Coupling coordination evaluation and sustainable development of "Three Waters" system and impulse response analysis in the Yellow River Basin

Yue Li [a], Yangxi Lv [a], Zixuan Zhang [a], Xue Feng [a], Xudong Chen [a,*]

[a] College of Management Science, Chengdu University of Technology, Chengdu 610059, China

Correspondence: Chengdu University of Technology, School of management sciences Chengdu, CN, Email: chenxudong198401@163.com

Coupling coordination evaluation and sustainable development of "Three Waters" system and impulse response analysis in the Yellow River Basin

Highlights

1. A novel coupled coordinated study on water resources, water environment, and water ecology.

2. A decision systematic analysis framework for Yellow River Basin is provided.

3. The intrinsic mechanism of influence of the "Three Waters" system is clarified.

Abstract

The interaction and mutual influence of water resources, water environment, and water ecology play a crucial role in integrated basin water system planning and the harmonious development of a high-quality economy. In this study, a coupling coordination model was established to assess the development of coupling and coordination among water systems in the Yellow River Basin (YRB). By applying a Vector Auto Regression (VAR) model, it explores the influence mechanisms of key indicators on the sustainable coordinated development of the "Three Waters" system (TWS). Findings from 2005 to 2021 indicate a positive trend in the comprehensive development level of the YRB's TWS. The degree of coupling ranges from good to high-quality, and the coupling and coordination level progresses from near-dysfunctional to highly coordinated. Moreover, the study highlights the alternating effects of 10^4 yuan of GDP water consumption and wastewater treatment rates on the water resources-water environment system (WRS-WES); Sewage treatment rates and the greening coverage of urban built-up areas have significant and enduring promotional effects on the water environment-water ecology subsystem (WES-WELS). These insights lay the groundwork for the development of innovative ideas and strategies aimed at promoting the integrated and coordinated advancement of the TWS in the YRB.

Keywords: "Three Water" system; Coupled coordination; Impulse response; Evaluation indicator; Yellow River Basin

1. Introduction

Water environmental governance, specifically focusing on sustainable water and sanitation, constitutes a central element within the United Nations Sustainable Development Goals (SDGs). It exhibits significant interdependencies and potential conflicts with other SDGs, operating at a regional to global scale (Wang et al., 2022; Di et al., 2021). In the context of the 14th Five-Year Plan in China, water ecological environmental protection is undergoing a transformation. It is shifting its focus from historical pollution management to a more holistic and synergistic approach, which encompasses the integrated enhancement of various river basin elements, including water resources, water ecology, and the water environment. This integrated approach is commonly referred to as "Three-Waters integration." In April 2023, the Ministry of Ecology and the Environment, in collaboration with five other relevant government departments, issued the "Key River Basin Water Ecological Environmental Protection

Plan." This plan underscores the importance of promoting the transformation of water ecological and environmental management during this new era, aiming to establish a new framework for systematic management and the integrated promotion of "Three Waters integration." Concurrently, China's rapid population growth and economic development have led to an acceleration of industrialization and urbanization processes. These trends have brought the pressing issues of water resource scarcity, water pollution, and water ecological degradation to the forefront of national concerns (Chapagain et al., 2022; Bai et al., 2023; Hu et al., 2021).

Water resources, water ecology, and water environment are inherently interrelated. The effective provision of water resources serves as the cornerstone for enhancing water environment quality and safeguarding water ecology. Xiang et al., (2023) introduced an Adaptive Intelligent Dynamic Water Resource Planning (AIDWRP) and examined its implications for managing water resources dynamically within watersheds; Biggs et al. (2017) recommended the inclusion of small water bodies in management and monitoring to achieve the objective of improving the water environment. They emphasized the significance of planning for small water bodies in realizing this goal. Water ecology reflects the environmental conditions where humans, plants, and animals coexist, constituting a comprehensive representation of water resources and the water environment; Yuan et al. (2022) investigated the substantial impacts of confluences on the water environment and ecology of river systems, focusing on the dynamic changes in river confluence synthesis; Wang et al. (2019) employed the Water Quality Simulation Module to optimize the simulation methodology for assessing watershed water quality. They observed that water resource and water environment proxies can contribute to improving the water environment in regulated watersheds.

In the aforementioned studies on the TWS issue, the focus has traditionally been on individual systems or the interaction between two systems, often overlooking the intricate interconnections within the TWS. This oversight results in a lack of comprehensive consideration of the interactions among the TWSS. Coupling, as a fundamental concept, describes the phenomenon in which two or more systems or modes of operation mutually influence each other through various interactions. Building upon this concept, researchers have conducted numerous coupling studies. These studies encompass urbanization and ecological quality coupling (Xu et al., 2021), energy-environmental coupling (Wang et al., 2019), land resource coupling (Xiao et al., 2021), agro-ecological coupling (Cai et al., 2021), and more. These investigations shed light on the intricate interplay and interdependencies among various systems, providing a more comprehensive understanding of the TWS and its dynamic interactions.

Similarly, in the context of the TWSS interacting with environmental science, economics, sociology, population, and other factors, various coupling and coordination models have emerged (Zhang et al., 2022; Zhu et al., 2023); Wei et al. (2021) considered the policy mandates of "three waters under common control" and "red line control." They evaluated the water resources recycling carrying index and coupling coordination degree of the Qingjiang River Basin by employing a single evaluation method and a coupling coordination analysis method, aligning with the policy requirements of "three waters under common control" and "red line control." Yang et al. (2022) built a comprehensive evaluation index system of water environment carrying capacity for the Yangtze River Economic Zone within the framework of the coupling system of water resources, water environment, society, and the economy. They utilized a diagnostic model of obstacles to elucidate the path toward enhancing the water environment carrying capacity, taking into account the coupling of sub-systems and driving factors. In addition to the evaluation of carrying capacity, coupling coordination finds applications in the assessment of the coordinated development of the Three Water Subsystems in conjunction with energy and food, as demonstrated by Li et al. (2022). They explored the synergistic effects in the water-energy-food relationship in Shenzhen city by constructing a synergistic network. Xu et al. (2022) assessed the key factors influencing the sustainable development of the system by establishing an index system for evaluating the coupling and coordination of the Water-Energy-Food (WEF) core network.

As a crucial economic and ecological region in China, the YRB currently confronts significant challenges, including the degradation of water ecosystems, escalating water pollution, and water resource scarcity (Han et al., 2021). A detailed analysis of the development status of the YRB's three water subsystems reveals the following: (1) Water Resources: The YRB is endowed with abundant water resources and stands as a vital water resource replenishment region in China. However, the stability of water resource supply in the YRB is increasingly threatened by climate change and human activities. This has resulted in significant issues of water resource scarcity and uneven allocation (Wang et al., 2023). (2) Water Environment: The YRB faces a substantial discharge of industrial wastewater, agricultural pollution, and urban sewage, leading to severe water pollution and the deterioration of water quality. These challenges pose substantial risks to the ecosystem and human health. (3) Water Ecology: Notably, the water ecosystem in the YRB exhibits evident concerns, including wetland degradation, declining river levels, and diminished biodiversity. These multifaceted challenges necessitate comprehensive and sustainable strategies to address the issues plaguing the YRB's water systems.

The Ecological Environment Protection Plan for the YRB underscored that the "integration of the three waters" is pivotal for effectively addressing the prominent environmental issues within the basin and enhancing its ecological and environmental quality. Notably, in studies focusing on the TWS of the YRB: Sadat et al. (2019) employed the Fuzzy Object Element Method (FME) and Harmonious Degree Evaluation (HDE) to comprehensively evaluate the health status of rivers in the lower reaches of the YRB. Their findings highlighted the influence of changes in flow dynamics on both water resources and water ecology within the basin; Li et al. (2023) established a comprehensive index system for assessing water-energy-food coupling security risks in the YRB, encompassing dimensions of reliability, harmonization, and restoration. They utilized the Copula method for risk probability calculations, with a focus on understanding the conflicts related to water-energy-food coupling security risk; Zhao et al. (2021) conducted an analysis of the temporal and spatial evolution trends in economic development and ecological status, coupled with assessments of coupling degree and coordination degree within the YRB. Their analysis incorporated economic data, energy consumption data, ecological data, and water resources data; Tao et al. (2022) delved into the coupling and coordination of the water-ecology-economy system in the Wuding River Basin between 2001 and 2020. Their conclusions indicated that the coupling and coordination of the water-ecology-economy system was approaching a state of disorder and decline, with water and ecology serving as primary influencing factors. These studies predominantly applied various methodologies such as nonlinear dynamics models, coupling degree models, gray correlation analysis, dynamic coupling models, coupling coordination degree models, and spatial regression models (Wang et al., 2023; Zhang et al., 2023; Li et al., 2020).

