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Original Research

A quantitative assessment framework for water-related policies in large river basins

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A B S T R A C T

Effective water management in large river basins requires a comprehensive understanding of policy effectiveness and regulatory frameworks. However, quantitative assessments of water-related policies remain limited. Here, we propose a novel quantitative framework for evaluating water policies in large river basins, providing an intuitive and systematic approach for decision-makers. Using the Yellow River Basin—the second-largest river basin in China—as a case study, we constructed a database of 1271 water-related policies spanning 68 cities. We assessed the completeness of nine representative policies, identifying key gaps in water environment governance. To evaluate management effectiveness, we developed a system integrating two key subsystems: water resource utilization and water environment treatment, incorporating climatic, economic, and industrial factors. Our findings reveal that water environment governance policies were more effective than those targeting water resource utilization, though their impact was delayed by one to two years. Furthermore, a risk-based analysis pinpointed critical water management challenges in each city, offering actionable insights for policy optimization. This framework provides a robust and scalable approach for assessing the effectiveness of complex water policies in large river basins, with global applicability for improving water governance.

1. Introduction

The management of large river basins is a crucial issue that must be considered by local and national governments worldwide. In addition, establishing appropriate water-related laws and regulations to create management models adapted to specific basins is essential in achieving effective basin management. However, some large river basins cover multiple administrative regions, thus requiring coordinated governance across different areas. The numerous water-related policies enacted in these regions have complex contents, and their effectiveness is often difficult to quantify, thus posing challenges for managers regarding overall basin management and policy optimization. Research on quantifying policy assessment frameworks for large river basins remains relatively scarce. Therefore, a systematic organization of the numerous water-related policies within large river basins must be carried out, along with establishing a scientific framework for quantifying policy effectiveness, thereby providing managers with guidance for policy optimization. This study uses the Yellow River Basin in China as an example and constructs a database of water-related policies, facilitating the quantitative evaluation of policy completeness and effectiveness to assist in basin management. Using similar management models, the resulting framework can be applied to other large river basins worldwide.

The Yellow River Basin, the second-largest river basin in China, covers a total area of 795,000 km^2, including nine provinces and 68 cities (municipalities/autonomous regions) spread across the region (Fig. 1). However, due to the influences of natural climate and human activities, this basin has been confronted with serious

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environmental issues, including water resource shortages and pollution. Indeed, the per capita water resources in the nine provinces in the basin in 2022 accounted for only 56.6% of the national average. Furthermore, water resources in 2020 did not meet the water quality standards set by the Chinese government at about 20% of the 282 monitoring sections across the Yellow River Basin, thereby posing significant water environmental risks. Chen et al. [1] highlighted that the sustainability of water resources in the Yellow River Basin is at risk in terms of quality and quantity, particularly due to severe contamination from heavy metals and nitrogen-phosphorus pollutants. Furthermore, the basin suffers from other problems, such as water scarcity per capita [2], fragile ecosystems [3], and low levels of green development [4]. Therefore, addressing these challenges requires urgent policy interventions by Yellow River Basin managers to tackle these critical water resource and environmental issues.

Thus far, the Chinese government has implemented several policies to address water scarcity and pollution in the Yellow River Basin. For example, in October 2021, the Central Committee of the Communist Party of China (CPC) and the State Council issued *Opinions on Strengthening Ecological Protection and Promoting High-Quality Development in the Yellow River Basin*, thus ensuring the region's ecological protection and high-quality development.

Furthermore, in January 2022, the National Development and Reform Commission and the Ministry of Water Resources introduced the 14th Five-Year Plan for Water Security, which outlined specific water resource management policies to be implemented for the Yellow River Basin. In response to the government's focus on water resources and environmental management, provinces and cities within the basin have introduced water management policies under the framework of the 14th Five-Year Plan. These early management strategies for the Yellow River Basin were supply-driven and engineering-focused. In comparison, current strategies have gradually shifted toward more comprehensive, demand-based approaches that integrate social, economic development and ecological preservation [5]. However, some studies have suggested that some areas in the basin still pay limited attention to environmental protection [6]. Existing policies also show gaps in pollution permit regulation [7], and obsolete water allocation schemes require updating [1,8]. Therefore, continuous policy and management optimization is essential to achieve high-quality development throughout the Yellow River Basin, especially in light of growing calls for more comprehensive and integrated basin management approaches [5,9]. Moreover, there is a lack of research that comprehensively reviews water-related policies in the Yellow River Basin in recent years. In this context, conducting studies to effectively optimize water resource management in basins is crucial, as these can provide valuable insights for policymakers. There should be a focus on ensuring efficient water resource utilization and implementing effective measures to reduce water pollution in the basin.

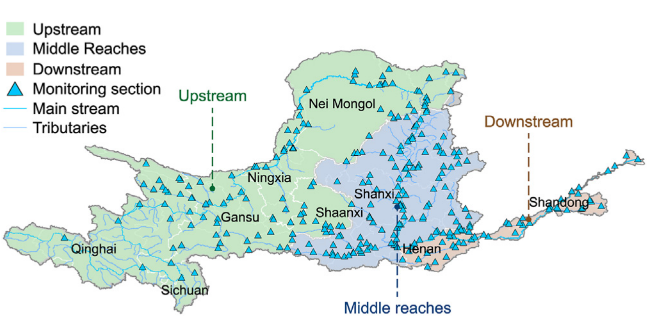

Fig. 1. The geographic information, administrative divisions of the Yellow River Basin, and the spatial distribution of the 282 monitoring stations used in this study.

In the literature, numerous studies have analyzed and evaluated water management policies implemented in the Yellow River Basin. For example, Song et al. [10] discussed changes in governance regimes in the Yellow River Basin by developing an integrated water governance index (IWGI) at the basin scale. Lu et al. [11] assessed the effectiveness of the Yellow River Water Allocation Management Scheme by examining changes in irrigation water consumption in Yucheng City, Shandong Province. Their findings highlight the crucial need to optimize the current irrigation water allocation in the basin. Wang et al. [12] analyzed the evolution of soil and water conservation policies in the basin, identifying three stages of interactions between soil and water conservation policies and systems, financial resources, and technical support.

Meanwhile, Li et al. [13] employed the propensity score matching and difference-in-difference (PSM−DID) estimator to evaluate the impacts of ecological compensation policies (ECPs) on water pollution levels throughout the cities surrounding the Dawen River Basin (a sub-basin of the Yellow River). Their findings highlighted the positive effects of ECPs on the water environment in the target areas. Liu et al. [14] demonstrated the reasonability of nine Basin Ecological Compensation Policies (BECP) implemented in the Yangtze and Yellow River Basins using the policy modeling consistency (PMC) index, despite the deficiencies found in terms of the timeliness of the policies, the incentives, and policy receptors.

Overall, the abovementioned studies have comprehensively discussed poler resource utilization and management in policies the Yellow River Basin. However, these studies have mostly focused on individual water policies in the Yellow River Basin at the sub-basin or local scales. Furthermore, aside from some limitations in the methods used to assess water policies, there is still a lack of research proposing a comprehensive organization and analysis of water policies in various basin areas On the one hand, previous studies have mainly used general indicators in the PMC-based evaluation system, such as policy timeliness and policy nature, without extensively using specific environmental indicators. On the other hand, previously employed methods (e.g., DID) only generally analyzed individual policies instead of multiple policies. While these studies revealed the potential differences between implemented and unimplemented policies, they failed to reflect the difference depending on the number of policies.

In this context, our research provides a comprehensive review and quantitative analysis of water-related policies in nine provinces and 68 cities throughout the Yellow River Basin. Specifically, this study aims: (1) to identify and categorize the implemented water-related policies and regulations in the selected provinces and cities over the 2018−2022 period to construct a water management policy and regulation database for the Yellow River Basin; (2) to evaluate the perfection of representative policies in the nine provinces using an improved PMC index, driven by the goal of proposing specific directions for addressing existing related challenges; (3) to construct an evaluation system that can quantitatively assess the effectiveness of existing policies and regulations on water resource utilization and treatment in the basin, using the eXtreme Gradient Boosting (XGBoost) model, SHapley Additive exPlanations (SHAP), and Pearson coefficient to comprehensively verify the positive effects of existing policies on water management benefits and considering several factors, such as climate, economy, and industry; and (4) to identify key issues in the selected cities in the Yellow River Basin using exploratory factor analysis (EFA), thus providing basin managers with a convenient reference for related policy optimization. The present study ultimately aims to provide a quantitative framework for classifying and evaluating the effectiveness of water management policies in other large river basins, thereby ensuring improved water-related policy optimizations. The methodology of the present study is shown in Fig. 2.

Compared to existing research, the current study has several innovations and contributions to the literature.

(1) While many studies focus on individual policies [12,15], our research considers multiple policies and the complexity of multiple management units in a major river basin, such as the Yellow River. This work comprehensively reviews all recent water-related policies, addressing a gap in existing studies that often overlook differences in policy quantity and implementation timing across administrative entities within the basin.
(2) Rather than focusing solely on the impacts of policies on individual indicators, as seen in other studies [11,16], the current research develops a more comprehensive evaluation system for assessing water management effectiveness. By incorporating confounding factors, such as climate, economy, and industry, this study applies the XGBoost model, SHAP analysis, and Pearson correlation to confirm the positive effects of policies on overall water management effectiveness, thereby offering a more holistic perspective on the phenomenon being studied.
(3) Compared to other studies using the PMC method to assess policy completeness [17,18], our research further refines the method by introducing a richer set of secondary indicators and addressing the common issue of excessive redundancy found in previous studies.
(4) Finally, the present study conducts a city-by-city risk assessment within the Yellow River Basin. Thus, the resulting information can enable policymakers to quickly identify potential risks and take immediate action.

