



OPEN Human settlement water security in Northern Xinjiang China based on DPSIR model

Haoyuan Guo¹, Hanru Zhou², Yanlong Guo²✉ & Jie Huang³

Water resource ecological security is a key foundation for ensuring human survival and maintaining ecosystem stability. A comprehensive evaluation index system is developed using the 'driving force-pressure-state-impact-response' (DPSIR) paradigm to examine the state of regional water ecological security. Entropy weight TOPSIS was used to determine the weights of each index, and the spatial differentiation characteristics and temporal and spatial deduction characteristics were analyzed. According to the research results, the weight coefficients obtained from the DPSIR mathematical model reveal a clear stratification of spatial differentiation features. From 2014 to 2023, the ecological water environment in the northern border areas showed an overall trend of early (2014–2017) increase, followed by decline (2018–2020), and then recovery or secondary increase (2020–2023), indicating the existence of spatiotemporal fluctuation patterns. Regional ecological carrying capacity essentially illustrates that the tendency of development is low in the northeast and strong in the southwest. Tacheng has the highest ecology load carrying capacity, with an average value of 0.478. The top three water resources carrying capacities are Tacheng, Ili Kazakh Autonomous Prefecture and Urumqi.

Keywords Northern border, Water environment, DPSIR principle, TOPSIS, Differentiation in space, Spatiotemporal deduction

Water ecological security is a critical component of environmental security, playing a fundamental role in maintaining ecosystem health and supporting the sustainable development of human society. The water environment forms the basis of modern ecological culture¹. As both a vital natural and economic resource, water is essential for human survival, ecological balance, and coordinated socioeconomic development^{2,3}. However, with rapid urbanization and increasing water demand, water resources are under growing pressure. This has led to serious water security challenges, including pollution, resource scarcity, and rising demand. Over the past two decades, more than 11,000 water-related incidents have occurred, and approximately two-thirds of Chinese cities now face varying degrees of water scarcity⁴. In 2014, the Chinese government introduced a new strategic framework for water resources management to address the country's uneven spatial and temporal distribution of water and the growing tension between supply and demand. This strategy emphasizes four key principles: prioritizing water conservation, promoting spatial balance, implementing systematic and integrated management, and encouraging joint participation from both the market and the government. It serves as a fundamental guideline for reconciling the development and utilization of water resources with socioeconomic growth and environmental protection.

The ability to carry water resources has received a lot of attention from the academic community. It is presently a prominent topic in water resources science research, serving as a basis for studies on sustainable development and water security⁴. Although research on water resources and their capacity for carrying has advanced significantly since Shi Jianjun and others introduced the idea in China, its theoretical and methodological frameworks are still not generally recognized⁵. According to Ren Jianjun et al.⁶, who presented the idea of the biological metabolism model, water resources are used as inputs in the socioeconomic system and produced as goods, services, and pollution. Using a multifaceted view of water resource systems, ecosystems, and considering socioeconomic systems, they employed this model to thoroughly assess the theoretical capacity of water resources at the regional level. The study of water resources' carrying capacity has been thoroughly investigated by academics both domestically and internationally in a variety of domains, including theoretical frameworks, techniques, model building, and real-world applications. Karbani's research is especially excellent⁷. A comprehensive evaluation of the Sultanate of Oman's sustainable use of its local water resources should be

¹School of Architecture and Art, Hefei University of Technology, Hefei 203106, China. ²Social Innovation Design Research Center, Anhui University, Hefei 203106, China. ³Psychology Department, Durham University, Durham DH1 3LE, UK. ✉email: 20106@ahu.edu.cn

conducted using the DPSIR approach and the capacity to carry water. Lijian et al. employed principal component analysis to do a thorough and systematic evaluation of water resources' carrying capacity^{8,9} observed that the carrying ability of regional water sources has some unclear and erratic components, so fuzzy mathematical techniques should be introduced in the evaluation process. Nowadays, the ecological security of the water supply is the primary focus of national environmental management initiatives. In the face of future urban development, one of the main issues and crucial areas for growth is harmonizing the interaction between socioeconomic culture and water resources¹⁰.

The availability of water is significantly impacted by climate change, especially in arid and semi-arid regions. Water resources are crucial for preserving biological processes and socioeconomic advancement^{11,12}. The northern portion of Xinjiang is a very arid, sparsely vegetated, and economically underdeveloped region that is situated in northwest China, in the middle of the Asian continent. With a variety of geological and climatic variables in the basin and a desert environment downstream, the majority of the rivers in this area have their source in the nearby high glaciers and snow cover. To better comprehend the geological and meteorological conditions within the watershed, crustal rock weathering, evaporation in arid climates, and the effects of human activity on the chemical characteristics of natural water bodies, geochemical research on these bodies of water is crucial.

