

Original Articles

Comprehensive evaluation and scenario simulation of water resources carrying capacity: A case study in Xiong'an New Area, China

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ABSTRACT

Water resources play a pivotal role in sustaining and shaping urban development. To assess the suitability of a site for urban construction, a water-resource-carrying capacity (WRCC) assessment is typically conducted. Here, we expand on the concept of the WRCC and construct an evaluation system based on the water quantity, quality, watershed and flow (WQQSF). Using this WQQSF evaluation system, we investigated the suitability of water resources for the development of the Xiong'an New Area (XNA) in China. Specifically, we evaluated the WRCC of XNA from 2010 to 2020 and identified the main obstacle factors. By building a system dynamics (SD) model, we analyzed projected changes in the carrying capacity of XNA from 2021 to 2035. The main findings were as follows: (1) the average WQQSF-index was 0.32 from 2010 to 2017, which corresponds to the overload condition, and rises to 0.41 from 2018 to 2020, which corresponds to the critical overload condition. (2) From the perspective of obstacle factors, the water quantity factor has a large influence on the water resources bearing condition of XNA accounting for about 40%. (3) Considering that XNA is a water-scarce area, we should first ensure the balance between the supply and demand of water resources, and secondly, choose the optimal scenario for the carrying capacity. Among the five scenarios based on uncertainty, the S3 scenario not only meets the balance of water resources supply and demand but also has the best-carrying index, which is 0.7, showing a weak carrying condition. To ensure the sustainable development of WRCC in XNA, water conservation and strict control of population size should be adhered to in the future while increasing water recharge through multiple channels. This study provides a decision basis for the management, rational development, and allocation of WRCC in XNA.

1. Introduction

Water resources play a crucial role in shaping and enabling the socio-economic development of urban areas. A common measure of the ability of a region's water resources to support such development is the water resources carrying capacity (WRCC). This directly or indirectly affects a region's resident population, surrounding environment, interacting ecological systems, and economic and social development (Liu, 2021). With continued urban expansion globally, our demand for water resources is increasing. Given the critical role of such resources and their finite nature, a thorough understanding of a region's WRCC is essential for sustainable urban development, especially in the pre-construction phase. This is especially relevant for the development of high-profile

urban areas, intended to be of significant social, cultural, political, and economic importance.

Whilst urban development has typically focused on meeting socio-economic criteria, minimizing environmental harm has become increasingly important. To achieve this, many large and densely populated cities, including London, Manchester, New York, and Chicago, have implemented expansion or relocation programs, utilizing surrounding undeveloped land (Li et al., 2022). The overarching aim of these projects is to solve prominent issues, such as high population density, traffic congestion, environmental pollution, and resource scarcity (Zou and Zhao, 2018). In China, a parallel project was set up in 2017 with the announcement of the Xiong'an New Area (XNA). This region was established to relieve the capital, Beijing, of high resource demand

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and traffic congestion by relocating non-capital functions to the periphery, while also supporting the synergistic development of the Beijing-Tianjin-Hebei (BTH) region XNA (Huang et al., 2021). However, the per capita annual water resources of XNA, at $<200\text{ m}^3$, fall far below the internationally recognized standard for extreme water scarcity (at 500 m^3 per capita). This high water scarcity is therefore a major potential constraint to development here (Zou and Zhao, 2018). Due to this, a development model adapted to the WRCC condition of XNA has been proposed. This model will include short- and long-term strategies to ensure efficient development and utilization of XNA's water resources, thus helping realize the above-mentioned goals of XNA. A central part of this plan is to first better understand XNA's WRCC and how it could be better managed and utilized.

Many studies thus far have investigated regional WRCC and the concept of WRCC more broadly. As such, a multitude of different definitions of WRCC exist; the first step of any investigation into WRCC, or how to better manage or utilize it, is to therefore select an appropriate definition. By investigating the existing research into WRCC (Zhao et al., 2021a; Feng et al., 2017), we found that three mainstream definitions exist. These alternately focus on (1) the scale of water resources development and utilization, defining WRCC as the largest scale of development and utilization that enables both economic development and environmental protection; (2) the region's capacity for the sustainable development of water resources, defining WRCC as the greatest capacity of water resources that can be harnessed for sustainable socio-economic development which occurs in harmony with the surrounding environment; (3) the maximum population that can be supported by the available water resources, defining WRCC according to the maximum population that can support regional socio-economic development through rational allocation and efficient utilization of water resources with due regard for the environment. Considering these previous definitions of the WRCC, this study, unless otherwise stated, refers to the definition used by the United Nations Educational, Scientific and Cultural Organization (UNESCO); where the WRCC is the maximum carrying capacity that can sustainably support long-term regional socio-economic development without adverse environmental impacts (Feng et al., 2017).

As understanding of the WRCC has deepened, the research methods exploring WRCC have become increasingly diverse. However, these numerous methods fall into three main categories, which include the (1) empirical formula method whereby researchers estimate the carrying capacity of regional water resources based on professional knowledge and analyses, such as analogy analysis, trend analysis, and quota analysis (Zuo et al., 2021); (2) indicator system evaluation method which establishes a representative index system to comprehensively evaluate the WRCC, using various techniques such as principal component analysis, the entropy weights method, fuzzy comprehensive evaluation (Wang et al., 2021b), and projection tracing. These various techniques of WRCC estimation do not currently use unified criteria but certain commonly used criteria include the water resources' economic, social, and ecological environment (Guo et al., 2022; Wang et al., 2022a; Wang et al., 2022c), and the Driving force, Pressure, State, Impact, and Response (DPSIR) criteria (Zare et al., 2019; Zhao et al., 2021a); (3) system analysis method (Yang et al., 2019), which takes into account the many potential factors affecting water resources to establish a complex comprehensive system. Thus far, the most widely used system focuses on the water resources impact on the economy, social development, and the environment. To establish this system, the multi-objective decision analysis and system dynamics methods are the most widely used (Ostad-Ali-Askari, 2022; Ostad-Ali-Askari et al., 2017). However, these three major methods all have certain limitations. For example, although the empirical formula method is straightforward to use, factor choice is subjective, and it can be easy to miss out on important factors. This can in turn make it difficult to quantify the subsequent WRCC regulation and control scheme and to develop sufficient technical support. Similarly, the index system method is often constrained by its traditional framing

of water resources, which focuses heavily on water quantity but neglects other dimensions such as water quality and aquatic ecology. It is therefore not a suitable method for fully realizing the aim of both urban development and environmental improvement. Meanwhile, the system analysis method is highly influenced by user expertise, such that the simulation scenarios can lack the mechanistic support of influencing factors.

To improve the shortcomings in the above research methods, and meet the more environment protection-centric focus of XNA development, improvements to the study and concept of WRCC are necessary. In addition, according to the literature, most of the WRCC studies that have been conducted in XNA only focus on the current situation or independent future scenarios (Chen et al., 2020; Sun and Yang, 2019), but do not consider trends in WRCC development from the current situation and into the future. As such, their results can only reflect the WRCC situation at a specific time-point so have limited value for the formulation of water resource policies in XNA.

To overcome these limitations, we selected four aspects of water resources—water quantity, quality, watershed, and flow (WQSF)—to give deeper insights than was possible in past studies, which focused solely on water quantity. Utilizing the WQSF assessment model, we can comprehensively evaluate the current WRCC in XNA, and identify, using the obstacle factor model, the main obstacles to developing XNA's water resources. Building on this foundation, we then set up a system dynamics model to analyze the feedback and interactions among the system's variables under various future development scenarios. The aim of this process was to aid our decision-making; specifically, the identification of the most suitable WRCC in XNA. The objectives of this study are three-fold: (1) to establish a comprehensive WQSF evaluation model; (2) to apply it to XNA to assess its WQSF status between 2010 and 2020, and to identify the main obstacles to achieving a high WRCC in XNA. (3) to explore the most suitable scenarios for the development of XNA's water resources and to provide several effective water resource management strategies, using multi-objective development scenarios. Our results will provide the first comprehensive analysis of the current and future WRCC of the XNA, thus providing a basis for decision-making in this water-scarce region.

2. Study area and data sources

2.1. Study area

XNA is located on relatively undeveloped land outside Beijing, Tianjin, and Baoding. Its geographical placement lends itself to relieving the densely populated capital. However, with an average annual precipitation of 478 mm, its per capita water resources (at greater than 200 m^3), fall far below the internationally recognized standard for extreme water scarcity (at 500 m^3 per capita).

Although XNA includes the Baiyangdian Lake (BYD), the largest lake in the North China Plain, the water resources are nonetheless limited. BYD dried out completely for four consecutive years between 1984 and 1987, before gradually recovering. To enhance this recovery, various water transfer schemes were employed since 2000, including water diversion from the Yuecheng Reservoir and the Yellow River. These projects have substantially increased water surface area and wetland area. However, surface water and groundwater extraction increased by 96 and 127 %, respectively, between 1956 and 2016. According to monitoring data in 2016, the water quality of BYD is poor, with the proportion of class IV, class V, and inferior class V being 12.4 %, 71.1 %, and 16.5 %, respectively (Li, 2020). In summary, the location of XNA has experienced multiple water resource problems for several decades, comprising water shortages, unsustainable extraction, and poor water quality.

