Hydroeconomic Optimization of Water Management in the Yellow River Basin: Dealing with Scarcity ~~at the Basin Scale~~

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Abstract

Water scarcity is a key limiting factor for sustainable socioeconomic development especially in arid and semi-arid basins, and managing water effectively there often requires coherent and holistic policies and regulations at the basin scale. This study develop~~ed~~s an integrated basin-scale hydroeconomic optimization model. The model reasonably details the representation of the hydrologic, infrastructural, water demand and regulatory components, with an objective to maximize overall economic benefits of irrigated crop production, water supply and hydropower generation, subject to resource, infrastructural, operational and policy constraints. A baseline calibration enhances the model's reliability and empirical validity for analyzing interconnected physical processes and decision-making, based on the interdependence of hydrologic and economic components. The model is applied to the Yellow River Basin (YRB), where water has been fully allocated and intense competition exists among different water users across the basin. Results show that water availability decreases by approximately 75% from upstream to downstream, with the corresponding marginal values rising from 0 to 9.14 yuan/m^3 along the river in a severe dry year ~~the coupling of water availability decreases and water value increases along the river from upstream to downstream~~, implying a more challenging issue for downstream water security (especially the critical ecological requirements) and a larger requirement for water saving in upstream areas. Basin-wide management strategies highlighted in this study include: ~~transferring water allocation~~reallocating water to economically high-value production sectors; coordinating the operation of ~~multiple~~ cascade reservoirs ~~in the basin,~~and taking advantage of ~~the~~ reservoirs ~~that have~~with inter-year operation capacity; monitoring and balancing water availability between upstream and downstream areas. The stabilization of water supply heavily relies on ~~the~~ coordinated operation of aquifers and reservoirs with inter-year storage capacity, which ~~can effectively~~ mitigates hydrologic variability and ~~safeguard~~ improves downstream water availability. Water valuation analysis based on marginal value underscores the potential benefits of water trading and inter-regional transfers. The results offer insights for basin-scale water management, showing potential~~s~~ of re~~-~~allocation strategies for improving management flexibility and increasing water productivity. Insights from the YRB are meaningful as guides for managing basins worldwide that face similar challenges.

Key Words: Hydroeconomic model, water allocation, optimization, calibration, supply-demand relationship, Yellow River Basin

1. Introduction

Water scarcity is a growing challenge in many river basins around the world where the demand for water, driven by population expansion, socioeconomic development, and evolving consumption habits, outstrips water supply (Hejazi et al., 2014; Kahil et al., 2018; Liu et al., 2017; Tian et al., 2021; United Nations, 2023). In many of those basins, water has already been overallocated, leading to river basin closure, pervasive water scarcity, groundwater overdraft, and ecosystem degradation (Hanasaki et al., 2013; Molle et al., 2010; Scanlon et al., 2023; Zhou et al., 2020). Particularly, as nations strive to sustain growing ~~and more prosperous~~ populations and economies under changing climatic conditions, ~~challenges such as~~pressures from water overuse, ecological degradation, and cross-regional cooperation in large arid and semi-arid river basins ~~within arid and semi-arid regions~~ are expected to intensify (Kahil et al., 2018). For instance, the Colorado River and Rio Grande basins face overexploitation dilemmas from historical agreements that overcommitted actual water availability (Ward et al., 2006). Similarly, the Murray-Darling Basin in Australia (Ejaz Qureshi et al., 2013; Thevs et al., 2015) and the Ebro River Basin in Spain (Baccour et al., 2021) struggle to reconcile water quality deterioration with economic development objectives. The Syr Darya in Central Asia (Cai et al., 2002) and the Nile (Basheer et al., 2023) are significantly impacted by challenges in transboundary water allocation coordination. These challenges highlight the need for a systematic framework to analyze spatial and temporal trade-offs across interconnected water-related systems in large river basins. ~~systematic approach is essential to analyze trade-offs spatially and temporally across water-related systems in large basins, including food production, energy supply, and ecosystem services.~~

Hydroeconomic ~~optimization~~ models (HEMs) have emerged as pivotal tools for guiding basin-scale water resources planning, incorporating both economic and hydrologic ~~considerations~~ representations of water supply and demand (Pulido-Velazquez, 2022). ~~Specifically, the~~Such models comprehensively characterize~~s~~ the infrastructure, management scheme and the economic value of water ~~resources~~ within the system (Harou et al., 2009; Ward, 2021), based on the mathematical framework ~~and an integrated representation of the~~ that links biophysical, technological, and economic ~~aspects of water resource systems~~ processes (Cai, 2008; Kahil et al., 2018; Pulido-Velazquez, 2022). Earlier ~~examples~~ applications ~~of such analysis~~ include ~~Draper et al.'s~~ basin-scale economic-engineering model of California's major water supply system ~~for operating~~to coordinate surface and groundwater ~~resources~~operations, and to optimiz~~ing the~~e statewide economic benefits ~~of~~ from rural and urban water use ~~statewide~~ (Draper et al., 2003). Considering conjunctive water use of surface and groundwater, Zhu et al. (2015) derived numerical solutions and analytical conditions for optimizing land and water use for crops, short-term and long-term urban water conservation alternatives, and water transfers. Kahil et al. (2016) strengthened the linkage between physically-based representations of water sources and uses through integrated ~~hydroeconomic modeling framework~~HEM to assess the impacts of climate change and policy options in the Jucar basin in Spain. ~~By combining climate projections, hydroeconomic simulators and machine learning techniques, Basheer et al. introduced a planning framework for adaptive management and multilateral cooperation of the Nile, aiming at relieving water-use stress and political tension in the riparian countries.~~ To explore ~~the~~ economic and environmental consequences of various policy scenarios, Cai et al. (2003) described interrelationships among hydrologic, agronomic, and ecological components in the Syr Darya River basin~~ of Central Asia~~, where irrigation-induced salinity is a major challenge. Together, these studies highlight HEMs to inform basin-scale water management under multiple and competing objectives.~~Determining urban water use though social surplus concepts in an empirical dynamic model, Baccour et al. identified land and water use patterns that maximize sustained income for both agricultural and urban sectors and minimize environmental damage for different levels of climate-water stress at the same time in the Ebro River Basin. However, few previous studies have provided basin-wide economic valuation of water considering joint operation of many reservoirs across a basin and coupled water availability and water value variation from upstream to downstream.~~

In this context, the Yellow River Basin (YRB) in northern China, offers a compelling case for examining basin development against severe water scarcity (Cai, 2008b; Peng et al., 2017; Shang et al., 2020). On the supply side, water availability in the YRB is constrained by decreasing streamflow from reduced precipitation, rising temperature and landscape evapotranspiration (Yin et al., 2021). On the demand side, with the total drainage area of 7.52×10^5 km^2, the YRB supports 12% of China's population and 15% of its farmland with only 2.5% of the country's total water resource (Wu et al., 2004; Zhang et al., 2017). Although infrastructure including reservoirs and dams has been constructed to regulate streamflow, and policies such as the "87 Water Allocation Scheme" (General Office of the State Council of the People's Republic of China, 1987) have been implemented for rational water allocation and conservation (Wang et al., 2020, 2018), competitions among water-use sectors have continued to intensify. Addressing the dual challenges of meeting development needs while ensuring reliable and sustainable water use therefore is of considerable concern for the YRB.

Previous studies on water management in the YRB have focused predominantly on supply-side issues (Xia and Pahl-Wostl, 2012; Yin et al., 2017), including the simulation of natural hydrologic responses to climate change (Bao et al., 2019; Chen et al., 2014; Zheng et al., 2009) and human interventions (Li et al., 2017; Wang et al., 2019; Yin et al., 2021), projections with hydrologic models (Cuo et al., 2013; Xu et al., 2011; Yuan et al., 2016; Zhang et al., 2017), and the optimization of reservoir operations (Bai et al., 2019, 2015; Chang et al., 2014; Meng et al., 2019; Peng et al., 2020). Nevertheless, a significant research gap remains in studies that integrate physical water availability on the supply-side and decision-making behaviors on the demand-side, and basin-wide water management regulations within a unified quantitative framework.

To reveal demand-side behaviors, HEMs have been applied to the YRB at individual or sub-basin scales. For example, Yang et al. (2012) used a decentralized, multiple-agent optimization method to explore water allocation management at the agent scale. Cao et al. (2023) developed an integrated hydro-agro-economic optimization model for the Hetao Irrigation District within the YRB, analyzing economically optimal land and water allocation, and environmental sustainability under water scarcity and soil salinization. Martinsen et al.(2021) formulated a linear programming-based HEM to assess the implications of perfect foresight of agro-hydrologic events for the South-to-North Water Transfer Project, addressing joint quantity and quality management. However, basin-wide models that holistically and quantitatively represent multiple water sources, diverse water-use sectors, coordinated reservoir operations, spatially coupled variations in water availability and value, and the supply-demand interactions under realistic regulatory and institutional settings remain largely absent. As a result, existing models remain misaligned with the practical needs of the Yellow River Conservancy Commission (YRCC), which urgently requires an integrated basin-wide framework to guide evidence-based water allocation decisions and long-term water governance.

This study develops a basin-wide hydroeconomic optimization model for the YRB, which represents hydrologic, infrastructure, and water demand components ~~of the basin~~ using a node-arc network in a spatially explicit manner~~,~~. The model follows the top-down hierarchical water management institutional setting in the YRB and integrates surface water, groundwater, and multi-reservoir operations with spatially distributed economic activities across the entire YRB, aiming to maximize the economic benefits at the basin scale, including hydropower generation, agricultural production and urban water uses. This unified modelling framework allows a quantitative assessment of basin-wide water allocation and trade-offs among various water users across the basin~~aiming to maximize the economic benefits of system operation for hydropower generation, agricultural production and urban water uses, while adhering to the operational and policy constraints~~. ~~. The objectives are to~~Specifically, this paper: (1) ~~elucidate~~ characterizes the relationships between water supply and demand under different hydrologic conditions; (2) investigates ~~the~~ synergies and trade-offs ~~of~~ in economic benefits among ~~different~~ water-~~-demand~~ use sectors; (3) assesses the marginal values of water and the degrees of water scarcity and provides insights for improving the current water governance in the basin. Notably, most previous optimization models for basin management are formulated as purely ~~a~~ normative tools to explore ~~an~~ ideally optimal solutions. To better reflect real-world management~~In this study, to explore more realistic basin management solutions~~, we adopt a~~n~~ "positive" optimization model, of which ~~the~~ irrigation water use ~~(crop acreage and water application per hectare)~~, the major water user in the YRB and many other basins, is calibrated to the observed conditions using ~~a~~ the ~~positive~~ Positive ~~mathematical~~ Mathematical ~~programming~~ Programming (PMP) approach (Howitt, 1995). The outputs of such a positive model show the adjustments from current practices, demonstrating that~~can inform us directly what changes are needed from the current practices. The model was applied to the Yellow River Basin (YRB) as a case study. The YRB faces serve water scarcity over many years . The management authority of the YRB, the Yellow River Conservancy Commission (YRCC), urgently needs a basin-wide model that represents the diverse water sources and sectoral water demands and can be used to quantitatively assess supply-side shortages and demand-side consumption patterns. This study will show that t~~the proposed basin-wide optimization ~~model~~ framework can be a ~~solid~~ useful scientific and practical tool to evaluate existing water allocation regulatory programs and policies and search for new alternatives ~~water allocation regulatory programs and policies~~ in the YRB~~. The case study with the YRB will demonstrate how a basin model facilitates evidence-based decision-making, aiming at assisting policymakers to design targeted interventions and ensure long-term water security~~.

2. Study Area and Data

2.1 Study Area

As the second longest river in China and the fifth longest in the world, the Yellow River (Fig. ~~2~~1) originates from the Tibetan Plateau, flows across nine provinces, and finally discharges into the Bohai Gulf (Zheng et al., 2014). ~~On the supply side, water availability in YRB is constrained by decreasing streamflow from reduced precipitation, rising temperature~~

~~and landscape evapotranspiration~~ The mean annual runoff of the Yellow River is 53.48 billion m^3, which has been decreasing in the p~~l~~ast 30 years, ~~worsening~~ exacerbating water scarcity in the basin (Shang et al., 2020). Runoff is ~~distributes very~~ unevenly distributed (Fig. S1) ~~in the basin~~ due to strong spatiotemporal variation in precipitation (Fig.S2). The average annual precipitation across the basin during the period from 1981 to 2010 varies spatially from 60 mm to 900 mm, ~~showing an~~ increasing ~~trend~~ from the northwest to the southeast (Yin et al., 2017). Precipitation in the basin is highly seasonal, with approximately 60% of the annual precipitation occurring during the wet season (July-October), while only 10–20% in the dry season (March-June).~~Precipitation concentrates in July to October when 60% of the annual flow occurs, while only 10% to 20% of precipitation is in the dry season (March to June).~~ ~~With~~ Under a continental monsoon climate, most of the ~~Yellow River basin~~YRB is in arid and semi-arid regions, with average annual potential evapotranspiration of 1199.7 mm (Peng et al., 2017). To mitigate adverse impacts ~~from~~ of floods and droughts, numerous dams and reservoirs have been constructed to regulate streamflow~~ in the basin~~. By 2020, ~~a total of~~ 224 large and medium-sized reservoirs have been built (YRCC, 2020). Large reservoirs, such as Longyangxia, Liujiaxia and Xiaolangdi, serve as both water storage and hydropower generation facilities.

The Yellow River is a major source of water supply ~~in~~ for northern China, ~~for~~ supporting ~~agricultural~~ irrigation, industries, domestic water uses and ecological ~~water compensation and so on~~flow requirements. With the development of the national economy, total water use in the basin, sourced from both surface water and groundwater, ~~has~~ increased from 44.63 billion m^3 in 1980 to 53.48 billion m^3 in 2015 (Peng et al., 2017). ~~With the total drainage area of 7.52×10^5 km^2, the YRB supports 12% of China’s population and 15% of its farmland with only 2.5% of~~

~~the country’s water resource , with the water resources utilization rate of 80% already .~~ Frequent drying up of the Yellow River’s main channel occurred between 1972 and 2000 (Liu and Cheng, 2000), highlighting severe spatial and temporal mismatches between water supply and demand. To address this issue, the Chinese government introduced the “87 Water Allocation Scheme” in 1987 (General Office of the State Council of the People’s Republic of China, 1987), using the average annual natural runoff of 58 billion m³ from 1919 to 1975 as a water availability baseline. After reserving 21 billion m³ for ~~sediment flushing~~environmental flow requirements, the remaining 37 billion m³ of water resources were allocated among the nine provinces and autonomous regions within the basin as well as Hebei Province and Tianjin City. ~~, a municipality directly under the Central Government. Both Hebei and Tianjin are located outside of the basin but rely on water transferred from the Yellow River.~~ However, significant discrepancies between actual runoff and this baseline water availability gradually emerged. Meanwhile, due to insufficient regulatory enforcement, the scheme was not effectively implemented, leading to frequent water overuse in provinces such as Inner Mongolia and Shandong. In response, the scheme was revised in 1998, alongside the implementation of the “Yellow River Water Allocation and Management Regulations”, which centralized water resource management under the YRCC (Wang et al., 2019a; Wang and Lou, 2022). Based on the original scheme, the regulations adhered to the principle of “increasing allocations in wet years and reducing them in dry years”, and water overuse by provinces was deducted from subsequent allocations to ensure compliance. Nevertheless, the contradiction between reduced water ~~sources~~ availability and ~~unmet~~ growing water demand is growing and needs to be solved urgently (Wang et al., 2018, 2020).

~~Previous studies on water management in the YRB have focused predominantly on supply-side issues , emphasizing the simulation of natural hydrologic processes with climate change and human interventions , as well as projections with hydrologic models including Budyko framework , SWAT and VIC model . Additionally, exiting studies examined optimizing reservoir operations to achieve synergistic benefits of water supply, flood control, power generation, and sediment management, contributing to better coping with cascade reservoir scheduling in the basin . Nevertheless, a significant research gap remains in studies that integrate quantitative representation of physical realities in the supply-side and decision-making behaviors in the demand-side as well as comprehensive water management regulations for the entire YRB.~~

~~So far, hydroeconomic models have been widely applied in the arid and semi-arid basins, including some sub-basins in the YRB. For example, Cao et al. set up an integrated hydro-agro-economic optimization model with positive mathematical programming calibration, reconciling agricultural net income, irrigation practices, and environmental sustainability faced with water shortage and soil salinization for the Hetao irrigation district in the upstream reaches of the YRB. Martinsen et al. estimated the impact of assuming perfect foresight of future agro-hydrologic events on the proposed water infrastructure of South-to-North Water Transfer Project (SNWTP), diverting Yellow River water to the Hai River basin for joint water quantity and quality management by formulating a linear program-based hydroeconomic model. Shang et al. and Wang et al. discussed competition, cooperation and fairness of water use in the YRB based on existing data, established indicators to measure the degree of collaboration and competition, and applied the Gini coefficient and the Lorentz curve, respectively. However,~~

~~there is a notable absence of models that holistically and quantitatively address multiple water sources, diverse water use sectors, and the intricate supply-demand relationships at the basin scale.~~

~~Fig.~~Figure ~~3~~ 2 depicts the basin network of water allocation among water sources (rivers, groundwater aquifers and reservoirs) and water users (hydropower stations, agricultural, industrial, municipal and ecological demand sites), detailed node-link information is listed in Table 1 and the ~~supplementary~~ Supplement~~material~~ (Table S2-1 to S2-6).