To summarize, prior research has often overlooked the critical investigation of coupling and coordination within the TWS, despite the inherent complexity and interdependence of its three subsystems. Consequently, there is an evident and pressing need to study the coordinated development of the TWS within the YRB. This study assesses the state of the water ecosystem, water environmental quality, and water resource utilization in the YRB. It evaluates the degree of coupled and coordinated development among the three water subsystems in the YRB, scrutinizes the interaction mechanisms of these subsystems, and elucidates the fundamental development challenges facing the TWS in the YRB. Additionally, it explores methods to strike a balance between economic and social development and environmental preservation. This research endeavors to offer novel insights and strategies for addressing the integrated and coordinated development issues concerning the TWS in the YRB. It aims to serve as a scientific foundation for the sustainable advancement of the YRB and a valuable reference for regional governance and policymaking.

2. Materials and methods

2.1. Research framework

This study investigates the coupling and coupling coordination of the TWS in the YRB through a four-step approach. **(1)** Initiated with a foundational understanding, it elucidates the interaction mechanisms within the TWS of the YRB and clarifies the interconnections among its components. **(2)** Tailored to the specifics of the YRB urban agglomeration, an evaluation index system for assessing the coupled and coordinated development of the TWS in the YRB is established, incorporating diverse dimensions of the TWS. This is achieved through the application of the entropy weight method and the system composite index evaluation method. **(3)** To gauge the degree of interrelation and the level of coordinated development within the TWS from 2005 to 2021, coupling degree model and coupling coordination degree model are employed. Mutual influences among the indicators from different systems are explored utilizing the gray correlation analysis method. The interactions among these indicators from various systems are further scrutinized using the vector auto regressive model (VAR). The VAR is also applied to examine the constraints of the indicator system on the coordinated development of the TWS in the YRB. **(4)** Combined with the results of the study, policy recommendations for promoting the coupled and coordinated development of the TWS in the YRB are presented. The comprehensive research framework is depicted in Figure 1.

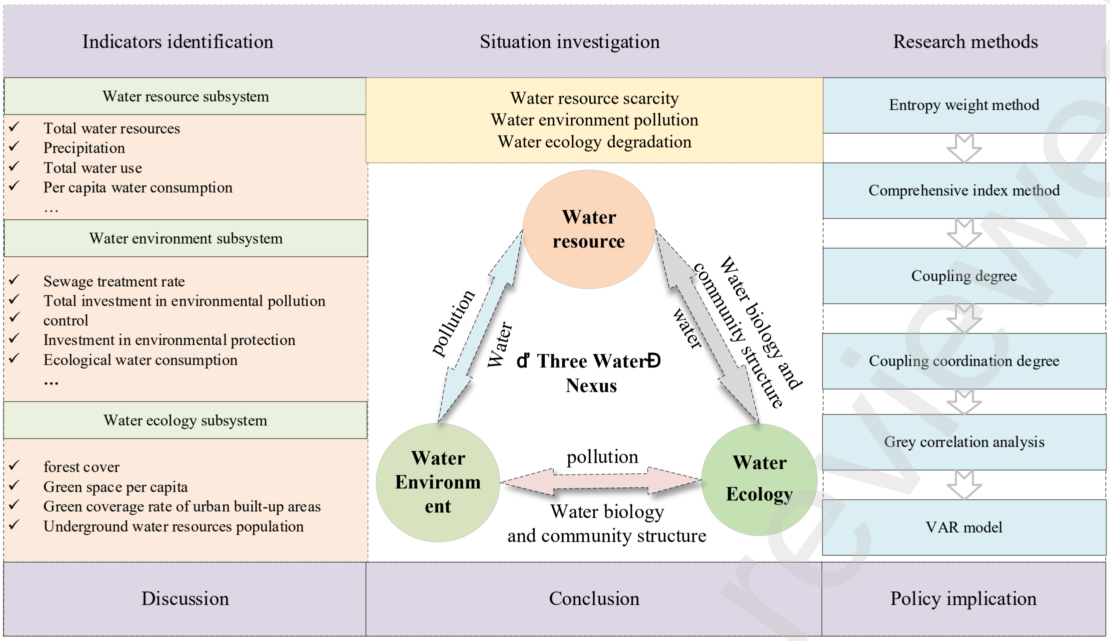

Fig. 1. Research framework

2.2. Study area overview

The YRB (32°N~42°N-96°E~119°E) is the second-largest river in China, flowing through nine provinces, namely, Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong (Fig. 2). As of 2019, the region is home to a total resident population of 4.22×10^{8}, representing 30.05% of the national populace. The YRB encompasses a land area of 3.57×10^{6} km^2, accounting for 36.91% of China's total landmass. Its Gross Regional Product (GDP) is recorded at 2.47×10^{12} Yuan, contributing 25.11% to the country's overall economic output. The YRB also boasts a total water resource volume of $5.41,1\times10^{14}$ cubic meters, amounting to 18.63% of the nation's total water resources. Consequently, the YRB holds paramount significance in China, serving as a critical hub for population activities and economic development, while playing an indispensable strategic role in the nation's comprehensive advancement.

Since the 19th National Congress, there has been steady improvement in the water ecological management of the YRB. However, due to the entanglement of historical liabilities and new ecological challenges arising from economic development, the water ecological situation in the YRB remains unfavorable. Key issues persist, encompassing: **(1)** Water resource scarcity and excessive utilization: The YRB grapples with water resource scarcity, with per capita water resources standing at a mere 647 cubic meters, a third of the national average, signaling severe water shortage. Furthermore, the water resources utilization rate has reached 80%, exceeding the national average by over 50%. Some tributaries have faced depletion, far exceeding the internationally recognized ecological threshold of 40% for water resources development. **(2)** Unstable water environment quality and local pollution: The quality of the water environment exhibits instability, coupled with pronounced local pollution. Key pollution indicators include ammonia nitrogen, chemical oxygen demand, and five-day biochemical oxygen demand. Surface water quality monitoring reveals that water quality in the YRB generally lags behind the national average. The main tributaries, in particular, suffer from fluctuating and subpar water quality levels. **(3)** Water ecosystem degradation and diminished ecological services: The YRB has witnessed significant alterations in its wetland structure, marked by a substantial decline in natural wetlands and a notable rise in artificial wetlands. Additionally, a considerable reduction in biodiversity is evident. In the 1980s, the YRB housed 191 species (subspecies) of fish, including 6 state-protected and endangered species. However, by 2007, the number had dwindled to a mere 47 fish species in the main sections of the primary streams, including 3 endangered species. These persistent challenges underscore the need for continued efforts to enhance water ecological management in the YRB.

The YRB serves as a representative water environment ecosystem. This study encompasses a 17-year timeframe, spanning from 2005 to 2021, and involves nine selected provinces (Wei et al., 2021). The selection of these provinces aims to preserve the integrity of critical ecosystems and ensure the rationality of resource allocation. The criteria for selection consider factors like natural conditions at the watershed level, the availability and comprehensiveness of provincial administrative division data, and the direct correlation between regional economic development and the YRB. Reference documents include the Comprehensive Basin Plan (2012-2030), the outline of the YRB Ecological Protection and High-Quality Development Plan, and the Key Basin Water Ecological Environment Protection Plan. These references guide the research in maintaining alignment with established regional development and environmental protection objectives.