2. Materials and methods

2.1. Data sources

2.1.1. Policy data

Following the Chinese government's requirements, all regional governments must disclose information on their official government websites, including plans, regulations, and policies. The policies and regulations used in this study were all derived from the statutory public content module found in the policy disclosure section of the official website of each provincial and municipal government. Policy data were collected in this study to reveal the

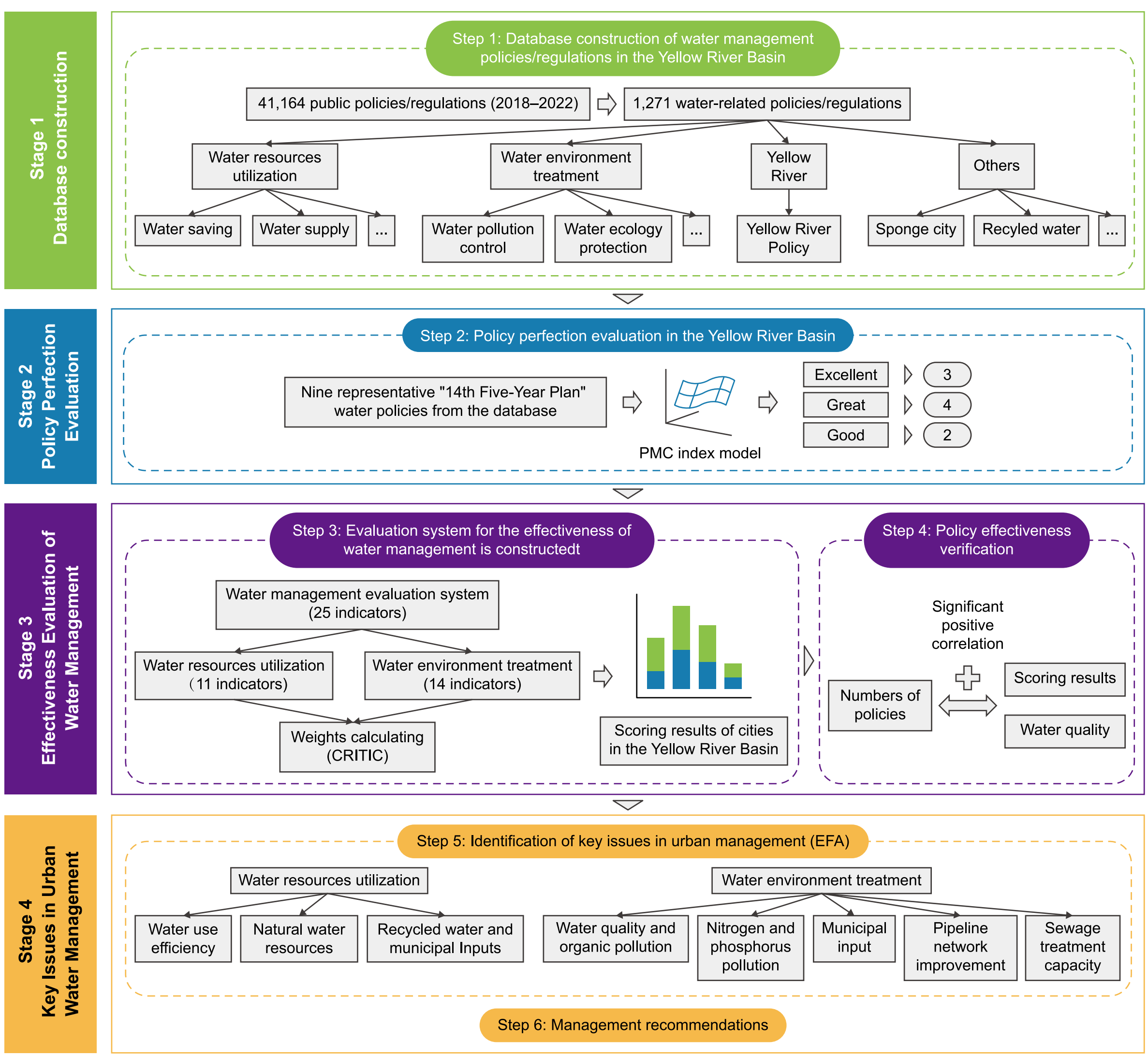

Fig. 2. The technical route of the research.

actual policies and regulations implemented in each province and city within the Yellow River Basin. Initially, these data were collected using Octopus software and then copied and organized manually to construct a database of the current policies and regulations in the basin. The collected data included policy titles, release dates, and issue numbers. Notably, considering the potential lag effect of policies, the policy data spanned an earlier period (2018–2022) compared to the water quality and city attribute data, which covered a latter period (2020–2022).

2.1.2. Water quality data

The water quality data used in this study came from 282 national surface water monitoring stations in China (regularly updated every 4 h). The distribution of these stations is shown in Fig. 1. The annual averages for 2020–2022 were calculated based on the daily sampling results. These data included eight water parameters: pH, dissolved oxygen (DO), ammonia nitrogen (NH_3-N), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD), total phosphorus (TP), and permanganate index (COD_{Mn}). The geographic coordinates of each monitoring station were also included in the collected data. The total number of valid data was 846. A single-factor evaluation method was used to classify the water parameters following the Surface Water Environmental Quality Standards (SWEQS) in China. Each indicator was classified into five quality classes, from I to V, at each monitoring station in this study. The higher the number of parameter classes, the poorer the water quality at the monitoring stations.

In addition, we determined the water quality rating at each monitoring station based on the lowest water parameter ratings. The water quality ratings within the I, II, and III classes were considered to comply with the SWEQS. Additionally, the results revealed 138 pieces of data with poor water quality, accounting for 16.31% of the total. The annual proportion of substandard water quality parameter i in city k from all monitoring stations is defined in this study as the substandard water quality rate of city k for the year considered, using the following formula:

$$P_{k,i}=\frac{A_{k,i}}{N_k} \tag{1}$$

where $P_{k,i}$ denotes the annual substandard rate of indicator i in city k, $A_{k,i}$ denotes the total number of monitoring stations with substandard water quality parameter i among all monitoring stations in city k for the considered year, and N_k denotes the total number of monitoring stations with effective data in the river basin of city k.

Average water values from other cities within the same province were used to fill in the missing values due to the lack of water parameter monitoring data from some cities in the basin.

2.1.3. City attribute data

In this study, we identified several factors reflecting the effectiveness of water measures and regulations in cities across the Yellow River Basin based on previous studies. Based on the data acquisition's reliability and the data cleaning and premodeling analysis results, a total of 25 indicators were selected. After the data cleaning and premodeling analysis, we constructed an evaluation index system to evaluate the effectiveness of the prevailing water resource utilization and treatment measures. The urban-related data were obtained from several sources: the China Urban Construction Statistical Yearbook, the China Urban Statistical Yearbook, the Water Resources Bulletin of the Yellow River Basin Provinces, and the Statistical Bulletin of National Economic and Social Development of Municipalities. All non-percentage data were adjusted according to the surface areas of the cities from which the data were collected. The data collection period spanned from 2020 to 2022.

2.2. Methods

2.2.1. Policy modeling consistency index

The PMC index is a quantitative policy evaluation method used to comprehensively evaluate policy texts. Specifically, the PMC index can be calculated to evaluate the perfection of each policy type, thus providing relevant optimization suggestions. Although numerous water management-related policies have been issued in the nine provinces as part of the 14th Five-Year Plan period, few comprehensive programs are still implemented for the Yellow River Basin. Therefore, the implemented "14th Five-Year Plan" water-related policies in the nine provinces in the basin were considered representative policies in this study to facilitate the evaluation of policy effectiveness. In particular, 34 water-related policies related to the 14th Five-Year Plan, including nine provincial and 25 municipal plans, comprised the policy text database (Supplementary Material Table S1). The nine provincial policies used for the PMC policy refinement evaluation are reported in Table 1.

In this study, a PMC index was proposed to assess the completeness of water-related policies in the Yellow River Basin over the 14th Five-Year Plan period based on previous research on environmental policy evaluations and the text mining results obtained using the Rost CM6.0 toolkit [19–23]. The framework comprised ten primary indicators (X_1–X_{10}) and 93 secondary indicators (Supplementary Material Table S2).

The calculation of the PMC index consisted of four steps [24,25]: (1) preparing a multi-input–output table (Supplementary Material Table S3); (2) assigning values to the variables based on the text mining results using equations (2) and (3) (each secondary indicator was within the [0,1] distribution range, following the scoring method reported in Supplementary Material Table S2); (3) calculating the primary indicator values of each policy using equation (4); and (4) summing up the obtained primary indicator values of each policy to determine the PMC index using equation (5) [23]. Equations (2)–(5) are expressed as follows:

$$X \sim N[0,1] \tag{2}$$

$$X=\{XR:[0-1]\} \tag{3}$$

$$X_i\left(\sum_{j=1}^{n}\frac{X_{i,j}}{T(X_{i,j})}\right) \tag{4}$$

$$PMC=\sum_{i=1}^{m}\left(X_i\left[\sum_{j=1}^{n}\frac{X_{i,j}}{T(X_{i,j})}\right]\right) \tag{5}$$

where X denotes a variable in the PMC framework; XR denotes the set of variables after the normalization process; i denotes the primary indicator; m represents the total number of primary indicators (i = 1, 2, 3, ⋯, m); j is the secondary indicator; n denotes the total number of secondary indicators associated with each primary indicator (j = 1, 2, 3, ⋯, n); and T represents the total number of secondary indicators.

To more intuitively present the PMC index, a 3 × 3 matrix was established in this study based on equation (6), including nine primary indicators from X_1 to X_9. Notably, X_{10} was not considered in the analysis because it was a non-differentiated indicator. The PMC surface was then plotted.

Table 1
Nine representative policies used to conduct the evaluation of policy refinement in the Yellow river basin.

Serial number	Policy name	Document number	Date issued
P_1	"14th Five-Year" Water Resources Development Plan of Gansu Province	No. 122 [2021] of Gansu Provincial Government Office	12-31-2021
P_2	"14th Five-Year Plan" Water Safety and Security and Water Ecological Environment Protection Plan of Henan Province	No. 42 [2021] of Henan Provincial Government	12-31-2021
P_3	"14th Five-Year Plan" for Water Safety and Security of Nei Mongol	No. 42 [2021] of Nei Mongol Provincial Government Office	09-08-2021
P_4	"14th Five-Year Plan" for Water Safety and Security of Ningxia	No. 82 [2021] of Ningxia Provincial Government Office	11-17-2021
P_5	"14th Five-Year Plan" for Water Safety and Security of QInghai Province	No. 99 [2021] of Qinghai Provincial Government Office	12-13-2021
P_6	"14th Five-Year" Water Resources Development Plan of Shandong Province	No. 157 [2021] of Shandong Provincial Government	09-06-2021
P_7	"14th Five-Year Plan" for Water Safety and Security of Shanxi Province	No. 34 [2021] of Shanxi Provincial Government	09-28-2021
P_8	"14th Five-Year" Water Resources Development Plan of Shaanxi Province	-	09-2021
P_9	"14th Five-Year Plan" for Water Security of Sichuan Province	No. 18 [2021] of Sichuan Provincial Government	08-30-2021

$$PMC-Surface=\begin{bmatrix} X_7 & X_4 & X_1 \\ X_8 & X_5 & X_2 \\ X_9 & X_6 & X_3 \end{bmatrix} \quad (6)$$

2.2.2. Determining the weight of criteria importance through inter-criteria correlation

The criteria importance through inter-criteria correlation (CRITIC) is an objective weight assignment method based on two fundamental, quantitative, multicriteria management concepts: comparison intensity (standard deviation) and conflicting evaluation criteria (correlation coefficient). The final weights were obtained by normalizing and multiplying the standard deviations with the correlation coefficients [26]. The CRITIC is suitable for analyzing datasets with repeatability between indicators, making it an appropriate method for the datasets used in the present study. In particular, this method was used to calculate the weights of the selected indicators in the assessment system and to evaluate the effectiveness of water management policies in the Yellow River Basin. Negative indicators representing unfavorable conditions were reversed using equation (7) before calculating the CRITIC-based weights. Equation (7) is expressed as follows:

$$x' = \frac{x - x_{\mathrm{Min}}}{x_{\mathrm{Max}} - x_{\mathrm{Min}}} \quad (7)$$

where x' denotes the reversed value of indicator x, and x_{Min} and x_{Max} denote the minimum and maximum values of indicator x, respectively.

