Spatiotemporal Differentiation Characteristics and Scenario Prediction of Water Resources Carrying Capacity in Shaanxi Province

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Abstract

Analysis of the spatiotemporal characteristics and scenario prediction of water resources carrying capacity can provide a scientific basis for water resources planning and management. In view of the significant regional differences among the "south-central-north" regions of Shaanxi Province and the limitations of traditional static evaluation of water resources carrying capacity, this study takes 10 prefecture-level cities in the province as research units, constructs an evaluation system covering four dimensions: "socioeconomy, water resources demand, environmental response, and water resources supply," integrates principal component analysis, the obstacle degree model, and the system dynamics model, and carries out dynamic evaluation of water resources carrying capacity from 2014 to 2023, identification of obstacle factors, and dynamic prediction of water resources carrying capacity under four scenarios from 2024 to 2030: baseline scenario, transformation-coordination scenario, climate-risk scenario, and water-saving-priority scenario. The results show that, on the temporal scale, the intensity of socioeconomic activities, the status of water resources supply and demand, and ecological water demand were the top three principal components affecting the water resources carrying capacity of the province from 2014 to 2023, with a cumulative contribution rate of 91.33%. The comprehensive score of water resources carrying capacity changed from negative to positive and gradually increased, while the potential for development and utilization continued to shrink. In terms of spatial distribution, the carrying capacity in Guanzhong (except Baoji and Xianyang) declined significantly, that in northern Shaanxi deteriorated rapidly, and that in southern Shaanxi showed a fluctuating decline. The top five obstacle factors and their frequencies were total water resources (49%), annual runoff depth (44%), gross domestic product (42%), total groundwater resources (36%), and total permanent population (35%). Because the baseline scenario continues the current development pattern, the transformation-coordination scenario focuses on green economic transformation and multi-factor coordinated optimization, the climate-risk scenario considers the impact of extreme climate associated with a reduction in total water resources, and the water-saving-priority scenario emphasizes water conservation in industry, agriculture, domestic use, and other sectors, the average comprehensive scores of water resources carrying capacity of the 10 prefecture-level cities in Shaanxi Province under the four scenarios changed from -3.12, 3.15, -4.98, and 3.10 in 2023 to 2.76, -2.39, 3.80, and -2.00, respectively; only the transformation-coordination and water-saving-priority scenarios showed an improvement in carrying capacity. Under the baseline scenario, the average water resources development and utilization rates of Xi' an, Xianyang, and Weinan in Guanzhong and Yulin in northern Shaanxi were 55%, 68%, 99%, and 53%, respectively, exceeding the threshold of 40%, indicating that water resources carrying capacity was in an overloaded state. By focusing on core water-saving areas in agriculture (a 30% reduction in irrigation water use per mu) and industry (a 35% reduction in water use) in the Guanzhong region, the water-saving-priority scenario reduced the utilization rates of Xi' an, Xianyang,

and Weinan to 45%, 56%, and 63%, respectively, significantly alleviating the support pressure on the water resources system and improving carrying capacity. However, due to the rigid water-use constraints of the energy industry in northern Shaanxi, the short-term water-saving effect was not significant. The results provide quantitative support for understanding the evolution of regional carrying capacity in Shaanxi Province and a scientific basis for differentiated water resources management.

Full Text

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Spatiotemporal Differentiation Characteristics and Scenario Prediction of Water Resources Carrying Capacity in Shaanxi Province

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Abstract: Analysis of the spatiotemporal characteristics of water resources carrying capacity and scenario prediction can provide a scientific basis for water resources planning and management. In view of the pronounced differences among the "southern–central–northern" regions of Shaanxi Province and the limitations of traditional static evaluations of water resources carrying capacity, this study takes the province' s 10 prefecture-level cities as research units. An evaluation system covering four dimensions– "socioeconomy, water resources demand, environmental response, and water resources supply" –was constructed. Principal component analysis, an obstacle-degree model, and a system dynamics model were integrated to conduct a dynamic evaluation of water resources carrying capacity from 2014 to 2023, identify obstacle factors, and dynamically predict water resources carrying capacity under four scenarios for 2024–2030: the baseline scenario, transformation-coordination scenario, climate-risk scenario, and water-saving-priority scenario. The results show that, on the temporal scale, the intensity of socioeconomic activities, the state of water resources supply and demand, and ecological water demand were the top three principal components affecting water resources carrying capacity across the province from 2014 to 2023, with a cumulative contribution rate of 91.33%. The comprehensive score of water resources carrying capacity shifted from negative to positive and rose gradually, while the potential for development and utilization continued to shrink. In terms of spatial distribution, carrying capacity in Guanzhong (except

Baoji and Xianyang) declined markedly, that in northern Shaanxi deteriorated rapidly, and that in southern Shaanxi showed a fluctuating decline. The top five obstacle factors and their frequencies were, in order, total water resources (49%), annual runoff depth (44%), gross domestic product (42%), total groundwater resources (36%), and total permanent resident population (35%). Because the baseline scenario continues the current development model, the transformation-coordination scenario focuses on green economic transformation and coordinated multi-factor optimization, the climate-risk scenario considers the impacts of extreme climate associated with reduced total water resources, and the water-saving-priority scenario emphasizes water saving in fields such as industry, agriculture, and domestic use, the average comprehensive scores of water resources carrying capacity for the 10 prefecture-level cities in Shaanxi Province under the four scenarios changed, respectively, from −3.12, 3.15, −4.98, and 3.10 in 2023 to 2.76, −2.39, 3.80, and −2.00; only the transformation-coordination and water-saving-priority scenarios showed improved carrying capacity. Under the baseline scenario, the average water resources development and utilization rates of Xi' an, Xianyang, and Weinan in Guanzhong and Yulin in northern Shaanxi were 55%, 68%, 99%, and 53%, respectively, exceeding the threshold of 40%, indicating that water resources carrying capacity was overloaded. The water-saving-priority scenario focuses on the core water-saving sectors of agriculture in Guanzhong (a 30% reduction in irrigation water use per mu) and industry (a 35% reduction in water use), reducing the utilization rates of Xi' an, Xianyang, and Weinan to 45%, 56%, and 63%, respectively; the support pressure on the water resources system was significantly alleviated, and carrying capacity improved. In northern Shaanxi, however, because water use in the energy industry is subject to rigid constraints, short-term water-saving effects were not significant. The research results provide quantitative support for understanding the evolution of regional carrying capacity in Shaanxi Province and a scientific basis for differentiated water resources management.

Keywords: water resources carrying capacity; principal component analysis; obstacle degree; system dynamics; scenario prediction

Water resources are the cornerstone of human social development, possessing multiple attributes as the source of life, the core of production, and the foundation of ecosystems[1]. However, with sustained economic growth and continuously increasing population density, problems such as water scarcity and water pollution have become increasingly severe and have become important factors constraining high-quality regional development[2]. Against this background, water resources carrying capacity has become an important indicator for measuring the sustainable use of regional water resources; in response to the needs of socioeconomic development and ecological environmental protection, the connotations of water resources carrying capacity have continued to evolve and improve[3]. The magnitude of water resources carrying capacity directly determines the severity of water-related problems and the direction in which water resources conflicts evolve. When the demand for socioeconomic development exceeds the carrying-capacity threshold, problems such as water shortage, imbalance between supply and demand, and deterioration of water quality will erupt in a concentrated manner[4–5].

Therefore, scientifically and effectively evaluating water resources carrying capacity, clarifying the key limiting factors and their degrees of influence on regional water resources carrying capacity[6], and deeply analyzing the current status and future trends of water resources carrying capacity[7] are of important theoretical and practical significance for identifying potential risks, promoting regional sustainable development, improving people' s quality of life, and rationally planning future development[8].