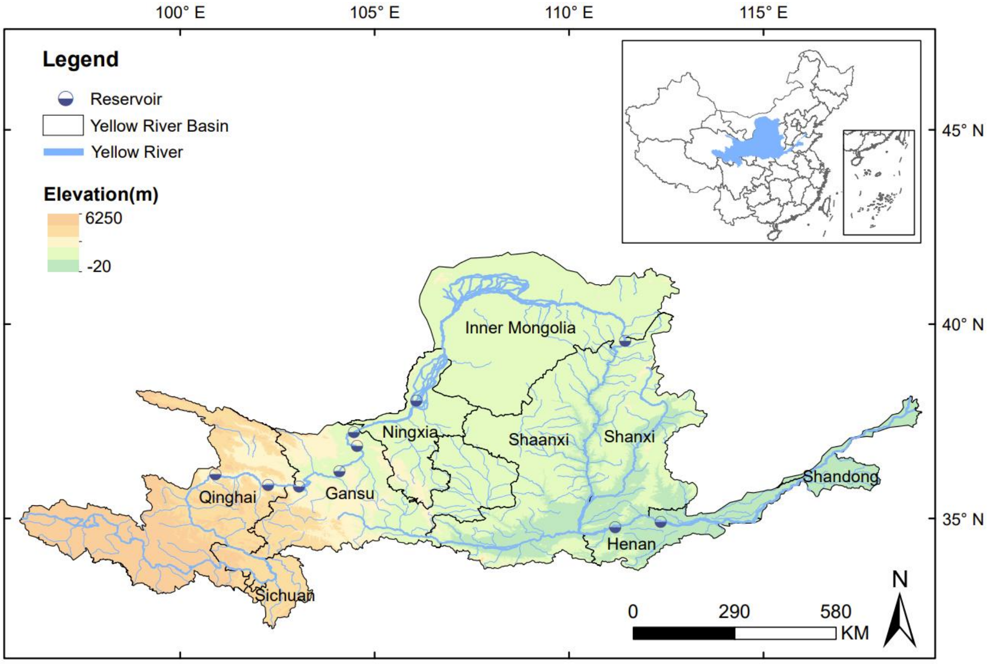


Fig. ~~2~~1. The ~~Yellow River basin~~YRB in China: general topography, mainstream and tributaries, provinces and key reservoirs.

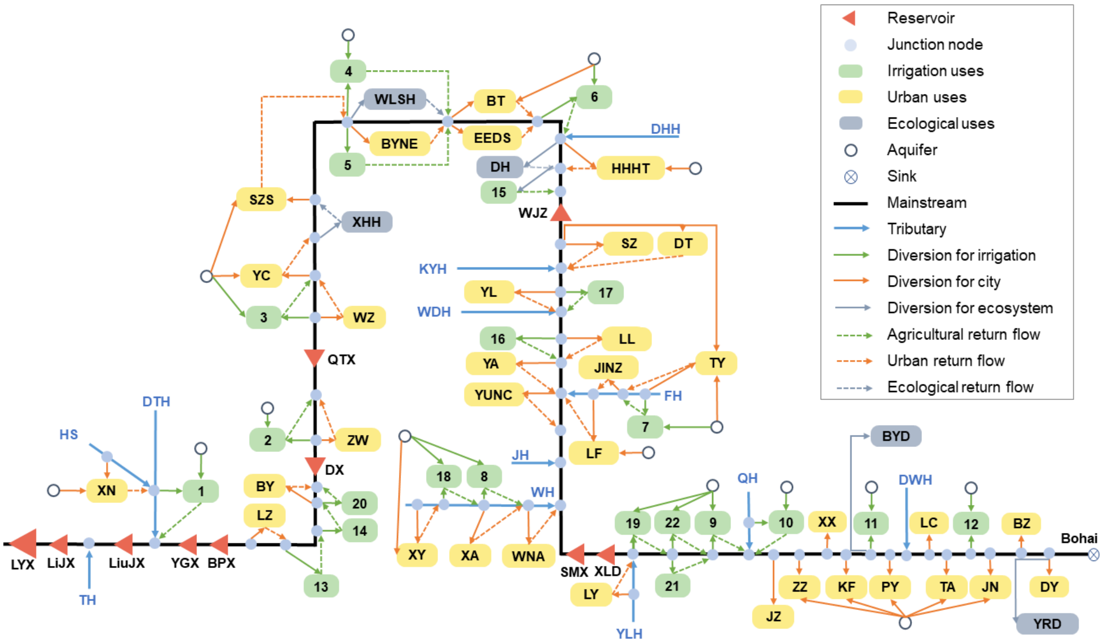


Fig. ~~3~~2. Schematic diagram of the river network system.

Table 1. Abbreviations and full names of nodes mentioned in the main text and associated provinces. Detailed node information is provided in the supplementary material (Table S2-1 to Table S2-6).

Node	Name	Province
I3	Ningxia irrigation district (NX)	Ningxia
I4	Hetao irrigation district (HT)	Inner Mongolia
I5	Nanan irrigation district (NA)	Inner Mongolia
I8	Weihe irrigation district (WH)	Shaanxi
I12	Shandong irrigation district (SD)	Shandong
EEDS	Ordos	Inner Mongolia
XA	Xi’an	Shaanxi
WNA	Weinan	Shaanxi
DY	Dongying	Shandong
WLSH	Wuliangsu Lake	Inner Mongolia
YRD	Yellow River Delta	Shandong
LYX	Longyangxia	Qinghai
LiuJX	Liujiaxia	Gansu
QTX	Qingtongxia	Ningxia
WJZ	Wanjiazhai	Shanxi
SMX	Sanmenxia	Henan
XLD	Xiaolangdi	Henan

2.2 Data

The ~~Hydroeconomic Model (~~HEM~~)~~ for the YRB requires extensive data to set up, calibrate, and run. These include monthly meteorological and hydrologic time series, aquifer attributes, characteristics of storage, conveyance and pumping facilities, factors that determine water demands of domestic, industrial, agricultural and environmental sectors, ~~in addition to~~and regulations and rules of water system management and operations. The data were acquired from various sources, such as governmental statistics, river basin agencies, research institutions, global databases, and ~~when necessary, ~~expert consultations. Table 2 lists the categories, specific parameters, attributes and sources of the datasets used in the model.

Integrating diverse data types and scales to develop a unified model remains challenging. Water source data ~~were ~~are evaluated based on hydrologic records reflecting ~~the ~~natural conditions before human interventions, while water use data are gathered from governmental or institutional statistics. Both supply and demand-side data ~~were ~~are subsequently aggregated to the source and demand “nodes” (Fig. ~~3~~2) defined in this study. Specifically, gridded meteorological data ~~were ~~are processed using geographic information systems (GIS) with the basin’s spatial configuration, and v~~econfigured for the spatial layout of the basin. V~~alues for each spatial unit ~~were ~~are extracted, aggregated and averaged at the node scale. For irrigation, primary data sourced from the MapSPAM database (International Food Policy Research Institute, 2019) ~~were ~~are also processed using ArcGIS and cross-validated against observations ~~provided by~~from local agencies to ensure accuracy and reliability.

Parameters ~~were ~~are either ~~calculated ~~estimated from ~~observation ~~empirically-observed data or derived from existing publications, and are further refined through contextual adjustments. Parameter estimation for crop growth involves geographic distribution, growth period, and hydrothermal conditions~~ of various crops~~, complemented by data from field observations and experiments. For reservoirs, key parameters of storage-elevation and storage-area curves, ~~were ~~are derived from real operation and fitted to a quadratic function assumption.

Economic items such as price elasticity coefficients for industrial and domestic water use, ~~were~~ are primarily obtained from literature at provincial or local levels.

Parameters with inherent uncertainties ~~were~~ are initially estimated through preliminary assessments and refined during model calibration. Sensitivity analyses of such parameters have been conducted in HEMs applied to some major regions located in the YRB (Cao et al., 2023). The current study adopts the prior results. Moreover, the crop prices used in this study fall within the range of prices observed historically. Because these prices place the values of agricultural use well below the economic values of water for industrial and domestic sectors, it is unlikely to see that realistic changes in agricultural prices dramatically alter operation of this model within constraints of water availability as well as capacity and policy constraints. In addition, we have strived to select reasonable and empirically-observed parameter values of other important economic parameters including electricity tariff (General Office of the State Council of the People's Republic of China, 2024) and demand elasticities (Qin et al., 2022; Zhang and Cheng, 2022). Nevertheless, it will be ideal to assess the sensitivity of such important economic parameters. However, this will require extensive sectoral survey data and econometric modeling, which is beyond the scope of the present study and be addressed in future studies. To enhance model stability, parameter and coefficient values ~~were~~ are adjusted to comparable magnitudes, ensuring consistent numerical scales across variables. This reduces the risk of non-convergence caused by excessively large numerical ranges, thereby preventing infeasible solutions in a large-scale nonlinear optimization model (Cai, 2008a).

Table 2. Sources and attributes of data used in the HEM.

Category	Content	Parameter	Resolution and period	Source
Hydrometeorology	Meteorology	Precipitation, vapor pressure, temperature, cloud cover, potential evapotranspiration	0.5°×0.5°, 1996-2015	CRU TS 4.06 (Harris, 2024)
	Surface water	Streamflow	Monthly, 1996-2015	YRCC, Ministry of Water Resources of the PRC
	Groundwater	Aquifer area, specific yield		Yellow River Water Resources Bulletin (2020)
Water Supply Infrastructure	Storage	Reservoir capacity, dead storage, storage-elevation curve, storage-area curve, tail water elevation		—
	Conveyance	Surface water division requirement		Chai (2015)
	Hydropower	Installed capacity, firm power		—
Demand Sector	Irrigation	Observed area, production and yield	1/12°×1/12°	MapSPAM (International Food Policy Research Institute, 2019)
			2020	Local governmental agencies
		Crop growth coefficients		FAO 56 (Allen et al., 1998)
		Crop price, pumping cost	2020	Compilation of National Income from Agricultural Products (2021)
	Urban	Industrial and domestic water demand, price and supply cost	2020	Provincial water resources bulletin, statistical yearbook
	Ecological	Off-stream ecological water demand, instream environmental flow requirements	Monthly	Yellow River Water Regulation Plan (YRCC, 2025)
Management and Policy	Regulation	Inter-provincial water allocation		1987 Water Allocation Scheme 单击或点击此处输入文字。
	Constraint	Reservoir operation, hydropower output coefficient, flood control water level		Chang *et al.* (2017), Yan et al.(2012), Wei et al. (2003)

3. Model Formulation

~~The hydroeconomic model is an integrated model to reveal and structure the interdisciplinary nature of river basin water management, for deriving economically promising water management and policy decisions.~~ As an optimization model, the HEM's objective is to maximize basin-wide economic benefits of water use to support economically efficient water allocation. ~~Designed from the perspective of management institutions, t~~The model assumes an idealized framework in which the ~~authority~~ YRCC achieves seamless information sharing across ~~all~~ water ~~supply~~ sources and water-use sectors, and has complete control over basin-wide ~~water resource~~ allocation decisions~~ across the basin~~. To certain extent, this setting aligns with real-world governance in the YRB, where the YRCC serves as a centralized authority with cross-provincial and cross-sectoral mandates for planning, water allocation, regulation, and emergency response~~,~~ , a top-down structure differing from decentralized and collaborative institutional frameworks (Giakoumis & Voulvoulis, 2018; Lawless et al., 2024; Rivera-Torres and Gerlak, 2021; Yang et al., 2013).

The HEM runs as a multi-year model with a monthly time step, using continuous monthly hydrologic data during the period of 1996-2015, while fixing socioeconomic and infrastructure conditions at the 2020 level. The monthly time step is adopted to capture seasonal hydrologic variability with computational feasibility, and matches the frequency of management reporting from provincial governments to the basin authority YRCC. The selected unimpaired 1996-2015 monthly hydrologic series represents the most recent continuous and reliable hydrologic record, captures hydrological stochasticity, and enables the HEM's realistic representation of inter-year reservoir regulation. This model formulation follows established modeling approaches for large-scale water resource planning (e.g., CALVIN; Draper et al., 2003; Harou et al., 2009), as well as YRCC's planning and practice (YRCC, 2015).

Fig~~.~~ure ~~1~~ 3 shows the overview of model framework. ~~input~~ Input data are categorized into data on the supply side and demand side, and data ~~for~~ specifying various operational, management and institutional rules ~~in the model~~. Structured in this way, the model includes benefit and cost computation of each modeled water-using sector ~~that~~ to ~~quantifies~~ quantify the economic value of water, while ~~besides~~ imposing constraints ~~applied to~~on the node-arc network to represent mass balance, infrastructure capacity limits, and policy requirements~~that reflect conservation of mass of water flow, capacity constraints of water infrastructure, and policy constraints~~. Outputs include~~s~~ water ~~resource~~allocation, economic performance, and management and policy results. The model ~~was~~ is written in the General Algebraic Modeling System (GAMS) language and solved with CONOPT (GAMS System Overview). Detailed descriptions and units of variables and parameters ~~used in the model~~ are in the ~~supplementary~~ Supplement~~material~~ (Table S1).

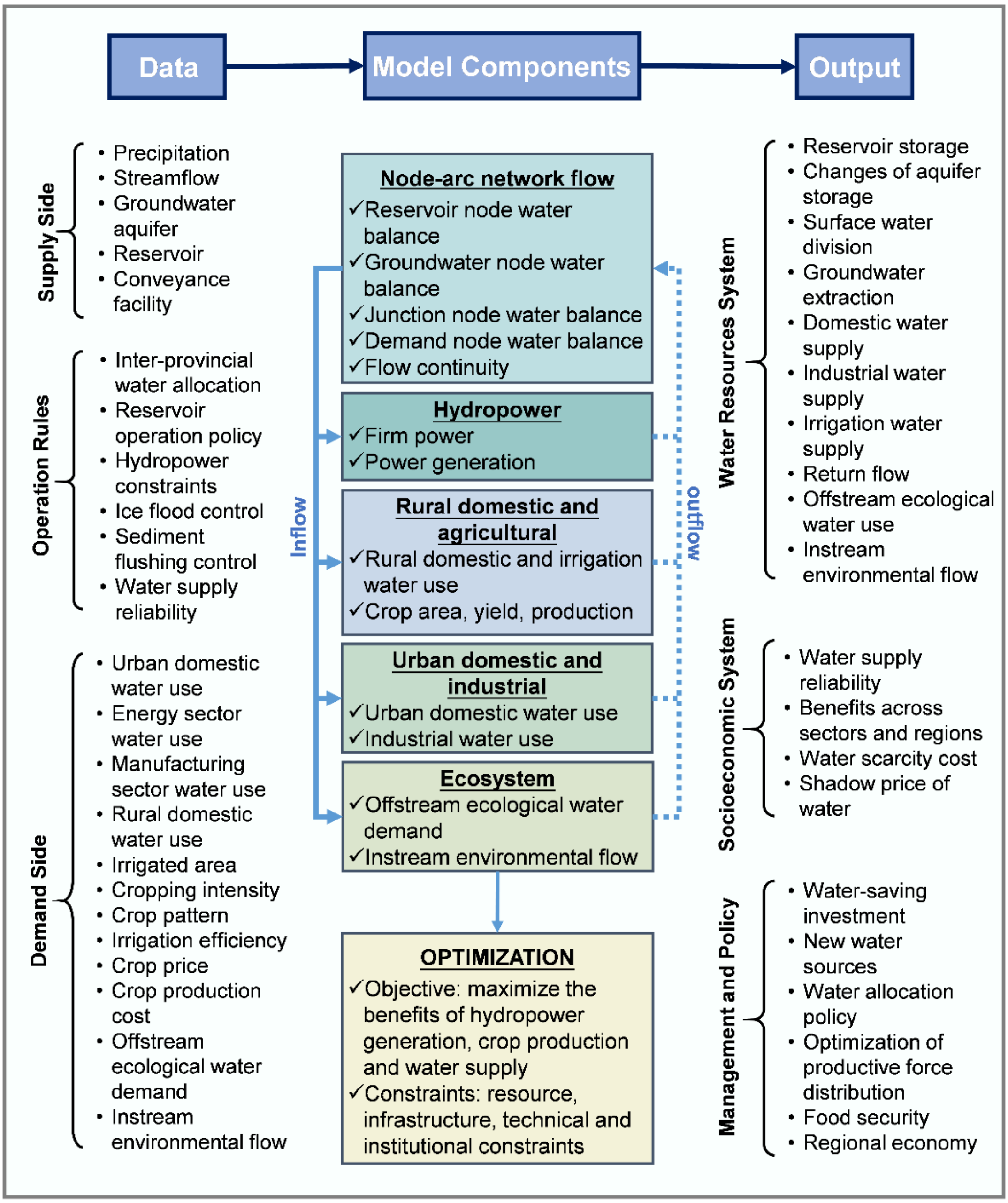


Fig. ~~1~~3. Overview of the model framework.

3.1 Objective Function

The objective ~~function~~ of the model is to maximize the total net ~~total economic~~ benefit of water-~~using~~ use sectors in the basin, including hydropower generation, irrigated agricultural production, ~~industrial water uses,~~ and urban domestic and industrial water uses. The objective function is formulated as:

$$
\begin{aligned}
Max\ Z = &\sum_t \sum_r HP_{r,t} + \sum_y \sum_i AG_{i,y} \\
&+ \sum_y \sum_c UR_{c,y} \\
&- \sum_y \sum_i Cost_{PMP}^{i,y} - \sum_t \sum_g Cost_{Pump}^{g,t} - \sum_t \sum_{d\cancel{n}} Cost_{water}^{d\cancel{n},t} \qquad (1)
\end{aligned}
$$

where the objective variable (Z) represents basin-wide net economic benefit ~~accrued~~ over the entire multi-year period (1996-2015)~~,~~. The right-hand side of Eq. (1) denotes gross revenue of hydropower $HP_{r,t}$ from reservoir r, irrigation $AG_{i,y}$ ~~on~~ in irrigated area i~~,~~ and industrial and municipal activities $UR_{c,y}$ in city c, subtracted by the sum of cost terms including pumping cost $Cost_{Pump}^{g,t}$ from groundwater aquifer g, water resources fees $Cost_{water}^{d\cancel{n},t}$ at every water ~~use sector~~demand node $d\cancel{n}$ (including agricultural, industrial, domestic uses)~~,~~ and total agricultural production cost ~~estimated~~ $Cost_{PMP}^{i,y}$. ~~The value of year index ($y = 1,2, \ldots Y$) can be determined using the value of the index for month sequence ($t = 1,2, \ldots T$) (Table S1).~~ The Positive Mathematical Programming (PMP) is used in this study to estimate parameter values in agricultural production cost functions, which enables replication of the observed land and water use patterns in the base year while adjusting smoothly to economic changes (Howitt, 1995; Zhu et al., 2015). ~~The~~Time value of year index ($y = 1,2, \ldots Y$) can be determined using the value of the index for month sequence ($t = 1,2, \ldots T$) (Table S1).