Next, all data were normalized to eliminate the influence of dimensionality. After data preprocessing was conducted, the amount of information for each indicator was calculated using equation (8), while the final weight of each indicator was determined using equation (9) [26]. Equations (8) and (9) are expressed as follows:

$$C_j = \sigma_j \sum_{k=1}^{m} \left(1 - r_{j,k}\right) \quad (8)$$

$$w_j = \frac{C_j}{\sum_{k=1}^{m} C_k} \quad (9)$$

where C_j denotes the amount of information of the jth indicator; σ_j represents the mean difference of the jth indicator; $r_{j,k}$ is the correlation coefficient between the jth indicator and the kth indicator; and w_j denotes the final weight of the jth indicator ($j = 1, 2, 3, \ldots, m$).

2.2.3. Exploratory factor analysis

Exploratory factor analysis is a multivariate statistical analysis method commonly used to reduce the features of original variables with minimal loss of information, thereby providing highly interpretable factor variables. Assuming that there are p measured variables and m factors, as shown in equation (10), the common factor model for each measured variable represents the observed variable z_j (j = 1 to p), which refers to the sum of m independent cofactors (F_1, F_2, …, F_m) and a single variable u_j [27]. Based on the Kaiser−Meyer−Olkin (KMO) and Bartlett's measure results, the data used in this study met the EFA criteria (Table S4 and Table S5 in the Supplementary Materials).

$$z_j = a_{j1}F_1 + a_{j2}F_2 + \ldots\ldots + a_{j,m}F_m + u_j \quad (10)$$

2.2.4. XGBoost regression and SHapley additive exPlanations

The XGBoost model is a gradient-boosting-based ensemble learning method widely applied in environmental risk assessment (Woo et al., 2024) [28] and pollutant prediction (Chen et al., 2024a) [29]. The model iteratively builds decision trees to minimize prediction errors, and each new tree is optimized based on the residuals of the previous one. XGBoost employs regularization to prevent overfitting and enhance generalization, while parallel processing and pruning techniques improve computational efficiency and prediction accuracy [30]. In the present study, an XGBoost regression model was used to assess the positive impact of policy quantity on water management efficiency. Input features, including policy numbers, climate, industry, and economic indicators of the Yellow River Basin, were used to predict management efficiency scores and water quality for various cities. The detailed modeling process is provided in the supplementary materials (Supplementary Material Table S5).

However, despite its strong regression performance, XGBoost does not explain the interactions and complex nonlinear relationships between features. In recent literature, SHAP, an advanced tool based on Shapley values, has addressed this limitation. In particular, SHAP accounts for feature interactions and provides a more reliable estimate of feature importance by calculating the average marginal contribution of a feature across all possible combinations of other features [31]. As SHAP values indicate the importance of each feature, this allows for the selection of top-ranked features in each model and a more accurate assessment of the impact of policies on water management efficiency. All operations were performed in this study using the SHAP package in Python 3.7.

3. Results and discussion

3.1. Database of water management policies and regulations implemented in the Yellow River Basin

Policies and regulations implemented from 2018 to 2022 in nine provinces and 64 cities within the Yellow River Basin were analyzed. Four cities were excluded due to incomplete public disclosure, resulting in missing data. After performing data cleaning and removing the policies with limited information (e.g., personnel appointments), the regulations were screened using water-related keywords (e.g., "water," "river/lake," and "watershed"). This process resulted in selecting 253 and 887 provincial and municipal water policies, respectively, along with the corresponding 65 and 66 regulations. The policies and regulations were then categorized into seven groups based on their purposes, including water resource utilization, water environment management, and Yellow River planning. Relevant keywords were assigned to each policy/regulation; some policies involved multiple keywords. Table 2 presents the classification criteria for each category and the corresponding results.

The analysis revealed that more attention was directed toward water resource utilization in alignment with current water management challenges in the Yellow River Basin. Specifically, 63.2% of provincial and 46.59% of municipal policies focused on water resource utilization. However, only a small fraction (4.72% and 5.35% provincial and municipal policies, respectively) was dedicated to direct Yellow River management, thus highlighting the need for more targeted policies in this area.

The descriptive statistics of water-related policies/regulations in each category for cities across the Yellow River Basin are shown in Fig. 2. While provincial policies covered broader aspects, the implementation of sponge city and black/malodorous water treatment plans was done primarily at the municipal level. This difference may be since provincial governments incorporate these plans into higher-level policy frameworks rather than issue independent policies. In particular, provincial capital cities demonstrated more active policymaking, with an average of 28 policies compared to 17.2 policies in noncapital cities. Capital cities focused on water resource utilization (7.1 policies on average) and water treatment (8.8 policies). Tongchuan and Xi'an in Shaanxi and Jining in Shandong had the highest water resource utilization policies, while Jincheng in Shanxi led policies about water environment treatment.

The current study also found that national model cities, particularly those designated for water-saving initiatives, were more effective in their policy implementation efforts. Among the 15 national water-saving cities, 12 (80%) introduced relevant policies. However, policies related to recycled water remain underdeveloped, with only 25% of model cities effectively adopting such measures. Thus, further efforts are needed to promote recycled water utilization as a key strategy for efficient water resource use.

Furthermore, policy keyword analysis (Fig. 3) revealed that the most frequent theme in water resource utilization was water saving (21.89%), followed by water supply (13.68%). In comparison, policies on nonconventional water sources, such as recycled water, accounted for only 1.49%. Previous studies support this perspective. For example, Hastie et al. [32] concluded that inadequate recycled water policies can hinder technological advancements in water reuse. Similarly, Li et al. [33] emphasized the need to optimize China's policies related to water recycling to establish a more comprehensive water policy framework. In water environment treatment, the dominant focus was pollution prevention (17.63%), with significantly less emphasis on advanced measures, such as rainwater and sewage diversion (only 2.5%). Additionally, current policies lack focus on advanced water treatment technologies. As Yu et al. [34] noted, although the emphasis on water resource policies in the Yellow River Basin has positively impacted water quality, further policy enhancements, particularly in sewage treatment technologies, are necessary to maintain a healthier water environment in the basin.

In summary, while the policy database constructed in the current study indicates comprehensive efforts across various themes, current policies are skewed toward water saving and supply management, neglecting unconventional water resources and advanced treatment measures. Therefore, more targeted policies must be implemented in recycled water utilization and innovative management techniques to ensure effective water resource management in the Yellow River Basin.

3.2. Perfection of representative policies in the Yellow River Basin

In this study, we selected representative policies from the constructed water-related policy and regulation database of the provinces and cities in the Yellow River Basin, including nine provincial-level policies related to the 14th Five-Year Plan. The selected policies and regulations were evaluated for perfection using the PMC index. The evaluation results revealed the high overall perfection of the nine policies. Policies with PMC scores of $\geq$9, 9−8.5, and 8.5−8 were classified as excellent, great, and good, respectively. In particular, Henan, Nei Mongol, and Qinghai exhibited excellent policies/regulations. Meanwhile, policies/regulations in Ningxia, Shanxi, Sichuan, and Gansu were classified as great, while policies/regulations in Shandong and Shanxi were classified as good (Table 3).

Provinces in the Yellow River Basin place greater emphasis on water resource management, indicating that policy guidelines generally align with the region's actual water scarcity conditions. Specifically, lower scores primarily result from inadequate attention to water environment management, signaling a need for improvement, particularly in water ecological protection and wastewater treatment systems. Several studies support this view. For instance, Chi et al. [3] highlighted the necessity for enhanced water ecological management, comprehensive water pollution control in the Yellow River Basin, and the adoption of new technologies. Among provinces rated as "excellent" in policy performance, Qinghai reported having no substandard water quality between 2020 and 2022, while Henan's rate was only 8.57%. However, in provinces rated as "good," Shanxi and Shandong demonstrated considerable room for further water quality improvement, with Shanxi having the highest substandard water quality rate at 32.68%. These findings suggest that well-formulated and rational policies may positively impact water quality—a finding supported by past research [15,35]. Despite having an "excellent" policy rating, Nei Mongol has a relatively high substandard water quality rate of 21.28%. Zhang et al. [36] also observed Nei Mongol's unique challenges in sustainable development, attributing them to the region's industrial structure. Thus, their findings suggest that policies should be tailored specifically to the region's distinct industrial characteristics.

Furthermore, a detailed analysis of the PMC framework can provide specific recommendations for policy optimization. For example, Sichuan's low score in water resource management can mainly be attributed to its insufficient consideration of water source conservation and recycled water/nonconventional water utilization. Gansu's lower scores are due to its relatively weak policies/regulations on aquatic ecosystem protection/restoration, sewage collection and treatment, and outfall management. Thus, its future policy development should focus on these areas. Fig. 4 provides a visual presentation of the PMC surface results for managers in the study area (see Fig. 5).

Table 2
Part of the categorize criteria and the results of water management policies in the Yellow River Basin.

Policy category	Evaluation criteria	Total number of eligible provincial policies/ regulations	Total number of eligible municipal policies/ regulations
Yellow River Management Plan	The title contains the keyword "Yellow River", and the policy is about management of the Yellow River.	15 (13 policies, 2 regulations)	54 (51 policies, 3 regulations)
water resource utilization	The content involves water abstraction, water supply, water use, water saving, drinking water sources, reservoir construction and management, and recycled water utilization, etc.	201 (158 policies, 43 regulations)	444 (402 policies, 42 regulations)
Water Environment Treatment	The content involves water pollution prevention and control, soil and water conservation, water ecology management, drainage, sewage treatment, aquaculture management, water quality management, river management, etc.	137 (113 policies, 24 regulations)	500 (465 policies, 35 regulations)
Sponge City Plan	The title contains the keyword "sponge city", and the content is about the construction and management of sponge city.	0	24 (23 policies, 1 regulations)
Black, Malodorous Water Bodies Treatment Plan	The title contains the keyword "black, malodorous water", and the content is about treatment of black, malodorous water bodies.	0	18 (18 policies)
Water Saving Plan	The title contains the keyword "water saving" or similar keywords, and the content is about water saving.	9 (5 policies, 4 regulations)	89 (88 policies, 1 regulations)
Recycled Water Utilization Plan	The title contains keywords such as "reclaimed water", "recyled water", etc., and the content is about utilization or reclaimed water.	1 (1 policy)	10 (8 policies, 2 regulations)