In 2017, China proposed to build XNA into a green nature-rich city centered around environmental protection. To that end, a series of measures were introduced, focused on water pollution prevention and

control, and the protection of BYD's natural environment. These measures, implemented from 2017 onwards, strongly affected the condition of the water resources in the XNA. Between 2001 and 2017, XNA's water resources underwent little change, with total water consumption remaining between 220 million m^3 and 270 million m^3 . This water supply comprised predominantly underground water (93 %) and some surface water (5 %). The consumption of this water was split between various sectors as follows: 78 % for agricultural use, 9 % for domestic use, 10 % for industrial use, and ecological water is less. From 2018 to 2020, with the construction of XNA, the water consumption and water use structure changed significantly. The total annual water consumption almost doubled, increasing to 600 million m^3 . This increased consumption was possible because of greatly improved river and lake replenishment, making the proportion of ecological water use more than 50 %. With regards to the structure of water use, agricultural and industrial water consumption decreased slightly, whilst domestic water consumption increased significantly. (A map of XNA's land use, as of 2020, is shown in Fig. 1).

2.2. Data sets

In this study, the term "current period" refers to the 2010–2020 data set, whereas the term "future period" refers to 2035 projections, with reference to "the 2018–2035 master plan for Xiong'an New Area". The statistical data used were obtained from several sources, including the Hebei Provincial Water Resources Bulletin, Hebei Provincial Statistical Yearbook, Hebei National Economic and Social Development Statistical Bulletin, Baoding Water Resources Bulletin, China Water Resources Statistical Yearbook, Water Resources Quality Status Bulletin (Annual Report), Environmental Statistics Yearbook, and other related reports. The monitoring data was sourced from the Baoding Hydrology Bureau's water resources management information platform and groundwater monitoring platform. The remote sensing data of waters and water flow were Landsat data, in particular, Landsat-7 (for 2010–2012 data) and Landsat-8 (for 2013–2020 data). We obtained this Landsat satellite data from the USGS website at <https://earthexplorer.usgs.gov/>, and processed it using strip restoration, radiometric calibration, and atmospheric correction.

3. Methodology

3.1. Study framework

In this study, the quantitative assessment of WRCC in XNA was based on water quantity, quality, watershed, and flow to study the dynamic changes of WRCC in XNA in current and future time periods. The research framework consisted of three steps. Firstly, given the complex relationship between the multiple factors that influence WQSF, 28 representative indicators were selected to build a comprehensive evaluation system of the WQSF level. This system was constructed using single index quantification and multiple index synthesis and poly-criteria integration (SMIP). This resulted in a comprehensive evaluation of WRCC in XNA from 2010 to 2020. Secondly, the obstacle factor model was used to analyze the main limiting factors to the sustainable development of water resources in XNA. Finally, based on the calculated main obstacle factors and the future development plan of XNA, a system dynamics (SD) model was used to a) predict the WRCC levels under different simulation scenarios, b) explore the optimal development scenarios, and c) propose relevant policy recommendations to guide the sustainable development of water resources in XNA, accounting for its unique nature and uncertain future development trajectory. The research framework of this study is shown in Fig. 2.

3.2. Comprehensive evaluation method

3.2.1. WQSF index system

3.2.1.1. Connotation of the indicator system. Human activities not only affect the quantitative elements of water resources, but also affect the quality of the aquatic environment, the watershed area overall, and the flow of water across a landscape. As such, any study into WRCC involves the four aspects of WQSF (Wang et al., 2017), in which water quantity and quality both effect and are affected by, human activities. Any deficiency in water quantity and quality will therefore affect the sustainability of socio-economic development. Watershed area and water flow mainly affect a river or lake system's ecological health and, as a consequence, the sustainability of the overall water system. If a river or lake system dries up, the river's flow-rate is low, or the watershed area becomes too small, the sustainability of the water system will decrease. As such, these indicators, watershed area and water flow are mainly related to the natural environment.

Analyzing the influencing factors and evolution process of the

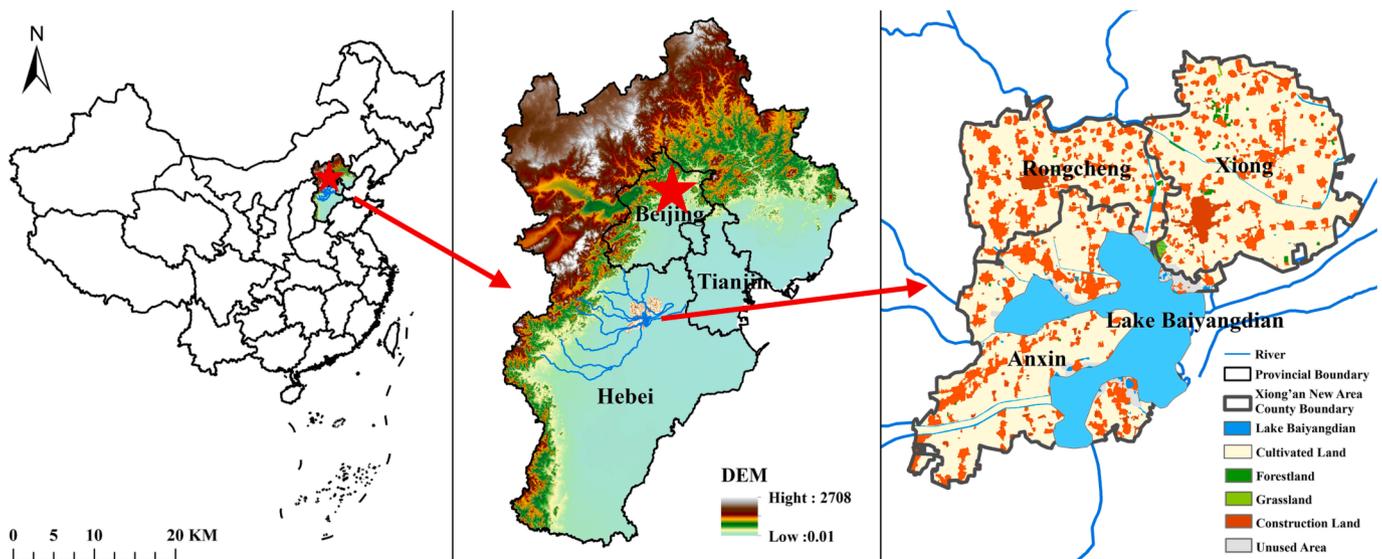


Fig. 1. Location of XNA and its land use in 2020.

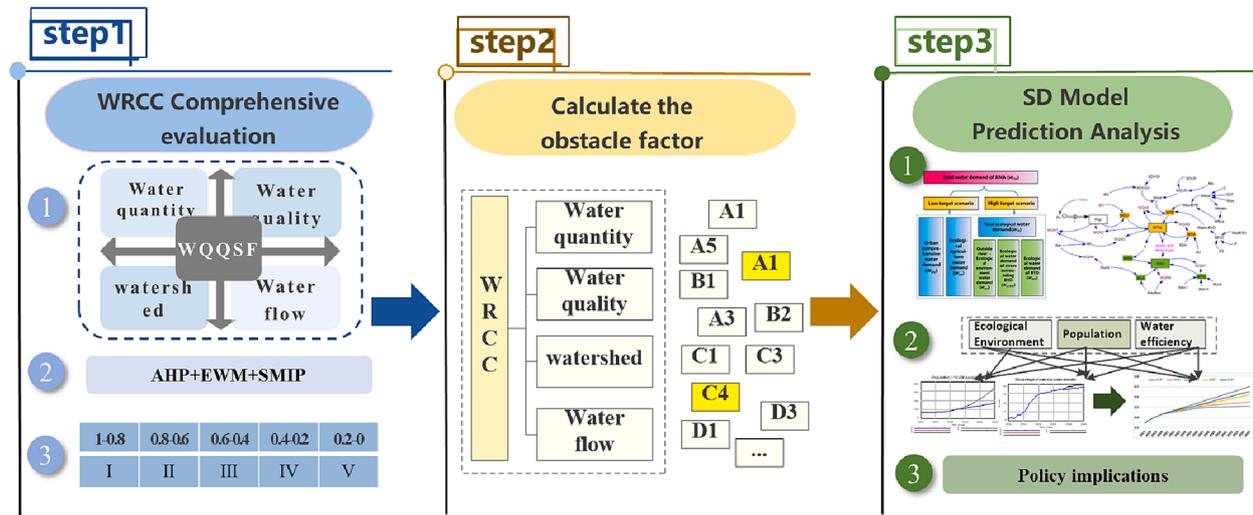


Fig. 2. The framework for evaluating XNA's WRCC.

