless exchange of data and insights among governing bodies, promoting informed decision-making and coordinated action. The ecological governance of the Yellow River Basin is a complex and ongoing endeavor that requires a multifaceted and regionally tailored approach. By focusing on specific regional strategies, fostering collaborative governance through pilot projects, maintaining continuous monitoring and adaptive management, and investing in capacity building and institutional innovation, China can effectively safeguard the ecological integrity of the Yellow River Basin. These comprehensive efforts will not only enhance environmental sustainability but also support the continued economic and social development of the regions dependent on this vital waterway.

5 Collaborative innovation among institutions, technologies and markets

The ecological environment governance of the Yellow River Basin is a complex and systemic undertaking that necessitates coordinated innovations across institutional frameworks, technological advancements, and market mechanisms. Achieving sustainable and high-quality development in this region requires a multifaceted approach that integrates various sectors and stakeholders. At the institutional level, it is essential to establish and refine cross-departmental coordination mechanisms to address the challenges posed by fragmented governance and policy conflicts. This involves creating a unified governing body or coordinating council that ensures seamless communication and cooperation among different governmental departments. Such measures can eliminate the inefficiencies caused by overlapping jurisdictions and conflicting policies, thereby enhancing the overall effectiveness of ecological governance.

Moreover, fostering collaboration among local governments within the basin is crucial. This collaboration should synchronize efforts

between upstream and downstream regions, as well as between the left and right banks of the river. Such cooperation ensures that ecological protection and socio-economic development are managed holistically, considering the interdependencies and unique characteristics of each sub-region. For instance, upstream regions focused on water conservation can collaborate with downstream areas prioritizing water usage efficiency, thereby creating a balanced and sustainable management system.

Advancing technological capabilities is a cornerstone of effective ecological governance. Significant investments in science and technology are essential for developing and implementing cutting-edge solutions tailored to the basin's unique environmental challenges. Establishing a coordinated scientific innovation mechanism for the basin ensures that major technological projects are strategically planned and executed. This coordinated approach facilitates the sharing of research findings and the deployment of innovative technologies across the entire basin.

Modern information technologies, including the IoT, big data analytics, and AI, play a crucial role in ecological governance. These technologies facilitate the intelligent regulation and management of key resources such as water, energy, agriculture, and ecosystems. For instance, IoT devices, by deploying sensors within watersheds, monitor water quality, soil moisture, and air pollution in real-time, enabling timely responses to environmental changes. Big data analytics can process vast amounts of environmental data, identify trends, predict future conditions, and optimize resource allocation. AI algorithms, through simulating various scenarios, provide decision-making recommendations for sustainable management, thereby enhancing the scientific rigor and efficiency of the decision-making process.On this basis, fully leveraging the role of market mechanisms in ecological governance is indispensable. By encouraging social capital to invest in watershed ecological projects, the efficiency of capital and resource allocation can be significantly enhanced. Green financial initiatives, such as green bonds and environmentally oriented investment funds, provide essential capital support for large-scale ecological restoration and conservation projects. Additionally, the ecological compensation mechanism, as another critical economic tool, incentivizes local governments and communities to prioritize environmental protection through fiscal transfers to regions that undertake significant ecological functions. For instance, areas implementing effective soil and water conservation measures can receive economic compensation to offset related costs, thereby promoting the continuous implementation and expansion of these measures. In summary, the organic integration of modern information technology with market mechanisms has not only enhanced the intelligence of ecological governance and the efficiency of resource allocation but also promoted the initiative and sustainability of environmental protection through economic incentives, forming a new pattern of ecological governance characterized by strong systematicity and significant synergistic effects.

The ecological governance and sustainable development of the Yellow River Basin necessitate a systemic, multi-stakeholder approach that harmonizes government leadership, market innovation, and societal engagement. Central to this framework is the government's role in establishing robust policies, regulatory standards, and financial incentives to guide green initiatives. By providing tax breaks, subsidies, and low-interest loans for sustainable projects, public institutions can catalyze private sector investment in ecological restoration, renewable energy, and pollution control. Simultaneously, market-driven mechanisms—such as competitive green financing, carbon pricing, and innovation incentives—enhance efficiency, attract diversified capital, and foster technological advancements in environmental management. Equally critical is the active participation of civil society. Public awareness campaigns, environmental education programs, and community-led monitoring initiatives are vital for cultivating a culture of ecological stewardship. Schools, media outlets, and NGOs must collaborate to emphasize biodiversity conservation, sustainable resource use, and pollution mitigation. Grassroots engagement, including participatory decision-making platforms and localized recycling programs, ensures that policies align with community values while empowering individuals to adopt eco-friendly practices in their daily lives.

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6 Future challenges and research directions

The Yellow River Basin, a vital ecological barrier and economic corridor in China, faces complex environmental challenges and issues related to resource utilization. Climate change has exacerbated water scarcity and increased the frequency of extreme weather events in the basin, intensifying pressures on flood and drought control, soil conservation, and disaster mitigation. Concurrently, excessive development and unsustainable resource practices in certain areas have worsened ecological degradation, including soil erosion and desertification. Addressing these challenges requires strengthened collaborative governance across upstream, midstream, and downstream regions, balancing ecological preservation with economic development through comprehensive, long-term planning.Future governance of the Yellow River Basin must leverage modern information technologies to enhance intelligent monitoring, early warning systems, resource allocation, and emergency response. The evolution of big data, cloud computing, artificial intelligence, and other next-generation technologies provides new tools for precision management and data-driven decision-making. Establishing an integrated sky-space-ground monitoring network—combining satellite remote sensing, drone surveillance, and IoT sensors—and applying machine learning algorithms to analyze multi-source data will enable dynamic, holistic insights into hydrological, meteorological, and ecological patterns. This approach will strengthen disaster prevention, optimize resource allocation, and inform policy formulation.

However, technological innovation alone is insufficient. Protecting the Yellow River necessitates coordinated efforts among all stakeholders. The nine provinces along the river, particularly those in the upstream, midstream, and downstream zones, exhibit divergent priorities regarding flood control, water allocation, and ecological compensation, which complicates collaboration. A key to success lies in establishing robust basin-wide management mechanisms that clarify responsibilities, enhance benefit-sharing frameworks, and foster cooperation under unified guidelines. Furthermore, ecological conservation and high-quality development in the basin represent a long-term, arduous endeavor that requires phased, adaptive planning and continuous refinement of policies. The governance of the Yellow River should also integrate international best practices. Integrated river basin management has emerged as a global standard for transboundary water systems, offering valuable lessons from other nations in areas such as ecological compensation, water pricing, and disaster preparedness. China should actively engage in global exchanges, adopt relevant international strategies, and address shared challenges such as climate change. Simultaneously, it must tailor solutions to the unique conditions of the basin, developing a replicable 'Chinese model' that contributes to global ecological civilization. Moving forward, the Yellow River Basin must pioneer a high-quality development path that prioritizes ecology and green growth, embodying the principle that 'lucid waters and lush mountains are invaluable assets.' This entails promoting water-efficient agriculture, eco-tourism, clean energy, and other green industries to drive economic transformation while safeguarding the environment. Holistic management of mountains, waters, forests, farmlands, lakes, grasslands, and deserts should be prioritized to enhance systemic ecological integrity. Concurrently, improving livelihoods and ensuring social equity must remain central, guaranteeing that communities across the basin share the benefits of sustainable development.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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