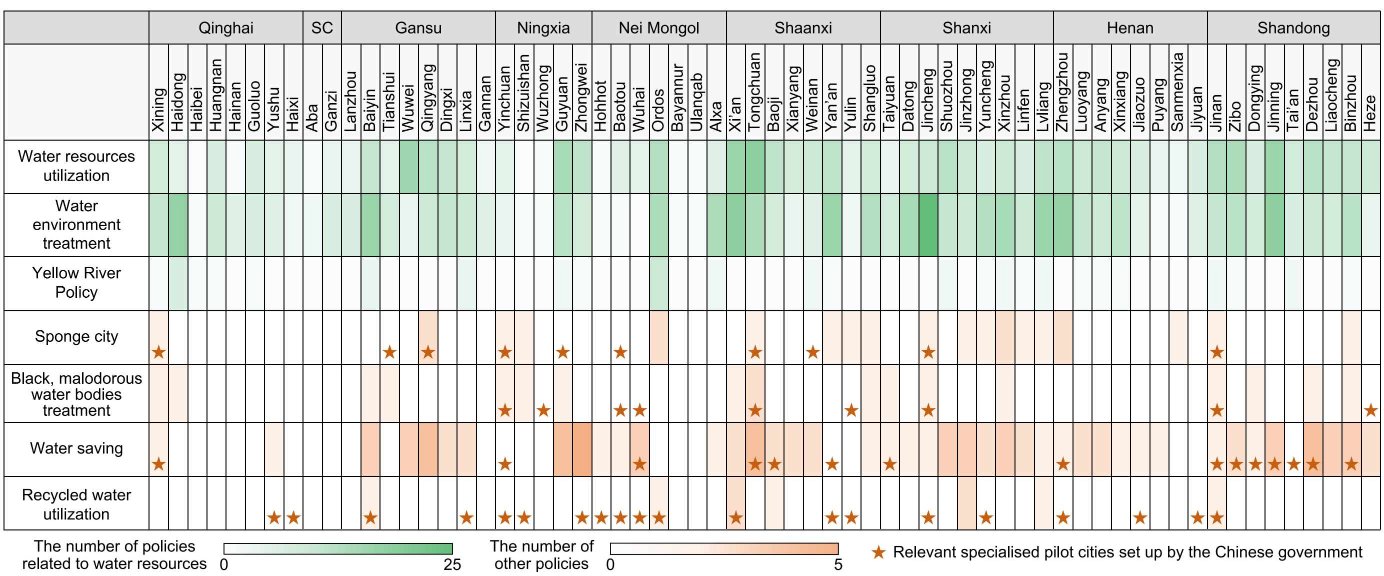

Fig. 3. Heatmap of policies or regulations issued by cities in the Yellow River Basin. The shades of green represent the number of policies related to water resources, water environment, and Yellow River-specific plans, while the shades of orange indicate the number of other policies. Stars mark cities designated as national demonstration sites for relevant policies.

Table 3
PMC evaluation results of nine representative "14th Five-Year Plan" water policies in Yellow River Basin Provinces.

Primary variable	P_1 Gansu	P_2 Henan	P_3 Nei Mongol	P_4 Qinghai	P_5 Shandong	P_6 Shanxi	P_7 Ningxia	P_8 Shaanxi	P_9 Sichuan
X_1 (Policy type)	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
X_2 (Policy time)	0.6667	1.0000	1.0000	1.0000	1.0000	0.6667	0.6667	1.0000	1.0000
X_3 (Policy geography)	0.8571	0.7143	1.0000	0.5714	0.5714	0.7143	0.7143	0.8571	0.7143
X_4 (Policy evaluation)	1.0000	1.0000	1.0000	1.0000	0.8333	0.8333	1.0000	0.8333	1.0000
X_5 (Policy guarantee)	1.0000	1.0000	1.0000	1.0000	0.8889	0.8889	1.0000	0.7778	0.8889
X_6 (Water resources utilization)	0.9583	0.9583	0.9583	0.9583	0.9583	0.9583	0.8750	0.9167	0.7500
X_7 (Water environment treatment)	0.3636	1.0000	0.7273	0.5455	0.2727	0.5000	0.6364	0.5455	0.5000
X_8 (Water security management)	0.8333	1.0000	0.8333	1.0000	0.8333	0.8333	0.8333	0.8333	0.8333
X_9 (Management support)	1.0000	1.0000	1.0000	1.0000	0.8182	1.0000	0.8182	0.9091	0.8182
PMC	8.6791	9.6726	9.5189	9.0752	8.1762	8.3948	8.5438	8.6728	8.5047
Rank	Great	Excellent	Excellent	Excellent	Good	Good	Great	Great	Great

3.3. Evaluating the effectiveness of water resource utilization and water environment treatment management in cities within the Yellow River Basin

After constructing the water-related policy/regulation database of the cities in the Yellow River Basin and evaluating the perfection of the representative policies, we further evaluated the management effectiveness of the current policies in the basin. To facilitate this evaluation, the results of this study's management effectiveness were visualized, thus providing useful policy formulation references to the basin managers.

In this study, we constructed a system for evaluating the effectiveness of water resource utilization and treatment management in the Yellow River Basin. The proposed evaluation system was classified into two major subsystems related to water resource utilization and treatment, considering 24 indicators that intuitively reflected the current management effectiveness in the basin (Table 4). On the one hand, the water resource utilization system included ten indicators of water supply, water use, and water resource status. On the other hand, the water environment treatment system included 14 indicators of water quality, drainage, and sewage treatment. The indicator weights were calculated based on the influences of the positivity and negativity of the indicators. Before calculating the weights of the 24 indicators using the CRITIC method, we first positively oriented the indicators with negative correlations with the health status of water systems (e.g., substandard water quality rates). The total score was 100, including 38.2 and 61.8 for water resource utilization and treatment systems, respectively.

From 2020 to 2022, the average total scores of cities in the Yellow River Basin increased from 51.9 to 54.9, with a three-year average of 53.6 (Figs. 6 and 7a). In particular, the water resource utilization system scored 15.0, 16.0, and 15.0, respectively (average: 15.3) (Figs. 6 and 7b), while the water environment treatment system scored 36.8, 38.1, and 39.9, respectively (average: 38.3) (Fig. 7c). These results indicate that while the overall scores of most cities improved from 2020 to 2022, the scores for some cities in the area of water resource utilization system declined, thus reducing the overall average. The average water resource utilization system score was below 50% of the full score, which was lower than that of the water environment management system. Therefore, this finding implies that more efforts are needed to improve water resource efficiency in the Yellow River Basin.

Next, we calculated the scores for cities in the basin's upstream, midstream, and downstream regions (Supplementary Materials Table S4). The findings revealed that, over three years, the downstream scores were consistently higher than those of the midstream and upstream regions for the total scores and the two subsystems. In comparison, the lower-scoring cities were mainly located in the midstream and downstream areas (Fig. 7), thus demonstrating a clear spatial disparity. Furthermore, many high-scoring cities implemented numerous water-related policies between 2018 and 2022. These cities include Zhengzhou (Henan Province), with 29 policies, Shangluo (Shaanxi Province), with 24 policies, and Xi'an (Shaanxi Province), with 22 policies.

In the next step, Pearson correlation analysis was performed between the annual governance scores (2020–2022) and the number of related policies (Table 5). This was done to further evaluate the impact of water management policies on governance effectiveness in the Yellow River Basin. The results showed a significant positive correlation between the total number of water-related policies and overall management effectiveness and subsystem scores, particularly for policies implemented in the current year and those from the preceding 1–2 years. This finding suggests that these policies may positively impact the overall water environment, even though some policies have a delayed effect. Meanwhile, we found a significant positive correlation between the number of water environment-related policies implemented in the current year and the preceding 1–2 years and the overall management effectiveness score. Such policies in the current and preceding years were also positively correlated with the water environment management score, while those lagging by 1–2 years correlated with the water resource system score. This finding suggests that, although some policies exhibit a lag of one or two years, water environment policies generally enhance overall management efficiency, water environment management, and water resource utilization. Conversely, water resource utilization policies lagging by two years showed a positive correlation with the water resource utilization score but not with the total or water environment management scores, thus indicating a delayed and weaker

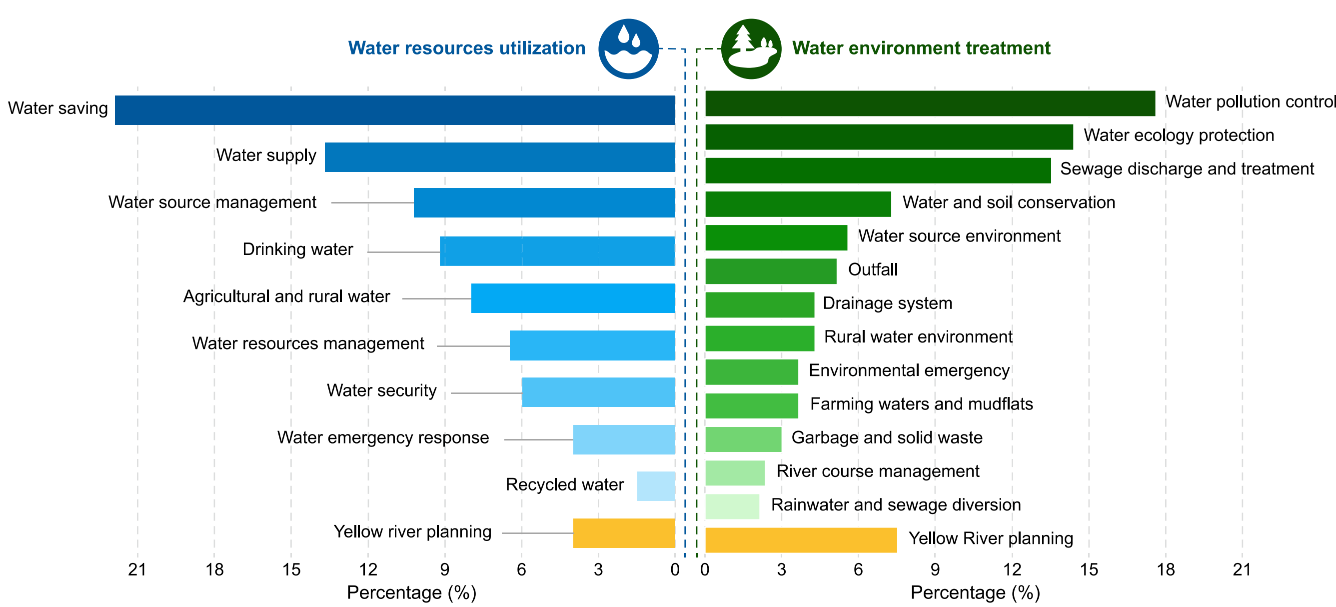

Fig. 4. High-frequency topics of policies or regulations related to water resource utilization and water environment treatment in cities across the Yellow River Basin.