International studies often incorporate water resources carrying capacity into the framework of sustainable development, emphasizing its coupling relationship with the socioeconomic system and the ecological environment[9]. The concept of water resources carrying capacity was first proposed by the Chinese scholar Xu Youpeng[10]. Current research methods mainly include the indicator-evaluation method and the system dynamics method[11]. The former achieves quantitative assessment of carrying capacity by constructing an indicator system, is highly operable, and is widely applied; the latter focuses more on examining it from a systems—

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analyze the complexity of the water-resource system and the interactions among its constituent components from a systems perspective. However, given the complexity of the water resources–ecology–society system, a single evaluation method can hardly reveal its multidimensional interactions and dynamic processes in a comprehensive manner[12]. Scholars have therefore proposed new research approaches by integrating the advantages of multiple methods. For example, Rijsberman et al.[13] coupled system dynamics with a multi-objective planning model to simulate the long-term evolution of the supply–demand balance of water resources in a watershed; Zhu Wei et al.[14] combined the analytic hierarchy process, the entropy-weight method, and a fuzzy comprehensive evaluation model to analyze the dynamic changes and regional differences in the carrying capacity of agricultural water and soil resources in Kazakhstan from 2001 to 2017, and quantitatively identified its influencing factors; Wu Mingyan et al.[15], based on the entropy-weight TOPSIS model and a coupling-coordination model, quantitatively characterized the spatiotemporal evolution of water resources carrying capacity in the five provinces and regions of Northwest China, and used an obstacle-degree model to identify key obstacle factors; Zhang Libing et al.[16] constructed a system-dynamics-based dynamic simulation and prediction model for water resources carrying capacity in the Chaohu Lake Basin, enabling dynamic prediction of the basin' s water-resource carrying status. These studies have made notable progress in evaluating water resources carrying capacity through the coupling of multiple methods. Nevertheless, existing studies mostly use either static analysis or system-dynamics methods alone, and have not yet, on the basis of introducing obstacle-factor identification and system simulation and prediction, carried out differentiated assessments of water resources carrying capacity for different regions or predicted changes in carrying capacity under different scenarios. Therefore, this study explores an integrated evaluation framework combining static, dynamic, and predictive approaches, which will help better elucidate regional differences and evolutionary processes in water resources carrying capacity and provide quantitative support for scientific decision-making and resource management.

Shaanxi Province lies in the core area of the Loess Plateau and the Yellow River Basin, and is a key early-warning area in China for ecological surplus and deficit in water resources carrying capacity[17-18]. Its water-resource constraints have far-reaching impacts on regional development strategies and the spatial planning layout. However, most existing studies concerning the water resources carrying capacity of Shaanxi Province have adopted only traditional static evaluation methods such as fuzzy comprehensive evaluation[19], TOPSIS[20], and analytic hierarchy process[21], making it difficult to capture the dynamic linkages among elements within the system. Most studies focus on a single watershed or economic zone[21-23], lacking systematic analysis of the province-wide pattern with pronounced "south-central-north" differences. Some studies assume fixed indicator weights[24] or analyze only a single year[25], thereby neglecting the temporal evolution of key driving factors in the water-resource system. In response to these issues, this paper takes Shaanxi Province as the study area and, based on the current status of water-resource utilization, integrates principal component analysis, an obstacle-degree model, and a system dynamics model to evaluate the water resources carrying capacity of Shaanxi Province from 2014 to 2023, clarify the influence levels of key constraint factors at different stages, and predict the changing trends of water resources carrying capacity under different future scenarios, with the aim of providing a scientific basis for future water-resource planning and management in Shaanxi Province.

1 Overview of the Study Area and Research Methods

1.1 Overview of the Study Area

Shaanxi Province (105°29′–111°15′E, 31°42′–39°35′N) is located in Northwest China, with a total area of approximately 2.06×10^5 km^2. It administers 10 prefecture-level cities: Xi' an, Baoji, Xianyang, Tongchuan, Weinan, Yan' an, Yulin, Hanzhong, Ankang, and Shangluo (Fig. 1). From north to south, the province's climate types are temperate semi-arid climate, warm-temperate semi-humid climate, and subtropical humid climate. Precipitation shows a distribution pattern of more in the south and less in the north; the annual precipitation in northern Shaanxi, Guanzhong, and southern Shaanxi is approximately 336–595 mm, 508–771 mm, and 690–1290 mm, respectively[26]. Precipitation is unevenly distributed by season, with rainy summers and dry winters. In 2023, the province's permanent resident population was 3.95×10^7, including an urban population of 2.58×10^7, and the urbanization rate reached 65.16%. The Guanzhong region concentrates more than 60% of the province' s population and total economic output; northern Shaanxi, as an energy base, relies on coal, oil, and gas resources to support industrial growth; while southern Shaanxi focuses on ecological agriculture and green industries. According to data from the *Shaanxi Province Water Resources Bulletin*, in 2023 the province' s total water use was 93.63×10^8 m^3, of which the proportions used for agriculture, domestic life, industry, urban public use, and the ecological environment were 58.76%, 15.51%, 11.22%, 6.63%, and 7.88%, respectively, showing an "agriculture-dominated" water-use pattern. In 2023, the province' s water use per ten thousand yuan of gross domestic product was 27.7 m$^3 \cdot (10^4$ yuan$)^{-1}$, lower than in 2014.

Fig. 1 Schematic map of the geographic location of the study area

Fig. 1 Location of the study area

decreased by 45.3%, lower than the national average of 46.9 m$^3 \cdot (10^4$ yuan$)^{-1}$, indicating that water-use efficiency had improved. In 2023, the proportion of ecological and environmental water consumption increased by 6.23% compared with 2014, and the support capacity for ecological water use was gradually strengthened.

1.2 Water Resource Carrying Capacity Evaluation Indicator System

Following the principles of scientific validity, regional applicability, and data availability, and with reference to relevant literature[20,27], this paper selects 16 representative indicators from four aspects—socioeconomics, water-resource demand, environmental response, and water-resource supply—to construct a comprehensive evaluation indicator system for water resource carrying capacity in the subregions of Shaanxi Province. The meanings of the indicators and data sources are shown in Table 1. Based on multisource data for prefecture-level cities in Shaanxi Province from 2014 to 2023, principal component analysis (Principal Component Analysis, PCA), the obstacle degree model, and a system dynamics model (System Dynamics, SD) are comprehensively applied to evaluate the spatiotemporal changes in water resource carrying capacity, identify obstacle factors, and, using the 2023 indicators as the initial values, predict the water-resource supply-demand balance and development and utilization rates of prefecture-level cities under different scenarios during 2024–2030.

1.3 Research Methods

1.3.1 Principal Component Analysis

Principal component analysis (PCA) extracts the core information of data through dimensionality reduction[28]. In the evaluation of water resource carrying capacity, PCA can effectively reduce redundancy among indicators, extract key influencing factors, and construct a comprehensive scoring model. Compared with subjective weighting methods such as the analytic hierarchy process, its advantage lies in using the variance contribution rates of the principal components as weights; no artificial setting is required, and it can objectively reflect the degree to which each indicator affects carrying capacity. The specific operational steps are as follows: (1) To eliminate dimensional differences among indicators, the original data are standardized using the Z-score method, and the correlation coefficient matrix of the indicators is calculated; (2) the eigenvalues and corresponding eigenvectors of the correlation coefficient matrix are solved, the eigenvalues are arranged in descending order, the variance contribution rate of each principal component is calculated, and principal components with a cumulative variance contribution rate $\geq$ 85% are selected; (3) principal component expressions are constructed using the eigenvectors, and the score of each principal component is calculated; (4) the variance contribution rate of each principal component is used as its weight, and the scores of the principal components are weighted and summed to conduct a comprehensive evaluation of water resource carrying capacity.

$$F = \omega_1 F_1 + \omega_2 F_2 + \cdots + \omega_i F_i \tag{1}$$

where F is the water resource carrying capacity score; F_i is the score of the i-th principal component; and ω_i is the variance contribution rate of the i-th principal component.