Research region and data sources

The study area is the northern region of Xinjiang, also known as Northern Xinjiang, which is geographically separated from Southern Xinjiang by the Tianshan Mountains. It encompasses prefectures such as Bortala, Changji, and is situated between 42° to 50°N latitude and 78°–90°E longitude, covering approximately 603,000 square kilometers. The region is bounded by the Altai Mountains to the north and the Tianshan Mountains to the south, forming a typical “two mountains and one basin” landform structure. Northern Xinjiang has a temperate continental arid to semi-arid climate, with average annual temperatures ranging from −4 to 9 °C and annual precipitation between 150 mm and 200 mm. The dominant land cover is grassland (Fig. 1).

The data used in this study span the period from 2014 to 2023 and were obtained from multiple official sources to ensure reliability and comprehensiveness: Socioeconomic indicators (e.g., population density, GDP per capita, natural growth rate, and birth rate) were extracted from the China County Statistical Yearbook (2014–2023) and the Xinjiang Economic Yearbook (2014–2023), both published by the National Bureau of Statistics and the local Xinjiang Statistics Bureau. Land and ecological data (e.g., grassland area, ecological water use, and green coverage rate) were collected from the China Environmental Statistical Yearbook (2014–2023), Bulletin on

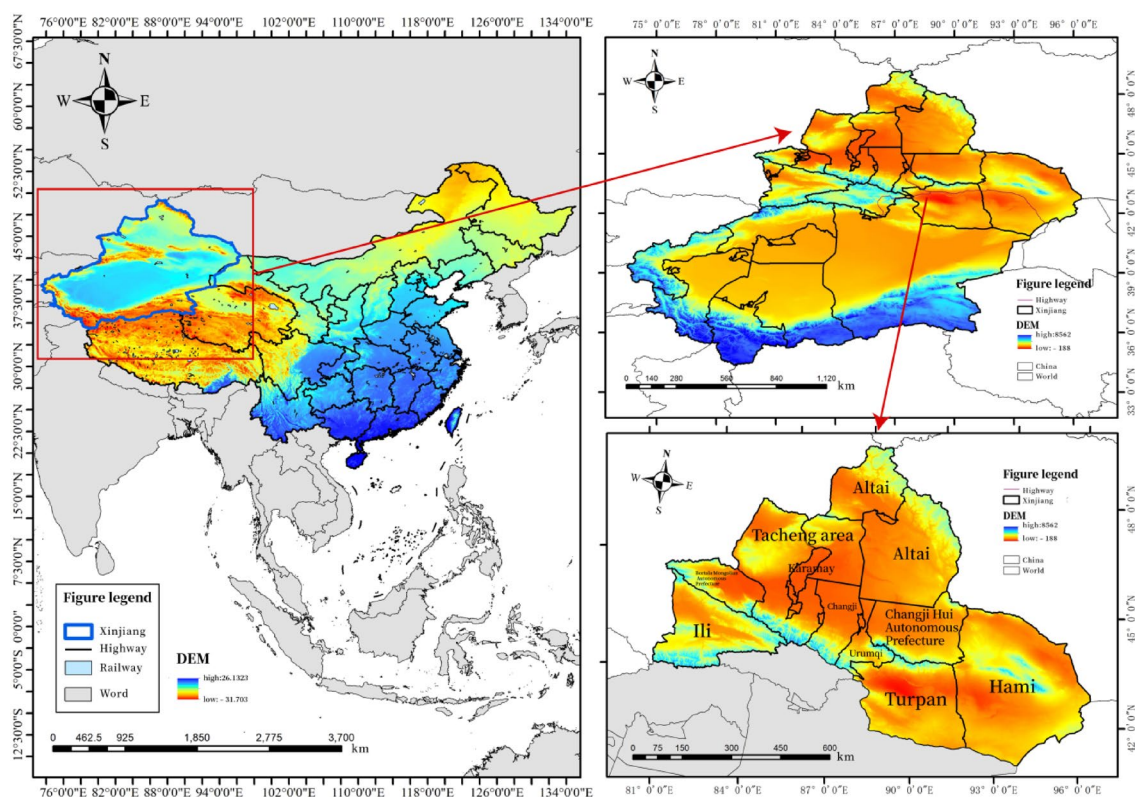


Fig. 1. Geographical location map of Northern Xinjiang. Maps were drawn by authors, using ArcGIS 10.8 (Environmental Systems Research Institute, USA. <https://www.esri.com/>), created based on China's 2022 prefecture and city administrative boundaries (<http://www.resdc.cn/>), Gaode map data, based on traditional village point data (<https://www.gov.cn/> & <https://www.ah.gov.cn/>).