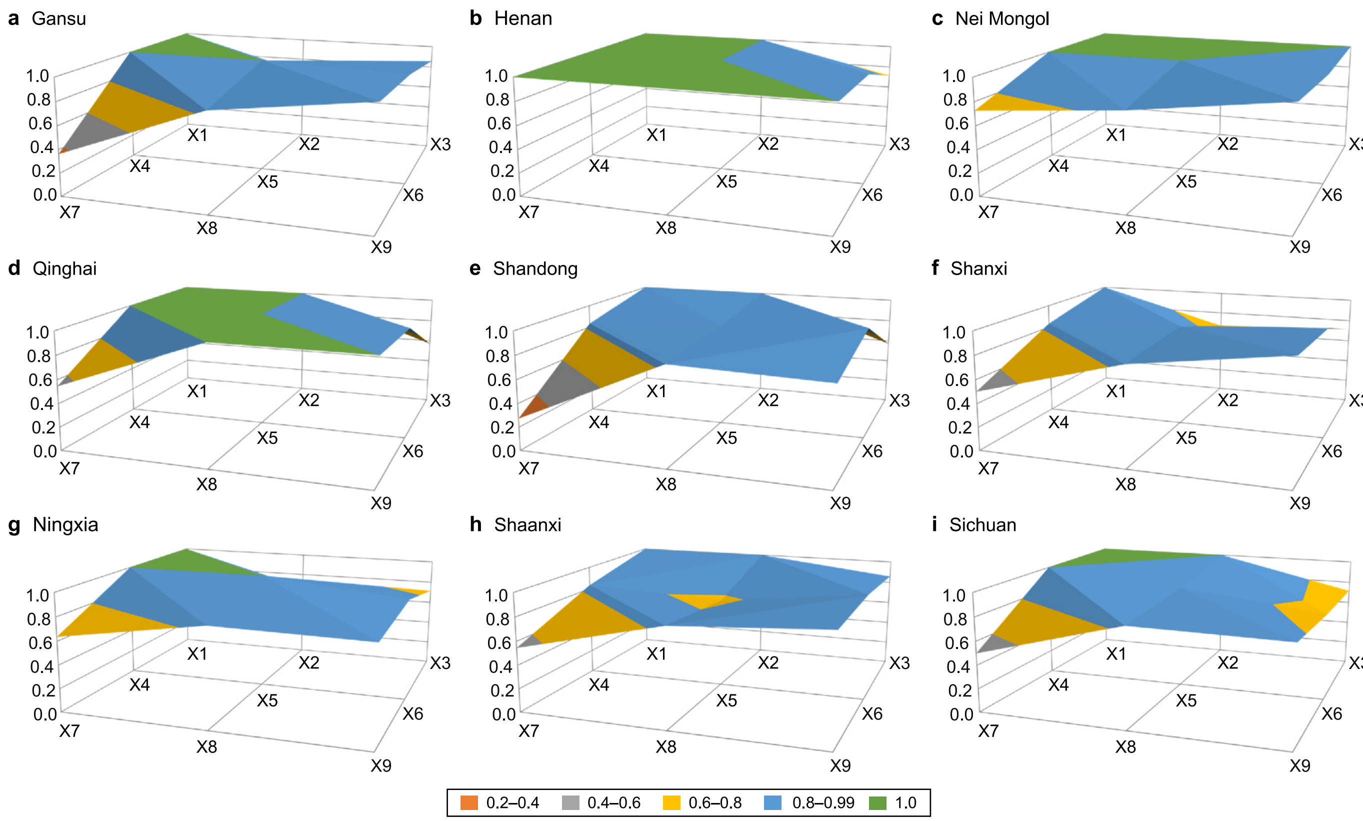

Fig. 5. Policy modeling consistency (PMC) Surfaces of the nine "14th Five-Year Plan" water-related policies from provinces across the Yellow River Basin. The horizontal plane represents nine effective primary policy effectiveness indicators, labeled as X1–X9, while the vertical axis indicates the PMC index values: **a**, Gansu; **b**, Henan; **c**, Nei Mongol; **d**, Qinghai; **e**, Shandong; **f**, Shanxi; **g**, Ningxia; **h**, Shaanxi; **i**, Sichuan.

Table 4
Evaluation indicators for urban management benefits in the yellow river basin.

System	Indicator name (unit)	Positive (+)/negative (−)	Weight
Water resources utilization	Water production modulus (10000 m^3 km^{-2})	+	4.90 %
	Water resources per capita (m^3 $person^{-1}$)	+	2.82 %
	Water consumption per RMB 10000 of GDP (m^3)	−	4.15 %
	Daily water consumption per capita (L)	−	4.67 %
	Percentage of water leakage (%)	−	4.62 %
	Water supply penetration rate (%)	+	3.81 %
	Density of water supply pipelines in built-up areas (km km^{-2})	+	3.39 %
	Municipal recycled water production capacity per unit area (m^3 km^{-2} d^{-1})	+	3.30 %
	Municipal recycled water consumption per unit area (m^3 km^{-2} d^{-1})	+	2.91 %
	Investment in water supply per unit area (RMB km^{-2})	+	3.62 %
Water environment Treatment	Substandard rate of water quality standard (%)	−	4.40 %
	Substandard rate of permanganate index (%)	−	4.13 %
	Substandard rate of COD (%)	−	4.23 %
	Substandard rate of BOD (%)	−	3.58 %
	Substandard rate of ammonia nitrogen (%)	−	4.81 %
	Substandard rate of total phosphorus (%)	−	4.18 %
	Percentage of production water (%)	−	5.12 %
	Density of drainage pipes in built-up areas (km km^{-2})	+	4.35 %
	Sewage discharge per RMB 10000 of GDP (m^3)	−	5.35 %
	Sewage treatment rate (%)	+	3.86 %
	Ratio of rainwater pipe length to drainage pipe length (%)	+	5.35 %
	Average sewage treatment capacity of a single sewage treatment plant (10000 m^3 d^{-1})	+	3.67 %
	Drainage investment per unit area (RMB km^{-2})	+	4.27 %
	Sewage treatment investment per unit area (RMB km^{-2})	+	4.53 %

effect.

We also assessed the correlation between water quality and the number of relevant policies (Table 6). The results showed a significant negative correlation between the water quality exceedance rate and the number of water quality improvement policies in the current and previous years. This finding implies that an increase in the number of water quality-related policies may lead to improvements in water quality, albeit with a one-year lag for some

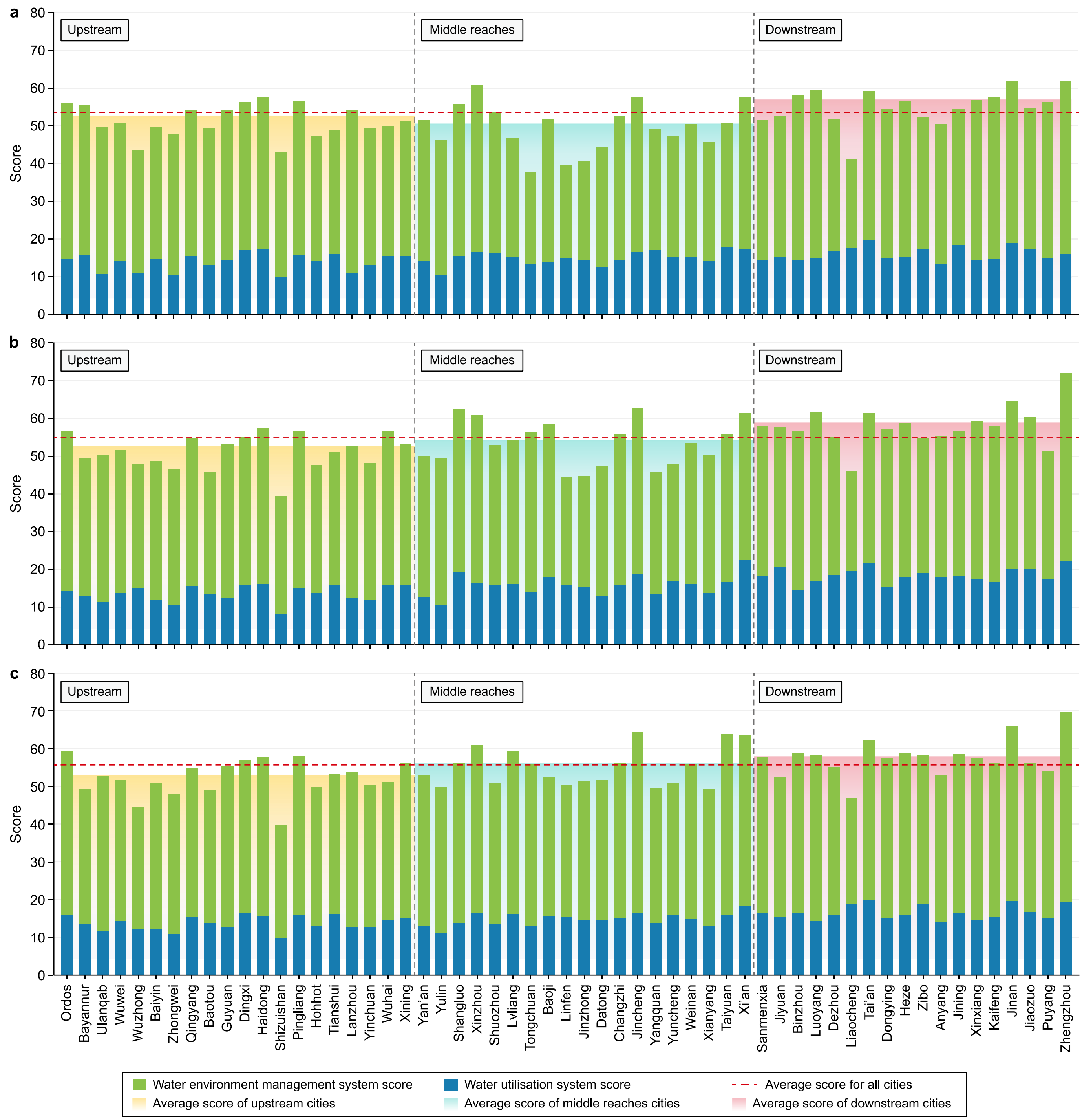

Fig. 6. Effectiveness evaluation of urban water resource utilization and water environment management in cities across the Yellow River Basin in 2020 (**a**), 2021 (**b**), and 2022 (**c**).

policies.

We comprehensively analyzed the factors affecting water management effectiveness to validate these conclusions. This was done by incorporating various indicators, including temperature, precipitation, population, economic activity, agriculture, and industry, into an XGBoost model (Table 7). In addition, SHAP was used to analyze the importance of the model's features. The detailed modeling process and parameter results are presented in the supplementary materials (Supplementary Material Table S5). The results demonstrated that water-related policies implemented in the current year and two years prior had the most significant impacts on overall management effectiveness, while water environment policies implemented 1–2 years prior also had a certain impact on it (Fig. 8a). This finding indicates that increasing the number of water-related policies and water environment treatment policies can enhance water management effectiveness in the Yellow River Basin, despite some policy delays.