1.3.2 Obstacle Degree Model

The water resource carrying capacity system in this paper covers four subsystems and is a complex dynamic system. The degree of influence of each factor on regional water resource carrying capacity changes with the development stage. Compared with the carrying status of a single indicator, which is difficult to fully reflect its influence on overall water resource carrying capacity, the obstacle degree model can not only compensate for the defects caused by single indicators but also dynamically identify key obstacle factors in different stages and different regions[29]. Therefore, this paper quantifies the degree of influence of each indicator on overall water resource carrying capacity using the obstacle degree model. First, the factor contribution degree U_j and deviation degree I_j

of the j-th evaluation indicator are calculated, and then the obstacle degree P_j of each evaluation indicator is calculated. The calculation formula is as follows:

Table 1 Comprehensive evaluation index system for water resource carrying capacity in Shaanxi Province

Tab. 1 Comprehensive evaluation index system for water resource carrying capacity in Shaanxi Province

Indicator type	No.	Indicator	Unit	Indicator meaning	Data source
Socioeconomic	X_1	Gross domestic product (GDP)	10^8 yuan	Reflects the level of economic development	*Shaanxi Statistical Yearbook*
Socioeconomic	X_2	Total resident population	10^4 persons	Reflects population size	*Shaanxi Statistical Yearbook*
Socioeconomic	X_3	Population growth rate	‰	Reflects population change	Statistical yearbooks of each city
Socioeconomic	X_4	Urbanization rate	%	Reflects the degree of urbanization (urban population / total population)	*Shaanxi Statistical Yearbook*
Socioeconomic	X_5	Added value of the secondary industry	10^8 yuan	Reflects the level of manufacturing	*Shaanxi Statistical Yearbook*
Water-resource demand	X_6	Total water consumption	10^8 m^3	Reflects water-use conditions	*Shaanxi Water Resources Bulletin*

Indicator type	No.	Indicator	Unit	Indicator meaning	Data source
Water-resource demand	X_7	Agricultural irrigation water consumption	10^8 m^3	Reflects agricultural water-use conditions	*Shaanxi Water Resources Bulletin*
Water-resource demand	X_8	Water consumption per mu of irrigation	10^8 m^3	Reflects agricultural water-use efficiency (irrigation water consumption / irrigated area)	*Shaanxi Water Conservancy Statistical Yearbook*
Water-resource demand	X_9	Industrial water consumption	10^8 m^3	Reflects industrial water-use conditions	*Shaanxi Water Resources Bulletin*
Water-resource demand	X_{10}	Domestic water consumption by residents	10^8 m^3	Reflects residents' water-use conditions	*Shaanxi Water Resources Bulletin*
Environmental response	X_{11}	Proportion of ecological and environmental water consumption	%	Reflects ecological and environmental water consumption (ecological and environmental water consumption / total water consumption)	*Shaanxi Water Resources Bulletin*

Indicator type	No.	Indicator	Unit	Indicator meaning	Data source
Water-resource supply	X_{12}	Total water resources	10^8 m^3	Reflects the abundance of water resources; its multi-year mean can be further converted into exploitable water resources, and it is a basic indicator representing the potential of exploitable resources	*Shaanxi Water Resources Bulletin*
Water-resource supply	X_{13}	Annual average precipitation	mm	Reflects precipitation conditions	*Shaanxi Water Resources Bulletin*

Indicator type	No.	Indicator	Unit	Indicator meaning	Data source
Water-resource supply	X_{14}	Total groundwater resources	10^8 m^3	Reflects the abundance of groundwater resources; combined with the groundwater exploitation coefficient, it can estimate exploitable groundwater and indirectly reflect the potential of exploitable resources	*Shaanxi Water Resources Bulletin*
Water-resource supply	X_{15}	Groundwater-source water supply	10^8 m^3	Reflects the water-supply capacity of groundwater resources	*Shaanxi Water Resources Bulletin*
Water-resource supply	X_{16}	Annual runoff depth	mm	Reflects surface water resources	*Shaanxi Water Resources Bulletin*

$$I_j = 1 - Z_j \tag{2}$$

$$P_j = \frac{U_j I_j}{\sum_{j=1}^{m} U_j I_j} \tag{3}$$

where U_j is the normalized weight of the indicator; Z_j is the indicator value of indicator X_j after standardization; j is the indicator number; and m is the total number of indicators.

1.3.3 System dynamics model

(1) Model construction System dynamics (SD) is a research method based on systems science and computer simulation, used to analyze the dynamic behavior of complex systems[30]. By constructing mathematical models, this method simulates the interactions and feedback mechanisms among the elements within a system, thereby predicting the evolutionary trends of the system under different conditions. The evolution of water resources carrying capacity is the result of dynamic system feedback, whereas static evaluation methods have difficulty depicting this process more effectively. Vensim software has the advantage of enabling real-time comparison among different schemes, making it convenient for analyzing the influence of different decisions on the system[31]. Therefore, this study uses Vensim PLE software to construct the SD model. The system flow diagram is the core component of the SD model, reflecting the dynamic feedback mechanisms of the water resources carrying-capacity system and its subsystems. By analyzing the structure of the water resources carrying-capacity system in each prefecture-level city of Shaanxi Province, an SD model applicable to all prefecture-level cities was established. The model mainly involves 38 variables, including 2 state variables, 2 rate variables, 9 constants, and 25 auxiliary variables (Fig. 2). Taking the administrative boundaries of each prefecture-level city as the spatial boundary and considering the availability of data, the temporal boundary was set as 2014-2030. The calibration and validation period of the model is 2014-2023, with the calibration period being 2014-2018 and the validation period being 2019-2023. The model uses the 2023 indicator values as initial values; the prediction stage is 2024-2030, and the time step is set to 1 a.

(2) Evaluation of model performance To ensure that the constructed SD model of water resources carrying capacity can accurately and realistically capture the characteristics and development laws of the system, historical testing of the constructed model is required. This study adopts the relative error method[32], selecting five representative indicators—GDP, total permanent resident population, total water use, proportion of ecological-environmental water consumption, and total water resources—to test the fitting effect between the simulated values of the SD model and historical values. The formula for calculating relative error is:

$$\text{Relative error} = \frac{|\text{simulated value} - \text{historical value}|}{\text{historical value}} \times 100\% \tag{4}$$

(3) Scenario design scheme To evaluate future trends in water resources carrying capacity, this study considers feasibility and rationality, and, in combination with multiple sources of information such as Shaanxi Province' s development plans, resource endowments, and climate risks, sets up four simulation scenarios: a baseline scenario, a water-saving priority scenario, a climate risk scenario, and a transformation-coordination scenario. The key changing indicators, setting rules, and bases for each scenario are shown in Table 2. Among them, the baseline scenario follows the principle of current development and considers conventional socioeconomic growth; the transformation-coordination scenario centers on the principle of green economic transformation and incorporates industrial upgrading and multi-factor coordination; the climate risk scenario is based on assumptions of extreme climate and considers reductions in total water resources and in some water use; and the water-saving priority scenario adheres closely to the principle of water-saving priority, focusing on water-saving potential in key fields. Through scenario simulation, the study predicts the 2024–

Fig. 2 System dynamics flow diagram of water resource carrying capacity in Shaanxi Province

Table 2 Four scenarios for water resource carrying capacity prediction in Shaanxi Province

Scenario type	Indicator	Change rule	Basis for change
Baseline scenario	GDP	Average annual growth of 6.5%	*Outline of the 14th Five-Year Plan and Long-Range Objectives for 2035 of Shaanxi Province*
Baseline scenario	Population growth rate	Average annual decrease of 1.2‰	Mean change over the past 5 a in the *Shaanxi Statistical Yearbook*
Baseline scenario	Urbanization rate	Average annual increase of 0.7%	*Implementation Plan of Shaanxi Province for Implementing the Five-Year Action Plan for a People-Centered New-Type Urbanization Strategy*