WQQSF indices is important for assessing the change in regional WRCC. This is a useful basis to then begin regulating and managing the WRCC. The WQQSF indexes are as follows: (1) Water quantity dimension; this refers to the amount of water than can support socio-economic development up to the maximum sustainable WRCC. The water quantity dimension in this study gives insights into key socio-economic parameters, such as population size, GDP, regional water resources endowment conditions, and water resources development and utilization status. This latter variable can be further sub-divided into the water consumption of key sectors and industries. (2) Water quality dimension; urban water resource utilization can produce pollutants, sewage, and sewage treatment emissions. These emissions and pollutants, if within the vicinity of the main water system, can cause ecological damage, and kill fish and plant life. Therefore, the water quality dimension focuses on identifying the discharged pollutants and their corresponding pollution level. We analyzed whether XNA's water quality meets the target requirements of water function zoning by measuring the discharged pollutants. (3) Watershed dimension; at the early stages of urbanization, encroachment onto the land surrounding rivers, lakes, and wetlands, is often inevitable. This can occur through various means, including agricultural and industrial activities, and can lead to reduced ecological and environmental security. By ensuring sufficient space around rivers and lakes, their capacity to purify water, degrade pollution, reduce flooding, and maintain a healthy groundwater level is increased. The water dimension should focus on feedback information such as water space and groundwater level changes. This study uses remote sensing data and well-monitoring data to analyze the area of regional water space and groundwater level changes through different periods. (4) Water flow dimension; this dimension mainly reflects the water flow barrier and flow velocity, flow state change, the key feedback water flow change, and ecological flow security information. This study uses remote sensing and monitoring data combined with historical data analysis under different periods of regional water flow development and utilization to show how water flow has changed through time. The relationship between the various dimensions of WQQSF is shown in Fig. 3.

3.2.1.2. *Constructing the index system.* The WQQSF-index system is divided into three levels: target level, criterion level, and indicator level; among which, the target level is the WRCC of XNA, the criterion level encompasses the sub-dimensions of water quantity, quality, watershed, and flow, and the indicator level covers the 28 evaluation indicators of WQQSF. These three layers and their components are shown in Table 1. The formula and selection basis of the WQQSF-index system is shown in Appendix Table 1.

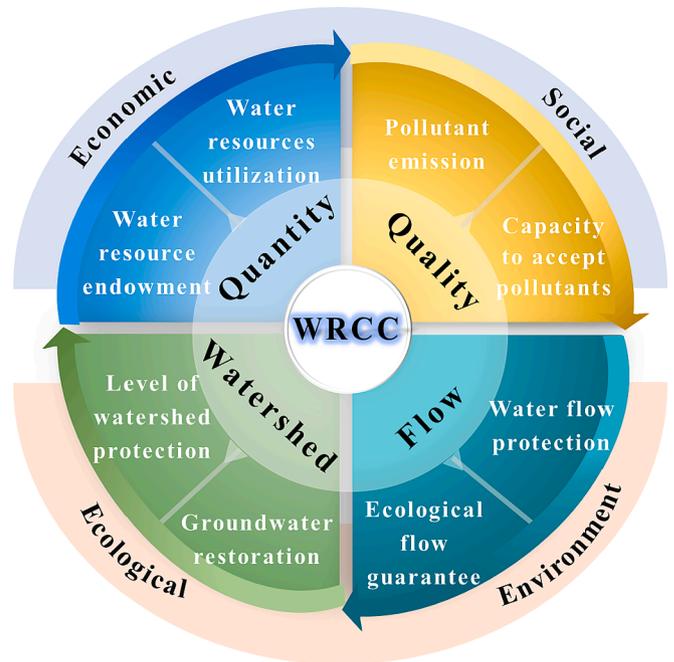


Fig. 3. Conceptual framework for WQQSF.

3.2.2. *Comprehensive evaluation method*

In this study, single-index quantification, multiple-index synthesis, and poly-criteria integration (SMIP) were used for system evaluation (Jiang et al., 2021). The steps were as follows:

3.2.2.1. *Single index quantification.* The evaluation indicators did not have the same magnitude, and the segmented linear affiliation function quantification method was used to uniformly map each evaluation indicator to the interval [0, 1] to obtain the WQQSF-index of evaluation indicators (Zuo et al., 2020). The characteristic node values of the evaluation indexes were determined based on the industry planning indexes, information, or standards, and relevant research results, including the worst value (a), worse value (b), pass value (c), better value (d) and optimal value (e), as shown in Table 1. The evaluation indicators were divided into positive indicators (indicators whose WQQSF-index increases with the indicator value, where larger values are more favorable to WQQSF), and inverse indicators (indicators whose

Table 1
Indicator system and characteristic node values of WQSF in XNA.

Target layer	Criterion layer	Index layer									
		Name	Code	Weight	Attribute	Grade classification standard					
				a	b	c	d	e			
WRCC	WQ _N 0.423	Per capita water capacity (m ³ /people)	WQ _N 1	0.073	+	500	1000	2000	3000	4000	
		Per capita water consumption (m ³ /people)	WQ _N 2	0.069	-	500	300	150	100	50	
		Water resource development and utilization rate (%)	WQ _N 3	0.072	-	100	85	70	55	40	
		Surface water resources development and utilization rate (%)	WQ _N 4	0.068	-	70	60	50	40	30	
		Water consumption per 10 ⁴ yuan of GDP (m ³ /10 ⁴ yuan)	WQ _N 5	0.072	-	150	125	100	75	50	
		Proportion of groundwater supply (%)	WQ _N 6	0.107	-	100	80	60	40	20	
		Percentage of inter-basin water transfer (%)	WQ _N 7	0.098	+	10	20	30	40	50	
		Proportion of agriculture water consumption (%)	WQ _N 8	0.116	-	80	70	60	50	40	
		Proportion of ecology water consumption (%)	WQ _N 9	0.105	+	20	30	40	50	60	
		Agricultural irrigation quota (m ³ /mu)	WQ _N 10	0.075	-	700	500	300	100	50	
	WQ _L 0.315	Urban per capita domestic water quota (L/person)	WQ _N 11	0.062	-	130	120	110	100	90	
		Reclaimed water reuse rate (%)	WQ _N 12	0.083	+	50	60	70	90	98	
		Wastewater treatment rate (%)	WQ _L 1	0.122	+	50	60	70	90	98	
		Water quality compliance rate of BYD (%)	WQ _L 2	0.304	+	0.4	0.6	0.7	0.8	0.9	
		Water quality compliance rate of water functional zone	WQ _L 3	0.145	+	0.4	0.6	0.7	0.8	0.9	
		COD (mg/L)	WQ _L 4	0.136	-	40	30	20	15	15	
		TP (mg/L)	WQ _L 5	0.147	-	0.4	0.3	0.2	0.1	0.02	
		TN (mg/L)	WQ _L 6	0.146	-	2	1.5	1	0.5	0.2	
		WS 0.157	Water area rate (%)	WS1	0.327	+	3	5	8	10	15
			BYD water level (m)	WS2	0.235	+	5.5	6	6.5	6.8	7
	Water surface area per capita (m ³ /people)		WS3	0.116	+	50	60	70	80	90	
	Forest cover (%)		WS4	0.108	+	10	20	30	35	40	
	WF 0.105	Percentage of groundwater overdraft area (%)	WS5	0.112	-	80	60	40	20	0	
		Groundwater exploitation coefficient	WS6	0.102	-	1	0.9	0.8	0.7	0.6	
River channelization rate (%)		WF1	0.227	+	20	40	60	80	100		
River network density (km/km ²)		WF2	0.234	+	0.5	1	1.5	2	3		
Flow rate of the river monitoring section into BYD (m ³ /s)		WF3	0.324	+	5	6	7	8	8.5		
Ecological flow guarantee degree (%)		WF4	0.215	+	70	75	80	85	90		

WQSF-index decreases with the increase of the indicator value, where smaller values are the more favorable to WQSF, and for a certain indicator k , its WQSF-index μ_k can be calculated according to the characteristic node value and Eq. (1). Positive and inverse indicators were calculated by the formula:

$$\text{positive : } \mu_k = \left\{ \begin{array}{l} 0, x_k \leq a_k \\ 0.3 \left(\frac{x_k - a_k}{b_k - a_k} \right), a_k \leq x_k \leq b_k \\ 0.3 + 0.3 \left(\frac{x_k - b_k}{c_k - b_k} \right), b_k \leq x_k \leq c_k \\ 0.6 + 0.2 \left(\frac{x_k - c_k}{d_k - c_k} \right), c_k \leq x_k \leq d_k \\ 0.8 + 0.2 \left(\frac{x_k - d_k}{e_k - d_k} \right), d_k \leq x_k \leq e_k \\ 1, e_k \leq x_k \end{array} \right\} \text{inverse : } \mu_k$$

$$= \left\{ \begin{array}{l} 1, x_k \leq e_k \\ 0.8 + 0.2 \left(\frac{d_k - x_k}{d_k - e_k} \right), e_k \leq x_k \leq d_k \\ 0.6 + 0.2 \left(\frac{c_k - x_k}{c_k - d_k} \right), d_k \leq x_k \leq c_k \\ 0.3 + 0.3 \left(\frac{b_k - x_k}{b_k - c_k} \right), c_k \leq x_k \leq b_k \\ 0.3 \left(\frac{a_k - x_k}{a_k - b_k} \right), b_k \leq x_k \leq a_k \\ 0, a_k \leq x_k \end{array} \right\} \quad (1)$$

where μ_k is the dimensionless index of indicator k ($k = 1, 2, \dots, n$, n is the number of indicators in each criterion layer); a_k, b_k, c_k, d_k, e_k are the

quantified characteristic node values of indicator k ; x_k is the value of the k th indicator.

3.2.2.2. Multi-index synthesis. According to the dimensionless index corresponding to the factor t in the criterion layer, the $WQWF_t$ index of the factor t in the criterion layer is obtained through the weight weighting method, which is shown in Eqs. (2):

$$WQWF_t = \sum_{k=1}^n \omega_k \mu_k \quad (2)$$

where $t = 1, 2, \dots, T$ (T is the number of criterion layers); ω_k is the weight of each indicator in the indicator layer, and the weight of each indicator is calculated in a two-step process, involving hierarchical analysis and entropy weighting in the following methods, $\sum_{k=1}^n \omega_k = 1$.