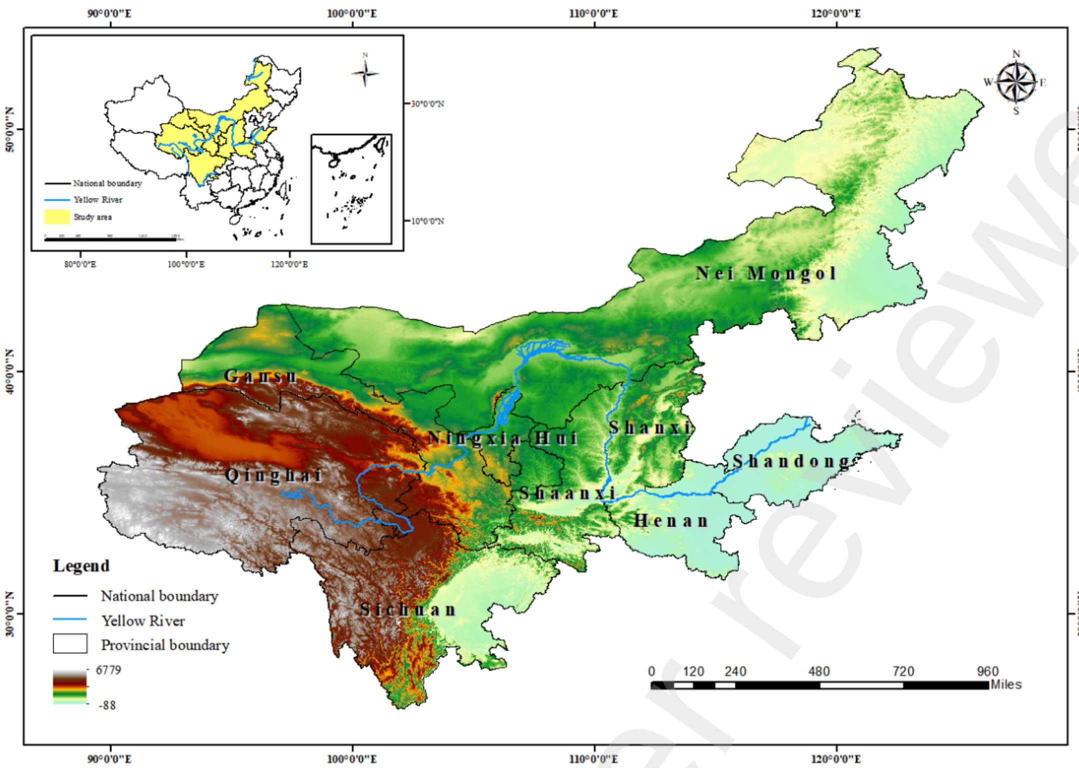

Fig. 2. Location of the YRB

2.3. Construction of the indicator system

The integrated and coordinated development of the TWS is a crucial means to achieve water ecological environmental protection. Water ecological environmental management is a complex system comprising three levels: the WRS, water ecology subsystem (WELS), and WES. **(1)** Water resource reflects the endowment of water resources and focus on water quantity considerations. This entails incorporating total water resources, precipitation, city's water resource utilization efficiency, per capita water consumption, and water consumption per 10^4yuan of GDP as indicators that gauge the effective utilization of natural resources. **(2)** Water environment reflects the quality of water resources. This dimension considers both environmental quality and pollution treatment, with indicators drawn from surface water functional zones, including the rate of surface water that meets quality standards, the proportion of poorly-rated surface water V bodies, sewage treatment rates, and wastewater emissions. The proportion of investment in environmental protection underscores the region's commitment to maintaining water quality. **(3)** Water ecology reflects the environmental conditions for the survival of humans, animals, and plants. It is a comprehensive manifestation of the interplay between water resources and the water environment. In this regard, factors like surface water and groundwater preservation capacity are considered. The former is measured through forest coverage rates, per capita park green space area, and greening coverage rates of urban built-up areas, while the latter is assessed by the per capita availability of underground water resources and the proportion of water allocated for ecological purposes. In this study, a coordinated development evaluation index system is constructed based on 15 secondary indexes within the three subsystems: WRS, WES, and WELS, as outlined in Table 1 below.

Table 1. Evaluation index system and weight of TWS coordinated development.

Primary Indicators	Secondary indicators	Unit	Indicator Attributes	Indicator weight
WRS	Total water resources(x1)	10^8 m^3	+	0.27
	Precipitation(x2)	10^8 m^3	+	0.13
	Total water use(x3)	10^8 m^3	-	0.11
	Per capita water consumption(x4)	m^3/person	-	0.22
	Water consumption per million-yuan GDP(x5)	m^3/10^4 yuan	-	0.26
WES	Sewage treatment rate(y1)	%	+	0.05
	Investment in environmental protection(y2)	%	+	0.17
	Surface water functional area compliance rate(y3)	%	+	0.10
	Proportion of poor class V surface water bodies(y4)	%	-	0.32
	Total wastewater discharge(y5)	10^8 ton	-	0.35
WELS	Forest coverage(z1)	%	+	0.20
	Green space per capita(z2)	m^2	+	0.12
	Green coverage rate of urban built-up area(z3)	%	+	0.07
	Ratio of water used for ecological environment(z4)	%	+	0.39
	Underground water resources per capita(z5)	m^3/person	+	0.22

2.4. Data sources

Considering the reasonableness and data availability, our study focused on nine provinces traversed by the YRB, namely Qinghai, Sichuan, Ningxia, Gansu, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong. Relevant index data were sourced from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Urban Statistical Yearbook, Sichuan Water Resource Bulletin, Sichuan Ecological Environment Condition Bulletin, and the environmental quality condition bulletins of each prefecture-level city in Sichuan province from 2005 to 2021. To address any missing data, we supplemented information from the Statistical Yearbooks of the respective provinces spanning 2010-2020 and the Statistical Bulletins of National Economic and Social Development.

2.5. Research methods

2.5.1. Data standardization

Referring to previous related studies (Zhang et al., 2022; Zhu et al., 2023), this study standardized the data to ensure comparability and eliminate the impact of the quantitative framework. This standardization process involved determining the positivity and negativity of the secondary indicators and applying the following formula：

$$x_{\lambda ij}' = \begin{Bmatrix} x_{\lambda ij} - x_{\min} / x_{\max} - x_{\min} \\ x_{\max} - x_{ij} / x_{\max} - x_{\min} \end{Bmatrix} \tag{1}$$

Where, $x_{\lambda ij}'$ is the processed standard value; $x_{\lambda ij}$ is the raw data of the j th indicator in the ith year of province λ; $1 \le \lambda \le m$, where m is the number of provinces; $1 \le i \le h$, h is the year; $1 \le j \le n$, n is the number of evaluation indicators; in order to avoid the appearance of 0 value, all the $x_{\lambda ij}''=x_{\lambda ij}'+0.001$.

2.5.2. Entropy weight method

Methods for determining weights typically include subjective assignment and objective assignment currently. However, the subjective assignment method is susceptible to subjectivity and arbitrariness. Therefore, this study employs the entropy value method, a common objective assignment approach, to determine these weights. This determination is based on a combination of standardized indicators and the proportion of each system indicator：

$$P_{\lambda ij} = x_{\lambda ij}'' \Big/ \sum_{\lambda=1}^{m}\sum_{i=1}^{h} x_{\lambda ij} \quad (2)$$

Information entropy is：

$$e_j = -\ln(h\times m)^{-1}\sum_{\lambda=1}^{m}\sum_{i=1}^{h} P_{\lambda ij}\ln P_{\lambda ij} \quad (3)$$

The coefficient of variation is：

$$d_j = 1 - e_j \quad (4)$$

Calculation of the weights of the indicators：

$$w_j = d_j \Big/ \sum_{j=1}^{n} d_j \quad (5)$$

According to the formula, the weights of the indicators are calculated as:

$$I_{\lambda j} = x_{\lambda ij}''\times w_j \quad (6)$$

2.5.3. Coupling degree and coupling coordination degree model

Upon analyzing the development indices of the TWS, this study proceeds to construct a coupling degree and coupling coordination degree model. This model is utilized to assess the level of coupling and coordination in TWS development and its evolving trends. The calculation of TWS coupling degree is as follows：

$$C = \left[U_1 \times U_2 \times U_3 \big/ (U_1 + U_2 + U_3/3)^3 \right]^{1/3} \tag{7}$$

$$U_1 = \sum_{i=1}^{l} a_i x_i, U_2 = \sum_{j=1}^{q} b_j y_i, U_3 = \sum_{k=1}^{s} c_k x_k \tag{8}$$

The larger the C value, the higher the coupling degree of each system, indicating a stronger association among the TWS components. However, as the coupling degree alone cannot adequately represent the dynamic and unbalanced characteristics of subsystem development, it becomes essential to further analyze the equilibrium and coordination among the TWS using the coupling coordination degree model. The formula for calculating the degree of TWS coupling and coordination is as follows：

$$D = \sqrt{C \times T} \tag{9}$$

$$T = \alpha_1 U_1 + \alpha_2 U_2 + \alpha_3 U_3, 0 < T < 1 \tag{10}$$

Where: D is the degree of coupling coordination, $0 < D < 1$; U_1, U_2, U_3 as above; T for the reconciliation coefficient of each system, reflecting the level of contribution to the degree of coupling coordination, α_1, α_2, α_3 indicating the weight of each system, $\alpha_1 + \alpha_2 + \alpha_3 = 1$, this study considers that the three subsystems of the TWS are equally important, and therefore take $\alpha_1 = \alpha_2 = \alpha_3 = \frac{1}{3}$. Taking into account the existing research on coupling degree and coordination, the ternary subsystem coupling degree is categorized into six levels, while the degree of coordinated development is classified into 11 levels. The specific standards for this classification are detailed in Table 2 below.