Scenario type	Indicator	Change rule	Basis for change
Baseline scenario	Groundwater-source water supply	Overexploitation rate maintained at 23%	*Monitoring Report on Groundwater Overexploitation Areas in Shaanxi Province*; *Shaanxi Province Water Resources Bulletin*
Water-saving priority scenario	Average irrigation water use per mu	Cumulative decrease of 30%	*Shaanxi Province Farmland Irrigation Development Plan (2023)*
Water-saving priority scenario	Industrial water use	Cumulative decrease of 35%	*Implementation Plan of Shaanxi Province for Promoting High-Quality Development of Manufacturing*; *Shaanxi Province Sectoral Water-Use Quotas*
Water-saving priority scenario	Residential domestic water use	Average annual decrease of 12%	*Shaanxi Province Sectoral Water-Use Quotas*
Water-saving priority scenario	Groundwater-source water supply	Average annual decrease of 5.2%	*Shaanxi Province Groundwater Regulations*
Water-saving priority scenario	Total groundwater resources	Average annual increase of 1.3%	*Shaanxi Province Groundwater Regulations*; *Groundwater Management Regulations*

Scenario type	Indicator	Change rule	Basis for change
Climate risk scenario	Total water resources	Cumulative decrease of 30%	*14th Five-Year Plan for Water Resources Development, Utilization, and Protection in Shaanxi Province*
Climate risk scenario	Agricultural irrigation water use	Average annual decrease of 25%	Level I response in the *Shaanxi Province Drought Emergency Plan*
Climate risk scenario	Industrial water use	Average annual decrease of 10%	*List of Key Water-Using Units under Supervision in Shaanxi Province*; *Shaanxi Province Sectoral Water-Use Quotas*
Transformation-coordination scenario	GDP	Average annual increase of 8%	*Outline of the 14th Five-Year Plan and Long-Range Objectives for 2035 of Shaanxi Province*
Transformation-coordination scenario	Total water resources	Average annual increase of 6%	*Shaanxi Province Water Resources Bulletin*; "Evolution Characteristics of the Spatial Distribution of Water Resources in Shaanxi Province from 1994 to 2021" [18]
Transformation-coordination scenario	Groundwater-source water supply	Cumulative decrease of 44%	*Shaanxi Province Groundwater Management Regulations*

Scenario type	Indicator	Change rule	Basis for change
Transformation-coordination scenario	Proportion of eco-environmental water consumption	Average annual increase of 10.4%	*Work Plan for Water Pollution Prevention and Control in Shaanxi Province*
Transformation-coordination scenario	Industrial water use	Average annual decrease of 6.8%	*Shaanxi Province Water Conservancy Statistical Yearbook*
Transformation-coordination scenario	Annual runoff depth	Average annual increase of 1.1%	*Shaanxi Province Water Resources Bulletin*

The change in water resource carrying capacity in 2030 is intended to screen out the optimal scheme consistent with sustainable development. The total water use and total water resources under each scenario are predicted, and the ratio of the two is calculated as the water resources development and utilization rate (E). The value of E is a key indicator for measuring regional water-resource stress. According to related literature[33-34], when $E < 10\%$, $10\% < E < 20\%$, $20\% < E < 40\%$, and $E > 40\%$, water-resource stress is classified as low, medium-low, medium-high, and high, respectively. In particular, $E > 100\%$ indicates that water use has exceeded the supply capacity of local natural water resources and that the region must rely on water transfer, groundwater overexploitation, or large-scale use of unconventional water sources, marking a state of severe overload in the water-resource system[35]. On the basis of analysis of supply-demand balance and the development and utilization rate, and using the input data and output results of the system dynamics model under different scenarios, the indicator system in Table 1 is used with 2023 as the starting point to predict and evaluate water resource carrying capacity under each scenario for 2024–2030.

2 Results and Analysis

2.1 Spatiotemporal variation in water resource carrying capacity in Shaanxi Province

There is a certain degree of correlation among the 16 evaluation indicators of water resource carrying capacity selected in this study (Fig. 3), indicating overlap and cross-linkage of information among factors from different dimensions in the indicator system. If these indicators are used directly for comprehensive evaluation, key information may be counted repeatedly, affecting the objectivity of the evaluation results. Therefore, it is necessary to apply PCA to reduce the dimensionality of the indicators and extract principal components that can reflect core information. Based on PCA (Table 3), the intensity of socioeconomic activities, the supply-demand status of water resources, and ecological water demand are the first three principal components affecting water resource carrying capacity in Shaanxi Province, with a cumulative contribution rate of 91.33%. This indicates that they can relatively comprehensively reflect the core driving factors of the province’ s water resource carrying capacity and its interannual changes.

The loadings of each variable on the three principal components (Fig. 4) show that the principal component with the highest contribution rate, F_1, has very strong positive correlations with GDP (X_1), urbanization rate (X_4), value added of secondary industry (X_5), and residential domestic water use (X_{10}), and very strong negative correlations with average irrigation water use per mu (X_8) and groundwater-source water supply (X_{15}). This indicates that F_1 mainly characterizes the intensity of socioeconomic activities. Principal component F_2 has strong positive correlations with total water resources (X_{12}), mean annual precipitation (X_{13}), and annual runoff depth (X_{16}), and a strong negative correlation with total water use (X_6), indicating that F_2 mainly characterizes the supply-demand status of water resources. Principal component F_3, which has relatively weaker explanatory power, shows the most significant positive relationship with the proportion of eco-environmental water consumption (X_{11}), indicating that F_3 mainly characterizes the influence of ecological water demand on water resource carrying capacity.

As shown in Fig. 5, the comprehensive score (which may be positive or negative) usually reflects the capacity for sustainable utilization of regional water resources: the lower the score, the stronger the water resource carrying capacity and the greater the development and utilization potential[36]. From 2014 to 2023, the comprehensive score of water resource carrying capacity in Shaanxi Province showed an overall trend of “shifting from negative to positive and continuing to rise” (Fig. 5), increasing from −2.91 in 2014 to a peak of 3.6 in 2021 and then declining slightly to 3.2 in 2023. This indicates that water resource carrying capacity gradually weakened and that development and utilization potential continued to decrease.

In the figure: axes—Indicator; color bar—Correlation coefficient.

Note: * denotes $P < 0.05$; ** denotes $P < 0.01$; *** denotes $P < 0.001$.

Fig. 3 Correlation coefficients of influencing factors of water resources carrying capacity in Shaanxi Province

Table 3 Principal component eigenvalues and contribution rates of water resources carrying capacity in Shaanxi Province

Principal component	Eigenvalue	Contribution rate/%	Cumulative contribution rate/%
F_1	10.866	67.916	67.92

Principal component	Eigenvalue	Contribution rate/%	Cumulative contribution rate/%
F_2	2.31	14.436	82.35
F_3	1.436	8.975	91.33

Furthermore, PCA was applied separately to the 10 prefecture-level cities in the province to extract principal components with a cumulative contribution rate $> 85\%$; for each prefecture-level city, the first three principal components were extracted. Based on the principal component loadings, the comprehensive scores of water resources carrying capacity for each prefecture-level city during 2014–2023 were calculated (Fig. 6). From 2014 to 2019, the comprehensive scores of most prefecture-level cities in the province were dominated by negative values, indicating relatively high carrying capacity; however, the scores increased year by year, and the carrying capacity gradually declined. Among them, the scores of Xi' an, Weinan, Yan' an, Yulin, Hanzhong, Ankang, and Shangluo increased from negative to positive values, indicating a decline in the water resources carrying capacity of these prefecture-level cities. This was mainly because key indicators such as GDP, total permanent resident population, industrial water use, and the added value of the secondary industry increased markedly in these prefecture-level cities. Taking Xi' an as an example, in 2019 the above indicators increased by 68.55%, 28.65%, 9.34%, and 43.62%, respectively, compared with 2014. In contrast, the scores of Baoji and Xianyang shifted from positive to negative values, indicating a relative enhancement of water resources carrying capacity. This was because these two

Fig. 4 Heat map of load matrix

Fig. 5 Comprehensive evaluation score of water resources carrying capacity in Shaanxi Province

Fig. 6 Comprehensive evaluation scores of water resources carrying capacity in each city from 2014 to 2023

the key indicators of the prefecture-level cities, such as the permanent resident population, added value of the secondary industry, total water use, agricultural irrigation water use, and industrial water use, all declined to some extent. Taking Xianyang City as an example, in 2019 the above indicators decreased by 16.04%, 17.07%, 18.26%, 25.45%, and 30.32%, respectively, compared with 2014.