Energy production and benefit: The revenue from hydropower generation is calculated by flow rate through the turbine, net hydraulic head that drives the turbine, generation efficiency and average monthly electricity price~~, namely~~:

$$HP_{r,t} = K_r \cdot QT_t^r \cdot (H_t^r - T_r) \cdot p_{HP_r} \qquad (2)$$

where K_r is the product of generation efficiency of the ~~hydroelectric~~ hydropower plant, density of water, and ~~the~~ gravitational acceleration, QT_t^r is solved monthly average flow through

~~hydroelectric~~ hydropower turbine, H_t^r is solved hydraulic head, T_r is tail water elevation, and p_{HP_r} is the price of electricity.

Energy consumption for groundwater extraction depends on the pumping rate, depth of groundwater table, and the efficiency of pumping set. The pumping cost is:

$$Cost_{Pump}^{g,t} = \frac{\rho G}{\eta} \cdot H_t^g \cdot Q_t^g \cdot p_{GW} \tag{3}$$

where ρ is water density, G is gravitational acceleration, η is pumping efficiency, H_t^g is pumping depth at groundwater aquifer g, Q_t^g is groundwater withdrawal, and p_{GW} is electricity energy price for pumping~~ groundwater in rural areas~~.

Agricultural production, cost and benefit: To reflect growing stage-specific crop sensitivity ~~of a crop~~ to water deficit ~~with~~ over the growing period, the Jensen's crop water production function (Kipkorir and Raes, 2002; Sun et al., 2012) is applied to estimating crop relative yield. The gross benefit of crop production ~~at~~ in an irrigated~~ion~~ area is determined by crop yields, harvested areas and prices.

$$AG_{i,y} = \sum_{cp} RY_{cp,y}^{i} \cdot Ymax_{cp}^{i} \cdot A_{cp,y}^{i} \cdot p_{AG\,cp} \tag{4}$$

$$RY_{cp,y}^{i} = \prod_{m=1}^{M} \left(\frac{ETa_{cp,t}^{i}}{ETc_{cp,t}^{i}} \right)^{\lambda_{cp}^{m}} \tag{5}$$

In equations (4) and (5), $RY_{cp,y}^{i}$ is solved relative yield for crop cp~~r~~ ~~at~~ in ~~irrigated~~ irrigation district i~~ for crop cp~~, $Ymax_{cp}^{i}$ is maximum crop yield without water stress, $A_{cp,y}^{i}$ is harvested area, $p_{AG\,cp}$ is ~~the~~ crop price, $ETa_{cp,t}^{i}$ is actual crop evapotranspiration, $ETc_{cp,t}^{i}$ is potential crop evapotranspiration, and λ_{cp}^{m} is the sensitivity factor in growing stage m for ~~the~~ crop cp~~,~~ ~~in the Jensen's crop water production function~~(Table S3). The growing stage m represents the order of months within the growing period in year y~~of crop cp in irrigation area i, which is harvested in year y~~.

A quadratic production cost function is estimated using the PMP approach for each crop ~~at~~ in each irrigation district~~ in the model~~:

$$Cost^{i,y}_{PMP} = \sum_{cp} (\mu^i_{cp} + 0.5\varphi^i_{cp} \cdot A^i_{cp,y}) A^i_{cp,y} \tag{6}$$

where μ^i_{cp} and φ^i_{cp} are the intercept and slope in the PMP production cost function for crop cp ~~at~~ in ~~irrigated~~ irrigation district i. In model calibration, the slope of the marginal crop is estimated by observed ~~planting~~ harvested area, land supply elasticity and gross margin. For other crops, cost functions are calculated based on the dual value of economic calibration using the PMP calibration constraint (Zhu et al., 2015).

Urban water-using benefit: Economic gains from water uses in urban industrial and domestic activities are determined based on urban water prices and costs (Cai et al., 2006; Gohar et al., 2019):

$$UR_{c,y} = \sum_{c}\sum_{k} CS^{k,y}_{c} + \sum_{c}\sum_{k} \left(p^{k,y}_{c} - cost^{k,y}_{c}\right) Q^{k,y}_{c} \tag{7}$$

where $CS^{k,y}_{c}$ is consumer surplus for city c and industrial or domestic water use activity k, $p^{k,y}_{c}$ is ~~the~~ urban water tariff, $cost^{k,y}_{c}$ is the cost from suppliers providing water to users, and $Q^{k,y}_{c}$ is industrial or urban domestic water use in year y. It is ~~worth mentioning~~important that $UR_{c,y}$ only represents the economic benefits that water, as a factor of production, contributes to industrial and/or domestic activities.

A demand function of ~~between~~ water price ~~and the demand for water~~with respect to water demand is ~~prescribed with~~specified as the following linear form:

$$p^{k,y}_{c} = \alpha^{k}_{c} - \beta^{k}_{c} \cdot Q^{k,y}_{c} \tag{8}$$

where α^{k}_{c} and β^{k}_{c} are the intercept and ~~the~~ slope of the demand function, respectively, estimated based on observed prices and price elasticity of demand adopted from the literature.

Consumer surplus is derived from the ~~area under~~integral of the demand function as:

$$CS_c^{k,y} = \int_{p_c^{k,t}}^{p_{max}} \left(\alpha_c^k - \beta_c^k \cdot Q_c^{k,y}\right) dQ = \frac{1}{2} Q_c^{k,y} \left(\alpha_c^k - p_c^{k,y}\right) \tag{9}$$

Water resource fees: Charges for water delivered to demand node *d* from both surface water and groundwater are calculated as:

$$Cost_{water}^{d,t} = \sum_{nu} cost_{sur}^{d} \cancel{cost_{sur}} \cdot Q_{sur}{}_t^{nu,d} + \sum_{g} cost_{gw}^{d} \cancel{cost_{gw}} \cdot Q_t^{g,d} \tag{10}$$

where $cost_{sur}^{d}$~~$cost_{sur}$~~ and $cost_{gw}^{d}$~~$cost_{gw}$~~ are surface water and groundwater resources fees, respectively; $Q_{sur}{}_t^{nu,d}$ is surface water used from upstream inflow node nu to demand node d, and $Q_t^{g,d}$ is groundwater used from aquifer g to demand node d.

3.2 Water Balance and Capacity Constraints

Flow balance: Mass balance requires that storage change at a node equals the total incoming flow minus the total outgoing flow during the period:

$$S_t^n - S_{t-1}^n = \sum_{nu} Q_t^{nu,n} - \sum_{nd} Q_t^{n,nd} \tag{11}$$

where S_t^n is storage of node n~~–~~ in period t, $Q_t^{nu,n}$ is inflow from upstream node nu to node n, and $Q_t^{n,nd}$ is outflow from node n to downstream node nd. Eq. (11) applies to node n types including surface reservoir, groundwater aquifer, river reach, artificial conveyance facility such as canals and pipelines, and junction node. River reaches, conveyance facilities, and junction nodes have negligible storage capacity, so the left-hand side of the equation becomes zero, forcing total incoming flow to equal total outgoing flow in any time period. Incoming flows~~ node types include ~~ to node n include flows from upstream river reaches, local streams, reservoirs, groundwater aquifers, and return flows from irrigated area or urban nodes. Outgoing flow node types include reservoir, river reach, groundwater aquifer, reservoir evaporation as a sink, river basin outlet as a sink, and demand site. Specifically, for a reservoir node r with hydropower plant, total release to the downstream equals:

$$\sum_{nd} Q_t^{r,nd} = QT_t^r + QS_t^r \tag{12}$$

~~Where~~ where QT_t^r is flow through turbine, QS_t^r is reservoir spill.

Water delivery: Total water delivery to demand node ~~*n*~~*d* in time period *t* equals the sum of surface water and groundwater deliveries~~ in the time period~~:

$$Q_t^{d\cancel{n}} = \sum_{nu} {Q_{sur}}_t^{nu,d\cancel{n}} + \sum_{g} Q_t^{g,d\cancel{n}} \tag{13}$$

where $Q_t^{d\cancel{n}}$ is total water delivery, ${Q_{sur}}_t^{nu,d\cancel{n}}$ is surface water from upstream node nu to node *d*~~*n*~~, $Q_t^{g,n}$ is groundwater from aquifer g to node *d*~~*n*~~.

Irrigation only occurs when crop evapotranspiration requirement exceeds effective precipitation. Water delivered to an irrigated area equals total delivery multiplied by irrigation efficiency:

$$Q_t^i \cdot e_i = \sum_{cp} IWD_t^i \cdot A_{cp,y}^i \tag{14}$$

where e_i is irrigation efficiency ~~at~~ in irrigation district i, and IWD_t^i is net irrigation water requirement determined by the difference between monthly effective precipitation and crop-specific monthly evapotranspiration when the latter is larger.

Capacity constraints: A set of constraints are applied, to set the upper and lower bounds ~~for~~ of decision variables, including, but not limited to, reservoir storage capacity and dead storage, installed hydropower generation capacity and firm power, conveyance capacity, river flow regime for aquatic ecosystem protection or minimum instream flow requirement, range of planted areas of certain crops and guaranteed urban water supply.

Particularly, to avoid storage depletion by ~~achieving~~ pursuing high net revenue and meeting high water demand, a constraint for major large reservoirs with inter-year storage capacity is added to reserve water for future use at the end of a water year:

$$S_{t_e}^r \geq S_{end}^r \tag{15}$$

where t_e is the last month of a water year and S_{end}^r is targeted carryover reservoir storage value.

3.3 Baseline calibration

Due to ~~the~~ incomplete representation of numerous implicit and qualitative factors in real-world physical processes and decision-making, the HEM is limited in ~~its ability to~~ reliably representing the actual water supply-demand dynamics ~~of water supply and demand~~ with sufficient details, before being calibrated for adequate model fidelity. Thus, a baseline approach is adopted for this study, i.e., using a starting point to compare and evaluate results against observations. Obtaining a baseline of observed ~~model~~ inputs and outputs is a crucial procedure to improve the model's applicability and reliability for policy analysis (Cai and Wang, 2006; Draper et al., 2003).

Calibration is usually used to develop a baseline for a computer-based model. The complexity to calibrate a ~~hydroeconomic model~~HEM is to calibrate the connected hydrologic and economic components (Cai and Wang, 2006). Given the interdependence among these parameters, calibration simultaneously helps to reflect how hydrologic variability propagates to economic outcomes, ~~while~~ and how economic behaviors conversely alter hydrologic regimes.

Hydrologic calibration is to adjust model parameters to ensure that system states closely match observed mass balance conditions (Baccour et al., 2022). This process involves maintaining water balance across the entire basin and at each individual node, balancing water supplies, uses, consumptions, and changes of surface reservoir and groundwater storages. For reservoirs, water storage-release relationships are ~~typically~~ governed by ~~the~~ physical characteristics ~~of the infrastructure~~ and operational rules with embedded economic drivers from demand sites (Cai and Wang, 2006). During the ice-flood control periods, strict constraints are imposed on water releases from major reservoirs ~~to safeguard ice-flood control~~ ~~in~~ to critical river reaches (Chang et al., 2014; Hu et al., 2023a, 2023b; Yan et al., 2012). Additionally, the operations of specific reservoirs during the flood season undertake sediment-flushing tasks, which align with ~~broader objectives of~~ basin-wide water regulation objectives (Gao et al., 2023; Zhai, 2004).

Economic calibration uses the PMP method (Howitt, 1995) to calibrate agricultural activities in the base year, replicating observed land and water use patterns while effectively addressing the issue of over-specialization inherent in ~~typical~~ traditional linear models. By incorporating nonlinearity into the objective function using the shadow values of the calibration constraints (Section 3.1), PMP replicates ~~base~~ base-year activity levels and resource allocation without introducing artificial constraints, ~~ensuring~~ allowing smooth adjustments to economic changes (Mérel and Howitt, 2014). This approach minimizes reliance on detailed information and facilitates ~~the~~ realistic representations of economic behaviors with limited data. The quadratic form of the cost function captures diminishing marginal returns on additional inputs, ~~and~~ accounts for ~~the~~ substitutability of different input factors, ~~focusing~~ focuses on the impacts of water and land on crop yields, ~~while~~ and ~~reflecting~~ reflects farmers' decision-making behaviors (Howitt, 1995; Medellín-Azuara et al., 2012, 2010). ~~To calibrate~~For industrial and domestic water demand, economic parameters such as price ~~elasticity~~ elasticities are adjusted~~.~~, and ~~Water~~ water withdrawals ~~at industrial and domestic sites~~ are calibrated to ~~align with~~

baseline observations through a value-demand search process (Cai et al., 2006).

A model performance evaluation is conducted to assess the consistency of the calibrated HEM with observed system behavior. Model outputs for major hydrological gauge stations, end-of-year reservoir storage, and agricultural water use are compared against observations using Percent Bias (PBIAS) and Normalized Root Mean Square Error (NRMSE). The performance check (Table S4) indicates that the modeled values fall within acceptable ranges relative to the observations, supporting the calibrated model for subsequent analysis.

4. Results

In this paper, the HEM ~~was~~ is solved ~~for~~ as an optimization model ~~run~~ which uses monthly hydrologic and meteorological data from 1996 ~~through~~ to 2015, while ~~the~~ socioeconomic and water management conditions~~, such as water infrastructure, urban water demand, irrigated area and crop mix, water use efficiency and ecological water requirements,~~ are fixed at the ~~base~~ base-year~~, –~~ (~~namely~~ 2020) level. ~~Notably, irrigation water requirements were derived monthly for the period 1996-2015, consistent with time period of streamflow data in the model run.~~ Hydrological year types ~~were~~ are determined by the frequency analysis of the unimpaired annual flow at the basin outlet, with the 5th (2002), 50th (1998), and 95th (2012) percentiles selected from the 1996-2015 period to represent dry, normal, and wet years, respectively.

4.1 Dynamics of Water Supplies and Uses

~~Fig.~~Figure 4 shows the supply of surface water and groundwater ~~for~~ under different hydrologic conditions. Total water withdrawal (TOT) is higher in dry years than in wet years, primarily due to higher irrigation requirements under water scarcity. Surface water is the

~~primary~~ dominant ~~supply~~ source in the basin. However, due to hydrologic and climatic variabilities, natural surface runoff (SWR) fluctuates sharply with annual inflow differences exceeding 20 billion m^3 between dry and wet years for the whole basin. The available surface water inflow is ~~lower than the~~insufficient to meet actual surface water withdrawal (SW) during dry years, and the unmet demand is compensated through reservoir releases and water transfer projects. ~~Groundwater~~ In contrast, groundwater supply (GW) ~~demonstrates~~ is ~~greater stability~~relatively stable across hydrologic conditions, compensating reduced surface water supplies in ~~drier~~ dry years. This highlights the important role of ~~Groundwater~~ groundwater ~~is a more stable source with importance~~ as a buffer resource to enhance the resilience of the basin’s overall water supply system ~~to~~ under unfavorable hydrologic conditions.

~~Fig.~~Figure 5 shows annual water withdrawals, aggregated by ~~the total amount of~~ various water ~~used for various water~~ uses ~~by~~ for each sub-basin~~s~~ and for the entire basin. Irrigation uses the largest amount of water among all sectors, accounting for more than 70% of total water withdrawals in the basin. The high demand is ~~due to~~from the extension of irrigated area, the diversity of crops, and the inconsistency between ~~the~~ peak of water requirements for crop growth and ~~the~~ rainfall seasonality. Agricultural water withdrawal decreases from upstream to downstream, in contrast to the increase in irrigated areas ~~from upstream to downstream. This~~, suggesting~~s~~ more irrigation water use per unit planting area ~~that~~ in the upstream ~~areas use~~regions ~~more irrigation water per unit crop area~~. ~~Specifically, b~~Because upstream regions have a more arid climate, only a relatively small portion of crop water requirements are met by effective precipitation, therefore increasing reliance on irrigation ~~requirements~~. Meanwhile, downstream irrigation districts, with more advanced irrigation technologies, have higher water use efficiency in reducing agricultural water withdrawals.

~~The middle reaches of the YRB have the highest industrial~~ Industrial and domestic water demands are highest in the middle reaches of the YRB. Shanxi and Shaanxi provinces in the midstream region, have water-intensive heavy industries such as energy production, steel manufacturing, and metallurgy (Wang, 2023), resulting in substantial industrial water use. ~~For domestic water use~~Additionally, 14 prefecture-level cities considered in these two provinces have large resident populations, leading to high ~~household~~ domestic water demand. ~~The provinces~~Henan and Shandong in lower reaches ~~such as Henan and Shandong,~~ receives water from the Hai~~he~~ River and the Huai~~he~~ River in addition to the Yellow River. Consequently, their dependence on water withdrawals from the Yellow River ~~is~~ are less than those upstream provinces~~ in the upstream of the YRB~~.

As this study only considers five major off-stream ecological replenishment areas, ~~the proportion of~~ ecological water withdrawal represents the smallest component of total water demand (1.6%)~~ is the smallest water demand~~. The primary objective of ecological water replenishment is to maintain the health of wetland environments rather than to achieve maximum economic benefit, therefore environmental water use ~~has been~~is enforced artificially through laws or regulations (Zhu and Sun, 2025).