Soil and Water Conservation (2014–2023), and regional Ecological Environment Bulletins, which are released annually by the Ministry of Ecology and Environment of China and corresponding regional environmental authorities. Hydrological and meteorological data (e.g., total water resources, precipitation, average annual temperature, and PM_{2.5} concentration) were obtained from the China Meteorological Administration and the Water Resources Bulletin of Xinjiang. Geospatial data for delineating the boundaries and land use patterns of Northern Xinjiang were acquired from the Geospatial Data Cloud Platform (<http://www.gscloud.cn>), which provides satellite-based remote sensing and vector datasets. To ensure data consistency and reliability over the 10-year study period, missing or inconsistent entries were handled using interpolation methods (e.g., linear interpolation for minor gaps) and cross-validated against multiple data sources. All data were standardized for compatibility within the DPSIR framework.

Research methodology

DPSIR framework

The DPSIR (driving force–pressure–state–impact–response) framework was first proposed by the Organization for Economic Cooperation and Development (OECD) in 1993. It integrates the PSR (Pressure–State–Response) model developed by the OECD and the DSR (Driving force–State–Response) model proposed by the United Nations Commission on Sustainable Development. As an environmental management tool, the core objective of the DPSIR framework is to address and reconcile the complex interactions between economic development and environmental change¹². The model consists of five categories—driving forces, pressures, states, impacts, and responses—each of which is further divided into multiple indicators depending on the evaluation method applied. Due to its logical structure and comprehensive scope, the DPSIR model is widely used in the management of water resources, land use, and the assessment of sustainable development capacity.

The DPSIR framework is introduced in this publication along with a summary of the five elements influencing the sustainability and safety of the water environment. Ecological security is seriously affected by human activities. Human activities (D) are the main driving force of socio-economic development, therefore, they exert pressure on water resources and the surrounding environment (P); Human activities have altered the initial state of water resource ecology (S); The changes in water resources ecology also affect the development speed of human and social production and life; Humans respond to these changes by formulating appropriate policies and measures (R) (Fig. 2). The DPSIR framework can cover the economic, social and environmental fundamentals of human production and life, which directly and insightfully influence the drivers, pressures and influences. The model can be used to effectively illustrate how human activity threatens ecological security and to give useful feedback on how the environment affects society.

Analysis of water environment ecological mechanism in Northern Xinjiang under DPSIR framework

The water resource performance evaluation system used in northern Xinjiang is based on the DPSIR framework. The goal layer, the factor layer, and the indicator layer are the three hierarchical levels that make up this system's 25 distinct indicators. The basic social and economic factors influencing the water environment are the main emphasis of the driving force dimension. We chose birth rate, natural growth rate, and population density as typical measures to quantify environmental stress caused by humans. These are frequently employed to represent labor intensity and demographic pressure in environmental research. Since economic activity and environmental impact are strongly related, per capita GDP is also included to show the degree of economic development and living standards.

The pressure dimension includes indicators reflecting direct environmental burdens caused by socioeconomic activities. These consist of sewage discharge, industrial water consumption, ecological water use, and per capita domestic water consumption all of which are widely recognized as key contributors to water resource pressure. The state and impact layers are represented by environmental conditions and their consequences. For instance, total available water resources, annual precipitation growth rate, average annual temperature, and per capita green space describe both natural and built environmental factors affecting water systems. PM_{2.5} concentration and urban green coverage rate are included as indicators of air and ecological quality, influencing surface water conditions through atmospheric and land-based interactions. The response dimension captures human interventions and policy efforts. These include the number of sewage treatment plants, centralized sewage treatment rate, solid waste treatment rate, industrial water reuse rate, and forest coverage rate, reflecting both institutional capacity and sustainable development strategies. All indicator data were obtained from authoritative sources such as the China County Statistical Yearbook and the Xinjiang Economic Yearbook (2014–2023) (Table 1).

TOPSIS model

The TOPSIS (technique for order preference by similarity to an ideal solution) model was first proposed by Hwang and Yoon in 1981¹³. It evaluates alternatives based on their relative distance to an ideal solution and a worst (negative ideal) solution using Euclidean distance. The model selects the option closest to the ideal solution as the best choice, while also considering its separation from the worst-case scenario¹³. In recent years, the entropy weight TOPSIS model has been widely applied to evaluate environmental systems such as water carrying capacity and land use efficiency, due to its ability to integrate objective weighting and multi-criteria decision-making¹⁴.