After 2020, the scores of seven prefecture-level cities—Xi' an, Tongchuan, Weinan, Yan' an, Yulin, Hanzhong, and Shangluo—rose to positive values, indicating a decrease in carrying capacity. Only Baoji and Xianyang saw their scores fall to negative values, indicating an increasing trend in carrying capacity. This was related to the combined effects of declines in total water use, permanent resident population, irrigation water use per mu, groundwater-source water supply, and

Figure 7. Obstacle degree and rankings for each prefecture-level city from 2014 to 2023. Labels in the figure: City; Xi' an, Baoji, Tongchuan, Weinan, Xianyang, Yan' an, Yulin, Hanzhong, Ankang, Shangluo; Indicator; Year; Obstacle degree.

Figure 1: Figure 7. Obstacle degree and rankings for each prefecture-level city from 2014 to 2023. Labels in the figure: City; Xi' an, Baoji, Tongchuan, Weinan, Xianyang, Yan' an, Yulin, Hanzhong, Ankang, Shangluo; Indicator; Year; Obstacle degree.

domestic water use, together with an increase in total water resources in the two cities. Taking Baoji City as an example, compared with 2020, in 2023 its permanent resident population, population growth rate, irrigation water use per mu, and domestic water use decreased by 1.81%, 132.19%, 18.34%, and 3.33%, respectively. Overall, changes in the comprehensive score of water resources carrying capacity in the Guanzhong region showed regional differences. In northern Shaanxi, the comprehensive score rose sharply, and the deterioration trend became evident after 2020. In southern Shaanxi, the scores fluctuated markedly, but the overall carrying capacity tended to decrease. Among them, Ankang City reached an extreme score of 8.39 in 2021, indicating a drastic change in carrying capacity and increased pressure. This was because, in that year, Ankang' s GDP and annual average precipitation increased by 30.21% and 43.07%, respectively, compared with the multi-year averages, while its population growth rate and irrigation water use per mu decreased by 81.33% and 40.96%, respectively, compared with the multi-year averages.

2.2 Obstacle Factors of Water Resources Carrying Capacity by Region

The obstacle degree and ranking of each factor of water resources carrying capacity for the prefecture-level cities across the province from 2014 to 2023 are shown in Fig. 7. Based on an analysis of the frequency share with which each indicator entered the top five rankings of obstacle degree[37], the key obstacle factors with widespread influence across the province were identified as follows: total water resources (X_{12}), 49%; annual runoff depth (X_{16}), 44%; GDP (X_1), 42%; total groundwater resources (X_{14}), 36%; and permanent resident population (X_2), 35%.

From 2014 to 2023, the obstacle factors exhibited clear temporal trends. The persistently dominant type, represented by total water resources (X_{12}), occurred in 7 of the 10 prefecture-level cities; its annual average obstacle-degree ranking remained consistently high. In essence, this reflects the constraint of "insufficient usable capacity under total-volume constraints"on carrying capacity. When total water resources are at a relatively low level, regional avail-

Figure 7. Obstacle degree and rankings for each prefecture-level city from 2014

to 2023

Fig. 7 Obstacles level and rankings in each city from 2014 to 2023

the space for developing water resources and the supply capacity of water resources will accordingly be constrained, and the balance between supply and demand for available water resources can easily be disrupted, thereby restricting water resources carrying capacity. The continuously rising type, represented by population growth rate (X_3) and groundwater-source water supply (X_{15}), shows an overall upward trend in obstacle-degree ranking, indicating that population-growth pressure and groundwater-source water supply problems are increasingly becoming the main factors constraining the province' s water resources carrying capacity. The markedly declining type, represented by GDP (X_1) and urbanization rate (X_4), shows an overall downward trend in obstacle-degree ranking, implying that the relative pressure of economic-scale expansion and accelerated urbanization on carrying capacity shows signs of weakening.

The dominant types of obstacles also varied across different periods. During 2014–2017, the main obstacle factors were socioeconomic indicators (such as X_1, X_4, X_5, etc.). In this stage, the province' s gross domestic product grew at an average annual rate of 7.2%, and the urbanization rate rose from 52.57% to 56.8%, causing the carrying-capacity score to rise from -2.91 to -0.7, which reflects the enormous pressure placed on water resources by rapid economic development. During 2018–2020, obstacle degrees for water-demand indicators (such as X_7 and X_9) showed an upward trend, driving the score from -0.38 to 0.26, highlighting the sharp increase in agricultural and industrial water use as the main contradiction. During 2021–2023, obstacle degrees increased for water-supply indicators (such as X_{15}), environmental-response indicators (X_{11}), and population indicators (such as X_2 and X_3), keeping the score at a relatively high level of 1.46–3.6. This marked the emergence of a new set of core constraints jointly formed by ecological-environmental water-demand 保障, sustainable groundwater use, and population pressure. Overall, the types of obstacle factors across the province exhibited a transition from a "socioeconomic-dominated" type to a "resource–ecology–population composite" type.

Among the five prefecture-level cities in the Guanzhong region, the obstacle-degree rankings of groundwater-source water supply (X_{15}) and population growth rate (X_3) rose overall, making them the main causes of the decline in carrying capacity in Guanzhong. In the later period, groundwater-source water supply ranked near the top in all prefecture-level cities, especially Xi' an and Tongchuan, where it ranked first and second, respectively, reflecting the severity of groundwater-source water supply problems in the Guanzhong region. In northern Shaanxi, the main obstacle factors in Yan' an during 2014–2019 included total water use (X_6), GDP (X_1), and industrial water use (X_9), which were important drivers pushing the city' s carrying-capacity score up to 0.9 in 2020. However, after 2020, the obstacle degrees of GDP and industrial water use showed a downward trend, indicating that the obstructive effects of economic growth and industrial water use on water resources carrying capacity gradually weakened, and the carrying-capacity score also declined. In Yulin, the rising obstacle-degree rankings of population growth rate (X_3) and the proportion of ecological-environmental water consumption (X_{11}) were key factors behind the weakening trend of the city' s water resources carrying capacity (from -2.47 in 2014 to 2.9 in 2023), indicating that the pressures of population growth and the ecological environment on water resources gradually became prominent. Among the three prefecture-level cities in southern Shaanxi, the total permanent resident population (X_2) was the main obstacle factor, while the obstacle-degree rankings of urbanization rate (X_4) and the proportion of ecological-environmental water consumption (X_{11}) were high during 2014–2019, making them key factors driving the decrease in carrying capacity. In the later period, the main constraints in Ankang, Hanzhong, and Shangluo involved irrigation water use per mu (X_8), industrial water use (X_9), and agricultural irrigation water use (X_7), respectively, causing carrying capacity to continue decreasing; these factors respectively reflect the pressures on water resources from inefficient agricultural water use, industrial development, and agricultural irrigation water use.

2.3 Scenario prediction of water resources carrying capacity

Table 4 presents the ranges of relative errors between the simulation results and historical data for five key variables: GDP, total permanent resident population, total water use, the proportion of ecological-environmental water consumption, and total water resources. The relative errors of GDP, total permanent resident population, total water use, the proportion of ecological-environmental water consumption, and total water resources were $0\% \sim 14.8\%$, $0\% \sim 13.9\%$, $0.3\% \sim 15.0\%$, $0.2\% \sim 11.8\%$, and $0\% \sim 14.5\%$, respectively; all were no more than 15%, and most were controlled within 5%. According to the relevant criteria for validation of system dynamics models [38–39], this indicates that the constructed SD model has relatively high simulation accuracy for each key variable and good reliability, and can be used for scenario simulation and prediction of future water-resource supply and demand.