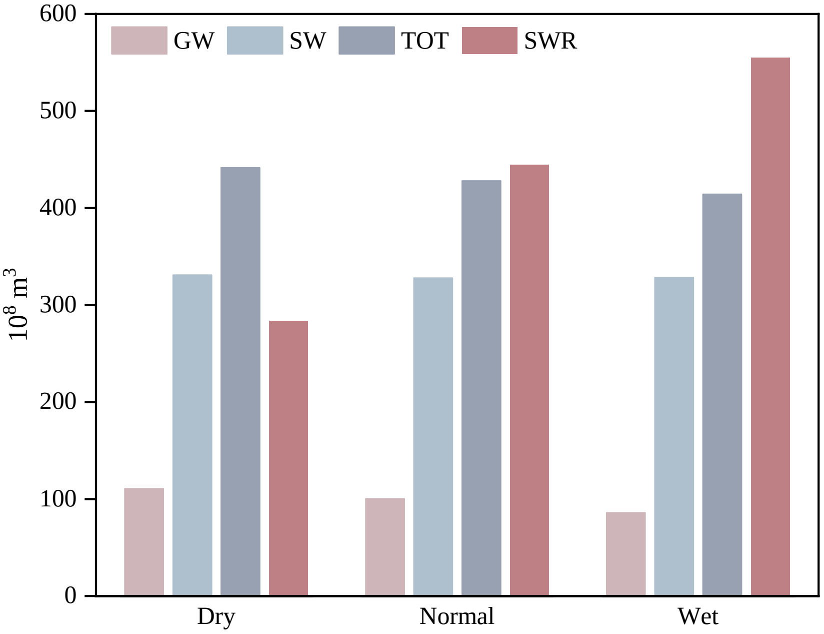


Fig. 4. Water supply by hydrological year type in the entire YRB (10^8 m^3). GW = groundwater withdrawal; SW = surface water withdrawal; TOT = GW + SW; SWR = natural surface runoff.

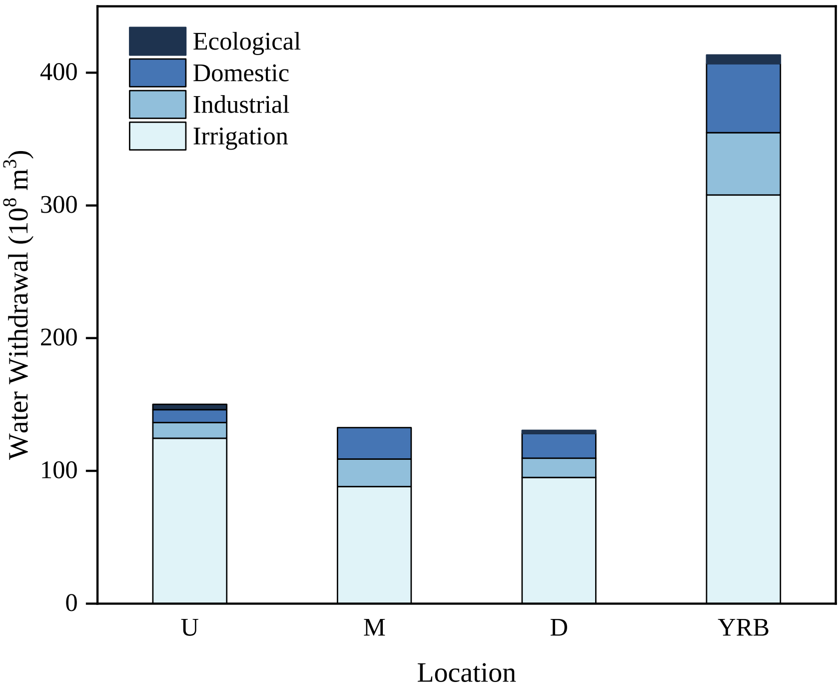


Fig. 5. Water withdrawal by water demand sectors and locations (10^8 m^3). U = upstream region; M = middle-stream region; D = downstream region; YRB = the Yellow River Basin.

4.2 Demand Sector Behaviors

4.2.1 Irrigation and crop cultivation

For different hydrologic scenarios, the ~~absolute planting~~harvested area expands with improved water availability (Fig. 6), underscoring a positive correlation between water availability and land use. In wet years, grain crops have the largest expansion (330,000 hectares), while oil crops, vegetables, and ~~commercial~~ cash crops have comparatively smaller increases, reflecting constraints on total arable land ~~availability~~ and agricultural infrastructure associated with crop patterns. However, the optimal cropping pattern of area shares across the entire basin shows relatively small variations (Fig. S3). Grain crops consistently occupy the largest share of the total ~~cropping~~ planting area, maintaining a highly stable proportion regardless of hydrologic conditions~~.~~ , which reflects their~~The~~ cultivation prioritization in ~~of grain crop cultivation~~ ensuring~~es~~ the security and resilience of food supply system. The shares of other crops increase in water-scarce conditions, suggesting farmers' willingness to cultivate drought-resistant or high-value crops ~~to maximize revenues~~ with limited water. However, their overall share of non-grain crops remains small, exerting negligible impacts on the basin-wide cropping structure.

Table 3 shows the water productivity (WP, defined as crop production per unit of water) of major crops by different locations and hydrological year types in the YRB~~, derived using the model results~~. The WP values differ significantly across crops. Vegetables have substantially higher WP than other crops, primarily from their ~~effective~~ efficient water use for biomass accumulation and higher crop prices. ~~Cotton~~ In contrast, cotton and rice have lower WP, reflecting their higher water requirements. Particularly, under drought conditions, the WP of rice is only 1.5% that of vegetables.

WP increases with improved water availability for most crops, indicating that sufficient water supply enhances crop growth and thereby increases crop yields. Notably, rice as a water-intensive crop, exhibits minimal WP variation between dry and normal years, whereas its WP doubles in wet years.~~but surges 100% in wet years,~~ This response is associated with rice’s high sensitivity of stomatal conductance to water stress, as its photosynthetic rate increases by more than 40% when soil moisture exceeds 70% of field capacity ~~directly linked to its stomatal conductance sensitivity to water stress — when soil moisture exceeds 70% of field capacity, rice photosynthetic rates can increase more than 40%~~ (Bouman et al., 2007).

~~The behaviors of~~ WP of each crop varies spatially ~~by~~ under different hydrologic conditions ~~varies spatially~~. For instance, cotton’s WP in downstream regions increases by 158% in wet years compared to dry years, whereas the corresponding increase in upstream regions ~~show only a~~is only 32%~~ increase~~. This difference stems from the synergistic effects of the North China Plain’s favorable soil and hydrothermal conditions, along with the implementation of water-saving irrigation systems in ~~the~~ that region. Additionally, this spatial sensitivity is driven by the “dual dependence” of downstream irrigation on both local precipitation and water availability from upstream regions, making downstream WP more sensitive to hydrologic variability.

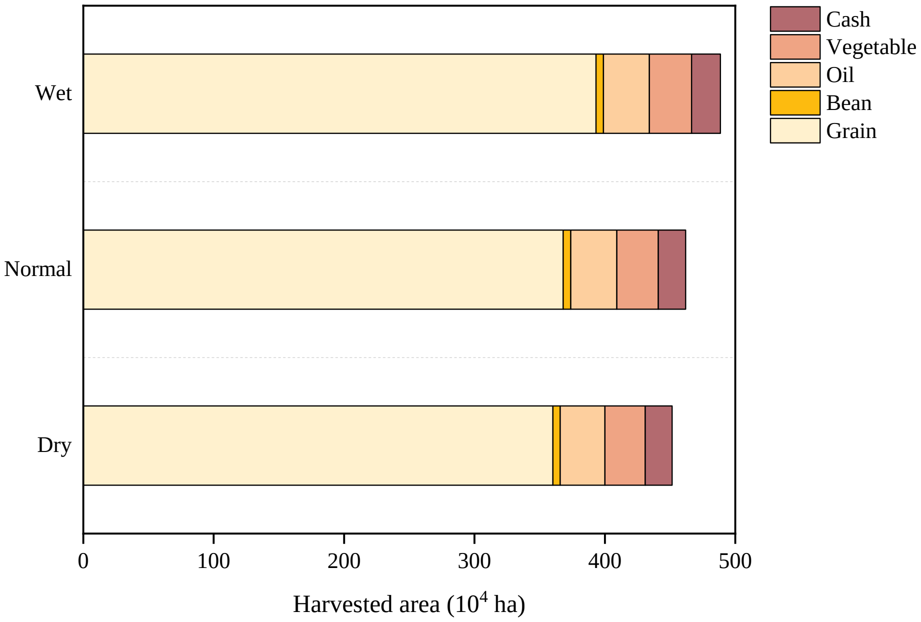


Fig. 6. Harvested area (10^4 ha) by crop and hydrological year type.

Table 3. Crop water productivity by location and hydrological year type (kg/m^3).

Crop Type	Location	Dry	Normal	Wet
Wheat	U	0.73	0.73	0.74
	M	0.81	0.94	0.93
	D	0.76	1.00	1.05
	YRB	0.77	0.95	0.98
Rice	U	0.08	0.11	0.20
	M	0.10	0.10	0.19
	D	0.12	0.12	0.19
	YRB	0.10	0.11	0.20
Maize	U	0.56	0.64	0.68
	M	0.85	1.21	2.55
	D	1.01	2.69	13.68
	YRB	0.81	1.35	2.39
Potato	U	1.69	1.84	1.93
	M	2.15	2.37	2.60
	D	2.61	6.57	5.18
	YRB	1.89	2.06	2.21
Cotton	U	0.26	0.30	0.35
	M	0.41	0.57	0.96
	D	0.44	0.68	1.15
	YRB	0.44	0.66	1.10
Vegetable	U	6.88	7.25	7.54
	M	6.33	6.79	8.35
	D	6.36	7.26	10.49
	YRB	6.47	7.02	8.51

4.2.2 ~~Urban~~ Water Use Structure

~~Fig.~~Figure 7 shows provincial variations in sectoral water use structure within the basin. Provinces in the middle and lower reaches ~~of the Yellow River~~ display higher proportions of industrial and domestic water uses than those in the upper reaches. Particularly, Shanxi ~~demonstrates~~ has a distinct water use pattern, with a relatively low irrigation share (35%) and significantly higher industrial (28%) and domestic (37%) uses compared with other provinces. This structure is largely driven by the dominance of~~Industrial water demand in Shanxi is dominated by~~ water-intensive industries such as coal mining and metallurgy (Wang, 2023), which account for a substantial portion of industrial water demand in Shanxi~~thereby elevating its industrial water use level~~. Shandong and Henan, with advanced industrial systems, prioritize urban and industrial water allocation through stringent policies that constrain agricultural water quotas (Lyu et al., 2022; Yin and Yi, 2016; Yu, 2023). Concurrently, higher urbanization rate and population density in the middle and lower reaches result in higher domestic water demand, contrasting sharply with the sparsely populated upstream areas (Fig. S4). In ~~contrast, in~~ upstream regions (Qinghai, Gansu, Ningxia, and Inner Mongolia), ~~the~~ agricultural sector plays a more important role in provincial economic development, and irrigation requirement is ~~generally~~ high due to ~~the~~ semi-arid and arid climate there.

Compared to irrigation, urban water uses ~~tend to~~ vary less in response to climatic and hydrologic fluctuations. ~~During~~ Under water ~~shortages~~scarcity, water is allocated based on the~~ir~~ respective economic values of competing water use, provided all constraints regarding water allocation in the model are met. As a result, ~~The~~ agricultural sector faces greater pressure to adapt when water availability declines. Thus, as hydroclimatic changes intensify, diminishing water supplies will exacerbate competitions for water ~~between~~ among sectors and regions.

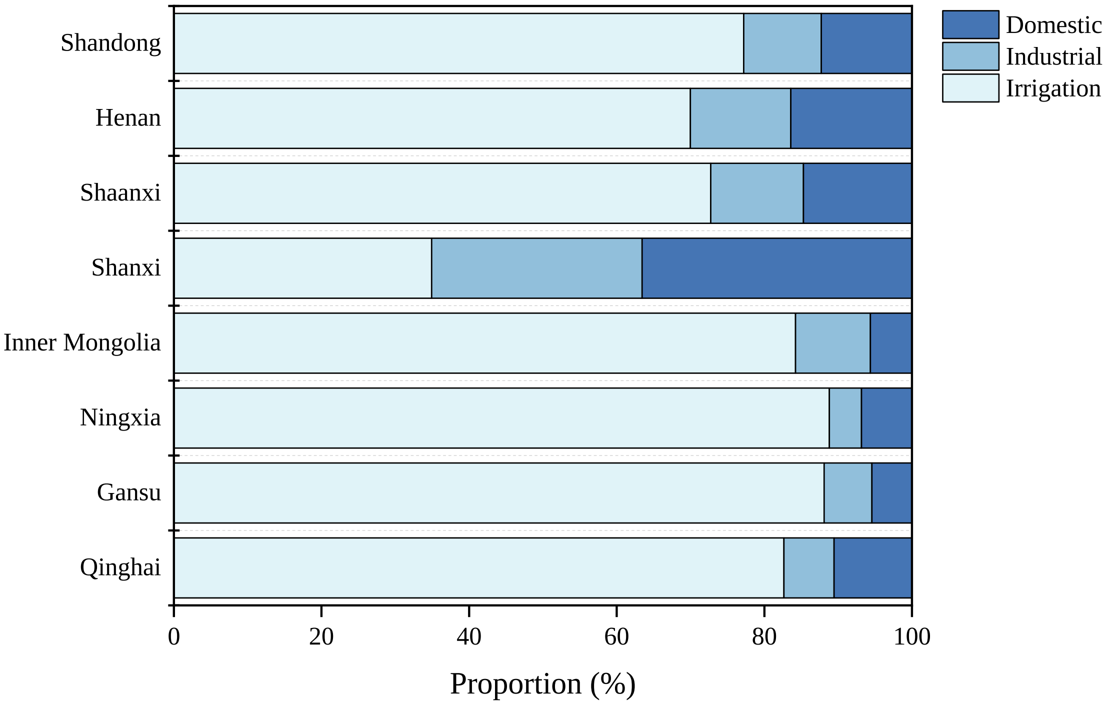


Fig. 7. Water use proportion (%) by sector and province.

4.2.3 *Reservoir Operation*

~~Fig.~~ Figure 8 compares the Longyangxia Reservoir (LYX) annual storage change with ~~reservoir~~ its inflow from 1996 to 2015. A proportional relationship between ~~runoff~~ reservoir inflow and storage shows that the reservoir ~~released~~ releases water in dry years with low inflow and ~~stored~~ stores water in wet years with high inflow. As the only reservoir on the Yellow River with multi-year regulation capability, LYX is critical for inter- and intra-annual regulation, thereby improving water security, protecting ecological health within and outside the river channel, and meeting water demands for basin-wide economic and social development ~~in the entire basin~~. Given the substantial inter-annual variability in ~~the~~ streamflow and the frequent occurrence of consecutive dry years (e.g., 2000-2002), ~~having more~~ additional multi-year regulation reservoirs would benefit the YRB. However, constructing such reservoirs in the middle and lower reaches of the Yellow River is highly challenging due to the lack of suitable dam sites and the high sediment concentration.~~, but it is highly challenging to build such reservoirs on the middle and lower reaches of the Yellow River due to lack of suitable dam sites and high sediment concentration.~~

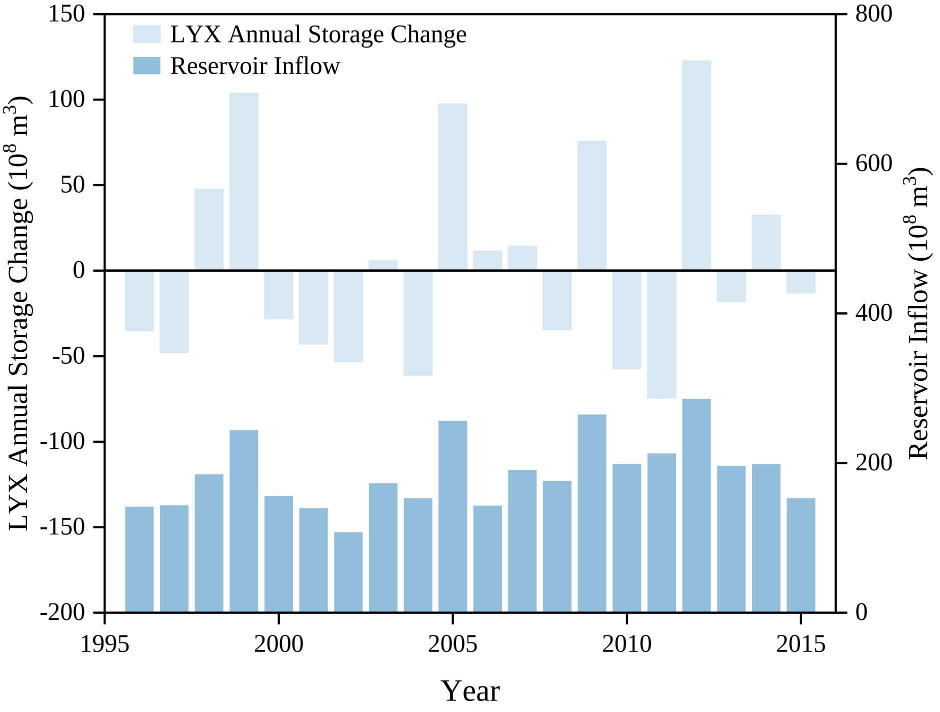


Fig. 8. Longyangxia reservoir (LYX) annual storage change and inflow from 1996 to 2015 (10^8 m^3).