Table 2. Grading standard of coupling degree and coupling coordination degree

Range of C	Coupling type	Range of D	Coordination level	Degree of coupling coordination
0	Mutually independent	0	A1	Independent dissonance
		[0.0，0.1]	A2	Extreme dissonance
(0.0, 0.3]	Low level coupling	(0.1，0.2]	A3	Severe dissonance
		(0.2，0.3]	A4	Moderate dissonance
(0.3, 0.5]	Medium level of friction	(0.3，0.4]	A5	Mild dissonance
		(0.4，0.5]	A6	Nearly dysfunctional
(0.5, 0.7]	Good coupling	(0.5，0.6]	A7	Barely dysregulated
		(0.6，0.7]	A8	Elementary coordination
(0.7, 0.9]	High level of coupling	(0.7，0.8]	A9	Intermediate coordination
		(0.8，0.9]	A10	Good coordination
(0.9, 1.0]	High-quality coupling	(0.9，1.0]	A11	Quality coordination

2.5.4. Gray correlation analysis

In the realm of research on systematic synergistic development, the degree of correlation between specific indicators can be assessed using gray correlation analysis. The gray correlation model involves transforming discrete data in a sequence into a continuous curve via linear interpolation. The correlation between indicators is determined by comparing the curves derived from two indicator sequences. The more closely the curves resemble each other, the stronger the correlation between the indicators. Greater correlations among indicators from different systems imply a more significant influence on the relationship between the two systems, effectively serving as an indicator of their coordinated development. The procedural steps are as follows: **(1)** Calculate the correlation coefficient between two indicators from different systems using formula (11); **(2)** Ascertain the correlation degree between these two indicators according to formula (12); **(3)** Identify the indicators that play a role in affecting the level of coordinated development between different systems.

$$\zeta_{ij}(t)=\frac{\min_{i}\min_{t}\left|X_{j}(t)-X_{i}(t)\right|+\rho\max_{i}\max_{t}\left|X_{j}(t)-X_{i}(t)\right|}{\left|X_{j}(t)-X_{i}(t)\right|+\rho\max_{i}\max_{t}\left|X_{j}(t)-X_{i}(t)\right|} \tag{11}$$

$$\gamma_{ij}=\frac{1}{N}\sum_{t=1}^{N}\zeta_{ij}(t) \tag{12}$$

2.5.5. Vector Auto Regression model

The VAR model is a multi-equation model that employs an unstructured approach to establish relationships between variables. It constructs the model by considering each endogenous variable in the system as a function of the lagged values of all endogenous variables in the system. This allows for the estimation of the dynamics of all endogenous variables, making it a valuable tool for forecasting time series systems and analyzing the dynamic effects of random perturbations on the system.

In this study, we integrate the evaluation indices of the TWS with the coupling and coordination degrees of the TWS and employ the VAR model to identify and analyze the key indices influencing the development of the TWS in the YRB. The following steps are undertaken: **(1)** Establish the VAR model connecting the coupling degree of coordination and the evaluation indices, as presented in Equation (13); **(2)** Develop the impulse response function based on the VAR model, as depicted in Equation (14); **(3)** Select the relevant indices as impact variables for conducting impulse response analysis. This helps in assessing the extent of influence exerted by both current and future values of the system's coupling degree of coordination. The analysis aids in uncovering the long-term and dynamic mechanisms governing the impact of these indices on the system's coordinated development.

$$Y_t = \mu + \prod{}_1 Y_{t-1} + \dots \dots \prod{}_P Y_{t-1} + \varepsilon_t \tag{13}$$

$$Y_t = \mu + \sum_{k=1}^{p} \lambda_k Y_{t-k} + \varepsilon_t \tag{14}$$

where Y_t is a column vector of $k \times 1$ th order endogenous current variables including coupling coordination and evaluation indicators, k is the number of variables; u is a vector of $k \times 1$ th order constant terms; $\prod{}_1 \dots \dots \prod{}_P$ is a $k \times k$ th order parameter matrix; ε_t is a vector of $k \times 1$ th order random error columns; p is the lag order; and λ_k denotes a one-unit shock from the k th variable.

3. Results and discussion

3.1. TWS development index analysis

Based on equations (1)-(6), we derive the development index scores for the three subsystems and the Comprehensive development index (CDI) of the TWS. The trend of CDI is depicted in Figure 3-a. It illustrates the upward trend in the comprehensive development level of the TWS from 2005 to 2014. During this period, the CDI exhibited consistent growth, increasing from 0.31 in 2005 to 0.39 in 2014, with an average annual growth rate of 2.58%. This growth was primarily driven by the rapid development of the water environment index, which contributed to the steady improvement in the overall development level of the TWS. However, there were abrupt declines in the CDI during the periods of 2014-2015 and 2017-2019. These downturns marked a sudden drop in the comprehensive development level of the entire three-water system. Nevertheless, the CDI gradually resumed an upward trajectory after 2019.

(1) Regarding the development status of the WRS (Figure 3-b), the development index of the WRS exhibits relatively modest changes, characterized by minor fluctuations with some periods of decline followed by recovery. More specifically, Gansu, Ningxia, and Inner Mongolia display lower water resources indices during the years 2005-2021. This suggests potential issues such as drought, suboptimal water resource management, and water pollution in these regions. In contrast, Sichuan and Shanxi provinces record notably higher water resources indices, attributed to their ample precipitation resources and the presence of numerous large rivers traversing these areas.

(2) Regarding the development status of the WES (Figure 3-c), it exhibits the most rapid development, increasing from 0.20 in 2005 to 0.40 in 2021, with an average growth rate of 8.1%. Specifically, in the early years, Sichuan focus on economic development resulted in neglect of industrial and agricultural pollution and incomplete sewage treatment, causing significant harm to the water environment. However, in recent years, increased attention and improvements have led to a steady increase in the index, ultimately reaching 0.63. Shanxi, after 2015, has witnessed gradual improvements in its water environment, reaching a score of 0.75. Besides, Henan experienced a declining trend in water environment quality from 2005 to 2013.

(3) Regarding the development status of the WELS (Fig. 3-d), the water ecology index exhibited fluctuating growth during 2005-2014. After a slight decline in 2014, it experienced a significant increase with a growth rate of 11.5%. By 2021, the water ecology index had more than doubled in comparison to the 2005 levels, as shown in Figure 2-d. Nevertheless, the favorable development trend of the water environment in

Qinghai, Gansu, Ningxia, and Shanxi lags significantly behind the other five provinces. Consequently, these provinces should intensify water ecological protection measures and enhance their efforts in water ecosystem protection.

To summarize, the TWS indexes have shown varying improvements compared to the year 2005, reflecting the positive impact of economic and social development, as well as the national emphasis on water ecology and environment. Consequently, the state of the TWS in the YRB is on an upward trajectory, indicating a favorable trend in the integrated and coordinated management of the TWS in the region. It's important to note that the development of TWS within each province varies due to distinct governance schemes and other contributing factors.