The average total water use and total water resources of each prefecture-level city under the four scenarios during the prediction period are shown in Figure 8. The differences in total water use among scenarios are most significant in the Guanzhong region. Under the transformation-coordination scenario and the baseline scenario, water use increases sharply; for example, the baseline scenario is 12.48×10^8 m^3 higher than the climate-risk scenario. Total water use in northern Shaanxi is lower than that in the Guanzhong and southern Shaanxi regions, with Yulin accounting for more than 70% of total water use in northern Shaanxi. Under all scenarios, total water use in southern Shaanxi is higher than that in northern Shaanxi and Guanzhong; under the baseline scenario, total water use reaches 59.97×10^8 m^3, and total water use in Hanzhong exceeds 30×10^8 m^3. In terms of total water resources, the Guanzhong region has about $125 \times 10^8 \sim 142 \times 10^8$ m^3 under the four scenarios; although it is the core region for population growth and economic development, its water resources are limited. Total water resources in northern Shaanxi are only $35 \times 10^8 \sim 40 \times 10^8$ m^3, indicating relatively poor water-resource endowment. Under all scenarios, water resources in southern Shaanxi exceed 400×10^8 m^3, which is 3–4 times that of Guanzhong and 10–13 times that of northern Shaanxi. Across the province, total water resources are highest under the transformation-coordination scenario.

The water resources development and utilization rate (E value) of each prefecture-level city under the four scenarios during the prediction period is shown in Figure 9. The central part of the Guanzhong region is densely populated, economically and industrially developed, and has large water demand. Under the four scenarios, the average E values of Xi' an, Xianyang, and Weinan are 45%–55%, 56%–68%, and 61%–99%, respectively, all exceeding 40%. This indicates that the intensity of water-resource development has exceeded the range of water resources carrying capacity, making these cities the core areas bearing water-resource pressure. By contrast, the E values of Baoji and Tongchuan remain below 40%, indicating sufficient carrying-capacity potential. In Yulin, located in northern Shaanxi, the average E value under the four scenarios ranges from 48% to 54%, all exceeding the threshold. Because Yulin' s energy industry has driven an increase in total water use, water-resource pressure is high, and the water-saving effect is not obvious. In the Yan' an area, although water-resource endowment is poor, water-use demand

Table 4 Relative errors of the system dynamics model for each prefecture-level city in Shaanxi Province /%

Prefecture-level city	GDP	Total permanent resident population	Total water consumption	Proportion of ecological-environmental water consumption	Total water resources
Xi' an	0.0~8.0	0.0~10.6	2.2~12.6	0.4~9.2	0.8~12.4
Tongchuan	0.0~13.3	0.0~11.3	3.8~15.0	0.5~9.1	0.5~11.9
Baoji	0.0~9.1	0.0~9.7	1.6~11.9	1.5~9.6	0.1~9.5
Xianyang	0.0~14.3	0.0~13.9	0.5~12.0	0.8~6.9	0.1~14.5
Weinan	0.0~8.3	0.0~11.3	0.3~13.2	0.4~11.8	0.2~14.5
Hanzhong	0.0~5.5	0.0~11.2	0.3~13.6	0.9~11.6	0.8~14.5
Ankang	0.0~13.4	0.0~3.2	1.0~6.1	1.0~8.8	1.8~13.9
Shangluo	0.0~13.4	0.0~4.5	0.5~9.6	0.2~8.3	0.0~9.9
Yan' an	0.0~11.6	0.0~3.4	0.5~7.2	0.3~10.8	0.9~10.1
Yulin	0.0~14.8	0.0~2.6	1.0~11.1	0.4~8.5	2.5~14.3

Fig. 8 Average total water consumption and total water resources under four scenarios in each city

Embedded text in Fig. 9: (a) Baseline scenario type; (b) Transformation-coordination type; (c) Climate-risk type; (d) Water-saving-priority type. Vertical axis: Water-resources utilization rate / %. Cities: Xi' an, Tongchuan, Baoji, Xianyang, Weinan, Hanzhong, Ankang, Shangluo, Yulin, Yan' an. The dashed reference line is at 40%.

Annotated values in Fig. 9:
(a) Xi' an 55%, Tongchuan 26%, Baoji 4%, Xianyang 68%, Weinan 99%, Hanzhong 18%, Ankang 5%, Shangluo 16%, Yulin 53%, Yan' an 27%.
(b) Xi' an 50%, Tongchuan 23%, Baoji 3%, Xianyang 59%, Weinan 80%, Hanzhong 18%, Ankang 4%, Shangluo 8%, Yulin 49%, Yan' an 25%.
(c) Xi' an 54%, Tongchuan 25%, Baoji 4%, Xianyang 61%, Weinan 61%, Hanzhong 18%, Ankang 3%, Shangluo 4%, Yulin 48%, Yan' an 28%.
(d) Xi' an 45%, Tongchuan 22%, Baoji 4%, Xianyang 56%, Weinan 63%, Hanzhong 17%, Ankang 4%, Shangluo 3%, Yulin 54%, Yan' an 26%.

Figure 9. Water-resources development and utilization rate under four scenarios in each prefecture-level city

Fig. 9 Utilization efficiency of water resources under four scenarios in each city

demand is not high, and the E value remains stable below the threshold of 40%; the transformation-coordination scenario can effectively improve carrying capacity. Hanzhong, Ankang, and Shangluo, located in southern Shaanxi, have abundant water resources. Under the four scenarios, their average water-resources development and utilization rates are 17%-18%, 3%-5%, and 3%-16%, respectively, none exceeding the threshold; under all scenarios, their carrying capacity remains at a relatively high level. Overall, the baseline scenario continues the current development status. The E values of the great majority of prefecture-level cities are higher than those under the other three scenarios, and the E values of Xi' an, Xianyang, and Weinan show relatively large interannual variation, reflecting interannual fluctuations in water-resource supply and demand. The transformation-coordination type emphasizes green transformation and multi-indicator coordination, and the development and utilization rate decreases compared with the baseline scenario type. Under the climate-risk scenario setting, climate change leads to a reduction in water resources and an increase in water use, and the interannual variation ranges of the E values of Xianyang and Weinan decrease. Under the water-saving-priority scenario, strengthening water-saving efforts not only reduces the average E value of each prefecture-level city, but also narrows the interannual variation range of the E value.

Under the four scenarios, taking 2023 as the starting point, the evolution characteristics of water-resources carrying capacity in Shaanxi Province from 2024 to 2030 are predicted (Fig. 10). The baseline scenario type continues the current development model and does not take into account major adjustments to water-saving policies or water-resource protection measures. Under this scenario, the average comprehensive carrying-capacity score of the

10 prefecture-level cities rises from −3.12 in 2023 to 2.76 in 2030, and the water-resources carrying capacity of most cities gradually weakens. By contrast, the transformation-coordination scenario comprehensively considers multiple factors, including economic-structure adjustment, water-resource supply, and the ecological environment. The average comprehensive carrying-capacity score of the 10 prefecture-level cities decreases from 3.15 to −2.39; moreover, as time progresses, the scores of some prefecture-level cities, such as Baoji, Weinan, Xianyang, and Yan' an, show a downward trend, while some prefecture-level cities, such as Xi' an, Yulin, and Hanzhong, show a fluctuating decline. This indicates that under this scenario, water-resources carrying capacity remains relatively good and even improves to some extent. The climate-risk scenario mainly considers the impact of climate change on water resources, such as reductions in total water resources and reductions in industrial and agricultural water use. These factors directly affect the rational allocation and utilization of water resources. Therefore, under this scenario, from 2023 to 2030, the average comprehensive carrying-capacity score of the 10 prefecture-level cities rises markedly from −4.98 to 3.8, indicating that climate risk has a serious negative impact on water-resources carrying capacity and causes a sharp increase in urban water-resources carrying pressure. Among them, because Yulin is an important energy base and its main industries are energy-based industries, while agricultural water use accounts for a small proportion, although the total amount of water resources decreases, industrial water use also decreases; consequently, its comprehensive carrying-capacity score decreases from 0.25 to −0.19, and its carrying capacity instead rises slightly. Finally, the water-saving-priority scenario, through

Figure text: Common legend: **Comprehensive score** (−8, −4, 0, 4, 8); x-axis: **Year** (2023–2030).