Table 4 summarizes the frequencies of full/empty storage (i.e., the upper/lower bound of active storage) ~~reservoir storage full/empty (i.e., the upper/lower bound of active storage) occurring with~~ for the major cascade reservoirs ~~in the YRB~~ during 1996~~–~~-2015. LYX, with a total storage capacity of 24.7 billion m^3, ~~was~~ is designed for prolonged drought mitigation, and therefore ~~it~~ rarely ~~reached~~ reaches full or empty storage levels except in exceptionally wet or dry years. LiuJX, with about 23% of ~~the~~ LYX's storage capacity, serves as a primary peak-shaving power station in the northwestern power grid of China and ~~was~~ is full several times every year in the study period, which ~~was~~ is likely driven by electric power generation requirements. WJZ ~~showed~~ shows high frequencies of being completely empty or full, due to its limited regulating storage capacity (896 million m^3), which is only 3.6% of LYX's capacity~~.~~ ~~The role of the reservoir is to~~, and its role in ~~regulate~~ regulating water diversion from the Yellow River to Shanxi Province. SMX and XLD never reach~~ed~~ full capacity, because ~~of~~ their key functions of flood control and sediment flushing~~, which~~ require strict water-level management to preserve adequate flood regulation space and to flush sediment ~~out of the reservoir~~ *via* generated “artificial floods” to downstream (Wu et al., 2021). To mitigate flood risks in the lower reaches~~ of the Yellow River~~, SMX is often preemptively drawn down during the flood season to accommodate potential flood peaks.

During 2000~~–~~-2005, ~~the~~ all five reservoirs experience~~d~~ varying ~~levels~~ degrees of empty storage, ~~due to~~as consecutive dry years ~~leading to reduced~~reduce basin-wide water availability. These full~~–~~-empty storage occurrences ~~with the cascade reservoirs~~are closely associated with inter-annual ~~variations in reservoir inflows~~inflow variability, multi-objective operational requirements (flood control, water supply, sediment transport, and ecological protection), and the joint operation of ~~these~~ cascade reservoirs~~. The interplay between inflow variability and operational priorities necessitates a dynamic approach for reservoir scheduling to ensure water resource utilization while mitigating flood risks.~~, highlighting the need for dynamic reservoir scheduling to balance water use and flood risk mitigation.

Table 4. The frequency of full (○) and empty (☒) storage ~~capacity~~ in the cascade reservoirs from 1996 to 2015. The numbers in parentheses indicate the monthly occurrences of reservoir emptying or filling in the given year.

Reservoir	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
LYX				○(1)				☒(4)		☒(3)				○(2)			○(2)	○(1)		○(1)
LiuJX	○(5)	○(4)	○(4)	○(4)	○(5)	○(6)	○(6)	○(3) ☒(2)	○(2)	○(2)	○(4)	☒(1)	○(4)	○(2)	☒(2)	☒(3)	☒(2)	○(4) ☒(1)	○(3) ☒(1)	○(6)
WJZ	○(3) ☒(4)	○(4) ☒(5)	○(2) ☒(3)	○(5) ☒(3)	○(3) ☒(5)	○(5) ☒(5)	○(3) ☒(4)	○(1) ☒(6)	○(4) ☒(4)	○(2) ☒(4)	○(2) ☒(4)	○(2) ☒(5)	○(4) ☒(4)	○(2) ☒(8)	○(3) ☒(7)	○(6) ☒(5)	○(4) ☒(5)	○(3) ☒(6)	○(5) ☒(3)	○(3) ☒(5)
SMX	☒(4)	☒(4)	☒(4)	☒(3)	☒(3)	☒(5)	☒(4)	☒(3)	☒(3)	☒(3)	☒(4)	☒(3)	☒(4)	☒(5)	☒(4)	☒(4)	☒(4)	☒(4)	☒(3)	☒(3)
XLD	☒(2)			☒(1)	☒(1)		☒(2)	☒(3)	☒(2)	☒(2)	☒(2)				☒(3)	☒(1)		☒(2)		☒(2)

4.3 Economic Welfare

Table 5 presents the economic benefits and costs by ~~water-~~water-use sectors under ~~dry, normal and wet~~various hydrologic conditions. The majority of the economic benefits are from agricultural production, with ~~revenues for~~ an average value of 78.54 billion yuan, consistent with its dominant role in basin water use.~~which aligns with the fact that agriculture is the largest water users in the basin~~ Benefits from domestic water use remain relatively stable across different climatic and hydrologic conditions due to ~~its~~ low price elasticity and stable water demand. Industrial benefits, ~~However~~however, ~~due to its higher price elasticity, industrial benefits~~ are more sensitive to reductions in water availability due to higher price elasticity. Hydropower ~~generation~~ benefits ~~are~~ depend directly ~~related to the~~on natural runoff, and consequently vary more with water variability.

Net benefit is calculated by the difference between total benefits and costs (Fig. 9). For a wetter hydrology case, total benefit (176.54 billion yuan), cost (18.51 billion yuan), and net benefit (158.04 billion yuan) are higher than those in dry years, ~~consistent with the~~reflecting higher water availability and larger water withdrawals in the basin. ~~The~~ Nevertheless, the relatively small difference in net benefits across hydrologic years is attributed to several synergistic mechanisms: (1) As the dominant component of total benefits, agricultural revenue is stabilized through a minimum cultivated area constraint in the optimization model~~. This policy~~, which prevents excessive land fallowing while maintaining regional cropping patterns. Although grain crop ~~cultivation~~areas expand preferentially ~~during~~ in wet years, their limited contribution to total agricultural revenue persists due to low commodity prices~~;~~. (2) Due to the prioritization of guaranteed water use ~~in~~ for domestic and industrial sectors, urban water use

~~shows only modest variation~~varies little across water years~~ and small reduction of water consumption under water scarcity, with~~, resulting in stable ~~net ~~benefits from ~~industrial and domestic~~these sectors even under water scarcity~~;~~. (3) Although hydropower benefit fluctuates significantly with water availability (Fig. S5), the small share of total benefits minimizes its overall impact~~;~~. (4) The cascade reservoir system along the mainstream, particularly the L~~ongyangxia Reservoir~~YX with its multi-year regulation capacity, enables inter-annual water reallocation. ~~This infrastructure stores s~~Surplus water is stored during wet years and ~~releases~~ released ~~strategic reserves ~~during droughts, effectively decoupling water availability from sectoral demands. ~~The ~~Overall, the HEM optimization framework demonstrates robust ~~benefit~~ stabilization of economic benefits, maintaining total net benefit fluctuations across all hydrologic scenarios.

Table 5. Economic benefits and costs by water demand sectors under different hydrological year types (billion yuan).

	Sector	**Dry**	**Normal**	**Wet**	**Average**
Benefit	Agricultural	73.49	78.60	85.48	78.54
	Domestic	59.39	59.62	59.97	59.49
	Hydropower	5.45	4.87	6.53	6.31
	Industrial	23.29	23.93	24.57	23.85
	Sum	161.61	167.02	176.54	168.20
Cost	PMP	16.78	16.96	18.32	17.21
	Pumping	0.06	0.05	0.02	0.07
	Resource	0.28	0.21	0.17	0.25
	Sum	17.13	17.22	18.51	17.32

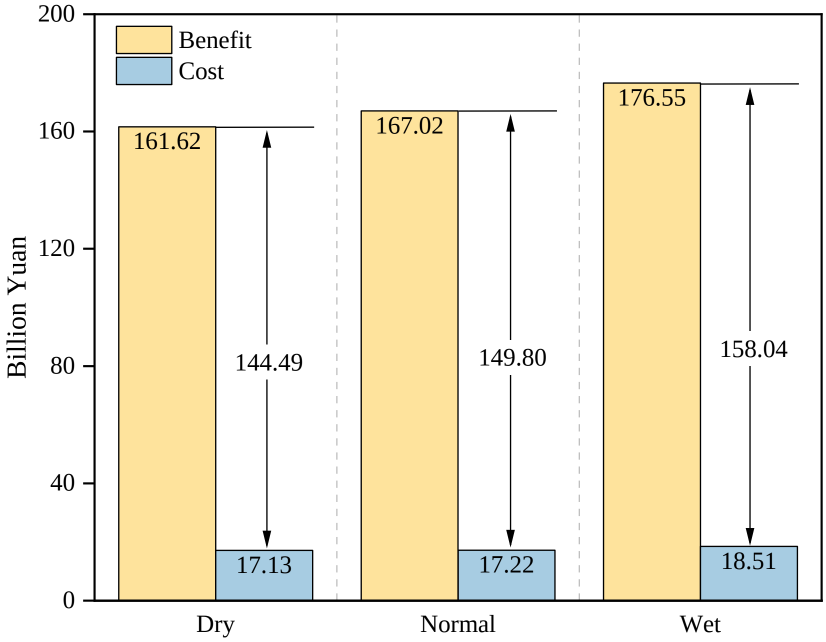
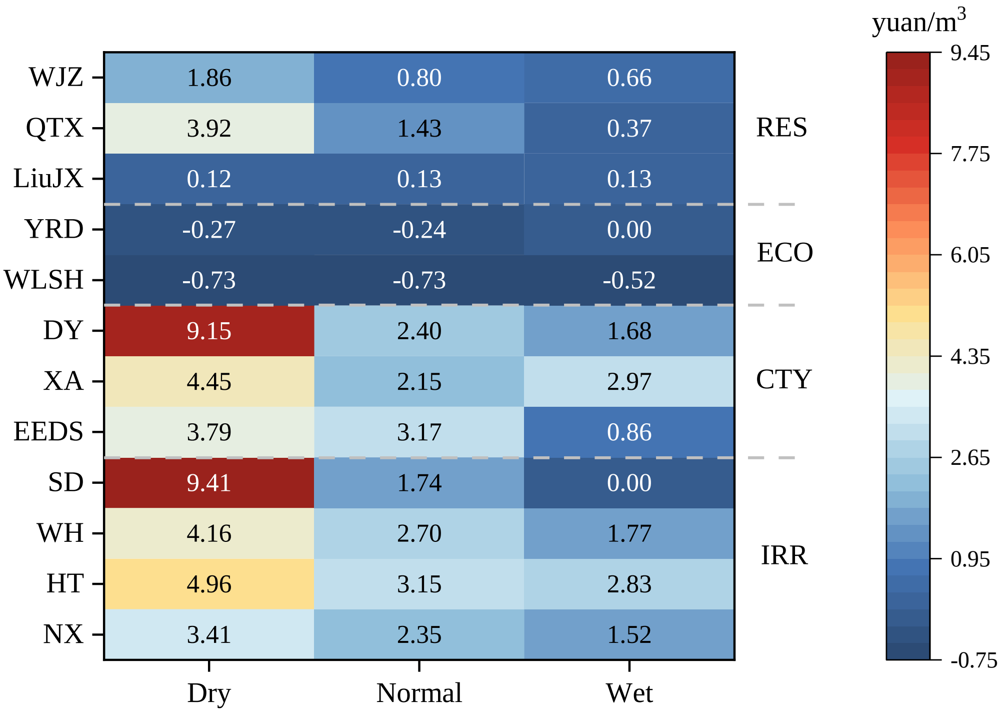


Fig. 9. Benefits and costs by dry, normal and wet hydrologic cases (billion yuan).

4.4 Marginal Values

Marginal values (or equally shadow prices) offer decision-makers and water stakeholders' essential insights by quantifying the value of additional water and reflecting the degree of water scarcity. ~~Fig.~~Figure 10 presents shadow prices ~~across ~~for various demand sectors ~~and ~~under different hydrologic conditions. For a given hydrological year type, the marginal value represents the economic gain (or cost reduction)~~, in expected value,~~ for one additional unit of water available in that month for ~~the ~~irrigation, urban use, and ecological replenishment~~ sectors,~~, and annually for reservoirs. When water scarcity intensifies, shadow prices are higher. In this study, marginal values of water are determined based on ~~the ~~total water withdrawals at the demand sites.



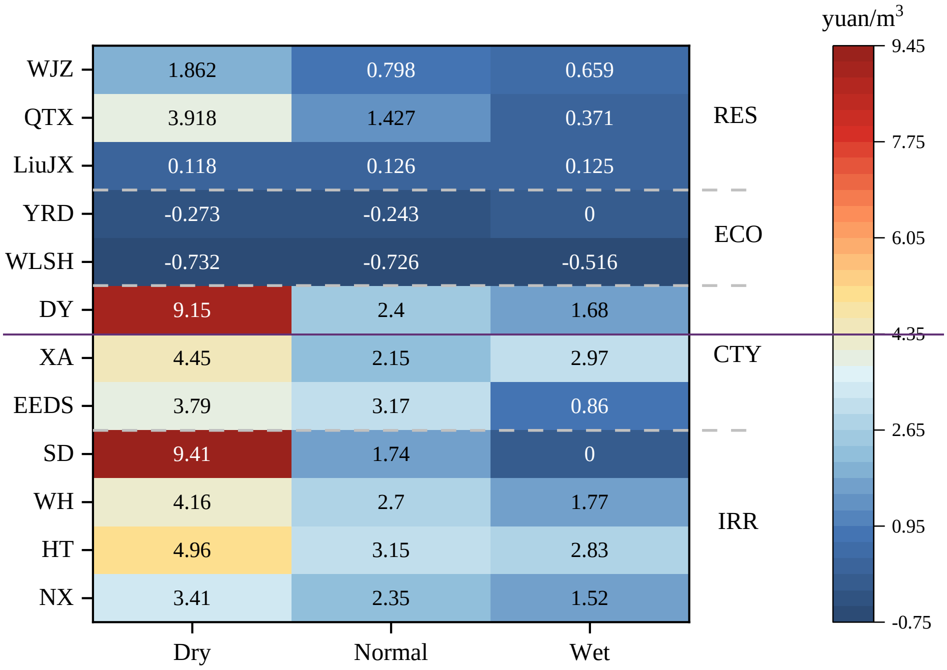


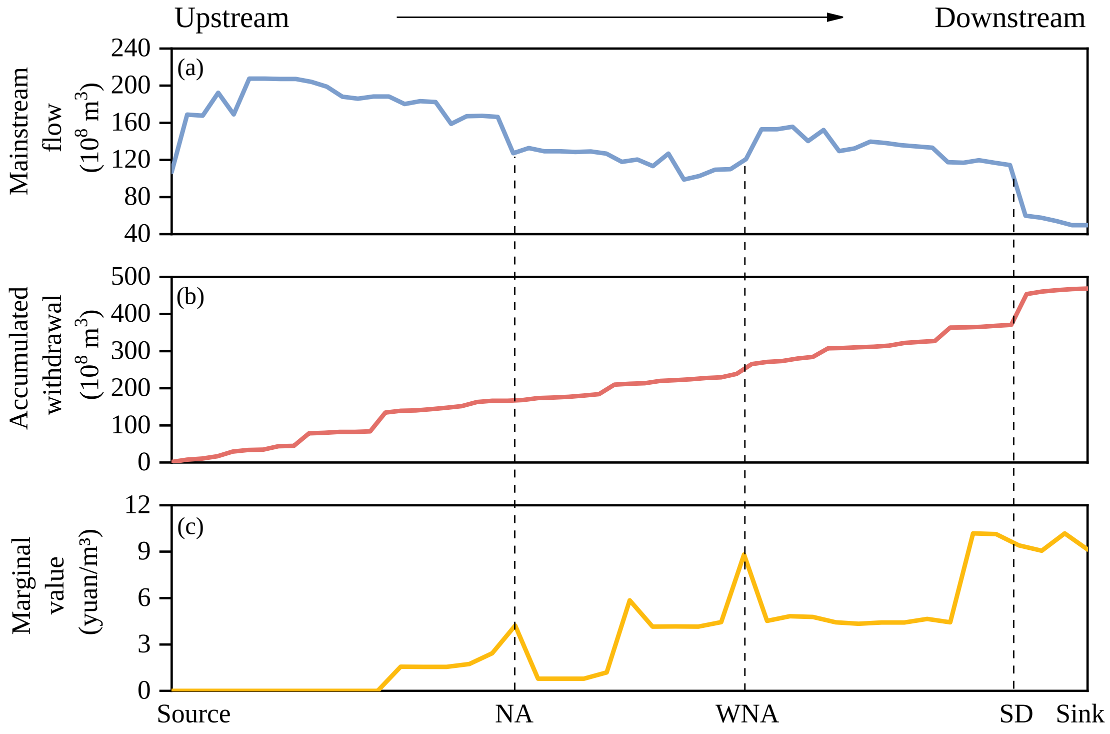
Fig. 10. Marginal values of water by water demand sectors under dry, normal and wet hydrologic conditions (yuan/m³) in different parts of the YRB. IRR = irrigation district; CTY = city; ECO = off-stream ecological replenishment area; RES = reservoir. See Table 1 for detailed node interpretation.

***Irrigation*:** Marginal values appear only in months when irrigation demand exists in the ~~relevant~~ corresponding irrigation district. NX and HT upstream, WH in the middle reaches, and SD downstream are selected as representatives~~ of each region~~. Compared to wet years, ~~the~~ shadow prices in these major irrigation districts rise sharply in dry years, suggesting that reduced Yellow River water supply exacerbates shortages of irrigation water and reduces agricultural revenues. In the downstream, the shadow price of SD remains ~~at~~ zero ~~in~~ under wet conditions, indicating farmers' unwillingness to pay for additional delivered water since additional water supply ~~will~~ does not increase additional returns.