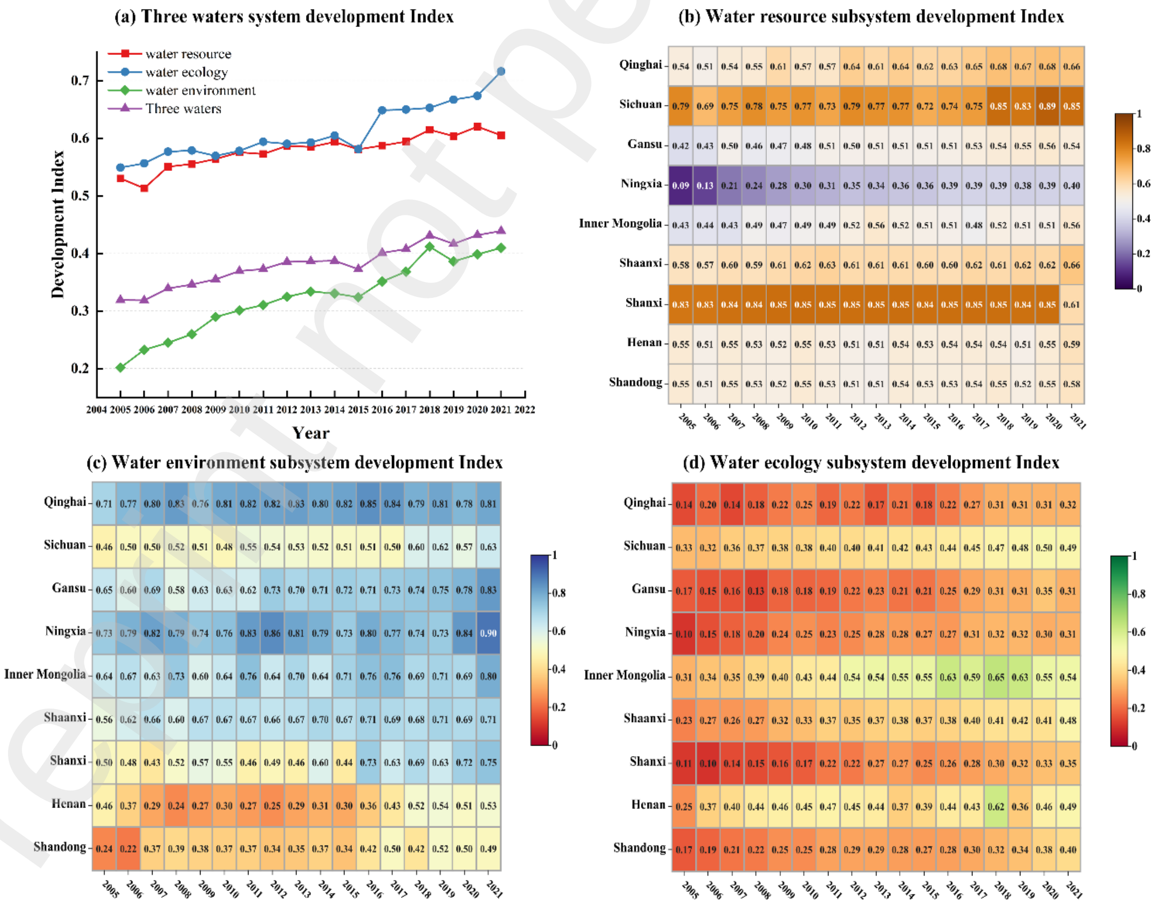

Fig. 3. TWS, WRS, WES, and WELS development index for 2005–2021

3.2. Coupling degree analysis

According to Equation (7), the calculated results for the coupling degree of the TWS in the YRB are presented in Figure 4 below. Overall, the coupling degree of the nine provinces in the YRB ranges from a minimum of 0.6142 to a maximum of 0.9973, indicating a spectrum from good coupling to high-quality coupling. Most areas fall within the high coupling stage, signifying the close interconnection of the three subsystems: water resources, water ecology, and water environment in the YRB. The coupling among these systems is steadily progressing toward a high-level state. Specifically, Qinghai Province maintained a high coupling stage during 2010-2017 and later stabilized in a high-quality coupling stage after 2018. Sichuan Province exhibited significantly higher coupling compared to other provinces, consistently belonging to the high-quality coupling stage from 2005 to 2021, reflecting a stable and positive development trend. Gansu Province transitioned from a highly coupled stage before 2012 to high-quality coupling after 2013, which has been maintained since. Ningxia was initially in a good coupling stage in 2005, subsequently reaching high coupling in 2006 and eventually achieving quality coupling in 2016. Besides, Inner Mongolia, Shaanxi, and Henan maintained high coupling throughout the period, with coupling values consistently exceeding 0.9, signifying stable development trends without departing from the quality coupling category. Shanxi Province was in a high coupling stage between 2005 and 2013, and it transitioned to high-quality coupling after 2014. Sichuan Province exhibited significantly higher coupling compared to other provinces during 2005-2021 and consistently remained in the high coupling stage, indicating a stable and positive development trend. Shanxi Province was in the high coupling stage from 2005 to 2013, progressing to high-quality coupling after 2014. Shandong Province initially belonged to the high coupling stage in 2005-2006, rapidly advancing into high-quality coupling after 2006.

In summary, the provinces within the YRB exhibit close interrelations, emphasizing the necessity for integrated management to support the robust development of the basin's water system.

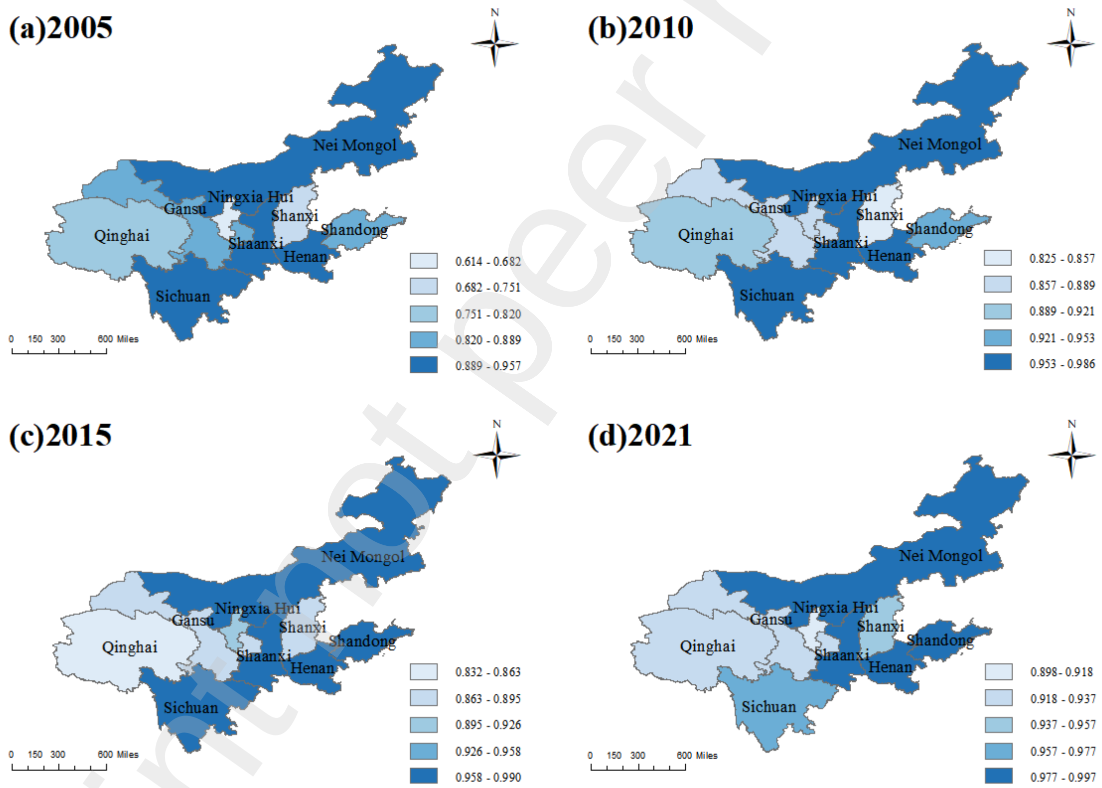

Fig. 4. Coupling level of the TWS in the YRB.

3.3. Coupling coordination degree analysis

The coupling coordination degree of the TWS for the years 2005, 2010, 2015, and 2021 in each province of the YRB have been calculated using equations (9) and (10), and the results are presented in Figure 5 below. While the data exhibit some localized fluctuations, the overall trend for the coupling coordination degree of each province in the YRB from 2005 to 2021 is positive. In Qinghai province, the data fluctuation is more pronounced, with the coordination level showing jagged fluctuations during 2005-2015. Subsequently, it began to rise steadily and gradually from 2015, eventually reaching a value of 0.7438. Sichuan province has consistently maintained a high coordination level since 2005, with values exceeding 0.7 throughout the period and reaching a maximum of 0.8011 in 2021; Gansu province witnessed a small downward trend in coordination level during 2005-2008, followed by a continuous year-on-year increase from 2009, culminating in a coordination level of 0.7204 in 2021. Ningxia Autonomous Region started with relatively lower coordination but exhibited a faster development in coordination level during the 2005-2008 period, with an average annual growth rate of 13.6%. Although it continued to rise after 2008, the growth rate was relatively modest; Inner Mongolia Autonomous Region demonstrated relatively high levels of coupled coordination, surpassing the coordination levels of all other provinces during 2012-2017. It experienced a slight decline after 2017, ultimately reaching 0.7878 in 2021. Shaanxi province's coordination level showed an overall upward trend, increasing from 0.6512 to 0.7807 and resuming growth after a minor decline in 2007, with a growth rate of 5%; Shanxi province exhibited growth after a slight decline in coordination level in 2005, with steady annual increments during 2006-2014. However, it experienced a significant increase followed by a sharp decline during 2014-2016. Subsequently, it displayed slower year-by-year growth, reaching a coordination level of 0.7351 in 2021; Henan Province showed unstable fluctuations in coordination level, with a minor year-on-year decline during 2010-2015, a sudden increase in 2017-2018 (with a growth rate of 9.3%), and a subsequent decrease in 2018-2019 (with a 9% decrease). It ultimately reached a coordination level of 0.7313 in 2021; Shandong pbetrovince started with a low coordination degree, experiencing substantial growth in 2006-2007, with a growth rate of 12.7%. However, from 2010 to 2019, it had the smallest coordination degree compared to other provinces, consistently maintaining the lowest coordination level during this period. In 2020, it surpassed the coordination degree of Ningxia Autonomous Region, ultimately reaching a coordination level of 0.6965 in 2021.

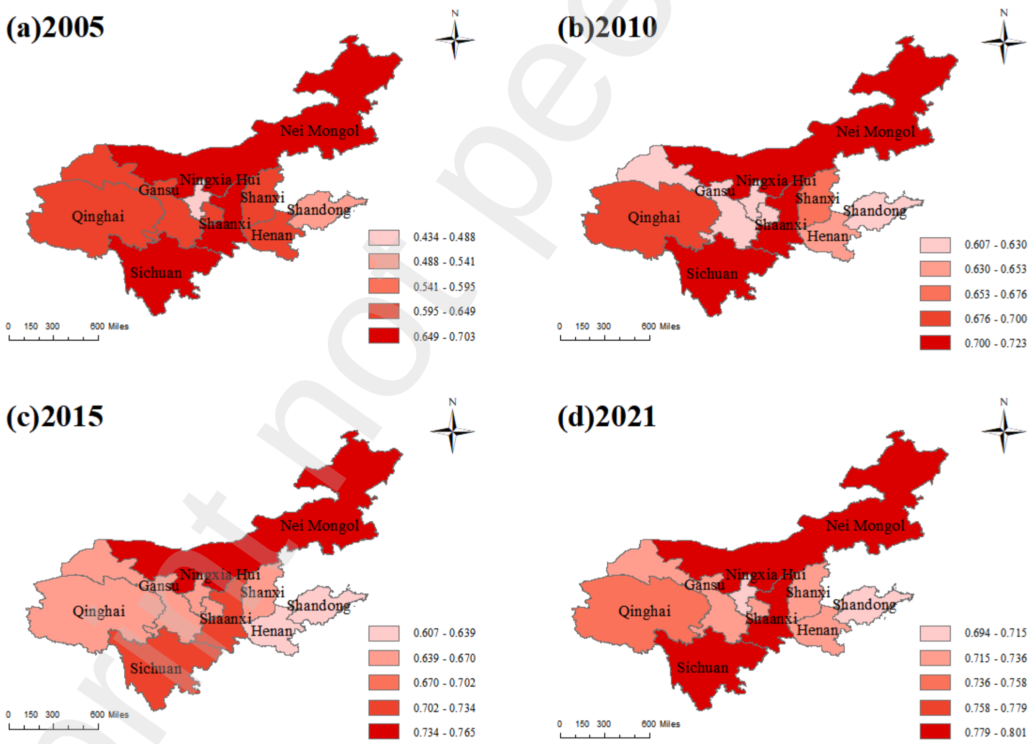

Fig. 5. Coupling coordination level of the TWS in the YRB

3.4. Coupled coordinated response relationships analysis for TWS

To further investigate the interrelationships among the indicators within each subsystem, a gray correlation analysis was conducted on the TWS, as illustrated in