(a) Baseline scenario

Values by city for 2023–2030:

- Shangluo City: −0.56, −3.66, −0.27, −1.95, 1.77, 0.91, 1.27, 2.47
- Ankang City: −1.70, −3.43, 0.11, −2.25, 2.16, −0.23, 2.45, 2.90
- Hanzhong City: −2.66, −1.39, 1.11, −1.17, 2.46, −0.97, 2.31, 0.30
- Yulin City: −2.76, −1.71, −0.97, −1.39, −0.09, 3.15, 1.49, 2.28
- Yan' an City: −2.55, −1.08, −1.83, −0.25, 0.32, 1.36, 2.10, 2.75
- Xianyang City: −4.46, −2.78, 0.52, −0.27, 1.21, 0.86, 1.59, 3.32
- Weinan City: −5.01, −3.38, −1.41, −0.62, 0.57, 2.40, 3.31, 4.15
- Tongchuan City: −3.58, −3.94, −2.31, −0.76, 0.62, 2.02, 3.32, 4.62
- Baoji City: −6.04, −2.67, −1.28, 0.07, 0.68, 1.97, 3.03, 4.23
- Xi' an City: −1.86, −3.06, 0.24, −1.28, 2.21, −0.19, 3.36, 0.58

(b) Transformation-coordination scenario

Values by city for 2023–2030:

- Shangluo City: 0.54, 3.63, 0.26, 1.95, −1.76, −0.89, −1.26, −2.47

- Ankang City: 1.93, 1.17, −0.02, 0.01, −0.02, −0.03, 0.04, −0.08
- Hanzhong City: 2.66, 1.38, −1.11, 1.17, −2.46, 0.97, −2.31, −0.31
- Yulin City: 2.82, 1.65, 0.93, 1.38, 0.09, −3.14, −1.46, −2.27
- Yan' an City: 4.02, −0.84, 2.70, −0.14, −0.17, −1.43, −1.89, −2.26
- Xianyang City: 3.34, 2.87, 0.17, 0.71, −0.92, −1.00, −1.91, −3.70
- Weinan City: 5.01, 3.34, 1.39, 0.61, −0.56, −2.38, −3.29, −4.14
- Tongchuan City: 2.90, 3.30, 2.08, 0.80, −0.34, −2.79, −2.50, −3.46
- Baoji City: 6.10, 2.68, 1.27, −0.10, −0.71, −1.99, −3.03, −4.21
- Xi' an City: 2.16, 3.04, −0.11, 1.34, −2.08, 0.12, −3.46, −1.02

(c) Climate-risk scenario

Values by city for 2023–2030:

- Shangluo City: −5.81, −2.79, −1.25, −0.05, 1.05, 2.07, 2.97, 3.82
- Ankang City: −5.86, −3.72, −1.96, −0.39, 1.04, 2.37, 3.64, 4.89
- Hanzhong City: −5.49, −3.36, −1.49, −0.21, 1.58, 1.89, 2.91, 4.18
- Yulin City: 0.25, 0.16, 0.08, 0.01, −0.05, −0.10, −0.15, −0.19
- Yan' an City: −6.23, −3.83, −2.04, −0.39, 1.11, 2.55, 3.90, 4.93
- Xianyang City: −4.84, −3.04, −1.56, −0.26, 1.05, 2.05, 2.63, 3.97
- Weinan City: −5.58, −3.02, −1.01, −0.36, 0.76, 2.23, 3.08, 3.91
- Tongchuan City: −4.42, −3.63, −1.26, 0.06, 0.84, 2.01, 2.26, 3.16
- Baoji City: −5.67, −3.91, −2.21, −0.69, 0.94, 2.41, 3.87, 5.26
- Xi' an City: −6.10, −3.63, −1.68, −0.04, 1.42, 2.59, 3.39, 4.05

(d) Water-saving-priority scenario

Values by city for 2023–2030:

- Shangluo City: 0.14, 3.47, 0.04, 1.80, −1.91, −0.84, −0.93, −1.77
- Ankang City: 1.37, 3.15, −0.25, 2.19, −2.08, 0.38, −2.19, −2.57
- Hanzhong City: 2.32, 0.93, −1.46, 1.05, −2.48, 1.21, −1.96, 0.40
- Yulin City: 2.71, 1.67, 1.00, 1.53, 0.27, −3.10, −1.53, −2.56
- Yan' an City: 4.12, −1.25, 2.51, −0.29, −0.18, −1.32, −1.63, −1.97
- Xianyang City: 4.62, 2.49, −0.14, 0.43, −0.93, −0.94, −2.04, −3.49
- Weinan City: 4.79, 3.46, 1.49, 0.66, −0.54, −2.37, −3.31, −4.18
- Tongchuan City: 3.42, 2.92, 1.88, 0.75, −0.36, −2.57, −2.52, −3.52
- Baoji City: 5.98, 0.33, 0.02, −0.02, 0.00, 0.02, 0.04, 0.01
- Xi' an City: 1.51, 2.71, −0.54, 1.20, −2.23, 0.43, −3.07, −0.02

Fig. 10 Comprehensive evaluation scores of water resources carrying capacity in each city from 2023 to 2030 under four scenarios

By limiting industrial, agricultural, and residential water use and reducing groundwater supply, among other measures, water demand is lowered and the relationship between water-resource supply and demand is improved. As can be seen from Fig. 10, under the water-saving-priority scenario, as time advances, the average comprehensive carrying-capacity score of the 10 prefecture-level cities decreases from 3.1 to −2. This indicates that, through the implementation of water-saving measures, urban water resources carrying capacity has been effectively improved.

3 Discussion

This paper focuses on 10 prefecture-level cities in Shaanxi Province. Through a zonal study, it reveals significant differences in water resources carrying capacity among the three major regions of Guanzhong, northern Shaanxi, and southern Shaanxi—especially the differentiation of water-resource pressure within the Guanzhong region, the continuing deterioration trend in northern Shaanxi, and the fluctuating characteristics in southern Shaanxi. Compared with Qianyang et al. [40], who used the entropy-weighted TOPSIS-SD model to focus on the water resources carrying capacity of a single city, the analysis in this paper can more comprehensively reflect regional water-resource conditions. Using the obstacle-degree model, this paper identifies

the cumulative contribution rate of the first three principal components reached 91.33%, indicating that they can effectively summarize the core information of the 16 indicators. The study by Cao Lijuan et al. [36] also showed that the PCA method can be used for regional water resources carrying-capacity evaluation. This study finds that socioeconomic factors such as GDP, urbanization rate, and value added of the secondary industry, as well as dependence on groundwater resources and agricultural water-use efficiency, are the core driving factors affecting the carrying capacity of Shaanxi Province. The study by Tang Jiakai et al. [41] showed that the water resources carrying capacity of Shaanxi Province is constrained by total water resources, the groundwater overexploitation rate, the urbanization rate, and the proportion of water used for the ecological environment, which is relatively consistent with the key influencing factors identified in this paper. In the scenario design, the water resources development and utilization rate declines significantly under the water-saving-priority scenario, confirming the conclusion proposed by Tang Xiaoling et al. [42] and Yan Chenjian et al. [43] that industrial and agricultural water-saving measures can effectively reduce water resources pressure. In the climate-risk scenario, however, the reduction in total water resources leads to a rebound in pressure, which is consistent with the climate-change sensitivity of water resources in Shaanxi Province proposed by Han Xinze et al. [18]. This indicates that the model can effectively reflect the dynamic changes in driving factors under different scenarios.