The hierarchical analysis is straightforward to implement, whilst the entropy weight method determines the information entropy by normalizing the data, and then determines the weight. This combined approach, using both hierarchical analysis and the entropy weight method, has several advantages; namely, reducing the interference of subjective factors, whilst also avoiding a situation where the weights are determined by purely objective methods and do not match the real-world importance of the indicators. and can truly represent the evaluation index weights (Jiang et al., 2021). The final weight determined by the combination of hierarchical analysis and entropy weighting method was w_j , which is shown in Eqs. (3) to (6).

$$x'_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (3)$$

$$E_j = -\frac{1}{\ln(n)} \sum_{j=1}^n x'_{ij} \ln x'_{ij} \quad (4)$$

$$w''_j = \frac{1 - E_j}{n - \sum_{j=1}^n E_j} \quad (5)$$

to the WQN-index system in WQQSF, and the pink index to the supply and demand gap. The model was built using Vensim software, and the model's main variable types are shown in Appendix A.1.

3.4.2.1. Water demand subsystem. The water demand subsystem predominantly covers demand from the urban core, agricultural sector, and the ecological system itself. Given the difficulty in predicting XNA's future economic development and the interdependent nature of water utilization, it is difficult to distinguish between water demands in urban life, construction, and tertiary industry. Therefore, the per capita urban comprehensive water demand quota method was used to calculate the urban comprehensive water demand. The calculation framework of the water demand subsystem model is shown in Appendix A.2.

a. Urban comprehensive water demand:

$$W_{DU} = M_1 \cdot P_{op} \quad (11)$$

where W_{DU} is the comprehensive water demand of the urban (m^3), M_1 is the comprehensive urban water demand quota per capita ($m^3/person$), and P_{op} is the population size (persons).

b. Ecological agriculture water demand:

$$W_{DA} = M_2 \cdot S_{DA} \quad (12)$$

where W_{DA} is the water demand for ecological agriculture (m^3), M_2 is the irrigation quota for ecological agriculture (m^3/km^2), and S_{DA} is the irrigated area for ecological agriculture (km^2).

c. Ecological environment – outside river -Ecological environment water demand:

$$W_{DUGI} = M_3 \cdot S_{DUGI} \quad (13)$$

$$W_{DUR} = M_4 \cdot S_{DUR} \quad (14)$$

where W_{DUGI} is the urban green space irrigation water demand (m^3), M_3 is the urban green space irrigation water demand quota (m^3/km^2), S_{DUGI} is the urban green space irrigation area (km^2); W_{DUR} is the urban ring water system water demand (m^3), M_4 is the ring water system water demand quota (m^3/km^2), and S_{DUR} is the urban ring water system water demand area (km^2).

Therefore, the ecological water demand of outside river (W_{out}) formula is Eqs. (15):

$$W_{out} = W_{DUGI} + W_{DUR} \quad (15)$$

d. Ecological environment – inside river – Ecological water demand of rivers surrounding BYD:

$$W_{blue} = L \cdot S_{ST} \cdot W_{se} \quad (16)$$

where W_{blue} is the ecological water demand of the blue river (m^3), L is the length of the treated river section, S_{ST} is the water surface area of the treated river section (km^2), and W_{se} is the water demand of evaporation, and seepage from the water surface of the calculated area of the river section (m^3/km^2). The ecological water demand of the rivers around the sediment is calculated by the internationally recognized Tennant method:

$$W_{flow} = W_{blue} + W_{basic} \quad (17)$$

where W_{flow} is the ecological water demand of the flowing river (m^3), and W_{basic} is the minimum amount of water required to maintain water flow in the river section (m^3).

Therefore, the formula for the ecological water demand of rivers

surrounding BYD (W_{su-BYD}) is Eqs. (18):

$$W_{su-BYD} = W_{blue} + W_{flow} \quad (18)$$

e. Ecological environment – inside river – Ecological water demand of BYD:

$$W_{BYD} = S_{BYD} \cdot (E_s - P + W_{seBYD}) \quad (19)$$

where W_{BYD} is the ecological water demand of BYD (m^3), S_{BYD} is the surface area of BYD (km^2), E_s is the evaporation water demand of the calculated surface area (m^3/km^2), P is the multi-year average precipitation of BYD (m^3/km^2), and W_{seBYD} is the seepage water demand of the calculated surface area. The ecological water demand of BYD is calculated using the water balance method.

Therefore, the total ecological environment water demand (W_{TE}) formula is Eqs. (20):

$$W_{TE} = W_{out} + W_{su-BYD} + W_{BYD} \quad (20)$$

To summarize, the total water requirement (W_{TW}) of XNA is calculated by Eqs. (21). The calculation framework of the water demand subsystem model is shown in Appendix A.2.

$$W_{TW} = W_{DU} + W_{DA} + W_{TE} \quad (21)$$

3.4.2.2. Available water supply subsystem. The water supply sub-system is combined with the actual water supply situation of XNA and comprehensively considers the existing water supply engineering pattern and the future planned supporting facilities. These supporting facilities comprise the local water resources, external water transfer, and urban recycled water, and the formula is as follows.

f. Available local water supply:

$$W_{LA} = W_{urIs} + W_{sufIow} \quad (22)$$

where W_{LA} is the locally available water supply, W_{urIs} is the upstream reservoir and locally available surface water supply, mainly considering the local Wangkuai reservoir, Xidayang reservoir, and future available stormwater resources (m^3) Upstream reservoirs and local surface water; W_{sufIow} is the water balance principle of recharge and discharge of the available local groundwater, which is determined in combination with regional groundwater recharge and mining conditions.

g. Water supply available for external water transfer:

$$W_{TO} = W_{snI} + W_{snII} + W_{yrs} \quad (23)$$

where W_{TO} is the amount of water available for transfer from other areas. Currently, planning considers the possibility of water transfer for the first and second phases of the Middle Route of South-to-North Water Diversion Project (M-SNWDP), and the Water Transfer from Yellow River to BYD Lake Project (YRBLP). W_{snI} is the water supply available for the Middle Route of South-to-North Water Diversion Project Central Line Phase I Project (M-SNWDP-I), W_{snII} is the water supply available for the Middle Route of South-to-North Water Diversion Project Central Line Phase Project (M-SNWDP-II), and W_{yrs} is the water supply available for the YRBLP.

h. Reclaimed water supply availability:

$$W_{RM} = W_{re} \cdot \delta \quad (24)$$

where W_{RM} is the amount of reclaimed water supply available, and δ is the reclaimed water utilization rate.

To summarize, the formula for calculating Available water (W_{AV}) in XNA is shown in Eqs. (25):

$$W_{AV} = W_{LA} + W_{TO} + W_{RM} \quad (25)$$

3.4.3. Scenario settings

The development of XNA is intended to relieve the Beijing of resource stress, promote ecologically-focused low-carbon development, and put greater emphasis on energy saving and water conservation than exists for northern China’s current urban construction. The trajectory of XNA’s development will also influence its future resource needs. In this context, there are four main factors affecting the amount of water resources: (1) population; (2) ecological and environmental construction; (3) water conservation level; (4) external water transfer scenarios. These uncertainty indicators are combined to form five simulation scenarios, the specific scenario is shown in Table 3.

Scenario 1, primary development model (PDM): The population size in the primary development scenario was 2.5 million in 2035, around double that of 2020 (Xia and Zhang, 2017). The irrigation area fell from 113 million mu in 2020 to about 400,000 mu. To maintain a basic wetland function, BYD maintained the lowest ecological water level, at 6.5 m (85 elevation), with a surface area of approximately 300 km². The river around BYD formed a blue river, and the Tennant method was used to calculate the low-target scenario to take 10 % of the multi-year runoff as the ecological water volume; that is, to ensure that the river maintains a certain water surface throughout the year. The specific parameters for these different scenario settings are shown in Appendix Table 2.

Scenario 2, primary development + environmental friendly mode (PDEFM): Scenario 2 focuses more strongly on the protection of the natural environment than scenario 1, but leaves the other settings the same. In scenario 2, BYD is maintained at an ecological water level of 7 m (85 elevation), and the water surface area is about 350 km², to maintain the function of a normal wetland. The rivers around BYD formed a flowing river, and the Tennant method was used to calculate the high target scenario to take 20 % of the multi-year runoff as the ecological water volume to create a suitable ecological environment (Li, 2020).

Scenario 3, primary development + environment-friendly + efficient water-saving mode (PDEFESM): based on scenario 2, in line with intense water conservation, using the most advanced water-saving quota standards., including a 10 % smaller quota for per capita urban water usage and irrigation usage, as compared to scenario 2.

Scenario 4, population development + environment-friendly + efficient water-saving development model (PEFESM): population increase expands the development and utilization of water resources, which challenges the environmental development of XNA. This scenario was modelled on a population of 5.31 million. This figure was derived from reference to the current population density surrounding XNA, which is ≤10,000 people/km². Since this population size is the maximum population capacity, we chose a more conservative figure of 5 million for this scenario. All other settings were equal to scenario 3.