Figure 6-a. This analysis revealed the mutual influence effects among the indicators, as depicted in Figures 6-b, 6-c, and 6-d below. Overall, the correlations among the indicators consistently exceed 0.4, indicating a strong positive correlation and significant mutual influence among the indicators of the three subsystems. Within these three sets of systems, the key indicators exhibiting the highest correlation and coupling coordination between the two subsystems were selected for constructing VAR models. These key indicators were used as the shock sequences for the impulse response analysis, along with stability testing. The key indicators, along with their respective correlation coefficients (R), encompass the following pairs: Water consumption of 10^4yuan GDP and sewage treatment rate in the water resource-water environment system (R=0.798); Precipitation and per capita underground water resources in the water resource-water ecosystem (R=0.787); Sewage treatment rate and green coverage of built-up urban areas in the water environment-water ecosystem (R=0.776).

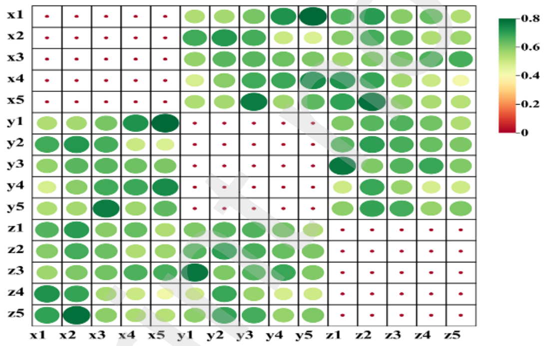

Fig.6-a Gray correlation between indicators of Three Waters System

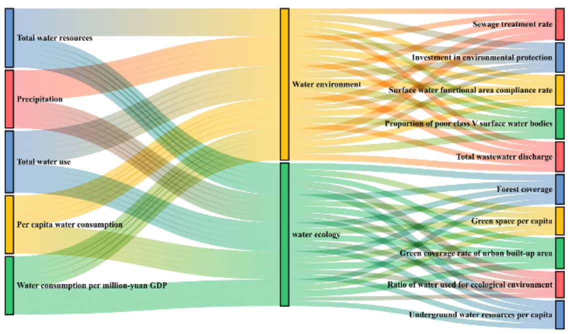

Fig. 6-b Grey correlation of WRS to WELS and WES indicators

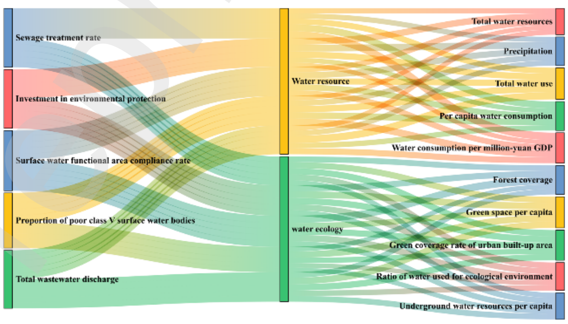

Fig. 6-c Grey correlation of WELS to WRS and WES indicators

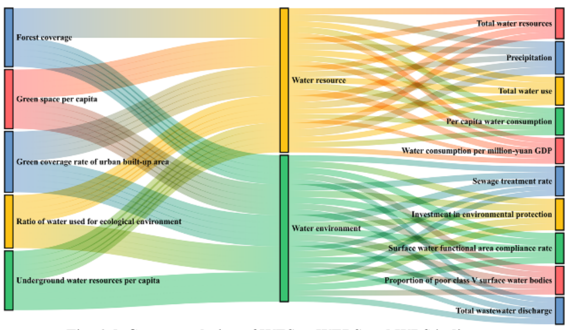

Fig. 6-d Grey correlation of WES to WELS and WRS indicators

Fig. 6. Gray correlation analysis of the TWS in the YRB

3.4.1. WRS-WES impulse response analysis

Before establishing the VAR model, it is essential to subject the data to testing to prevent spurious regression and ensure model stability and accuracy. An ADF unit root test was conducted using EViews 9.0, revealing that the water consumption and sewage treatment rate of 10^4yuan GDP were stationary series at the 5% significance level, as was the degree of coordination of the coupled WRS-WES. The lag order was determined to be second order based on the AIC, SC, and HQ information criteria. Furthermore, the AR root test for model stability confirmed that the characteristic root of each variable remained within the unit circle, affirming the stability of the established VAR model. Consequently, impulse response analysis was carried out, utilizing water consumption of 10^4yuan GDP and sewage treatment rate as shocks, and the results are depicted in Figure 7. Notably, when a shock was applied to the sewage treatment rate during this period, the positive influence peaked in the first period and gradually leveled off by the sixth period, stabilizing at a value of 0. Conversely, providing a shock to the water consumption of 10^4yuan GDP in this period led to a peak of negative influence in the first period, followed by a gradual increase, ultimately reaching 0. This indicates that the sewage treatment rate has a short- and medium-term positive influence, exerting a promotional effect on the coupling coordination degree of the two systems. Additionally, it was observed that the water consumption of 10^4yuan GDP negatively impacts the system, with the effect of the sewage treatment rate significantly surpassing that of 10^4yuan GDP water consumption. This suggests that increasing the sewage treatment rate can effectively promote the sustainable and stable development of WRS-WES.

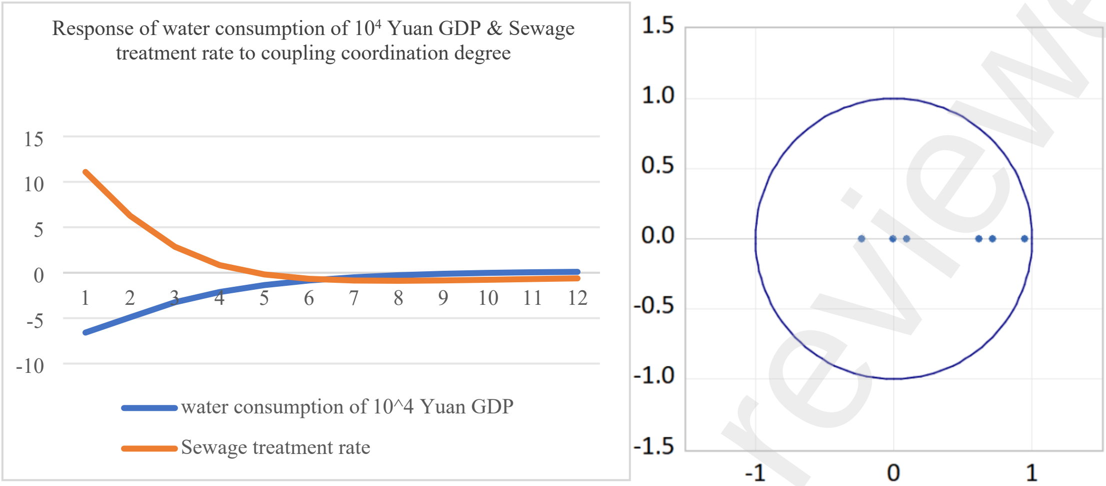

Fig. 7. Impulse response of coupling coordination degree of WRS-WES to water consumption of 10^4Yuan GDP and sewage treatment rate

3.4.2. WRS-WELS impulse response analysis

Following the unit root test, it was found that precipitation and per capita groundwater resources were non-stationary series at a 5% significance level. However, the first-order difference series of precipitation and per capita groundwater resources proved to be stationary series. Consequently, the data for precipitation and per capita groundwater resources were subjected to a first-order differencing treatment. As a result, the WRS-WELS coupling coordination degree became stationary at a 5% significance level. Using the information criterion, the second order was selected as the most appropriate lag order. After the AR root stability test, a VAR model was established, and impulse response analysis was conducted, with the results illustrated in Figure 8. The response of the coupled WRS-WELS coordination degree to shocks from these two indicators displayed a consistent pattern. Specifically, a significant positive impact was observed in the first period. After reaching its peak, the impact declined sharply and reached the lowest point of negative impact in the second period. Subsequently, from the third to the fifth period, the impact persisted, albeit diminishing in magnitude. Ultimately, it approached zero. This indicates that an increase in precipitation and per capita groundwater resources can rapidly enhance coordination between the two systems. However, the impact is characterized by volatility and is less sustainable over time.