Because there are significant spatial differences in water resources carrying capacity, obstacle factors, and the supply–demand balance and development/utilization efficiency of water resources under different scenarios in Shaanxi Province, corresponding strategies should be formulated according to regional differences. The Guanzhong region should strictly control groundwater extraction and implement groundwater recharge projects; it should optimize the population distribution and guide the rational distribution of population through industrial policies so as to alleviate population pressure in Weinan and Tongchuan. Northern Shaanxi should focus on reducing water use by energy enterprises and strengthening ecological water replenishment. Southern Shaanxi should improve agricultural water-use efficiency. Hanzhong and Ankang have relatively abundant water resources, and their utilization rates have remained at relatively low levels; they may therefore serve as water-resource support areas, providing assistance to surrounding regions and playing a role in regional water-resource allocation. At the same time, Shaanxi Province should promote synergy between water-saving technologies and ecological protection, which can effectively alleviate the risk of overloading water resources carrying capacity and provide a reference for water-resource management in other areas of the Yellow River Basin.

This study is limited by the data: the time span for analysis and prediction is relatively short, and the obstacle-degree model does not deeply analyze interactions among indicators. Future research could expand the data dimensions and combine a coupling-coordination model to deepen the analysis of internal system relationships, thereby improving the comprehensiveness and reliability of the study. In addition, this study uses total water resources and total groundwater resources as supply-type indicators, mainly because of the availability of comparable long time-series data from 2014 to 2023. In subsequent research, after the data have been improved, the available amount of water resources and the exploitable amount of groundwater could be incorporated into the indicator system, together with the utilization of unconventional water sources, to further enhance the precision of the evaluation and more directly reflect the supporting role of actually available water resources for carrying capacity, thereby providing a more accurate quantitative basis for regional water-resource management.

4 Conclusion

(1) From 2014 to 2023, the comprehensive score of water resources carrying capacity in Shaanxi Province gradually increased from a negative value to a positive value, indicating that the potential for water resources development and utilization continued to weaken. The carrying capacity in the Guanzhong region (except Baoji and Xianyang) continued to decline; the deterioration trend in northern Shaanxi accelerated; and southern Shaanxi showed a fluctuating weakening trend. The cumulative contribution rate of the three extracted principal components reached 91.33%, revealing that socioeconomic factors such as GDP, urbanization rate, and value added of the secondary industry, as well as irrigation efficiency and dependence on groundwater resources, are the core driving factors affecting the carrying capacity of the whole province.

(2) The obstacle factors of water resources carrying capacity in Shaanxi Province show staged evolution and regional differentiation. From 2014 to 2017, the obstacle factors were dominated by economic and social indicators such as GDP and urbanization rate; from 2018 to 2020, they shifted toward water-demand indicators; and from 2021 to 2023, they evolved into a "resource-ecology-population composite" type centered

on ecological water consumption, groundwater overexploitation, and population growth. At the spatial scale, the Guanzhong region is doubly constrained by groundwater overexploitation and population pressure; northern Shaanxi is limited by shortages of available water and conflicts involving ecological water demand; and southern Shaanxi is significantly affected by agricultural irrigation water use, the intensity of industrial development, and the size of the permanent resident population.

(3) Under different future scenarios, water resources pressure differs markedly. Under the baseline scenario, the average water resources development and utilization rates of Xi' an, Xianyang, and Weinan in the Guanzhong region reach 55%-99%, while the average value for Yulin in northern Shaanxi reaches 53%; these values far exceed the threshold of 40% and show large interannual fluctuations. The water-saving-priority scenario has a significant effect: for example, the utilization rates of Xi' an, Xianyang, and Weinan decrease to 45%, 56%, and 63%, respectively. In the climate-risk scenario, because the total amount of water resources decreases, water resources pressure in some cities is further intensified compared with the water-saving-priority scenario. By contrast, the transformation-synergy scenario achieves a balance between water resources pressure and economic development through green transformation and multi-indicator coordination, making it the optimal 方案. Under different scenarios, Guanzhong remains the core pressure area of the province; Yulin in northern Shaanxi and Hanzhong in southern Shaanxi also have relatively prominent pressure. Under the four scenarios—baseline, transformation-synergy, climate-risk, and water-saving-priority—the average comprehensive scores of water resources carrying capacity for the 10 prefecture-level cities in Shaanxi Province change from the 2023 values of −3.12, 3.15, −4.98, and 3.10 to 2.76, −2.39, 3.80, and −2.00, respectively. Carrying capacity improves only under the transformation-synergy and water-saving-priority scenarios, indicating that these two schemes are more effective and have reference value for water-resource management in Shaanxi Province.

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Spatio-temporal differentiation characteristics and scenario predictions of water resources carrying capacity in Shaanxi Province

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Abstract: Analyzing the spatiotemporal characteristics and scenario predictions of water resources carrying capacity (WRCC) provides a vital scientific basis for water resources planning and management. To address the pronounced regional disparities across Shaanxi Province from south to north and the limitations of traditional static evaluation methods, this study selected the 10 prefecture-level cities in the province as research units. A comprehensive evaluation system was established encompassing four dimensions: socioeconomic development, water resources demand, environmental response, and water resources supply. By integrating principal component analysis, the obstacle degree model, and the system dynamics model, this research conducted a dynamic evaluation of WRCC from 2014 to 2023, identified key obstacle factors, and predicted WRCC dynamics under the four scenarios (i.e., baseline scenario, coordinated transformation scenario, climate risk scenario, and water-saving priority scenario) for the period 2024–2030. The results were as follows: (1) On the temporal scale, the intensity of socioeconomic activities, the balance between water supply and demand, and the ecological water demand were the three principal components affecting WRCC in Shaanxi Province from 2014 to 2023, with a cumulative contribution rate of 91.33%. The comprehensive WRCC score has shifted from negative to positive and gradually increased, whereas the potential for water resources development and utilization has continued to decline. On the spatial scale, WRCC in central Shaanxi (excluding Baoji and Xianyang cities) has declined markedly, WRCC in northern Shaanxi has deteriorated rapidly, and WRCC in southern Shaanxi has exhibited a fluctuating downward trend. (2) The five most significant obstacle factors and their frequencies were total water resources (49%), annual runoff depth (44%), gross domestic product (42%), total groundwater resources (36%), and permanent population (35%). (3) Due to the baseline scenario continuing the current development model, the coordinated transformation scenario focusing on green economic transformation and multifactor collaborative optimization, the climate risk scenario accounting for the impact of extreme climate with reduced total water resources, and the water-saving priority scenario emphasizing water conservation in agricultural, industrial, and domestic sectors, the average comprehensive WRCC scores of the 10 prefecture-level cities in Shaanxi Province under the four scenarios have changed from −3.12, 3.15, −4.98, and 3.10 in 2023 to 2.76, −2.39, 3.80, and −2.00 in 2030, respectively. Only the coordinated transformation scenario and the water-saving priority scenario have led to improved WRCC. In contrast, under the baseline scenario, the average water resources development and utilization rates in central Shaanxi (Xi' an 55%, Xianyang 68%, and Weinan 99%) and northern Shaanxi (Yulin 53%) exceeded the 40% threshold, indicating that WRCC in these cities is overloaded. By targeting key water-saving areas in central Shaanxi, including agriculture (reducing irrigation water use by 30% per unit area) and industry (reducing water consumption by 35%), the water-saving priority scenario has reduced water utilization rates in the three cities to 45%, 56%, and 63%, significantly easing pressure on the water resources system and improving WRCC. However, due to rigid constraints on water use in the energy industry in northern Shaanxi, short-term water-saving effects remain limited. Overall, these findings provide quantitative evidence for understanding the evolution of regional WRCC in Shaanxi Province and offer a scientific basis for differentiated water resources management.

Keywords: water resource carrying capacity; principal component analysis; obstacle degree; system dynamics; scenario prediction

Note: Figure translations are in progress. See original paper for figures.