The analysis also revealed a strong positive correlation between the gross domestic product (GDP) and the total score (Fig. 9a). The economy was also found to substantially impact the scores of the

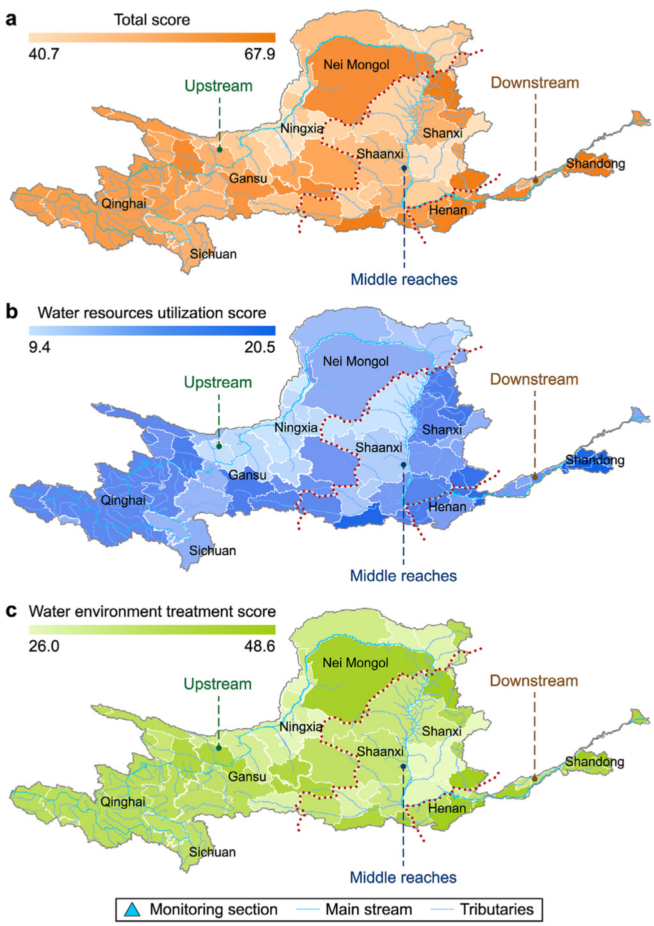

Fig. 7. Average scores on water management effectiveness of cities in the Yellow River Basin from 2020 to 2021, where darker colors represent higher scores. **a**, Total scores; **b**, Water resource utilization scores; **c**, Water environment treatment scores.

water environment management system (Fig. 8c) and water quality (Fig. 8d), with higher GDP levels positively influencing both aspects

Table 5
Pearson correlation between number of policies and scores.

Content of the indicators	Total score	Water resources utilization score	Water environment treatment score
Total number of policies (current year)	0.259[b]	0.190[a]	0.270[b]
Total number of policies (1 year's lag)	0.253[b]	0.221[b]	0.245[b]
Total number of policies (2 years' lag)	0.262[b]	0.283[b]	0.245[b]
Number of water resources policies (current year)	−0.047	0.156	−0.097
Number of water resources policies (1 year's lag)	0.059	0.160	0.037
Number of water resources policies (2 years' lag)	0.182	0.186[a]	0.100
Number of water environment policies (current year)	0.287[b]	0.140	0.303[b]
Number of water environment policies (1 year's lag)	0.264[b]	0.197[a]	0.247[b]
Number of water environment policies (2 years' lag)	0.209[a]	0.265[b]	0.157

[a] $p < 0.05$.
[b] $p < 0.01$.

(Fig. 9c and d). Previous studies have indicated that GDP significantly affects water environments in large river basins and is a key factor contributing to spatial differences [37]. This notion corresponds with our observations that downstream areas of the Yellow River Basin, which have stronger economic conditions, demonstrate better management effectiveness than midstream and upstream regions with weaker economies. Although some studies have suggested that economic growth negatively impacts water environments in regions like Kenya, Pakistan, and parts of China [38–40], other studies have reported a positive effect on the resources and the environment of the Yellow River Basin [37,41]. Based on the results of the current study, we find that economic development can positively contribute to improving the water environment, particularly through implementing appropriate water resource and environmental management policies. Such a strategy can lead to high-quality ecological and economic development in the Yellow River Basin. This finding may be because economically developed regions are generally better equipped to adopt advanced technologies or attract specialized talent for effective policy implementation than less economically developed regions. Studies by Cai et al. [42] and Zhao et al. [43] also confirm that economic development requires the regulatory role of government-initiated environmental policies toward an improved and more effective water management system.

Our analysis of the water resource utilization system further revealed that water-related policies lagging by two years had a considerable impact on the utilization score, while water resource utilization policies lagging by two years and water environment treatment policies lagging by a year had relatively weaker effects (Fig. 8b). Compared to the total score and the water environment management system, the impact of policies on the water resource utilization system was less pronounced, along with a more evident lag effect. Furthermore, the effectiveness of water resource management was significantly influenced by climate factors, such as temperature and precipitation, as confirmed by some studies [44–46]. Specifically, temperature changes can modify precipitation patterns, in which higher temperatures can potentially increase precipitation [47]. This phenomenon is beneficial for maintaining adequate water resources. Therefore, climate may be an important factor contributing to the spatial variation in water resource management effectiveness in the Yellow River Basin, as supported by the studies of Yang et al. [48] and Liu et al. [49]. However, our results show that enhancing water resources through policy implementation remains more viable due to the difficulty of controlling natural factors (e.g., climate in the short term).

Moreover, the proportion of the service industry also positively impacted water resource utilization (Fig. 9b), as it consumed less water compared to the more water-intensive primary and secondary industries [50]. The service industry also includes sectors such as water supply services, which directly benefit water resources. An analysis of the water environment treatment system revealed that water-related and water environment treatment policies implemented in the current and previous years also significantly improved the treatment score.

Apart from the previously mentioned economic factors,

Table 6
Pearson correlation between water quality and related policies.

Content of the indicators	Water quality exceedance rate
Number of water quality related policies (Current year)	−0.267[a]
Number of water quality related policies (1 year's lag)	−0.246[a]
Number of water quality related policies (2 years' lag)	−0.139

[a] $p < 0.05$.

Table 7
Comparison of the names and contents of indicators.

Code	Content of the indicators (unit)	Abbreviation
01	Annual precipitation (mm)	Precipitation
02	Average annual temperature (°C)	Temperature
03	Per capita gross domestic product (GDP; RMB)	GDP_Per_Capita
04	Ratio of agriculture to GDP (%)	Agriculture
05	Ratio of industry to GDP (%)	Industry
06	Ratio of service industry to GDP (%)	Service
07	Population density (people km^{-2})	Population_Density
08	Green space coverage in built-up areas (%)	Green_Coverage
09	Total number of policies (current year)	Policies_Current_Year
10	Total number of policies (1 year's lag)	Policies_1_Year_Lag
11	Total number of policies (2 years' lag)	Policies_2_Year_Lag
12	Number of water resources policies (current year)	WRU_Policies_Current_Year
13	Number of water resources policies (1 year's lag)	WRU_Policies_1_Year_Lag
14	Number of water resources policies (2 years' lag)	WRU_Policies_2_Year_Lag
15	Number of water environment policies (current year)	WET_Policies_Current_Year
16	Number of water environment policies (1 year's lag)	WET_Policies_1_Year_Lag
17	Number of water environment policies (2 years' lag)	WET_Policies_2_Year_Lag
18	Water quality exceedance rate (%)	Water_Quality_Exceedance_Rate
19	Number of water quality related policies (current year)	Relevant_Policies_Current_Year
20	Number of water quality related policies (1 year's lag)	Relevant_Policies_1_Year_Lag
21	Number of water quality related policies (2 years' lag)	Relevant_Policies_2_Year_Lag

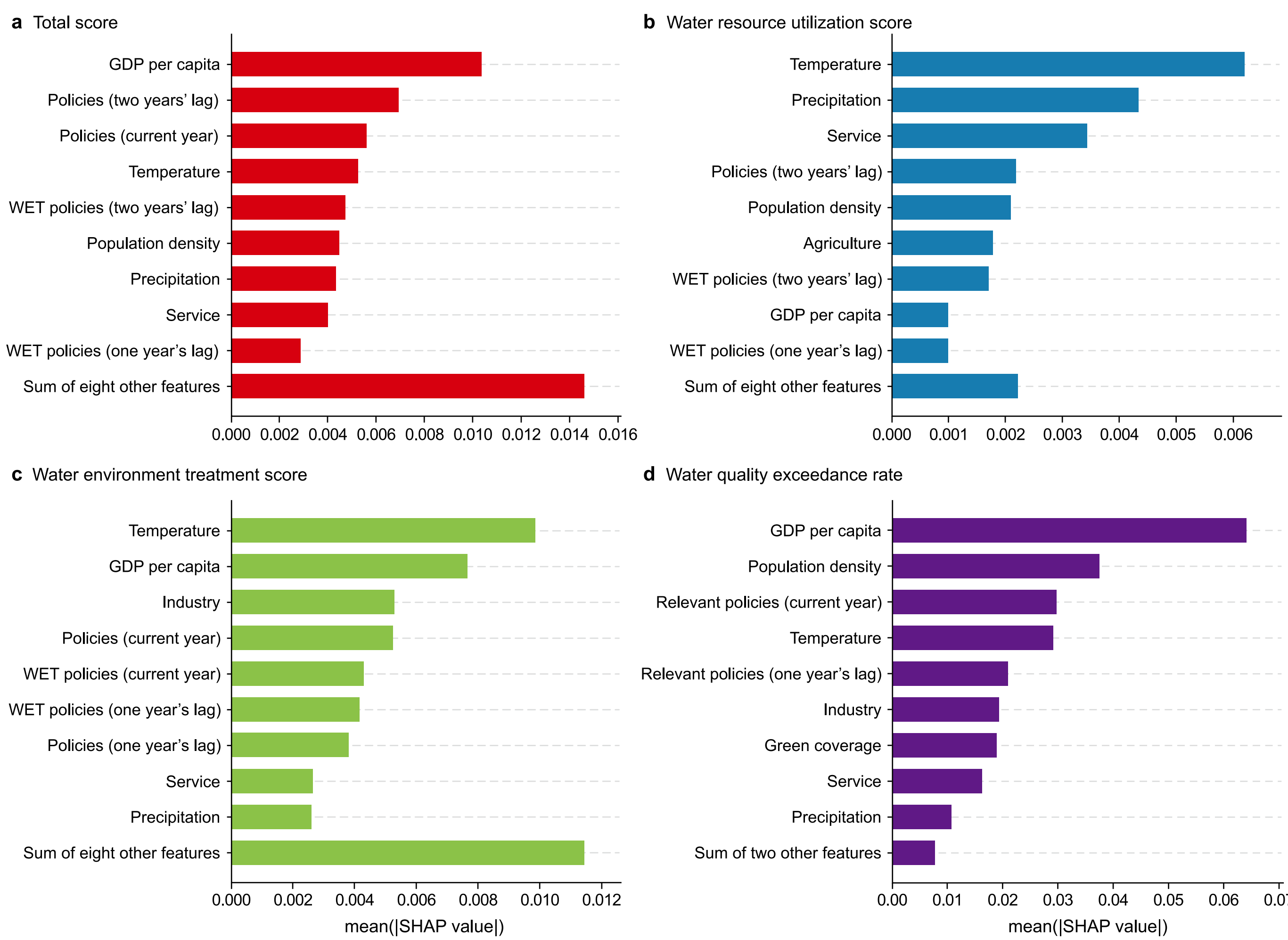

Fig. 8. Key features that significantly impact water management effectiveness and water quality in the Yellow River Basin identified by the XGBoost regression model. The figure displays the top ten ranked features with a strong influence on: **a**, total score; **b**, water resource utilization subsystem score; **c**, water environment governance subsystem; **d**, water quality exceedance rate. GDP, gross domestic product; WET, water environment treatment.