Urban use: ~~The m~~Marginal values of urban water use in three representative cities~~—~~, EEDS (upper region), XA (middle region), and DY (lower region)~~—~~, reflect their varying dependence on the Yellow River as a primary water source. Higher marginal values under water scarcity indicate greater stress on urban water supply. From dry to wet years, shadow prices decrease by 77.3% in EEDS and 33.3% in XA, while DY shows a larger decline of 81.6%, highlighting its greater sensitivity to hydrologic variability. In dry years, an additional unit of water supply provides substantially higher benefits to urban activities in DY, consistent with its industrial-dominated economic structure.~~The higher marginal values during water shortages highlights that water stress produces more difficulty in delivering water. Comparing to EEDS and XA with the reduction of 77.3% and 33.3% in shadow prices from dry years to wet years, DY demonstrates a more pronounced decline of 81.6%. Increasing water supply by one additional unit significantly increases benefits to urban activities in DY in dry years, coinciding with its industrial-dominated economic structure.~~

Ecological replenishment: WLSH and YRD, as main off-stream ecological replenishment areas, are excluded from directly achieving economic value objectives. However, water replenished to these areas indirectly affects available water supply and related economic benefits ~~from~~ for other water-use sectors. The negative sign means that using an additional unit of water for environmental protection reduces total (urban, agriculture, and hydropower) economic benefits. The absolute values of these shadow prices are high in dry years due to prioritization of high-value economic sectors, but decline in wet years as increased water availability allows more water to be allocated to less economically productive uses.~~As water scarcity prioritizes water resources allocation for economically high-value production sectors, the absolute values of shadow prices are large in dry years. However, in wet years, the absolute values of shadow prices decrease as water availability allows for expanded use for less economically productive uses.~~

Reservoirs: ~~The m~~Marginal values of reservoirs refer~~s~~ to the benefits of increasing one additional unit of maximum reservoir storage capacity~~by one additional unit of water~~, related to both generating hydropower and meeting downstream water ~~uses and~~ requirements. ~~During dry years,~~ LiuJX, ~~as the~~a large-capacity reservoir and major hydropower station on the main stem, shows lower marginal values ~~compared to~~than smaller reservoirs such as QTX and WJZ, reflecting both the limited contribution of additional ~~water~~ storage to power generation and ~~satisfying water requirements in surrounding areas~~the satisfaction of local water demands. QTX primarily~~serves to~~ supports irrigation in~~the~~ surrounding~~irrigation~~ districts, while WJZ ~~additionally~~ diverts water from the Yellow River to Shanxi Province through the water transfer project. Both reservoirs alleviate water shortages~~for maintaining requirements of water-consuming sectors~~, as demonstrated by their high marginal values. Higher values for the smaller reservoirs may be associated with more frequent refilling and ~~might occur because these reservoirs can likely refill more often and might produce~~ greater hydropower head per unit of additional storage (Table 4). These marginal values ~~must~~ should ultimately be compared with the costs of expanding ~~these~~ reservoir capacities, ~~where~~ as different sites can ~~very~~ vary different economies or diseconomies of scale in construction.



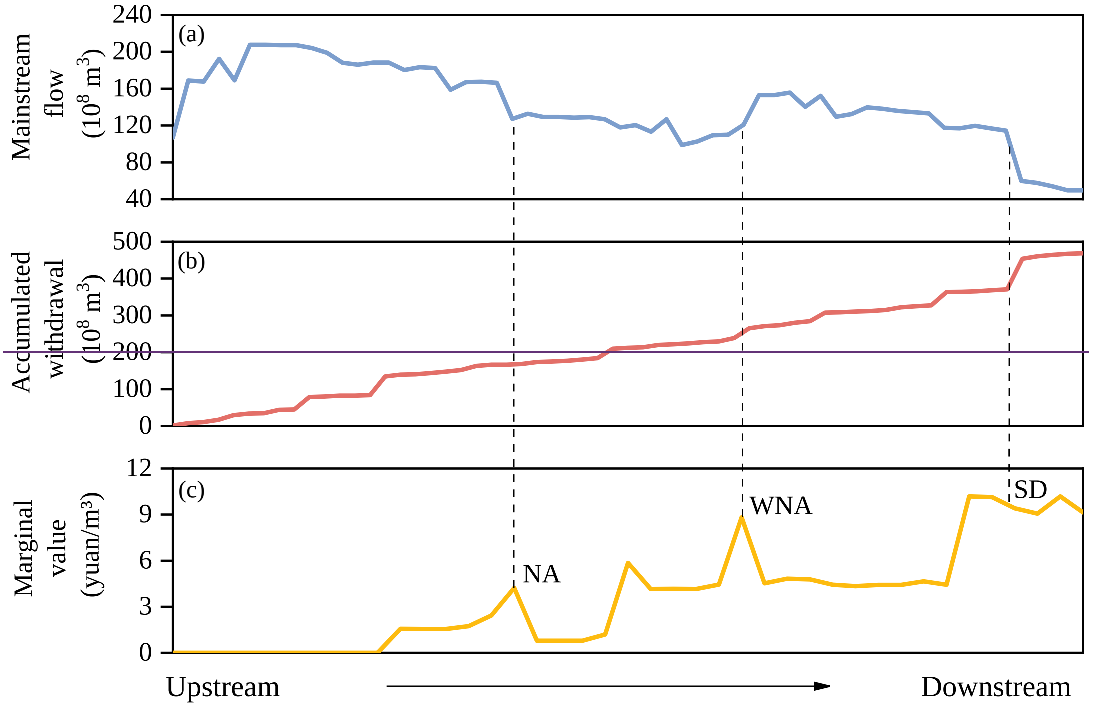


Fig. 11. Spatial dynamics of (a) mainstream flow (10^8 m^3), (b) ~~accumulated~~ cumulative withdrawals (10^8 m^3), and (c) marginal values of water (yuan/m^3) along the Yellow River in a typical dry year.

~~Fig.~~Figure 11 illustrates the spatial variations in streamflow (Fig. 11a), ~~accumulated~~ cumulative withdrawals (Fig. 11b), and marginal values of water (Fig. 11c) along the main stem of the Yellow River during a representative dry year. The ~~coincidence~~ co-occurrence of decreasing flow, increasing withdrawals, and rising marginal values highlights the intensification of water scarcity from upstream to downstream. Upstream regions, where flow remains relatively high, have low marginal values due to adequate water supply. However, cumulative withdrawals substantially reduce available water along the mainstem,~~as withdrawals accumulate, water availability is reduced,~~ ~~driving an increased~~increasing the economic value of water. The ~~sharpest~~ most pronounced marginal value peaks ~~correspond to~~occur in regions ~~lacking~~ with limited alternative water sources and/or ~~with~~ high-intensive production activities, such as NA relying solely on the Yellow River for irrigation, WNA depending on the Wei~~he~~ River for industrial and domestic use but facing competition from its upstream ~~cities and irrigation areas~~users, and SD with extensive ~~irrigation~~ irrigated areas but very limited water availability near the estuary.

Several factors affect marginal value spatial dynamics. First, intensive agricultural withdrawals ~~deplete~~ reduce local water availability, increasing the value of ~~making~~ additional ~~units of~~ water ~~more valuable~~ for sustaining crop yields. Second, growing industrial and urban water demands ~~enhance~~ intensify water use competition, particularly in downstream cities with ~~growing~~ expanding populations and economic activities. Finally, institutional water allocation constraints, including inter-basin transfer regulations and environmental flow requirements, further restrict access to water, amplifying marginal values.

The strong correlation between withdrawal amount and marginal value underscores the need for targeted conservation and allocation strategies. ~~Enhancing~~ Improving irrigation efficiency, optimizing industrial water use, and refining allocation mechanisms can mitigate excessive withdrawals and alleviate pressure on downstream users. Furthermore, market-based approaches such as water pricing and trading could facilitate more efficient allocation, ~~ensuring~~ supporting sustainable water management in ~~scarcity-prone~~water-scarce areas (Ringler et al., 2010; Trail and Ward, 2024; Zhao et al., 2023).

5. Discussion

5.1 Implications

Our results have some key implications for improving water management flexibility and water use efficiency.

Spatiotemporal water supply variations (Fig. 5) across the basin highlight opportunities for more adaptive water management that can serve as a reference for planners to make better decisions to meet demand requirements. As irrigation water use occupies 74% of ~~the~~ total basin~~'s total~~ water use, improv~~ements in~~ing irrigation water-use efficiency is critical. Furthermore, to mitigate the impacts of water shortages that may lead to fallow land or shifts in cropping patterns, comprehensive reforms in agricultural water pricing and reward mechanisms for water conservation are essential. Additionally, most crops experience yield reductions under water-deficient conditions, while drought-resistant crops maintain relatively high productivity levels (Table 3). ~~Increasing~~ Expanding the cultivation of low-~~-~~water-consuming and drought-resistant crops, together with improvements in crop varieties through genetic enhancement, ~~and improving genetically engineered plants with high quality and~~

~~quantity,~~ can help ~~ensure~~ stabilize agricultural production ~~stability~~ under increasing water stress.

For industrial activities, water withdrawal in midstream and downstream cities accounts for 74.9% of total industrial water ~~usage~~ use across the basin (Fig. S4), with heavy industries dominating in these regions. Efforts should focus on maximizing the potential for water-saving by accelerating the adoption of advanced water-saving technologies and equipment. Priority should be given to water-saving measures in high water-consuming industries such as energy, chemical manufacturing, and construction materials production, as well as to improving ~~technologies for the reuse of~~ urban wastewater reuse technologies~~, ensuring both efficiency gains and reduced water demand~~.

Addressing the ~~threat~~ risk of severe water scarcity with consecutive dry-year conditions requires careful consideration of adaptive reservoir management strategies~~, particular attention should be paid to setting hedging rules for operating multi-year reservoirs to ensure the reliability of water supply planning~~. In particular, appropriate hedging rules for multi-year reservoir operation are essential to improve the reliability of long-term water supply planning. ~~In~~ While optimization models often assume~~, the assumption of~~ perfect hydrologic foresight~~—while practical~~ for computational convenience~~—~~, such assumption does not align with real-world conditions. Reservoirs may ~~perform storage and release operations~~operate based on "foreseen" future conditions that do not exist, leading to suboptimal storage and release decisions. Consequently, ~~the~~ analysis on carryover storage of multi-year regulating reservoirs, such as the ~~Longyangxia Reservoir~~LYX, is important to provide a physical buffer against hydrologic and demand uncertainties and for reducing reliance on unrealistic modeling assumptions.

Based on the spatial and temporal variability in the ~~varying~~ marginal values of water ~~during different water years and~~ across ~~various water use~~ hydrologic conditions, sectors and locations (Fig. 10 and Fig. 11), economically-oriented water transfers and water rights trading can enhance reallocation of water resources. During dry years, downstream ~~water use~~ sectors show~~s~~ higher marginal values ~~for~~ of water, indicating that transferring surplus water from upper to ~~middle and~~ lower reaches *via* water markets or other negotiated agreements could ~~achieve~~ generate greater economic benefits~~ and~~, foster inter-regional win-win outcomes, and mitigate water ~~shortages in water-stressed areas~~stress. Multi-purpose ~~Reservoirs~~ reservoirs, ~~such as the Qingtongxia reservoir exemplify a multi-purpose water management system~~play a key role in this process. ~~Its~~ Their high marginal values underscore~~s~~ the significant economic and social benefits generated by each unit of water in meeting diverse objectives, including hydropower generation, flood control, and water supply. However, ~~the reservoir's~~ current storage ~~capacity~~ capacities and regulation capabilities ~~appear~~ are insufficient to fully meet growing demands. Targeted investments in additional storage infrastructure or inter-basin water transfer projects could therefore enhance system resilience and improve overall water resource utilization~~To alleviate the pressure, investments in new storage infrastructure or inter-basin water transfer projects could enhance the system's resilience and optimize water resource utilization~~.

5.2 Limitations and Future Developments

The HEM developed in this study involves several simplifying assumptions. First, water allocation ~~in the model~~ is driven exclusively by the basin-wide economic objective as long as the constraints are met. However, in ~~the~~ real-world applications, water management is guided by broader criteria, including water supply reliability, environmental performance (Kahil et al., 2018), and political considerations. Second, representing basin components using a node-arc network, despite its convenience for modeling, assumes a representative water user at each demand node, thus ignoring ~~the~~ heterogeneities in ~~size~~scales, technologies, productivity and user preferences across different users within each demand area. At the node level, the model simulates the exchange and allocation of flows between nodes but does not capture detailed local dynamic feedbacks, such as interactions between groundwater aquifers and surface water systems. For the time scale, the monthly time step adopted in the model run limits the representation of short-term hydrological extremes, such as flood peaks, reflecting the HEM's focus on basin-scale water allocation rather than event-scale dynamics. Besides, the model broadly classifies water use into four sectors~~,~~: irrigation, urban (industrial and domestic) use, hydropower, and ecology. Livestock and forestry within agriculture, light industry, individual household water use behavior, or the functions of local ecological protection and aquaculture associated with reservoirs are omitted. Including these water users can improve the assessment of water competition among sectors and guide efficient allocation on a broader sectoral scale. Lastly, the model assumes that the river basin management authority has full control over all water-use sectors, possesses comprehensive access to and management of information from both ~~the~~ supply and demand sides, and can respond promptly to any changes or adjustments within the system. ~~Under these assumptions~~Accordingly, the management authority is conceptualized as an efficient decision-making entity capable of integrating information, optimizing resource allocation, and dynamically regulating operations. Consistent with this basin-level perspective, the model emphasizes coordinated allocation at the basin scale and therefore does not fully represent decentralized decision-making mechanisms operating at the provincial level. Thus, the model provides an idealized solution (rather than a directly implementable solution) including precise policy evaluation and strategy optimization that the basin authority can achieve if the flow of information and feedback within a complex water resource system can be followed. Nevertheless, idealized solutions provide insights and directions for policy and management improvements, they are not suitable for real-time scheduling and daily operational management, and face significant limitations at micro-level applications such as individual water users.

Another limitation of this study is the deficiency in information and data. Due to the lack of reliable biophysical and economic data, ~~this study does not fully account for~~ important local processes, impacts on water quality, interaction between surface water and groundwater, and changes ~~groundwater over-extraction, and potential increases~~ in the cost of water supply over time, etc., are not fully represented. Especially, ~~Data~~ data acquisition presents significant challenges, such as limited data sharing among institutions and concerns over confidentiality, which restrict access to comprehensive datasets and affect the validation of the basin-wide model. ~~Data from different sources have d~~Moreover, discrepancies in temporal and spatial resolution across data sources~~,~~ ~~complicating~~ complicate ~~their~~ data integration. Even after extensive processing ~~to ensure data usability~~, variability in numerical scales across datasets, combined with uncertainties from natural variability and measurement errors, poses difficulties in assessing the reliability of model outputs (Cai, 2008a).

Climatic water stress, population growth, and increasing concerns over regional water sharing and equity within many arid and semi-arid ~~watersheds~~ basins highlight the significance of designing models ~~and mechanisms~~that can adapt~~ed~~ to both natural change and socioeconomic development. Future research should prioritize sustainable water use ~~with~~ under long-term climate change and increasing extreme ~~climate~~events ~~conditions~~, with greater emphasis on incorporating stochastic optimization or scenario-based analysis to explore future climate and socioeconomic pathways. It is also vital to consider large-scale infrastructure projects under construction or ~~in preparation~~planning, including the western route of the South-North Water Transfer Project, ~~which is directly related to understanding and~~to support evaluation of investment feasibility and future economic benefits. Finally, ~~including~~ future model development should more explicitly represent conjunctive use of surface water, groundwater and other unconventional sources ~~is of great relevance~~, especially given the unreliability of relying on a single source and the derivative risks from groundwater over-exploitation.

6. Conclusions

This study ~~developed~~ develops a hydroeconomic optimization model that integrates surface and groundwater hydrology, water infrastructure, and sector-specific water demands ~~across a large basin~~ into a coherent analytical framework to assess ~~the~~ spatiotemporal variations of water availability and water value in a large basin. The model adopts a PMP calibration method to suggest an optimal water allocation plan in which the optimized baseline conditions are consistent with data observed ~~data in term of~~for irrigated areas, reservoir storage levels, and city water supplies ~~across the basin~~, allowing ~~to identify~~ identification ~~the~~ of impacts ~~of~~ from any new changes in policies and operational rules on water allocation and benefits at the basin scale. The ~~model provides a~~ framework ~~for understanding the~~captures trade-offs among competing water uses including agricultural production, industrial and domestic activities,

~~domestic consumption,~~ and ecological requirements, and offers quantitative support for ~~decision-making at the basin scale for the river basin management authority~~basin-wide water management decisions.

The ~~hydroeconomic model~~HEM ~~was~~ is applied to the ~~Yellow River basin~~YRB in China, a large basin with pressing water security issues and a centralized basin authority (YRCC) to coordinate basin-wide management activities. By investigating ~~the~~ supply-demand dynamics ~~in the basin~~ under different hydrologic ~~scenarios~~conditions, the results indicate that:

(1) Meeting water demands of the various sectors with reliability,~~—~~ without major economic losses or compromising critical ecological requirements~~—~~, depends heavily on coordinated reservoir operations and ~~extraction of~~ groundwater extraction, particularly during dry seasons or severe droughts.

(2) ~~Agriculture~~ Agricultural water use has significant spatial and climatic vulnerabilities. ~~Regions~~ Arid regions ~~constrained by aridity~~ face heightened water stress, ~~which~~ therefore need technological advances to enhance irrigation efficiency. ~~The model identifies c~~Differences in crop-specific water productivity~~ differentials~~ identified by the model~~,~~ ~~revealing~~ reveal opportunities to prioritize drought-resilient ~~cultivars~~ and high-value crops. Such ~~strategic shifts~~adjustments could reduce irrigation demand without compromising yield stability, offering a path to decouple agricultural ~~growth~~ production from water-intensive practices.

(3) Multi-year regulating reservoirs are pivotal in mitigating interannual hydrologic variability, ~~especially prolonged droughts. By~~ ~~redistributing~~ by reallocating water surpluses from wet to dry years~~, it~~ and bufferings~~s~~ against consecutive drought years. ~~An a~~Analysis of ~~the~~

storage ~~full-empty~~ cycles of the LYX ~~of multi-year regulating reservoirs~~ shows ~~that a~~its relatively low frequency of full or empty storage, implying that ~~the reservoir~~its capacity is sufficiently large to regulate extremely high and low flows, provided that ~~and it is important to maintain the~~ active inter-year regulation capacity is maintained.

(4) Marginal value analysis highlights ~~stark contrasts~~heterogeneity in water scarcity across sectors and regions. During periods of water scarcity, allocation priorities favoring ~~urban-~~industrial and domestic uses~~sectors~~ ~~for~~ as their higher water economic values often lead to ~~undersupply of~~ ecological flow~~s~~ deficits and destabiliz~~ation of~~ed agricultural systems, thereby increasing long-term sustainability ~~creating systemic~~ risks~~ for long-term basin sustainability~~. ~~This tension~~ These trade-offs necessitate~~s~~ adaptive allocation mechanisms that balance efficiency with equity, such as tiered pricing for high-value ~~sectors~~ uses and compensatory ~~frameworks~~ schemes for environmental and subsistence needs.