Scenario 5, population development + environment-friendly + efficient water saving + multi-channel water supply mode (PPEFESMM): Based on scenario 4; that is, based on the existing planning of the second phase of the M–SNWDP and the YRBLP into Hebei to supplement the BYD, other feasible water transfer methods are considered, mainly for

the second phase of the East Route of the South-to-North Water Diversion Project, the first phase of the North Extension Project of the East Route of the South-to-North Water Diversion Project, and the water supply planning of rivers and lakes in North China (Chen et al., 2020).

4. Results

4.1. WQQSF evaluation results and analysis

According to the calculation results of the WRCC evaluation index, as shown in Fig. 5, the dimension of quantity, quality, watershed and flow of water resources in XNA is the worst in 2013 and 2014, and the best in 2020, where the carrying index of each dimension reached 0.4. Overall, it showed a slight upward trend from 2010 to 2017, with a multi-year average index of 0.32, which represents an overloaded state. From 2018 to 2020, the index increased significantly, reaching an average of 0.41, which corresponds to a critical overload state.

- (1) WQ_N-dimension. The average value of the WQ_N-index of XNA from 2010 to 2020 was 0.39, which represents the best performance compared to the other dimensions. Moreover, it showed a fluctuating upward trend at this time. It was overloaded from 2010 to 2017, with an average index of 0.37. The fluctuation was more obvious in 2012 due to abundant precipitation. After the M–SNWDP was officially opened in 2014, the WQ_N-index showed a slight increase, from 0.21 in 2014 to 0.29 in 2017. From 2018 to 2020, the WQ_N-index value was in the critical overload state, with an average value of 0.44, compared with the 2010–2017 increase, an average annual increase of 0.007.

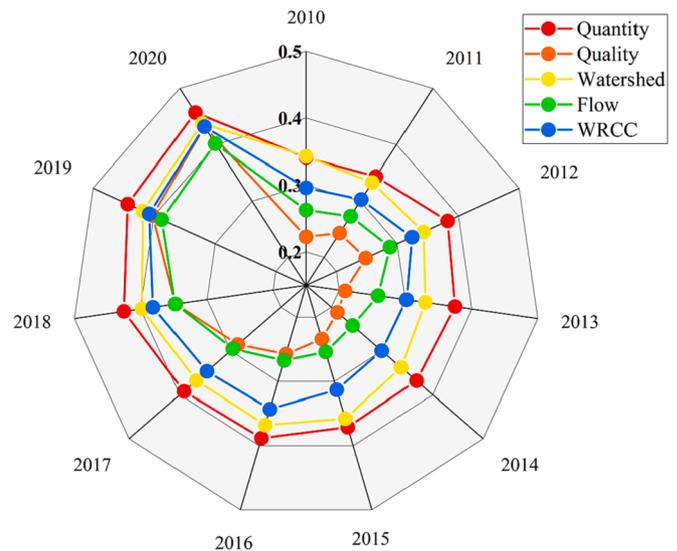


Fig. 5. The calculation results of WQQSF in XNA for 2010–2020.

Table 3
Development scenario setting of XNA.

Scenario	Model	Urban domestic water demand		Ecosystem water demand			water-saving level	Multi-channel water supply
		Population		Inside river		Outside river		
		Smaller	More	minimum ecological flow	optimal ecological flow	ecological afforestation		
S1	PDM	✓		✓			✓	
S2	PDEFM	✓			✓		✓	
S3	PDEFESM	✓			✓		✓	
S4	PPEFESM		✓		✓		✓	
S5	PPEFESMM		✓		✓		✓	✓

- (2) WQ_L -dimension. From 2010 to 2017, WQ_L has been in a serious overload state, with an average index of only 0.24, which is the worst of the four dimensions, of which 2013 is the worst. After 2017, the WQ_L carrying state has improved greatly. In 2019 and 2020, the WQ_L -index exceeded 0.4, thus reaching a critical overload state. The significant increase in the WQ_L -index after 2017 is predominantly due to the introduction of rigorous water quality control. This quality control was established because of the higher water quality requirements that accompanied the construction of XAN.
- (3) WS -dimension. From 2010 to 2020, the average value of the WS -index was 0.367, showing a slow increase between the years. From 2010 to 2017, the WS -index was 0.35, corresponding to the overloaded state. Between 2018 and 2020, it reached the critical overload state, at 0.42. In 2013 and 2014, there was a significant over-exploitation of groundwater in the watershed, resulting in a reduction of water body area. Since 2017, this phenomenon has gradually been restored.
- (4) WF -dimension. From 2010 to 2020, the WF -index was only 0.30, which was marginally better than the WQ_L -index. In 2012, the WF -index increased slightly due to increased precipitation. In 2014, the WF -index was the lowest. After the M-SNWDP in 2014, the amount of water entering BYD began to increase, and the WF -index showed an upward trend. By 2017, the rate of this upward trend increased substantially, with an average annual increase of 0.03.

4.2. Obstacle factor analysis

Using Eqs. (8) to (10) to calculate the obstacle degree of each indicator from 2010 to 2020, and selecting the indicators with multi-year average obstacle degrees greater than 5 %, reveals that WQ_N6 , WQ_N7 , WQ_N8 , WQ_N9 , WQ_L2 , $WS1$, $WS2$, $WF3$ are the eight major obstacle factors, as shown in Fig. 6. Of these eight factors, four belong to the WQ_N -dimension, one to the WQ_L -dimension, two to the WS -dimension, and one to the WF -dimension. Overall, the largest obstacle factor is WQ_L2 , followed by $WS1$. The remaining obstacle factors from the largest to the smallest are WQ_N7 , $WF3$, WQ_N9 , WQ_N6 , $WF3$, and WQ_N8 .

From the criterion level, the combined weighting is $WQ_N > WQ_L > WS > WF$, which indicates that the WQ_N -dimension has the greatest influence on the water-bearing condition of XNA, with a cumulative obstacle degree of more than 40 %. Among these indicators, only four, namely, WQ_N6 , WQ_N7 , WQ_N8 , and WQ_N9 , have a cumulative obstacle of

30 %. In the WQ_L -dimension, the average obstacle degree of WQ_L2 is larger, at approximately 12 %. The obstacles of $WS1$, $WS2$, and $WF3$ indicators in WS and WF are approximately 8 %, 5 %, and 7 %, respectively.

4.3. SD modeling results

XNA is a water-scarce shortage area. According to the comprehensive evaluation results of WQSF, the WQ_N -dimension accounts for a large proportion of this scarcity, with the cumulative barrier of indicators reaching 40 %. Considering uncertainty around the type and trajectory of future development of XNA, we only establish a small number of development scenarios for XNA in the WQ_N -dimension. From this, we analyze and predict the supply and demand gap of water resources and the bearing state of the WQ_N -dimension under different scenarios.

4.3.1. Model verification

To verify whether the operation results of the model correspond to real-life observation, we tested the model simulation results against actual XNA data from 2010 to 2020 (as shown in Fig. 7). From this model, only the relative errors of the simulated values of total water consumption (2010 and 2020), the proportion of groundwater consumption (2019), and the proportion of water transferred from outside (2016) exceed 10 %. The relative errors of the simulated values of the other variables all fall below 10 %, and the errors of most simulation results are within 5 %. Overall, the simulation results of the model accurately reflects the real-world observations.

4.3.2. Simulation results

4.3.2.1. Indicator change in multiple scenarios. The tested SD model was used to simulate five scenarios (as described in the Methods section), and four representative indicators were selected to analyze their trends under different scenarios, as shown in Fig. 8(a), the population in each scenario shows an upward trend, with an annual growth rate of 4 % in S1, S2, and S3, resulting in a final population of 2.5 million people by 2035, and an annual growth rate of 6 % for S4 and S5, reaching about 5 million people in 2035. Fig. 8(b) Scenario S1 shows a small decrease in the proportion of ecological water use due to the increase of urban domestic water use year on year, eventually reaching 52 % in 2035; S2 leads to a large proportion of ecological water use, to preserve ecological conditions, and maintain the status quo at about 60 %; Scenario S3 shows a small decrease in the proportion of ecological water use to 58 % in 2035 due to improvements water use efficiency, and S4 and S5 show a small decrease in the proportion of ecological water use due to the increase of urban domestic water use. Scenarios S4 and S5 have a continuous increase in urban domestic water use due to population growth, but the proportion of ecological water use only decreases slightly to about 50 % in 2035 due to improvements in water use efficiency and the support of a healthy ecological system. As shown in Fig. 8 (c), the groundwater supply ratio of all five scenarios from 2020 to 2035 shows a decreasing trend, eventually reaching about 13 %–15 %, which is in line with the target of groundwater overdraft management in Hebei Province, before gradually replenishing this deficit. As shown in Fig. 8 (d), S1, S2, S3, and S4 do not consider multi-water recharge, and the proportion of external water supply reaches about 55 %, while the S5 scenario considers multi-water recharge methods, such as the second phase of the South-North Water Transfer East Line, the northern extension of the first phase of the East Line, and ecological recharge. Under this multi-water recharge scenario, the proportion of external water supply reaches about 60 %.