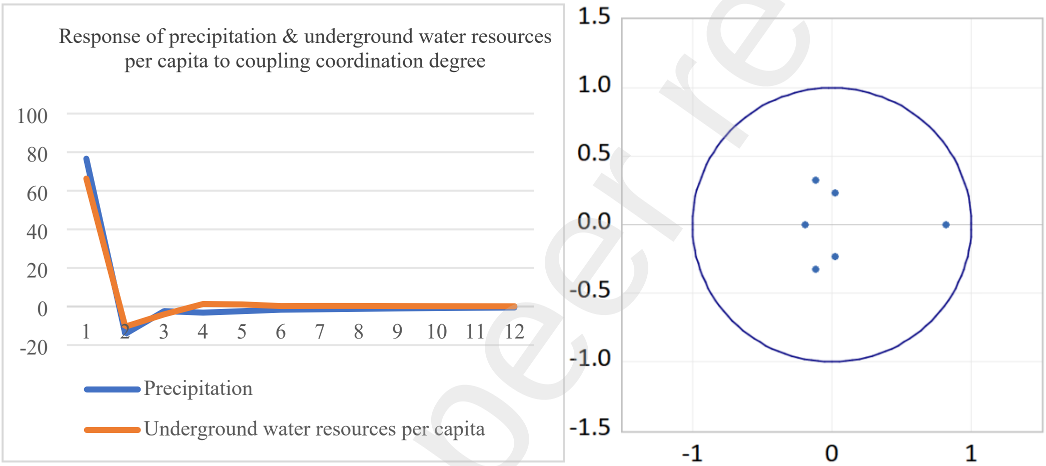

Fig. 8. Impulse response of coupling coordination degree of WRS-WELS to precipitation and underground water resource per capita

3.4.3. WES-WELS impulse response analysis

Following the unit root test, it was determined that the sewage treatment rate and the greening coverage of urban built-up areas in the context of WES-WELS coupling and coordination are both smooth series, exhibiting significance at the 5% level. To select the optimal lag order, the information criterion guided the choice of a second-order lag. After conducting the AR root stability test, a VAR model was established, and impulse response analysis was performed, with the results presented in Figure 10. The analysis reveals that the sewage treatment rate and the green coverage of urban built-up areas exhibit a positive impact in the current period. Notably, both indicators have a similar influence on the degree of coordination in WES-WELS coupling. The positive effect spans from period 1 to period 12, reaching its peak in the first period. However, it is worth noting that the sewage treatment rate attains a higher peak than the green coverage of urban built-up areas, indicating that, during the first period, the sewage treatment rate has a more substantial positive impact than the green coverage of urban built-up areas. Subsequently, the impact of both indicators gradually diminishes from the 2nd to the 7th period. This implies that, during this phase, the sewage treatment rate has a more significant effect compared to the green coverage of urban built-up areas. Among the 2nd and the 7th period, the influence of both indicators gradually wanes, eventually converging to zero in the 11th period. This suggests that improvements in the sewage treatment rate and the greening coverage of urban built-up areas exert a substantial and long-term promotional impact on the coordinated development of the two systems, characterized by a high level of sustainability.

Fig. 9. Impulse response of coupling coordination degree of WELS-WES to sewage treatment rate and green coverage rate of urban built-up area

4. Conclusions and suggestions

This study introduces an innovative approach to explore the relationships and influence mechanisms governing the coupled coordinated development of the TWS in the YRB. It conducts a comprehensive analysis of the water ecosystem, water environmental quality, and water resource utilization within the YRB, and assesses the state of coordinated development for the TWS across multiple dimensions. Furthermore, it sheds light on the inherent nature of the TWS issues in the YRB and their complex interaction mechanisms. The primary findings can be summarized as follows.

Regarding the comprehensive development status of the system, it is evident that the TWS subsystem state within the YRB has exhibited continuous improvement. This positive trend can be attributed to the concurrent economic and social development and the national emphasis on water resources and the ecological environment. However, it's worth noting that the development of TWS varies across provinces due to distinct governance strategies and other influencing factors. Specifically, provinces such as Gansu, Ningxia, and Inner Mongolia have shown lower water resources indices, implying potential issues such as drought, suboptimal water resource management, and water pollution. Sichuan Province, in its earlier stages of development, neglected the impact of industrial and agricultural pollution and suffered from an imperfect sewage treatment system, leading to significant damage to the water environment. However, recent years have witnessed a positive shift, with water environment issues receiving heightened attention and subsequent improvements. As a result, the water environment index has experienced consistent growth over time, reflecting the positive impact of policy measures and deployments aimed at addressing water environment concerns.

In terms of the development of coupling and coordination, it is evident that during the study period, the coordination level of the TWS across the nine provinces has made significant progress. Whatever seemed previously on the edge of being disorganized has now achieved effective coordination, and the degree of coupling coordination has gradually developed to a high-quality stage. This positive trend is marked by a narrowing gap in coupling and coordination levels among different regions, reflecting the strengthening mutual promotion among subsystems. It is apparent that the implementation of the "Three Waters integration" policy has played a crucial role in advancing the coordinated development of the water system. It's noteworthy that, based on the natural resources available, the quality of the water system in southern regions is more pronounced than in the north. Furthermore, this study has also unveiled the substantial impact and importance of interactions and coordinated development among the three water subsystems, which directly influences the overall development level of the basin. Therefore, when considering the basin system perspective, enhancing the degree of coupling and coordination of the TWS and fostering interactions and coordinated development among the subsystems are effective strategies for improving the basin's overall development level. Additionally, given the substantial variations in rainfall, geomorphology, water system distribution, and socio-economic development among different provinces and regions, it is imperative to customize the approach to coordinated development, considering the unique characteristics and foundation of each province. Adhering to the principle of adapting coordinated development to local conditions and specific provincial circumstances is of utmost importance.

Concerning the influence mechanism of the system indicators, it's evident that there exists a robust mutual influence effect among the subsystem indicators. **(1)** the WRS-WES demonstrates the highest degree of correlation. Based on the impulse response analysis of the water resource-water environment system in the YRB, the following recommendations are proposed: **(a)** Government bodies and relevant authorities within the basin should address the delicate balance among water utilization for residential and industrial purposes and water environmental protection. Encouraging both enterprises and farmers to adopt advanced water conservation technologies is crucial. Reducing water consumption for production and daily life while simultaneously enhancing water resource utilization efficiency is essential. **(b)** The establishment of a stringent water usage monitoring system is imperative. Increased management efforts and the imposition of penalties for water usage violations will contribute to the responsible management of this valuable resource. **(c)** Furthermore, it is recommended that additional support policies be introduced for enterprises, particularly in terms of talent development and the translation of scientific and technological innovations. Encouraging enterprises to engage in research, development, or the adoption of new technologies will not only ensure their economic production capabilities but also yield long-term benefits by promoting the efficient use of water resources and safeguarding water environmental protection.

(2) The coupled coordination degree of water resources and water ecosystems exhibits a consistent response to the influence of various indicators. Based on the impulse response analysis of the water resources and water ecosystems in the YRB, the following management recommendations are proposed: **(a)** Governmental attention should be directed towards inter-regional water resources allocation to ensure the rational distribution of water resources. Encouraging the implementation of water resources dispatching techniques, along with the transfer of water resources from regions with high precipitation to arid areas, is necessary to enhance the overall efficiency of water resource utilization. **(b)** The promotion of ecological engineering projects, such as afforestation and grassland restoration, can be instrumental in reducing soil erosion, enhancing soil water retention capacity, and boosting groundwater recharge. These measures will contribute to the sustainable management of water resources and ecosystems. **(c)** The development of rainwater collection systems and the utilization of rainwater for purposes like farmland irrigation and urban greening are essential. These initiatives effectively alleviate the strain on groundwater and surface water resources, ensuring their longevity and resilience.

(3) The enhancement of the sewage treatment rate and the green coverage rate in urban built-up areas within the water environment-water ecosystem demonstrates a significant and enduring positive influence on the coordinated development of both systems, underlining their sustainability. Based on the findings from the impulse response analysis, the following recommendations are proposed: **(a)** Increase investments in urban green infrastructure and encourage active involvement from enterprises, institutions, and social organizations to expand the extent of green coverage in urban areas and enhance the overall ecological environment. **(b)** Promote the adoption of ecological landscape design principles in urban planning and development.