Beyond the YRB, this study offers transferable modeling methods and insights for governance of other large river basins confronting scarcity and competition. The combination of the node-link representation, PMP calibration, and an integrated hydroeconomic model formulation provides a structured basis for evaluating basin-wide allocation strategies under diverse policy and hydrologic conditions. However, accomplishing such analyses in practice, depends on specific institutional settings. In the YRB, a strong centralized basin authority facilitates water governance. In more decentralized or collaborative settings, comparable outcomes may require stronger coordination mechanisms, legal alignment, stakeholder negotiation, or market institutions. Thus, while the modeling framework is broadly applicable, its operational deployment must be adapted to local governance contexts.~~a replicable method~~

~~for basins confronting scarcity and competition, where unified or coordinated basin-wide water resource management is essential. Additionally, the approach to coordinating water allocation across provinces provides valuable insights for managing transboundary or multi-regional basins, aiding in conflict resolution and promoting sustainable development.~~

While the model shows its usefulness as a planning tool for large basin ~~the~~ authorit~~y of a large basin~~ies, it is formulated with water demand of aggregated sectors without considering intra-sectoral heterogeneity. Given its focus on large-scale dynamics, the model lacks precision to capture technical variations, ~~water use efficiencies,~~ or behavioral preferences of individual users. Additionally, its emphasis on long-term planning and strategic analysis limits its applicability for real-time scheduling. Nevertheless, by adopting a macroscopic perspective, the model ~~provides valuable support to decision makers~~effectively ~~in~~ identif~~ying~~ies ~~critical~~ system-level bottlenecks and ~~devising~~ supports the development of sustainable strategies for ~~addressing complex water resources allocation and management challenges in a large and complex basin~~managing complex water allocation challenges.

Future research should focus on incorporating additional dimensions such as climate change impacts, water markets and exchanges, conjunctive use of surface water and groundwater, and inclusion of unconventional water sources in the water supply portfolio~~, to further enhance the model's applicability~~. Additionally, ~~addressing data limitations~~improving data availability and integrating socio-political factors can improve the robustness of decision-making frameworks, providing more actionable insights for sustainable water resource management in the YRB and similar arid basins worldwide.

~~Data~~ Code and Data Availability

The model was implemented in the General Algebraic Modeling System (GAMS), which is available under a license (https://www.gams.com/). Code and data used in this study are not publicly available but can be obtained from the corresponding author upon reasonable request.

Author Contributions

Yuhan Yan contributed to investigation, data curation, formal analysis, methodology, visualization and prepared the paper with contributions from all the co-authors, along with conducting review and editing. Tingju Zhu contributed to conceptualization, funding acquisition, project administration, supervision, validation, and review and editing. Ximing Cai contributed to visualization, validation and review and editing. Zhenxing Zhang, Yunlu Ma and Jay R. Lund contributed to review and editing.

~~Declaration of~~ Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplement

Hydroeconomic Optimization of Water Management in the Yellow River Basin: Dealing with Scarcity ~~at the Basin Scale~~

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Table S1. Key equations used in the YRB-HEM.

Equations	**Variable**	**Parameter**	**Description**
Objective function			
$Max\ Z = \sum_{t}\sum_{r} HP_{r,t} + \sum_{y}\sum_{i} AG_{i,y} + \sum_{y}\sum_{c} UR_{c,y} - \sum_{y}\sum_{i} Cost_{PMP}^{i,y} - \sum_{t}\sum_{g} Cost_{Pump}^{g,t} - \sum_{t}\sum_{d} Cost_{water}^{d,t}$	Z		Objective function: total net benefit (million yuan)
	$HP_{r,t}$		Hydropower revenue for reservoir r in time period t (million yuan/month)
	$AG_{i,y}$		Irrigated crop production revenue on irrigation area i in year y (million yuan/year)
	$UR_{c,y}$		Urban water use benefit in city c in year y (million yuan/year)
	$Cost_{PMP}^{i,y}$		Crop production cost in irrigation area i in year y estimated using PMP approach (million yuan/year)
	$Cost_{Pump}^{g,t}$		Pumping cost from groundwater aquifer g in time period t (million yuan/month)
	$Cost_{water}^{d,t}$		Water resource fees paid by water demand node d in time period t (million yuan/month)
Benefit			
$HP_{r,t} = P_{r,t} \cdot p_{HP_r} \cdot \varphi_h$		φ_h	Unit conversion factor
	$P_{r,t}$		Solved hydropower output (MW)
$P_{r,t} = K_r \cdot QT_t^r \cdot (H_t^r - T_r)$	QT_t^r		Solved monthly average flow through ~~hydroelectric~~ hydropower turbine (MCM/month)
	H_t^r		Solved reservoir water table (m.a.s.l.)
		T_r	Tailwater elevation (m.a.s.l.)
		p_{HP_r}	Price of electricity (yuan/kWh)
		K_r	Hydropower output coefficient, the product of hydropower generation efficiency, water density and gravitational acceleration ($kg \cdot m^{-2} \cdot s^{-2}$)

$AG_{i,y} = \sum_{cp} RY^{i}_{cp,y} \cdot Ymax^{i}_{cp} \cdot A^{i}_{cp,y} \cdot p_{AG\,cp} \cdot \varphi_a$	$RY^{i}_{cp,y}$ $A^{i}_{cp,y}$	$Ymax^{i}_{cp}$ $p_{AG\,cp}$ φ_a	Solved relative yield for crop cp at ~~irrigated~~ irrigation district i in year y Maximum yield (mt/ha) Harvested area (ha/year) Crop price (yuan/mt) Unit conversion factor
$UR_{c,y} = \sum_{c}\sum_{k} CS_{c}^{k,y} + \sum_{c}\sum_{k} (p_{c}^{k,y} - cost_{c}^{k,y}) Q_{c}^{k,y}$ $p_{c}^{k,y} = \alpha_{c}^{k} - \beta_{c}^{k} \cdot Q_{c}^{k,y}$ $CS_{c}^{k,y} = \int_{p_{c}^{k,y}}^{p_{max}} \left(\alpha_{c}^{k} - \beta_{c}^{k} \cdot Q_{c}^{k,y}\right) dQ = \frac{1}{2} Q_{c}^{k,y} (\alpha_{c}^{k} - p_{c}^{k,y})$	$CS_{c}^{k,y}$ $p_{c}^{k,y}$ $Q_{c}^{k,y}$	$cost_{c}^{k,y}$ $\alpha_{c}^{k}, \beta_{c}^{k}$	Consumer surplus for city c and industrial or domestic water use activity k (million yuan/year) Urban water tariff (yuan·m^{-3}·year^{-1}) Cost from suppliers providing water to users (yuan·m^{-3}·year^{-1}) Industrial or urban domestic water use (MCM/year) Intercept and the slope of the demand function
Cost			
$Cost_{Pump}^{g,t} = \frac{\rho G}{\eta} \cdot H_{t}^{g} \cdot Q_{t}^{g} \cdot p_{GW} \cdot \varphi_p$	H_{t}^{g} Q_{t}^{g}	ρ G η p_{GW} φ_p	Water density (kg/m^3) Gravitational acceleration (9.81 m/s^2) Pumping efficiency Solved pumping depth at groundwater aquifer g (m/month), constrained by minimum allowable water-table level Solved groundwater withdrawal (MCM/month) Pumping cost (yuan/kWh) Unit conversion factor
$Cost_{PMP}^{i,y} = \sum_{cp} (\mu^{i}_{cp} + 0.5\varphi^{i}_{cp} \cdot A^{i}_{cp,y}) A^{i}_{cp,y}$		$\mu^{i}_{cp}, \varphi^{i}_{cp}$	Intercept and slope for crop cp in ~~at irrigated~~ irrigation district i

$Cost_{water}^{d,t} = \sum_{nu} cost_{sur}^{d}\cancel{cost_{sur}} \cdot {Q_{sur}}_t^{nu,d} + \sum_{g} cost_{gw}^{d}\cancel{cost_{gw}} \cdot Q_t^{g,d}$	${Q_{sur}}_t^{nu,d}$ $Q_t^{g,d}$	$cost_{sur}^{d}\cancel{cost_{su}}$ $cost_{gw}^{d}\cancel{cost_{gw}}$	Surface water resources fees (yuan/m^3) Groundwater water resources fees (yuan/m^3) Solved total surface water used (MCM/month) Solved total groundwater used (MCM/month)
Constraints			
Flow Balance			
$S_t^n - S_{t-1}^n = \sum_{n} Q_t^{nu,n} - \sum_{n} Q_t^{n,nd}$	S_t^n $Q_t^{nu,n}$ $Q_t^{n,nd}$		Storage of node n at the end of period t (MCM/month) Inflow from upstream node nu to node n (MCM/month) Outflow from node n to downstream node nd (MCM/month)
Water Delivery			
$Q_t^{d\cancel{n}} = \sum_{nu} {Q_{sur}}_t^{nu,d\cancel{n}} + \sum_{g} Q_t^{g,d\cancel{n}}$	$Q_t^{d\cancel{n}}$ $\cancel{{Q_{sur}}_t^{nu,n}}$ $\cancel{Q_t^{g,n}}$		Total water delivery to node *n* (MCM/month) ~~Surface water from upstream node nu to node n (MCM/month)~~ ~~Groundwater from aquifer g to node n (MCM/month)~~
Irrigation			
Water consumption $Q_t^i \cdot e_i = \sum_{cp} IWD_{cp,t}^i \cdot A_{cp,y}^i \cdot \varphi_i$ Return flow ${Q_{RF}}_t^{i,nd} = Q_t^i \cdot I_r^i$	Q_t^i $IWD_{cp,t}^i$ ${Q_{RF}}_t^{i,nd}$	e_i φ_i I_r^i	Irrigation water delivery (MCM/month) Irrigation efficiency Irrigation water demand requirement (mm/month) Unit conversion factor Irrigation return flow (MCM/month) Coefficient of irrigation return flow
Water demand $IWD_{cp,t}^i = \begin{cases} ETc_{cp,t}^i - Pe_{cp,t}^i, & ETc_{cp,t}^i > Pe_{cp,t}^i \\ 0, & ETc_{cp,t}^i \leq Pe_{cp,t}^i \end{cases}$	$ETc_{cp,t}^i$	$Pe_{cp,t}^i$	Potential crop evapotranspiration (mm/month) Effective precipitation (mm/month)

Crop evapotranspiration		k_c	Crop coefficient
FAO:	ET_0		Reference-crop evapotranspiration (mm/day)
$ET_c = k_c \cdot ET_0 \cdot \varphi_c$		φ_c	Unit conversion factor
Priestly-Taylor:		α	Priestly-Taylor coefficient (default is 0.23 for surface covered with short reference crop)
$ET_0 = \alpha \dfrac{\Delta}{\Delta + \gamma}(R_n - G)$		Δ	Gradient of saturated vapor pressure (kPa/°C)
		γ	Psychrometric constant (kPa/°C)
		R_n	Net shortwave solar radiation (MJ·m^{-2}·day^{-1})
		G	Ground heat flux (MJ·m^{-2}·day^{-1})
Actual evapotranspiration	$ETa^i_{cp,t}$		Actual crop evapotranspiration (mm/month)
$\theta \cdot ETc^i_{cp,t} \leq ETa^i_{cp,t} \leq ETc^i_{cp,t}$		θ	Minimum evapotranspiration factor
Relative yield $RY^i_{cp,y} = \prod_{m=1}^{M} \left(\dfrac{ETa^i_{cp,t}}{ETc^i_{cp,t}} \right)^{\lambda^m_{cp}}$		λ^m_{cp}	Sensitivity factor at growing stage m of crop cp. The growing stage m represents the order of months within the growing period of crop cp in irrigation area i, which is harvested in year y.
Reservoir			
Evaporation	ER^r_t		Solved reservoir evaporation (MCM/month)
$ER^r_t = Emax^r_t \cdot A^r_t \cdot \varphi_r$		$Emax^r_t$	Open water evapotranspiration rate at reservoir r (mm/month)
	A^r_t		Solved reservoir surface area (km^2/month)
		φ_r	Unit conversion factor
Release	~~QT^r_t~~		~~Average flow rate through hydroelectric turbines in reservoir r (MCM/month)~~
$\sum_r Q^{r,nd}_t = QT^r_t + QS^r_t$	QS^r_t		Reservoir spill (MCM/month)
Elevation vs. storage $H^r_t = {h_1}^r + {h_2}^r \cdot (\dfrac{S^r_t + S^n_{t-1}}{2})^{{h_3}^r}$		${h_1}^r, {h_2}^r, {h_3}^r$	Reservoir water table curve coefficients (elevation vs. storage)

Area vs. storage $A_t^r = {a_1}^r + {a_2}^r \cdot (\frac{S_t^r + S_{t-1}^r}{2})^{{a_3}^r}$		${a_1}^r, {a_2}^r, {a_3}^r$	Reservoir area curve coefficients (area vs. storage)
Range control $S_{dead}^r \le S_t^r \le S_{max}^{r,t}$ $P_{min}^r \le P_{r,t} \le P_{max}^r$ $Q_t^{r,nd} \ge Q_{control,t}^{r,nd}$ $H_t^r \ge H_{control,t}^r$		$S_{dead}^r, S_{max}^{r,t}$ P_{min}^r, P_{max}^r $Q_{control,t}^{r,nd}$ $H_{control,t}^r$	Dead storage (MCM) and allowable storage upper limit (MCM) for reservoir r Firm power and installed hydropower capacity at powerplant r (MW) Minimum reservoir release for ice flood control and sediment flushing requirements (MCM/month) Minimum reservoir water table for ice flood and sediment flushing requirements (m.a.s.l.)
City			
Water use control $D_{min}^{k,y} \le Q_c^{k,y} \le D_{max}^{k,y}$~~$D_e^{k,y}$~~		$D_{max\cancel{e}}^{k,y\cancel{t}}, D_{min}^{k,y}$	Maximum and minimum industrial or municipal water demand (MCM/month)
Ecosystem			
Replenishment control $Q_{min}^{e,t} \le Q_t^e \le Q_{max}^{e,t}$	Q_t^e	 $Q_{min}^{e,t}$ $Q_{max}^{e,t}$	Delivered ecosystem flow to wetland area e (MCM/month) Ecosystem flow lower limit (MCM/month) Ecosystem flow upper limit (MCM/month)

Notes:

1. Node types: q-surface inflow; g-groundwater; r-reservoir; i-irrigation area; c-city; e-ecosystem; j-junction; s-sink; d-demand nodes; n-~~all nodes~~storage, conveyance and junction.
2. Year index value y can be determined using the time period value t (month sequence, $t = 1, \ldots, 240$ in this study): $y = \text{int}(\text{ord}(t - 1) / 12) + 1$, where "int" is the floor function that rounds down a fractional number to its nearest integer, and "ord" means ordinal number.
3. Units: MCM-million cubic meters; m.a.s.l.-meters above sea level.

Table S2-1 to **S2-6** provide details of each type of nodes, and related location information.

Table S2-1. Irrigation nodes, names, and provinces.

IRND	**Irrigated Area**	**Province**
I1	D02_QH_HuangShui	Qinghai
I2	D03_NX_WeiNing	Ningxia
I3	D03_NX_Qingtongxia	
I4	D03_NM_Hetao	Inner Mongolia
I5	D03_NM_Nanan	
I6	D03_NM_TMC	
I7	D05_SX_Fenhe	Shanxi
I8	D05_SN_Weihe	Shaanxi
I9	D06_HN_Xiaolangdi	Henan
I10	D06_HN_Yinqin	
I11	D07_HN_Henan	
I12	D07_SD_Shandong	Shandong
I13	D02_GS	Gansu
I14	D03_GS	
I15	D04_NM	Inner Mongolia
I16	D04_SN	Shaanxi
I17	D04_SX	Shanxi
I18	D05_GS	Gansu
I19	D05_HN	Henan
I20	D05_NX	Ningxia
I21	D06_HN	Henan
I22	D06_SX	Shanxi

Table S2-2. Secondary water resources regionalization of the YRB. Regionalization was delineated by official authorities, considering both natural characteristics and administrative boundaries. Endorheic basin areas are excluded from this study.

Code	**Region**
D01	Above Longyangxia
D02	Longyangxia to Lanzhou
D03	Lanzhou to Hekouzhen
D04	Hekouzhen to Longmen
D05	Longmen to Sanmenxia
D06	Sanmenxia to Huayuankou
D07	Below Huayuankou

Table S2-3. City nodes, names, and provinces.

CND	City	Province
XN	Xining	Qinghai
LZ	Lanzhou	Gansu
BY	Baiyin	
YC	Yinchuan	Ningxia
ZW	Zhongwei	
WZ	Wuzhong	
SZS	Shizuishan	
HHHT	Hohhot	Inner Mongolia
BYNE	Bayan Nur	
BT	Baotou	
EEDS	Ordos	
TY	Taiyuan	Shanxi
JINZ	Jinzhong	
DT	Datong	
SZ	Shuozhou	
LL	Lvliang	
YUNC	Yuncheng	
LF	Linfen	
XA	Xi'an	Shaanxi
XY	Xianyang	
YL	Yulin	
YA	Yan'an	
WNA	Weinan	
ZZ	Zhengzhou	Henan
LY	Luoyang	
JZ	Jiaozuo	
XX	Xinxiang	
KF	Kaifeng	
PY	Puyang	
JN	Jinan	Shandong
LC	Liaocheng	
TA	Taian	
BZ	Binzhou	
DY	Dongying	

Table S2-4. Ecosystem nodes, sites, and provinces.