4.3.2.2. Supply and demand analysis under multiple scenarios. Combined with the macro-allocation principle of water resources in XNA and considering the future layout of water resources and water supply

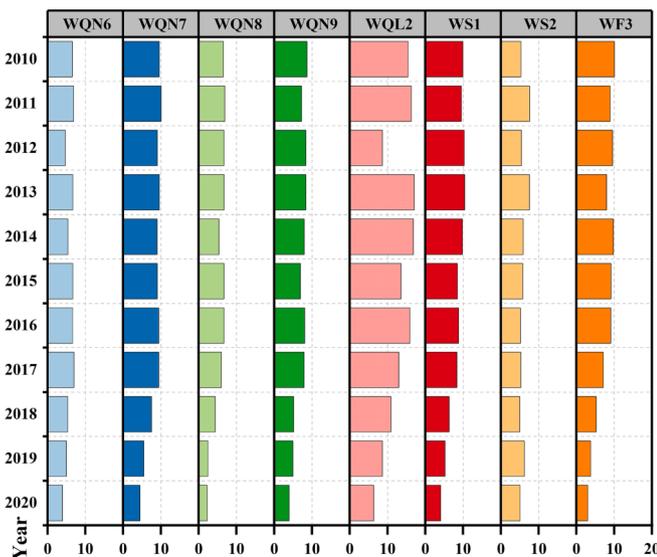


Fig. 6. WQSF-index obstacle degree of XNA.

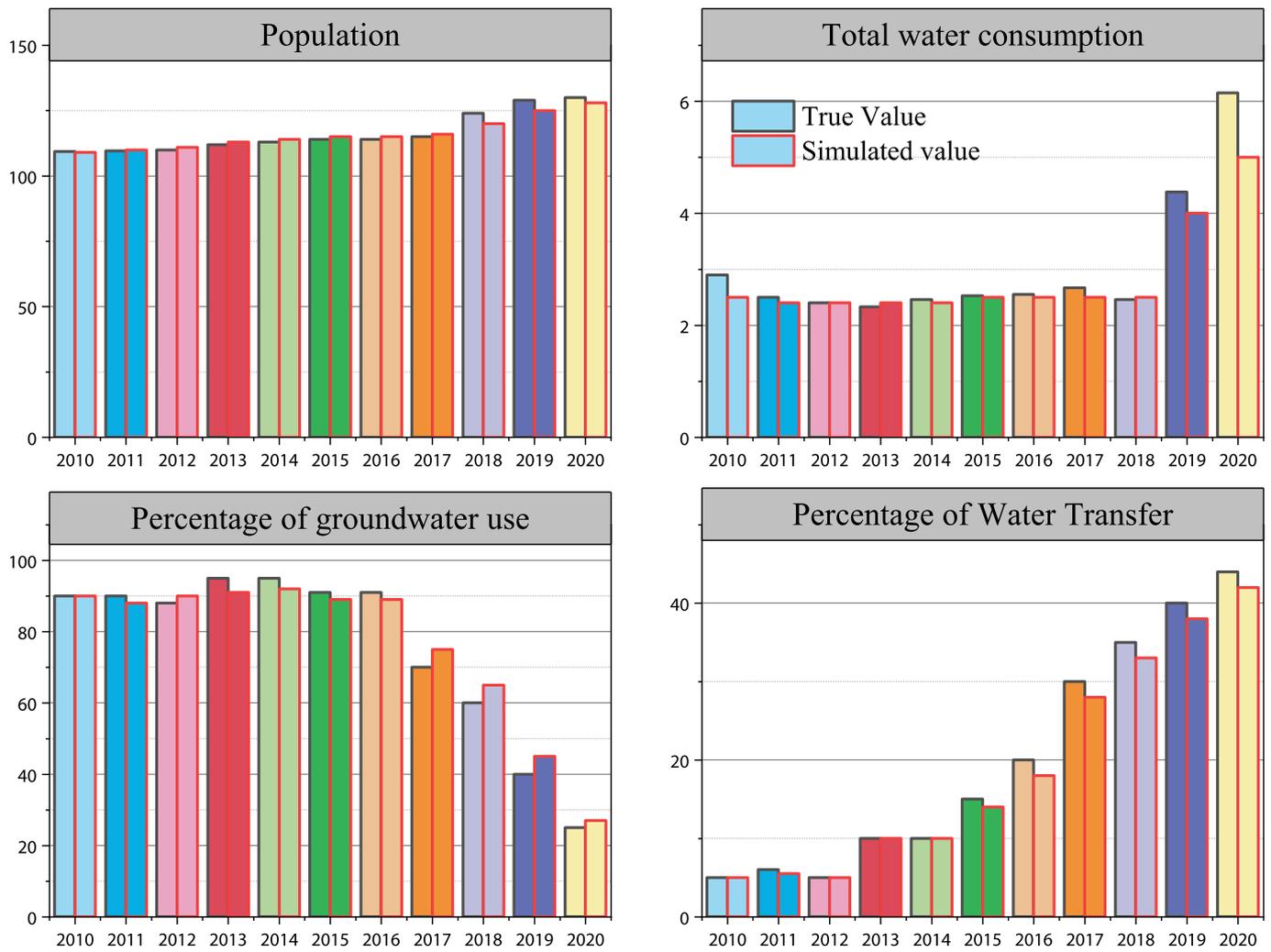


Fig. 7. Data comparison of the WQQSF-SD model with real-world observations in XNA.

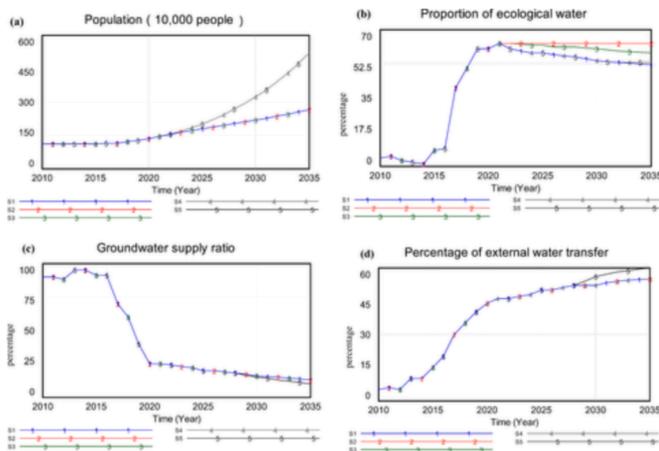


Fig. 8. Trend of representative indicators under different scenarios (a) Population; b_ Percentage of ecological water consumption; c) Percentage of groundwater supply; and d) Percentage of water supply from external transfer).

projects, the middle route of the M-SNWDP gives priority to urban domestic and production water; yellow water is mainly used to recharge BYD; reclaimed water is preferentially used for the landscape and some green belts, and is moderately used in the inside river system; groundwater is mainly used for agricultural irrigation, river ecological water,

and a small amount of production and living water; and, surface water priority to meet the requirements of ecological water. The principle of water resources allocation is to give priority to the use of regional external water sources, optimize the use of regional surface water sources, strictly control groundwater exploitation, and rationally use urban reclaimed water. The configuration results of each scenario were obtained, and the allocation results of the S5 scenario are shown in Appendix Table 3. The framework of water supply and demand allocation is shown in Appendix A.3.

It can be seen from Table 4 that under the primary development mode of S1, there is almost no water shortage in XNA in 2035, and there

Table 4 Simulation results of future multi-scenario water supply and demand in XNA.

water requirement	Scenario				
	S1	S2	S3	S4	S5
W_{DU}	3	3	2.5	4	4
W_{DA}	0.72	0.72	0.68	0.68	0.68
W_{out}	1.18	1.18	1.03	1.03	1.03
W_{su-BYD}	2.82	4.61	4.25	4.25	4.25
W_{TE}	4	5.79	5.28	5.28	5.28
W_{TW}	7.72	9.51	8.46	9.96	9.96
W_{AV}	9	9	9	9	11.6
$W_{AV} - W_{TW}$	1.28	-0.51	0.54	-0.96	1.64

Note: "+" "-" indicates whether the increase in the indicator value has a positive or negative effect on WRCC.

is a margin of 128 million m^3 . However, this scenario deems the ecological flow the least important objective. This scenario is therefore quite dissimilar to the high sustainability green future planned for XNA. The total amount of ecological water demand in the S2 scenario is greatly increased, mainly due to increasing ecological water demand in and around BYD. This result highlights the contradiction between the supply and demand of water resources. There is a water shortage of 51 million m^3 in this scenario. Therefore, we should take active measures to increase income and reduce expenditure to ensure ecological sustainability, and reduce the supply-demand gap. From the water demand side, the S3 scenario considers efficient water-saving control measures, which causes the urban comprehensive, agricultural, and ecological water demand to decrease slightly. The scenario can meet the supply and demand of water resources, leaving a margin of 54 million m^3 . The S4 scenario considers increased population growth, when the population increases to about 5 million m^3 , there is a large water supply gap in this scenario, which is larger than the S2 scenario, about 100 million m^3 , and multi-channel water replenishment needs to be considered. To support the uncertain development of XNA, the S5 scenario explores multi-channel water supply. The results show that the S5 development model can meet the balance of supply and demand and solve the contradiction between social and economic development and water resources under the demand model of population growth and ecological environment development, with the largest surplus of water of about 160 million m^3 .