temperature and industrial proportion also strongly influence the water environment. For example, studies have shown that temperature affects surface water environments through various mechanisms, such as dissolved oxygen levels, nitrogen cycling, and aquatic life [51–53]. The present study suggests that policy regulation can mitigate the uncontrollable impacts of temperature

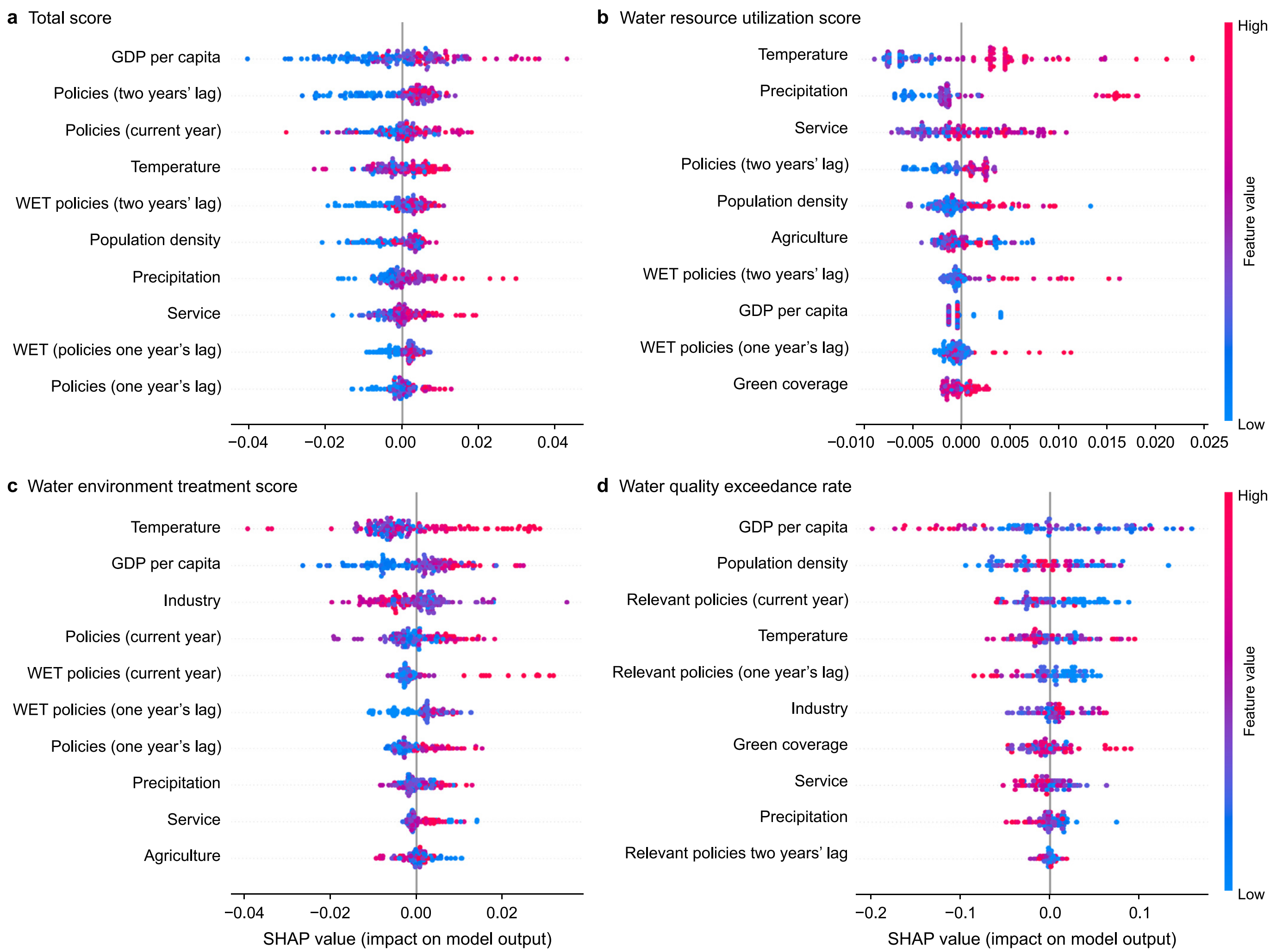

Fig. 9. Correlation between the top ten ranked features and: **a**, total score; **b**, water resource utilization subsystem score; **c**, water environment governance subsystem; **d**, water quality exceedance rate. Red represents higher driving factor values, while blue represents lower values. The *x*-axis origin indicates a positive impact on exceedance rates to the right and a negative impact to the left. Taking the gross domestic product (GDP) per capita as an example, in panel **a**, it is positively correlated with the total score, while in panel **d**, it is negatively correlated with water quality exceedance rates. WET, water environment treatment.

changes on the water environment. Based on the results, the proportion of industrial activities negatively impacts the water environment (Fig. 9c), as many sectors produce increased concentrations of pollutants, such as ammonia, nitrogen, and phosphorus, found in water bodies [54]. Therefore, implementing water management policies to regulate industrial activities is essential. Notably, the modeling results for water quality indicated that increased population density had a considerable impact on water quality improvement (Fig. 8d). However, no clear positive or negative correlation was observed (Fig. 9d). This phenomenon is possibly due to the complex interplay of human activities affecting water quality [55].

Furthermore, the observed policy lags in this study are reasonable. Indeed, effective policy implementation at the watershed scale requires extended periods due to the numerous management units involved. At the same time, water quality improvement is a long-term process—a notion consistently reported in previous studies. For example, Melland et al. [56] highlighted a one-to ten-year lag in water quality improvement from agricultural management practices, depending on the catchment area size. Wang et al. [17] found a nearly one-year lag in policy effects on the Yangtze River Basin, while Ren et al. [57] identified a three-year delay in the impact of the Energy Saving and Emission Reduction (ESSR) policy on carbon emissions in the Yellow River Basin.

In contrast, our results revealed that the positive effects of water environment treatment policies on watershed management were more pronounced and occurred earlier than those of water resource utilization policies. This difference may be related to changes in water use during the COVID-19 pandemic, which began in late 2019. Gu et al. [58] reported that, during that time, household water footprints in 15 Chinese provinces recovered to or exceeded historical levels, highlighting the negative impact of the COVID-19 pandemic on the country's water conservation. Similar trends were observed globally, including increased water consumption levels in Saudi Arabia, Germany, Indonesia, and other countries [59–61]. The results of the current study revealed that per capita daily water consumption rates increased in 54.39% and 77.19% of cities in the Yellow River Basin during the 2019–2020 and 2020–2021 periods, respectively. These increases likely resulted from changes in daily habits, such as more frequent handwashing, disinfection, and remote work, which may have reduced the effectiveness of certain water resource utilization policies.

This study demonstrates that implementing more policies can positively enhance water management in large river basins. Although policies were not the only factors influencing management effectiveness, they could help balance economic growth and environmental improvement while mitigating the impacts of uncontrollable factors, such as climate. Furthermore, we found that some policies exhibit a lag effect. In particular, the weaker and slower effects of water resource policies compared to those of water environment policies may be due to the impact of the COVID-19 pandemic.

3.4. Identification of key water management issues in cities within the Yellow River Basin

After evaluating the management effectiveness of urban water resource utilization and treatment policies in the Yellow River Basin, it is necessary to further determine the main causes of the low scores attributed to the selected cities in this study. Doing so can lead to information that can provide accurate policy optimization references to the basin managers. EFA was performed in this study to identify the key urban management issues causing the low attributed subsystem scores (<50%) to the cities.

Based on the EFA results, 66.6% of the variance related to water resource utilization can be explained by the first four factors. Therefore, four key water resource utilization-related issues were screened (Table 8). Factor 1, related to recycled water inputs, indicated high loadings on production capacity and consumption of municipal recycled water. Factor 2 had high loadings on water use per RMB 10,000 of GDP, daily water consumption per capita, and percentage of water leakage. Therefore, this factor was related to water use efficiency. Factor 3, related to natural water resources, indicated high loadings on water production and annual precipitation. Factor 4, related to the water supply system, had high loadings on the density of water supply pipelines in built-up areas and the water supply penetration rate.

At the same time, the first five EFA factors explained 78.0% of the water treatment variance. Therefore, five key issues were screened in this study (Table 9). Factor 1, associated with water quality and organic pollution, showed high loadings on the substandard water quality rates, permanganate index, COD, and BOD. Factor 2, associated with municipal inputs, indicated high loadings on drainage and sewage treatment investments. Factor 3 had high loadings on the substandard ammonia nitrogen and total phosphorus rates associated with nitrogen and phosphorus pollution. Factor 4, associated with pipeline networks, revealed high loadings on the drainage pipe densities in the built-up areas and the ratio of rainwater pipe length to drainage pipe length. Factor 5, related to sewage treatment capacity, showed high loading on sewage

Table 8
Results of EFA of water resource utilization system.

Code	EFA			
	Grouping 1	Grouping 2	Grouping 3	Grouping 4
Grouping 1: Recycled water production and utilization				
Municipal recycled water production capacity per unit area	0.882	-	-	-
Municipal recycled water consumption per unit area	0.915	-	-	-
Grouping 2: Water use efficiency				
Water consumption per RMB 10000 of GDP	-	0.689	-	-
Daily water consumption per capita	-	−0.725	-	-
Percentage of water leakage	-	0.678	-	-
Grouping 3: Natural water resources				
Water production modulus	-	-	0.777	-
Annual precipitation	-	-	0.820	-
Grouping 4: Water supply system				
Density of water supply pipelines in built-up areas	-	-	-	0.772
Water supply penetration rate	-	-	-	0.633
Eigenvalue	2.368	1.684	1.412	1.197
Variance (%)	23.681	16.840	14.120	11.968
Cumulative variance (%)	23.681	40.520	54.640	66.608

Table 9
Results of EFA of water environment treatment system.