This involves incorporating more green landscapes and ecological spaces into urban designs, thereby augmenting urban green coverage. **(c)** Implement a comprehensive system for the protection of urban green spaces, with a particular focus on safeguarding areas like parks, green spaces, and wetlands. **(d)** Establish a robust protection system for urban green spaces, intensify efforts to conserve areas such as parks, green spaces, and wetlands, and take measures to prevent unauthorized occupation and destruction of these vital green zones.

In conclusion, this study holds significant implications for understanding the status and mutual influence mechanisms in the context of integrated management of the TWS in the YRB. It serves as a valuable foundation for enhancing the level of coordinated development within the YRB system. Furthermore, this research can be seen as a stepping stone, paving the way for future investigations into the allocation of water resources, the optimal distribution of sewage rights, and the carrying capacity of the Three Waters in the region. Such endeavors may offer innovative insights for advancing the sustainable development of the basin's water system.

Acknowledgments

This work was supported by the Philosophy and Social Science Research Fund of Chengdu University of Technology (Grant No. ZDJS202204) and the Fundamental Research Funds for the Tuojiang River Basin High-quality Development Research Center of Sichuan Province Key Research Base of Social Sciences (Grant No. TJGZL2023-03).

References

Bai, X., Jin, J., Zhou, R., Wu, C., Zhou, Y., Zhang, L., & Cui, Y. (2022). Coordination evaluation and obstacle factors recognition analysis of water resource spatial equilibrium system.

Environmental Research, 210, Article 112913. https://doi.org/10.1016/j.envres.2022.112913

Cai, J., Li, X., Liu, L., Chen, Y., Wang, X., & Lu, S. (2021). Coupling and coordinated development of new urbanization and agro-ecological environment in China. *Science of The Total Environment*, 776, Article 145837. https://doi.org/10.1016/j.scitotenv.2021.145837

Chapagain, K., Aboelnga, H. T., Babel, M. S., Ribbe, L., Shinde, V. R., Sharma, D., & Dang, N. M. (2022). Urban water security: A comparative assessment and policy analysis of five cities in diverse developing countries of Asia. *Environmental Development*, 43, 100713. https://doi.org/10.1016/j.envdev.2022.100713

Cao X, Ci F. (2023). Study on the Coupling Development of Industry, City and Population in the Yellow River Basin from the Perspective of Green Economy[J]. *Sustainability*, 15(13): 10029. https://doi.org/10.3390/su151310029

Di Vaio A, Trujillo L, D'Amore G, et al. (2021). Water governance models for meeting sustainable development Goals: A structured literature review[J]. *Utilities Policy*, 72: 101255. https://doi.org/10.1016/j.jup.2021.101255

Han, H., Guo, L., Zhang, J., Zhang, K., & Cui, N. (2021). Spatiotemporal analysis of the coordination of economic development, resource utilization, and environmental quality in the Beijing-Tianjin-Hebei urban agglomeration. *Ecological Indicators*, 127, Article 107724. https://doi.org/10.1016/j.ecolind.2021.107724

Hu, G., Zeng, W., Yao, R., Xie, Y., & Liang, S. (2021). An integrated assessment system for the carrying capacity of the water environment based on system dynamics. *Journal of Environmental Management*, 295, Article 113045. https://doi.org/10.1016/j.jenvman.2021.113045

Kryston A, Müller M F, Penny G, et al. (2022). Addressing climate uncertainty and incomplete information in transboundary river treaties: A scenario-neutral dimensionality reduction approach. *Journal of Hydrology*, 612: 128004. https://doi.org/10.1016/j.jhydrol.2022.128004

Kong Y, He W, Gao X, et al. (2022) Dynamic assessment and influencing factors analysis of water environmental carrying capacity in the Yangtze River Economic Belt, China. *Ecological Indicators*, 142: 109214. https://doi.org/10.1016/j.ecolind.2022.109214

Li G., Wang Y., Li Y. (2019). Synergies within the Water-Energy-Food Nexus to Support the

Integrated Urban Resources Governance. *Water,* 11(11):2365. https://doi.org/10.3390/w11112365

Lei Y., Guoping C., Jiasheng W. et al. (2022). A quantitative analysis method for the degree of coupling coordination between drinking water carrying capacity and population spatial aggregation. *Environment, Development and Sustainability*, https://doi.org/10.1007/s10668-022-02229-2

Li, D., Zuo, Q., Zhang, Z. (2022). A new assessment method of sustainable water resources utilization considering fairness-efficiency-security: A case study of 31 provinces and cities in China. *Sustainable Cities and Society*, 81, 103839. https://doi.org/10.1016/j.scs.2022.103839

Li W, Jiang S, Zhao Y, et al. A copula-based security risk evaluation and probability calculation for water-energy-food nexus[J]. *Science of The Total Environment*, 2023, 856: 159236. https://doi.org/10.1016/j.scitotenv.2022.159236

Sadat M A., Guan Y., Zhang D. et al. (2020). The associations between river health and water resources management lead to the assessment of river state. *Ecological Indicators*,109:105814.1-105814.14. https://doi.org/10.1016/j.ecolind.2019.105814

Tao J, Xie Y, Zhou H, et al. (2022) Cross-County Characteristics of Water–Ecology–Economy Coupling Coordination in the Wuding River Watershed, China. *Land*, 11(12): 2283. https://doi.org/10.3390/land11122283

Wang, J., Wang, S., Li, S., & Feng, K. (2019). Coupling analysis of urbanization and energy-environment efficiency: Evidence from Guangdong province. *Applied Energy*, 254, Article 113650. https://doi.org/10.1016/j.apenergy.2019.113650

Wang. M, Annette B. G. Janssen, Jeanne Bazin, et al. (2022). Accounting for interactions between Sustainable Development Goals is essential for water pollution control in China[J]. *Nature Communications*, 13(1): 730

Wang Y, Song J, Sun H. (2023). Coupling interactions and spatial equilibrium analysis of water-energy-food in the Yellow River Basin, China. *Sustainable Cities and Society*, 88: 104293. https://doi.org/10.1016/j.scs.2022.104293

Xu S., He W., Shen J. et al. (2019). Coupling and Coordination Degrees of the Core Water–Energy–Food Nexus in China. *International Journal of Environmental Research and Public Health*, 16(9):1648. https://doi.org/10.3390/ijerph16091648

Xiang X, Li Q, Khan S, et al. (2020). Urban water resource management for sustainable environment planning using artificial intelligence techniques. *Environmental Impact Assessment Review*, 86. https://doi.org/10.1016/j.eiar.2020.106515

Xiao, R., Yu, X., Xiang, T., Zhang, Z., Wang, X., & Wu, J. (2021). Exploring the coordination between physical space expansion and social space growth of China's urban agglomerations based on hierarchical analysis. *Land Use Policy*, 109, 105700. https://doi.org/10.1016/j.landusepol.2021.105700

Xu D, Yang F, Yu L, et al. (2021). Quantization of the coupling mechanism between eco-environmental quality and urbanization from multisource remote sensing data. *Journal of Cleaner production*, (Oct.25):321. https://doi.org/10.1016/j.jclepro.2021.128948

Yimin Wang, Yang J, Chang J. (2019). Development of a coupled quantity-quality-environment water allocation model applying the optimization-simulation method. *Journal of Cleaner Production*, https://doi.org/10.1016/j.jclepro.2018.12.065

Yuan S Y, Xu L, Tang H W, et al. (2022). The dynamics of river confluences and their effects on the ecology of aquatic environment: A review. *Journal of Hydrodynamics*, 34(1):1-14. https://doi.org/10.1007/s42241-022-0001-z

Yang L, Xu C, Zhu H., et al. (2023). Dynamics of the water environment in a water quantity-quality-soil model of China's Yellow River basin: imbalance and driving factors[J]. *Environmental Monitoring and Assessment*, 195(3). https://doi.org/10.1007/s10661-023-11001-6.

Zhao Y, Hou P, Jiang J, et al. (2021) Coordination study on ecological and economic coupling of the yellow river basin[J]. *International Journal of Environmental Research and Public Health*, 18(20): 10664. https://doi.org/10.3390/ijerph182010664

Zhang X., Jie XW., Ning SN., Wang K., Li XP., (2022). Coupling and coordinated development of urban land use economic efficiency and green manufacturing systems in the Chengdu Chongqing Economic Circle. *Sustainable Cities and Society*, 85, 104012. https://doi.org/10.1016/j.scs.2022.104012

Zhang, KZ., Dong, ZC., Guo, L., Boyer, EW., Liu, JZ., Chen, J., Fan, BH., (2023). Coupled coordination spatiotemporal analyses inform sustainable development and environmental protection for the Yellow River Basin of China. *Ecological Indicators*,151, 110283. https://doi.org/10.1016/j.ecolind.2023.110283

Zhu C., Fang CL., Zhang LF., (2023). An analysis of the coupling coordinated development of the Population–Water–Ecology–Economy system in urban agglomerations and obstacle factors discrimination: A case study of the Tianshan North Slope Urban Agglomeration, China. *Sustainable Cities and Society*, 90, 104395. https://doi.org/10.1016/j.scs.2022.104359