4.3.2.3. Change of WQ_N -index under multiple scenarios. Using the simulation results combined with the index weight, the comprehensive evaluation method was used to calculate the comprehensive WQ_N -index in five scenarios. The results are shown in Fig. 9. The WQ_N -index of the S1 scenario does not change significantly after 2025, at about 0.5, which still represents a critical overload state. Moreover, this scenario simulates the minimum possible ecological flow, leading to a shortfall with the future construction goal of XNA. The WQ_N -index of the S2 scenario shows an increasing trend, indicating that environmentally friendly construction is conducive to improving the water carrying capacity, but the WQ_N -index is still lower than 0.6, which is in a critical overload state. After increasing the water use efficiency by 10 %, the WQ_N -index of the S3 scenario shows a significant improvement, which is the optimal state in the five scenarios. The WQ_N -index reaches 0.6 in

2035, with the potential to reach 0.7; this corresponds to a weak water-bearing state. In the S3 scenario, however, the supply and demand balance of water resources is met (Table 4), indicating that water conservation in XNA is a way to solve water scarcity and effectively improve the carrying capacity of water resources. The S3 scenario comprehensively considers water conservation and ecological environment construction, which not only meets the supply and demand of water resources but also improves the WRCC. This scenario is conducive to the coordinated development of population, water resources, and the ecological environment in XNA. The population of the S4 scenario is about twice that of the S3 scenario. Although the water-saving method improves the utilization efficiency of water resources, the increase in urban domestic water consumption nonetheless presents a real problem. Table 4 shows that there is a water supply gap in this scenario, and the S4 scenario can barely reach 0.6 in 2035, which is a weak carrying state, and the remaining years are still in a critical overload state. Compared with the S4 scenario, the S5 scenario increases the multi-channel water supply. The WQ_N -index of this scenario is higher than that of S4, exceeding 0.6 in 2032, which represents a weak carrying state, and finally reaching 0.65 in 2035. As shown in Table 4, this scenario meets the balance of supply and demand.

5. Discussion

5.1. Analysis of the factors influencing the change in WQ_N

Through the study of quantity, quality, watershed, and flow from 2010 to 2020, we found that 2017 was when the WRCC of XNA changed substantially. This was a universal effect: all the dimensional indicators changed significantly after 2017, specifically:

- (1) WQ_N -dimension-significant changes in water supply and consumption. After the establishment of XLN, the annual water transfer is approximately or, in some cases, over 200 million m^3 . In terms of water use, the proportion of ecological water use increased from 3 % to 67 % in 2020, and the proportion of agricultural water use decreased from 90 % in 2010 to 26 % in 2020. The change in water supply and water use structure has greatly alleviated the current regional water resources pressure (Chen, F. et al., 2020).

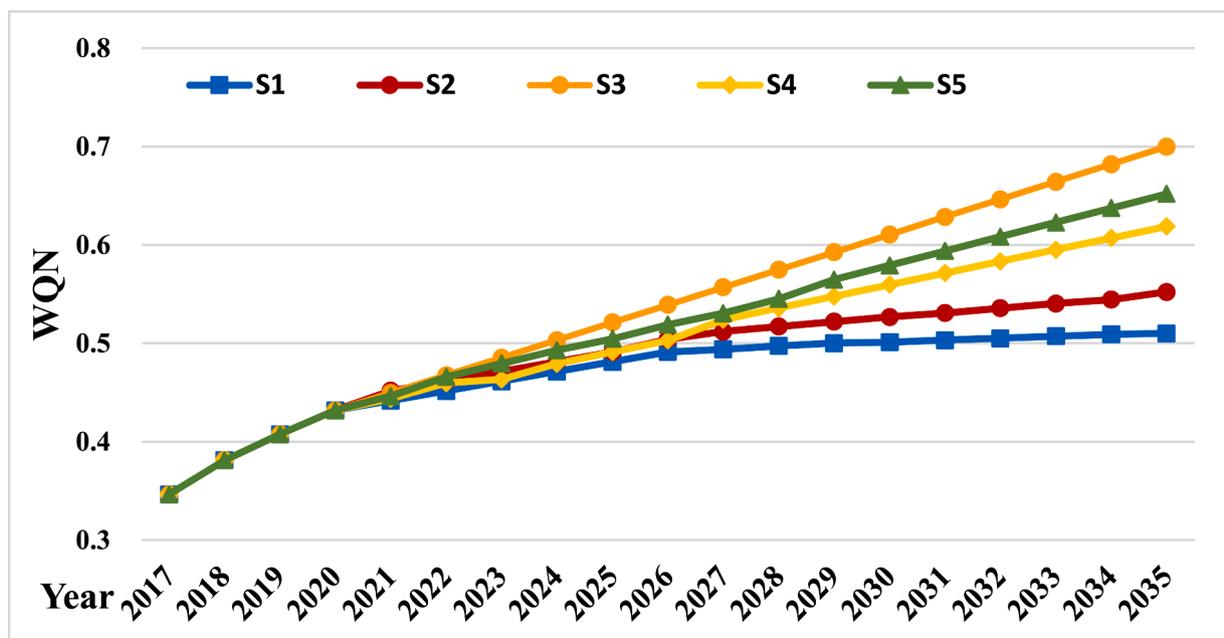


Fig. 9. Trend of WQ_N -index under multiple scenarios in XNA.

- (2) WQ_L -dimension-water quality improved significantly. BYD is the largest freshwater lake in North China. The water quality of XNA is therefore mainly affected by the water quality of BYD. Fig. 10. (a), shows that the water quality of BYD was in Class V for a long time before 2017, and even reached inferior Class V in 2013–2014. Due to water replenishment projects and the introduction of relevant policies in 2015, the water quality of BYD has gradually improved, reaching Class IV after 2017. As shown in Fig. 10. (b), there were high TP and TN concentrations in the BYD area between 2010 and 2017, especially for the TN concentration, which exceeded the Class V water standard in most years prior to 2017. After treatment, the concentrations of TP and TN decreased significantly by 2018, meeting the Class I water standards. In addition, according to relevant data, in 2021, the water quality of the BYD area and the upstream rivers with water inflow into the lake all reached standards of Class III and above, which was the best level since the water storage was restored in 1988 (Zhao et al., 2021b).
- (3) WS-dimension-water level and water surface area increased significantly. The amount of water flowing into the BYD continued to decline in the 1970s (Fig. 11.). Since the 1980s, there have been many dry lakes. The lack of surface water resources has led to a small amount of water flowing into the lake. Coupled with the large-scale development and utilization of the BYD, some of the lake's area has been occupied by cultivated land and construction land, making the water surface area of the BYD lower than 30 %, compared to baseline levels, for a long time after the 1980s. The area of BYD has shrunk significantly, from the largest 366 km² to the smallest 78.5 km². To help restore the water area of BYD, from 2012 to the present, China has carried out multi-source water replenishment projects such as the YRBLP and the M–SNWDP. These projects have gradually increased the amount of water entering the lake and restored the water surface of BYD (Zhao et al., 2021b), but there is still a big gap compared with the water level before 1980 (the water level of BYD is shown in the blue line of Fig. 11).
- (4) WF-dimension-increased significantly. Since the 1980s, eight rivers flowing into BYD were cut off, and many rivers have been cut off all year round, even reducing the amount of water flowing into the lake to zero. After 2010, the amount of water flowing into the lake is still small (Fig. 11. red histogram). The average amount of water flowing into the lake from 2010 to 2017 is only 50 million m³, which cannot guarantee its ecological flow, making the WF-dimension overload. After 2017, the ecological water supply of BYD gradually increased. The YRBLP and the M–SNWDP in 2018 respectively replenished about 255 million m³ and 100 million m³ to BYD every year, striving to restore the ecological vitality of BYD to the 1960s.

5.2. Policy implications

XNA is located in a water-scarce area. With a growing population,

economic growth, and ecological environment construction needs, meeting the supply and demand of water resources is essential for ensuring the sustainable development of WRCC. According to the scenario prediction of this study, when implementing integrated water resources management, we should adhere to open source and reduce expenditure. In addition to carrying out water supply management, it is also necessary to strengthen water demand management. Although increasing water supply can partially or temporarily alleviate water shortage, effective demand management is essential to overcome issues around insufficient supply and unsustainable demand. Therefore, water conservation is key to reducing the demand for water resources. In addition, measures such as controlling the total amount of water consumption, limiting the scale of use, and improving water efficiency should be adhered to. By reasonably planning the scale of development and carrying a population of XNA and gradually carrying out ecological restoration of BYD, the scientific allocation and joint dispatch of different water sources, for example, external water transfer, local water, and recycled water should be put in place. This will help to guarantee the security of WQQSF in XNA and support the green construction and development aims of XNA. On the whole, the specific policy recommendations are as follows:

- (1) Adhere to water conservation. According to the results of the S3 scenario, the balance between the supply and demand of water resources in the primary development + environment-friendly model can be achieved through efficient water-saving methods. Therefore, the future construction of XNA should be based on high standards of water-saving with the aim to build a water-saving smart city (Zou and Zhao, 2018). Specifically, we should ensure the sustainable and ecologically beneficial production of water, and reduce water consumption. In addition, there should be strategies to gradually reduce the area of agricultural planting, the development of water-saving agriculture, increase urban industrial and domestic water conservation efforts, and actively develop water-saving industries and enterprises, and gradually eliminate water-consuming inefficient technologies equipment in favor of the full implementation of water-saving water appliances. Secondly, we should strengthen the recycling of water resources, especially for water-scarce cities in northern China, and adhere to the concept of zero discharge of urban water. Where discharge is necessary, sewage treatment should occur underground where possible to minimize negative impacts on urban space and the surrounding environment.
- (2) Establish a multi-water replenishment mechanism. The S5 scenario shows that if the population reaches 5 million, it will be necessary to tap multi-channel water supplies to achieve the balance between the supply and demand of water resources. Therefore, to gradually restore the historical debt of water resources in XNA and adhere to sustainable development plans, multiple water replenishment and multi-channel water transfer mechanisms should be considered.