Code	EFA				
	Grouping 1	Grouping 2	Grouping 3	Grouping 4	Grouping 5
Grouping 1: Water quality and organic pollution					
Substandard rate of water quality standard	0.872	-	-	-	-
Substandard rate of permanganate index	0.912	-	-	-	-
Substandard rate of cod	0.912	-	-	-	-
Substandard rate of bod	0.895	-	-	-	-
Grouping 2: Municipal input					
Drainage investment per unit area	-	0.883	-	-	-
Sewage treatment investment per unit area	-	0.909	-	-	-
Grouping 3: Nitrogen and phosphorus pollution					
Substandard rate of ammonia nitrogen	-	-	0.840	-	-
Substandard rate of total phosphorus	-	-	0.856	-	-
Grouping 4: Pipeline network perfection					
Density of drainage pipes in built-up areas	-	-	-	0.848	-
Ratio of rainwater pipe length to drainage pipe length	-	-	-	0.692	-
Grouping 5: Sewage treatment capacity					
Sewage treatment rate	-	-	-	-	0.844
Average sewage treatment capacity of a single sewage treatment plant	-	-	-	-	0.551
Eigenvalue	3.705	2.230	2.072	1.676	1.232
Variance (%)	26.461	15.929	14.803	11.973	8.797
Cumulative variance (%)	26.461	42.390	57.194	69.167	77.963

treatment rates and average sewage treatment plant capacities.

The final risk scoring system for the key issues was determined by selecting indicators with higher loadings from each factor and calculating the scores for each factor based on the attributed indicator weights in the management effectiveness evaluation system. In addition, the cities were classified into five quintiles according to their rankings, reflecting their risk levels. The lower and upper quantiles were assigned ratings of 5 and 1, respectively.

The key issues in urban water management within the Yellow River Basin were visually represented using a radar chart of typical cities' risk levels. The radar chart displays risk factor ratings for 2020 and 2022 to accurately illustrate changes over time. The risk ratings revealed that the key issues with higher frequencies of high-risk levels (4 and 5) in upstream cities were natural water resources (70%), recycled water production and utilization (65%), municipal input (58.33%), and pipeline network perfection (58.33%), with Qingyang City (Gansu Province) serving as the main example (Fig. 10a and b). Among midstream cities, high-risk factors typically included sewage treatment capacity (50.88%), water supply system (49.12%), recycled water production and utilization (47.37%), and pipeline network perfection (47.37%), with Yulin City (Shaanxi Province) serving as a representative (Fig. 10c and d). The results showed that downstream cities were more prone to high risks in water-use efficiency (46.3%) and overall water quality and organic pollution (42.59%), as illustrated by Anyang City in Henan Province (Fig. 10e and f). These findings align with those of other studies [62], which identified natural water resource shortages in the Yellow River Basin and highlighted the need to improve reclaimed water use, pipeline infrastructure, water supply capacity, and sewage treatment capabilities.

We propose the policy recommendations below based on the key issues identified above.

For the water resource utilization system.

(1) Recycled water production and utilization. Cities facing issues with recycled water should focus on enhancing the relevant infrastructure and technologies to improve the efficiency of their recycled water production systems. Local governments can introduce subsidies and tax benefits to encourage industrial and agricultural users to adopt recycled water for nonpotable purposes [63]. Public awareness campaigns are also necessary to increase their acceptance of recycled water.
(2) Water use efficiency. Cities with low water use efficiency should promote water-saving technologies through policies and provide financial incentives to encourage residential, commercial, and industrial users to install such equipment. Local governments could also implement a tiered water pricing system to encourage conservation, with higher costs assigned for heavy users. Furthermore, public education on water conservation must be strengthened.
(3) Natural water resources. Especially in water-scarce areas, comprehensive water resource management plans should be developed, along with emergency response strategies, based on seasonal supply and demand changes. Furthermore, legal measures should be introduced to protect water sources and promote water conservation. At the same time, regional water resource sharing and allocation mechanisms should be established [64], along with rainwater harvesting and unconventional water use, to alleviate pressure on natural resources.
(4) Water supply system. Cities with inadequate water supply should focus on upgrading and expanding their old water networks to increase coverage and supply rates. Advanced technologies, such as internet of things (IoT) and geographic information system (GIS), should be used to implement smart water management systems.

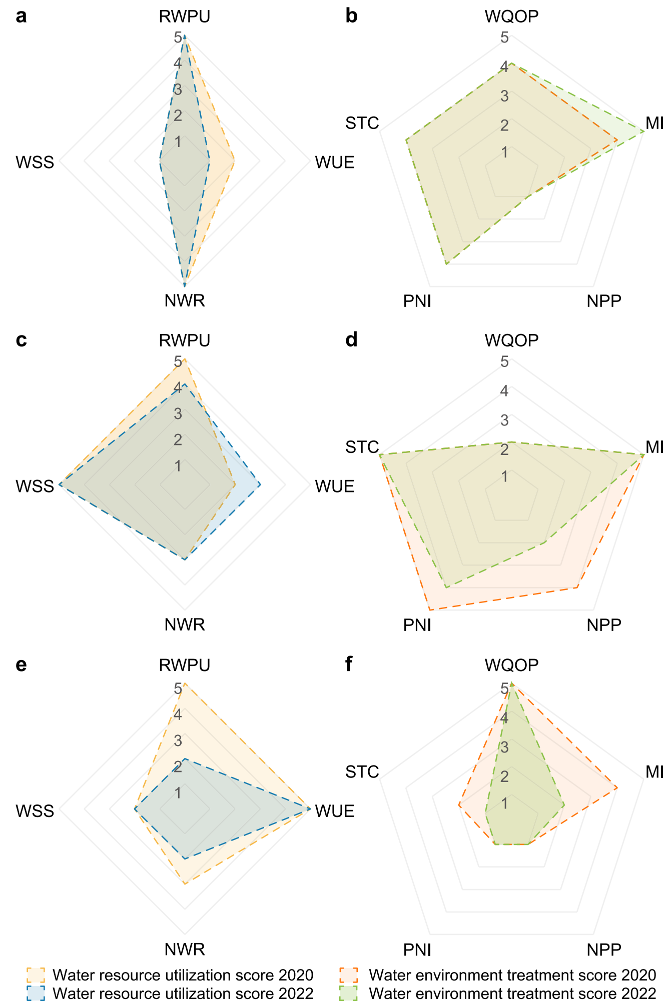

Fig. 10. Risk factor ratings for representative cities in the Yellow River Basin's upper, middle, and lower reaches on key water management issues in 2020 and 2022. The water resource utilization (**a**, **c**, **e**) and water environment treatment risks (**b**, **d**, **f**) for Qingyang (**a**, **b**), Yulin (**c**, **d**), and Anyang (**e**, **f**). RWPU, recycled water production and utilization; WUE, water use efficiency; NWR, natural water resources; WSS, water supply system. WQOP, water quality and organic pollution; MI, municipal input; NPP, nitrogen and phosphorus pollution; PNI, pipeline network improvement; STC, sewage treatment capacity.

For the water environment management system.

(1) Water quality and organic pollution. Local governments in areas with such issues should implement stricter regulations, enhance pollution control, enforce pollutant discharge permits, and promote clean production technologies [54]. Sewage treatment capacity should also be improved, and additional wetlands, ecological buffers, or sponge cities, among others, should be constructed [65] to filter organic pollutants and restore the self-purification abilities of existing bodies of water.
(2) Municipal input. Cities at risk in this area should prioritize increased municipal funding for water management, establish dedicated funds, and attract diversified financing, such as social capital or donations [66]. Local governments should

also implement transparent funding and auditing systems to prevent resource waste and misuse.

(3) Nitrogen and phosphorus pollution. The designated authorities in areas experiencing such an issue should strengthen legislation to control high-emission industries, such as the chemical and pharmaceutical sectors [54]. Nitrogen and phosphorus discharges from agriculture and households should also be limited by promoting precision fertilization and using low-pollution detergents. Furthermore, advanced nitrogen and phosphorus removal technologies should be adopted to enhance sewage treatment.

(4) Pipeline network perfection. Cities with network issues should accelerate new pipeline construction and old network renovations to increase investments and coverage. Well-planned water supply and drainage networks should be optimized.Additionally, the widespread use of rainwater pipelines should be promoted, along with the implementation of storm—sewage separation.

(5) Sewage treatment capacity. Local authorities overseeing regions at risk in this area should invest in and upgrade their sewage treatment facilities, adopt modern technologies to improve efficiency, and develop more advanced biochemical water treatment technology [67,68]. Operational management should also be strengthened through legislation to ensure that facilities are run efficiently with standardized procedures.

4. Conclusions

In this study, we proposed a quantitative assessment framework for large river basins to evaluate existing water-related policies. Taking the Yellow River Basin as an example, we provided comprehensive data on the water-related policies in the Yellow River Basin that were introduced over the 2018—2022 period. In addition, we evaluated the perfection and management effectiveness of these water resource utilization and treatment-related policies.

The results revealed the importance of devoting greater attention to water treatment policies in the Yellow River Basin, particularly on ecosystem management. A higher number of relevant policies significantly positively impacted the effectiveness of water management in the study area and the corresponding subsystems. Under suitable policies, economic development in the Yellow River Basin can contribute positively to improving the water environment in the basin. Although water resources are affected by climate to a certain degree, legislative improvements in water resource management can be introduced to mitigate uncontrollable climate impacts, thus enhancing water resource efficiency more effectively.

However, it should be noted that the impacts of some policies exhibited one-to two-year lag periods. In this study, we provided targeted policy optimization references to watershed managers by analyzing the key issues for each city. In addition, the results of the present study provide an important reference for developing management models and policies in the Yellow River Basin, resulting in more effective river basin management. The proposed framework can be applied to watershed management with similar management patterns worldwide.

This study has shortcomings that should be addressed in future related studies. Due to data availability limitations, we could only collect policy data after 2018, restricting our analysis to a policy lag of 1—2 years. As data updates become available in future research, longer policy lag periods should be explored. Moreover, further comprehensive research on related policies in typical cities is still required. We recommend that future studies on the development of evaluation systems consider more policy types, which may also impact water resource utilization and water environment treatment. Doing so could lead to the establishment of comprehensive policy/regulation databases of large river basins and, consequently, the provision of more detailed references to basin managers. The analytical model of the current study can also be applied to other large river basins (e.g., the Yangtze River Basin) to validate the results obtained in the current study and enhance the practical value of our work.

CRediT authorship contribution statement

Yi-Lin Zhao: Writing - Review & Editing, Writing - Original Draft, Validation, Supervision, Methodology, Formal Analysis, Data Curation, Conceptualization. **Han-Jun Sun:** Methodology. **Jie Ding:** Writing - Review & Editing, Validation, Supervision, Methodology, Funding Acquisition, Conceptualization. **Ji-Wei Pang:** Methodology. **Mei-Yun Lu:** Methodology. **Nan-Qi Ren:** Conceptualization. **Shan-Shan Yang:** Writing - Review & Editing, Validation, Supervision, Methodology, Funding Acquisition, Conceptualization.

Declaration of competing interest

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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Appendix A. Supplementary data

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