END	Site	Province
XHH	Xinghai Lake	Ningxia
WLSH	Wuliangsu Lake	Inner Mongolia
DaiH	Daihai Lake	
BYD	Baiyangdian Lake	Hebei
YRD	Yellow River Delta	Shandong

Table S2-5. Inflow nodes, names of tributaries, and locations.

QND	Tributary	Location	Notes
TP	Tibetan Plateau	Upper reaches	Main stem inflow to Longyangxia Reservoir
TH	Taohe		Tributary
DTH	Datonghe		
HS	Huangshui		
DHH	Daheihe		
KYH	Kuyehe	Middle reaches	
WDH	Wudinghe		
FH	Fenhe		
JH	Jinghe		
WH	Weihe		
YLH	Yiluohe	Lower reaches	
QH	Qinhe		
DWH	Dawenhe		

Table S2-6. Reservoir nodes, names and provinces.

RND	Reservoir	Province
LYX	Longyangxia	Qinghai
LiJX	Lijiaxia	
LiuJX	Liujiaxia	Gansu
YGX	Yanguoxia	
BPX	Bapanxia	
DX	Daxia	
QTX	Qingtongxia	Ningxia
WJZ	Wanjiazhai	Shanxi
SMX	Sanmenxia	Henan
XLD	Xiaolangdi	

Table S3. Crop calendar with sensitivity factor for all irrigated crops in the YRB.

Crop	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Spring wheat			0.04	0.13	0.57	0.35	0.37					
Winter wheat	0.12	0.10	0.18	0.32	0.24					0.14	0.11	0.12
Rice	0.29				0.36	1.05	0.95	0.60	0.58	0.60	0.58	0.60
Spring maize				0.11	0.75	1.40	0.26	0.22	0.09			
Summer maize					0.02	0.92	1.39	0.33	0.16	0.01		
Sorghum					0.08	0.35	0.35	0.25	0.11			
Other cereals				0.11	0.58	0.21	0.21	0.31				
Potato					0.52	0.67	0.43	0.23	0.04			
Bean					0.56	0.93	0.51	0.14				
Lentil				0.53	0.89	0.34	0.26	0.11				
Other pulses			0.13	0.90	0.61	0.14						
Soybean					0.12	0.85	0.29	0.52	0.25	0.01		
Groundnut					0.13	0.54	0.54	0.28	0.08			
Sunflower					0.27	0.36	0.68	0.84	0.21			
Rapeseed	0.71	0.54								0.27	0.27	0.56
Cotton					0.16	0.25	0.25	0.24	0.17	0.11		
Vegetable	0.12	0.11	0.56							0.20	0.25	0.14
Tomato	0.45								0.13	0.21	0.24	0.34
Melon				0.28	0.79	0.64	0.46	0.35	0.02			
Rest				0.74	0.76	0.56	0.15					

Table S4. Model performance for major hydrological gauge stations, reservoirs' end-of-year storage values, and agricultural water use against observed data, assessed with Percent Bias (PBIAS) and Normalized Root Mean Square Error (NRMSE).

Category	**Name**	**PBIAS (%)**	**NRMSE (%)**	**Period**
Hydrological station	Lanzhou	-5.48	15.99	1996-2015
	Xiaheyan	-9.61	18.50	
	Tongguan	10.22	21.34	
	Huayuankou	-0.99	18.69	
Reservoir storage	Longyangxia Reservoir	3.80	25.79	1997-2015
	Xiaolangdi Reservoir	0.40	25.96	2005-2015
Agricultural water use	Total irrigation withdrawal	7.66	10.58	1996-2015

~~**Table S4.** Crop production by location and hydrological year type (10^4 ton).~~

~~**Crop Type**~~	~~**Location**~~	~~**Dry**~~	~~**Normal**~~	~~**Wet**~~
~~***Cotton***~~	~~U~~	~~0.039~~	~~0.039~~	~~0.041~~
	~~M~~	~~7.27~~	~~7.58~~	~~8.90~~
	~~D~~	~~26.48~~	~~30.66~~	~~32.06~~
	~~YRB~~	~~33.79~~	~~38.28~~	~~41.00~~
~~***Vegetable***~~	~~U~~	~~244.96~~	~~253.01~~	~~268.33~~
	~~M~~	~~486.59~~	~~486.47~~	~~505.51~~
	~~D~~	~~243.27~~	~~240.87~~	~~234.04~~
	~~YRB~~	~~974.83~~	~~980.35~~	~~1007.87~~
~~***Maize***~~	~~U~~	~~167.68~~	~~179.95~~	~~168.73~~
	~~M~~	~~191.02~~	~~193.32~~	~~244.15~~
	~~D~~	~~334.88~~	~~441.14~~	~~494.47~~
	~~YRB~~	~~693.59~~	~~814.41~~	~~907.34~~
~~***Potato***~~	~~U~~	~~92.31~~	~~111.98~~	~~110.16~~
	~~M~~	~~85.82~~	~~89.70~~	~~103.20~~
	~~D~~	~~2.58~~	~~2.17~~	~~2.07~~
	~~YRB~~	~~180.71~~	~~203.86~~	~~215.43~~
~~***Rice***~~	~~U~~	~~5.43~~	~~7.84~~	~~15.89~~
	~~M~~	~~2.08~~	~~2.00~~	~~3.51~~
	~~D~~	~~4.67~~	~~3.41~~	~~4.16~~
	~~YRB~~	~~12.17~~	~~13.26~~	~~23.56~~
~~***Wheat***~~	~~U~~	~~65.37~~	~~64.79~~	~~66.44~~
	~~M~~	~~215.67~~	~~222.53~~	~~250.55~~
	~~D~~	~~517.54~~	~~534.47~~	~~577.64~~
	~~YRB~~	~~798.59~~	~~821.79~~	~~894.63~~

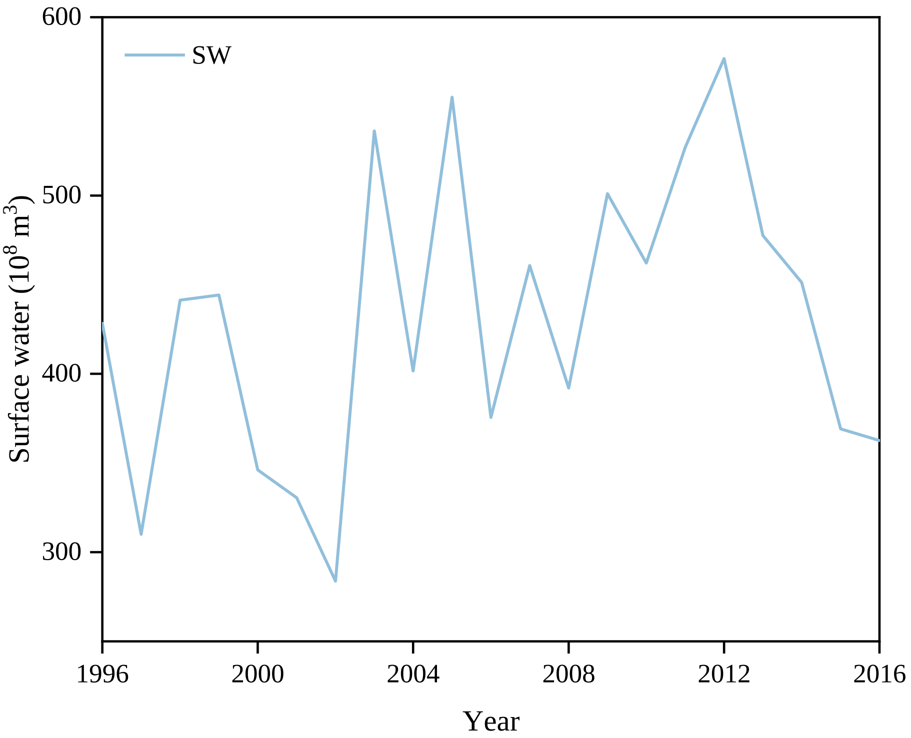

Fig. S1. Total surface water (SW) inflow during 1996 to 2016 in the YRB.

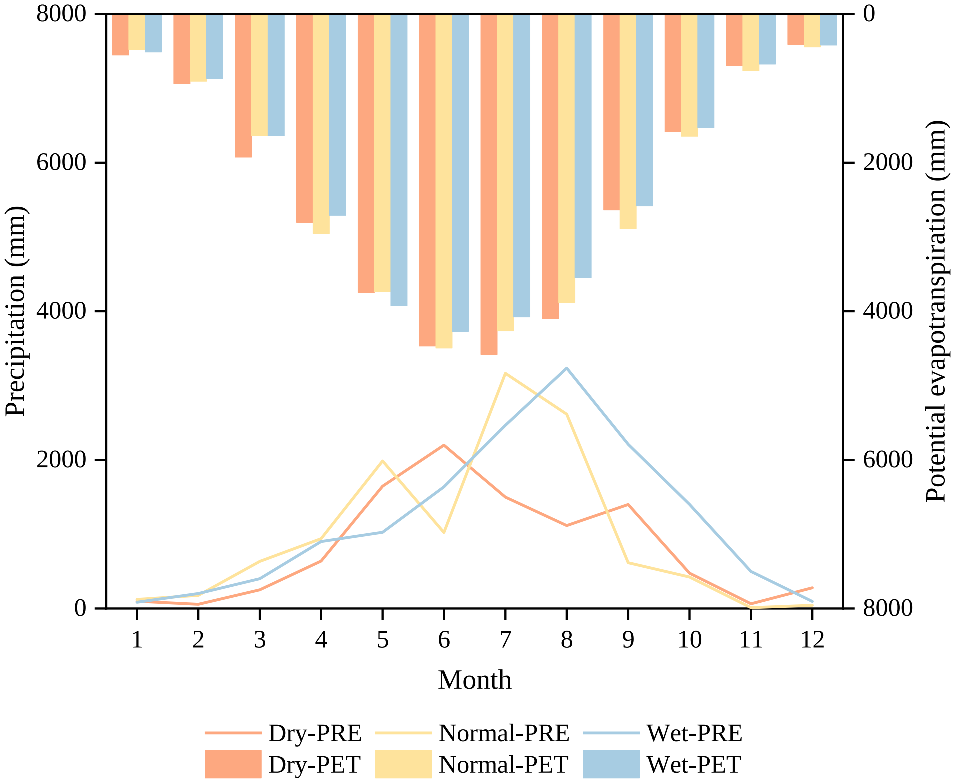

Fig. S2. Monthly precipitation (PRE) and reference evapotranspiration (PET) by hydrological year type, averaged over the entire YRB.

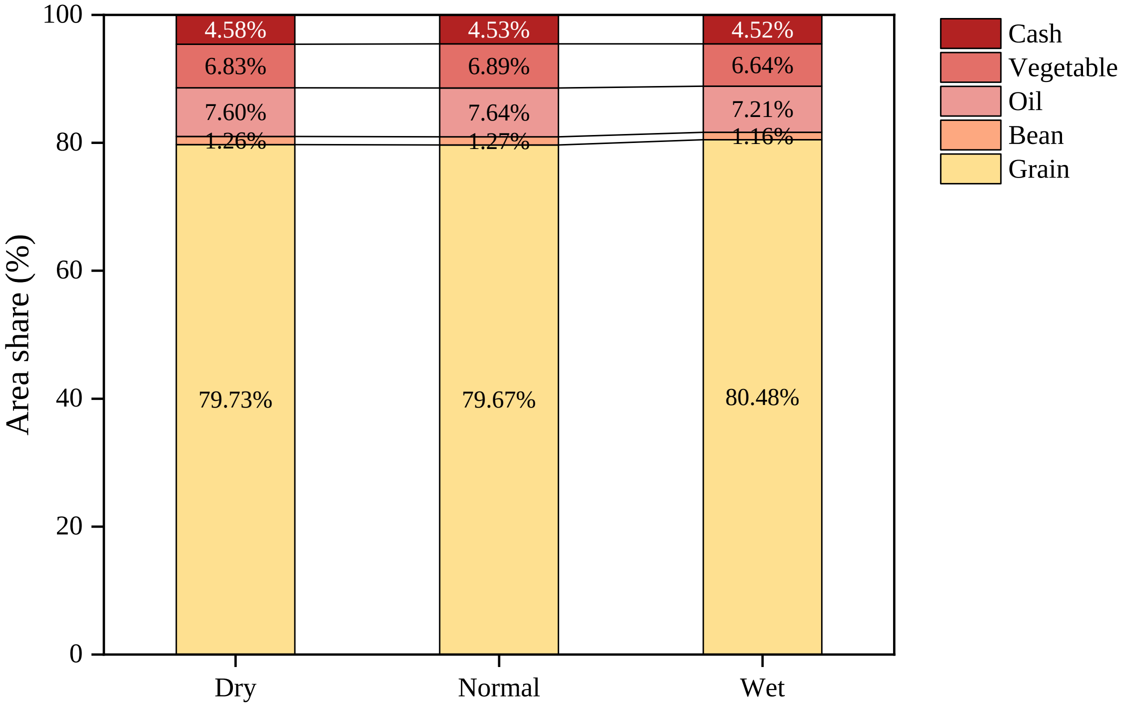

Fig. S3. Cropping patterns in the YRB by hydrological year type.

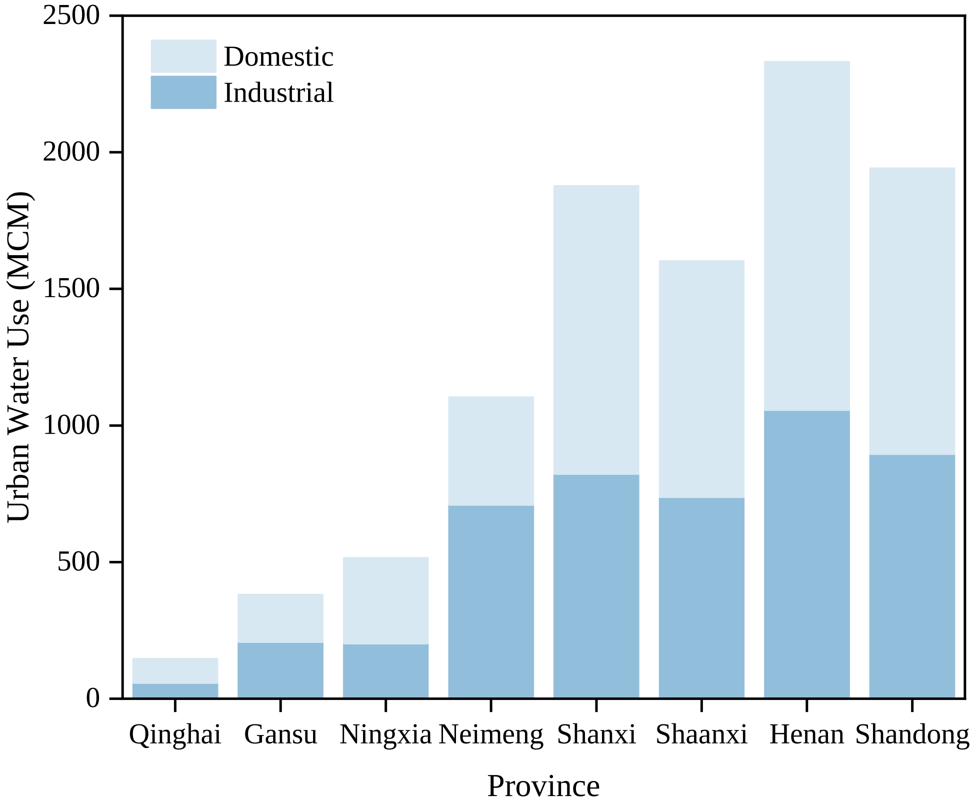

Fig. S4. Annual urban water uses by sector and province in the YRB.

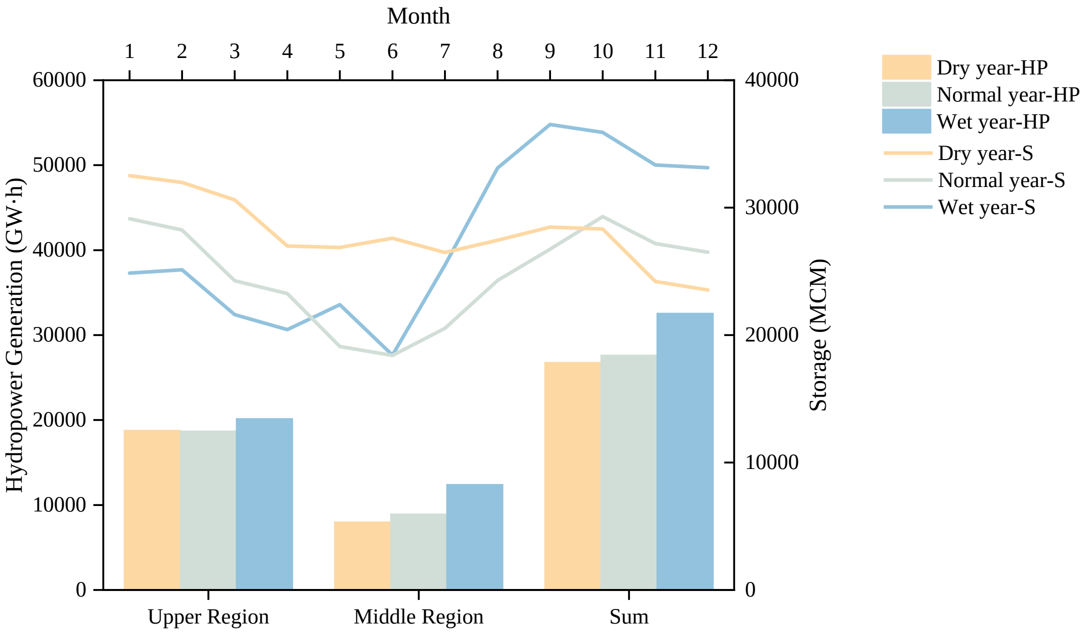

Fig. S5. Annual hydropower generation (HP) and monthly water storage (S) in the YRB, by hydrological year type.