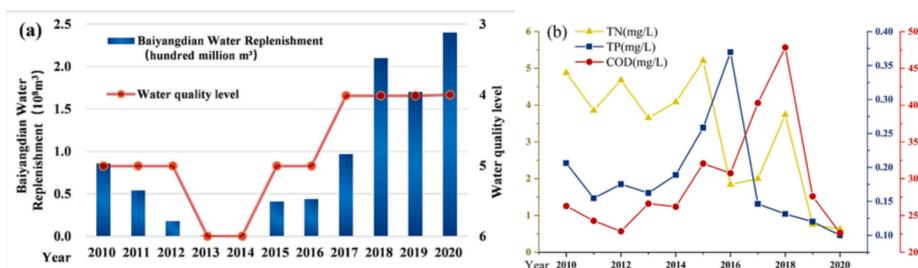


Fig. 10. Annual replenishment quantity and water quality grade of BYD ((a) BYD replenishment quantity and water quality grade, water quality grade 4,5,6 correspond to IV, V, inferior V; (b) Annual concentration of main water quality factors in BYD area, the main water quality factors are COD, TN, TP).

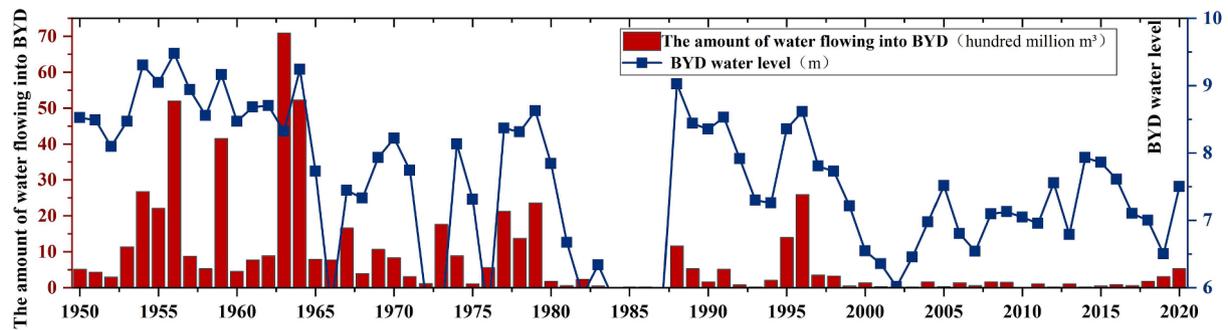


Fig. 11. Water inflow and water level of BYD from 1950 to 2020.

(3) Appropriately control the population to achieve coordinated development of population, water resources, and ecological environment. According to the results of the S4 scenario, when the population reaches 5 million, despite the implementation of efficient water conservation, there will still be a shortfall in water resources. Therefore, the scale of urban development population in the new district should be reasonably controlled, and the goal of non-capital function relief in XNA should be achieved. It is recommended that the population size should be controlled to 5 million. Reasonable control of population size and industrial structure, to avoid the emergence of resources and environment pressure XNA.

5.3. Limitations of the study

Referring to the uncertainty factors (Sun and Yang, 2019) proposed by existing scholars and the main obstacle factors in the current WRCC, this study selected the uncertainty factors that had the greatest impact on XNA's water resources, such as population size, ecological environment, and water saving level. Through a multi-scenario setting, the most suitable scenario is found to support the planning, management, and allocation of water resources in XNA in the future. Through comparison with existing research and comprehensive evaluation, our findings are similar to those of Chen et al. (2020) indicating an improvement in the sustainable development of water resources after 2015. In terms of scenario simulation, under similar conditions, Sun et al., (2019) predicted a water supply–demand gap of 113 million m^3 in XNA, whereas our study estimated the gap to be 128 million m^3 , with a small error of about 10%, indicating that our model has some scientific and rational basis. Nevertheless, our study has certain limitations and requires further research in the future:

- (1) WRCC is a complex multi-factor system. This study chooses a more comprehensive WQSF to construct a comprehensive evaluation index system. Although the relevant influencing factors involved in this study are more comprehensive, they still cannot cover all the influencing factors. Some influencing factors have been simplified or not considered, such as the impact of water price changes, climate change (Huang et al., 2021; Javadinejad et al., 2019), policy changes, etc. on WRCC (Yang et al., 2019), which can be further improved in future in-depth studies.
- (2) Relative accuracy of SD model input parameters. Uncertainty is a key consideration in the SD model, which can help monitor and evaluate policy changes because of its strong flexibility to reflect the complex relationships between water resources and economic, social, and ecological variables (Chen et al., 2022; Guo et al., 2022; Song et al., 2018). To ensure the rationality of these input parameters, the scenario setting data in this study mainly refer to the “2018–2035 master plan for Xiongan New Area” approved by the State Council of China, which is an important reference basis for the future development direction of XNA. We

sorted out the water resources-related indicators in the “master plan for Xiongan New Area”, as detailed in Appendix Table 4. In addition, we used a large number and determined the water consumption quota for XNA through a large number of comparisons, taking the comprehensive water consumption quota per capita as an example. By comparing and analyzing the per capita comprehensive water consumption indicators of cities with similar industrial structures and advanced water conservation in BTH, Pudong New Area, Shenzhen, Hong Kong, Macau, and Singapore (Appendix Table 5), we finally determined the comprehensive water consumption quota per capita of XNA to be 100–120 m^3 .

- (3) Development uncertainty of XNA. Combined with the future development uncertainty, this study sets up five development scenarios, and the scenario setting mainly refers to the “master plan for Xiongan New Area”. This plan is a national-level plan with a high level of implementation and a very high possibility of achieving the planning goals. In order to avoid the possibility of large policy changes for a long-time planning, which may affect the simulation effect, the end time of WRCC simulation in this study is chosen as 2035. However, due to the particularity of XNA positioning, XNA is a testing ground for the new urban development strategy and hopes to “draw a gorgeous picture on a blank sheet” (Zou and Zhao, 2018). Small-scale policy changes may occur in the future development process, which should be continuously monitored.

6. Conclusions

In this study, we constructed the WQSF-index system to explore changes in these indexes between 2010 and 2020, and how these changes relate to the WRCC of XNA. In addition, we identified the main obstacle factors to achieving a sustainable WRCC. Given the uncertainty around XNA's development, we performed simulations between 2021 and 2035 to identify the most significant water factor under the future development plan, and to investigate how the various scenarios affect the WRCC. From these scenarios, we sought to identify the most suitable scenario and to give relevant policy recommendations for future WRCC management in XNA. Our main conclusions were as follows:

- (1) The water quantity, quality, watershed, and flow of water resources in XNA did not change significantly from 2010 to 2017. The average WQSF-index in this period was 0.32, indicating an overloaded condition. Of these four indexes, the water quality and flow were the worst, and the WQSF-index was 0.25. However, from 2018 to 2020, the WRCC increased significantly. The average WQSF-index in these three years was 0.41, which could reach the critical overload state. In 2020, the WQSF-index was the best, and all dimensions reached 0.4.
- (2) According to the calculation results of obstacle degree from the criterion layer, the WQ_N -dimension strongly influences the

WRCC of XNA, accounting for about 40 %. From the index layer, the proportion of inter-basin water transfer, river flow, ecological water use rate, proportion of groundwater supply, BYD-water level, and the agricultural water use rate strongly influence WQQSF.

- (3) Considering the natural environment, water use efficiency, population size, and other metrics of XNAs five scenarios underwent SD simulation. Comparing the prediction results of multiple scenarios, scenarios S1, S3, and S5 meet the balance of supply and demand, scenarios S2 and S4 have a water supply gap, and the WQ_N -index S3 scenario is calculated to be the best, followed by S5, S4, S2, and S1.

Therefore, to ensure that XNA can relieve Beijing of its non-capital functions, and support its environmentally-conscious construction goals, our scenario simulation results show that it is necessary to adhere to water saving. As such, we propose that high-quality water-saving strategies are integral to all stages of XNA's construction. In addition, limiting the population to 5 million will help to balance water supply and demand, thus enabling sustainable development. On top of this increasing XNA's water supply through multiple channels will help to overcome its low levels of natural water resources. This will in turn help promote the sustainable development of WRCC in XNA, gradually improving its water security such that sustainable green construction goals can be met.

CRedit authorship contribution statement

Wei Li: Methodology, Conceptualization, Writing – original draft. **Shan Jiang:** Methodology, Conceptualization, Writing – review & editing. **Yong Zhao:** Funding acquisition, Methodology, Formal analysis, Supervision. **Haihong Li:** Funding acquisition, Conceptualization, Formal analysis, Supervision. **Yongnan Zhu:** Writing – review & editing. **Minhua Ling:** Methodology, Conceptualization, Supervision. **Tianxin Qi:** Writing – review & editing. **Guohua He:** Writing – review & editing. **Yuan Yao:** Writing – review & editing. **Hao Wang:** Supervision.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2023.110253>.

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