Indicator data matrix and standardized evaluation matrix

For the aquatic ecosystem in northern Xinjiang, indicator data and standardized evaluation matrices related to ecological sample data have been generated. This evaluation method aims to measure various indicators of the



Fig. 2. DPSIR model diagram.

improvement of water biodiversity in northern Xinjiang, including both favorable and unfavorable elements. The following formula is used for calculation:

Indicate the indicator data matrix and the standardized assessment matrix for the biological sample information of the water environmentally friendly surroundings in northern Xinjiang. This approach assesses the advantages and disadvantages of indicators of aquatic ecosystem expansion in various northern Xinjiang regions. The greater the positive indicator value, the more developed the region; conversely, the greater the negative indicator value, the less developed the region. The following is the establishing the following equation:

$$V = \begin{bmatrix} V_{11} & V_{12} & \cdots & V_{1y} \\ V_{21} & V_{22} & \cdots & V_{2y} \\ \vdots & \vdots & \ddots & \vdots \\ V_{x1} & V_{x2} & \cdots & V_{xy} \end{bmatrix} \quad (1)$$

$$W_{ij} = \frac{V_{ij} - \min(V_{1j}, V_{2j}, \dots, V_{nj})}{\max(V_{1j}, V_{2j}, \dots, V_{nj}) - \min(V_{1j}, V_{2j}, \dots, V_{nj})} \quad (2)$$

$$W_{ij} = \frac{\max(V_{1j}, V_{2j}, \dots, V_{nj}) - V_{ij}}{\max(V_{1j}, V_{2j}, \dots, V_{nj}) - \min(V_{1j}, V_{2j}, \dots, V_{nj})} \quad (3)$$

Here, W is defined as the indicator data matrix, while V_{ij} represents the standardized evaluation matrix. The element index is used to identify elements at specific positions within a matrix, represented in the form of $(i=1, 2, 3, \dots, x; j=1, 2, 3, \dots, y)$. This setting aims to achieve a specific purpose. J stands for the number of evaluation indicators, and I for the number of evaluated units. Normalize and standardize data using scope, which is seen as $(V_{ij})_{y \times x_0} = W$, to solve the problem of the irregular sizes and units of the initial information samples. W_{ij} Standardized indicators are used as evaluation criteria for evaluating objects. $W_{i\max}$ is represents the indicator's highest value, and represents its lowest value.

Category	Normative layer	Indicator layer	Unit	Convergence	Weighting(%)
Evaluation index system for ecological security of water environment in northern Xinjiang	D: Drive	D1 Registered residence population	people	-	4.893
		D2 Per capita GDP	Yuan per person	+	4.052
		D3 Natural growth rate of registered residence population	(%)	-	3.718
		D4 Birth rate of registered residence population	(%)		3.518
	P: Pressure	P1 Per capita water consumption	Billion cubic meters	-	15.402
		P2 Domestic water consumption	Billion cubic meters	-	3.456
		P3 Total production water consumption	Billion cubic meters	-	18.675
		P4 Ecological Water Consumption	Billion cubic meters	-	3.144
		P5 Total water consumption in the primary industry	Billion cubic meters	-	3.627
	S: State	S1 Total amount of water resources	Billion cubic meters	+	1.498
		S2 Annual precipitation	mm	+	3.606
		S3 Surface Water Resource Quantity	Billion cubic meters	+	1.296
		S4 Production of aquatic products	Ton	+	1.08
		S5 Number of villages benefiting from tap water	Individual	+	1.916
		S6 Number of reservoirs	Hectare	+	1.676
	I: Impact	I1 The percentage of days throughout the year when the air quality is at or above level 2	(%)	-	7.54
		I2 Cultivated land area	Hectares	+	2.137
		I3 Soil erosion control area	Hectares	+	3.103
		I4 Surface Water Supply Quantity	Billion cubic meters		1.752
	R: Response	R1 Aquaculture area of aquatic products	Hectare	+	3.495
		R2 Quantity of rural centralized water supply projects	Place	+	3.242
		R3 Artificial afforestation area	Hectare	+	2.116
		R4 Total afforestation area	Hectare	+	2.718
		R5 Repetitive amount of surface water and groundwater resources	Billion cubic meters	+	1.403
		R6 Water-saving irrigation area	Hectares	+	0.937

Table 1. Evaluation index system for water ecological security in Northern Xinjiang.

Entropy of details and weight values

$$E_j = -K \sum_{i=1}^m G_{xy} \ln G_{xy} \quad (4)$$

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

Among them, E_j is each indicator's information entropy, ω_j is the weight value, and G_{xy} is the x -th indicator's percentage in the y -th year. $G_{xy} = \frac{W_{ij}}{\sum_{i=1}^x W_{ij}}$. $K = \frac{1}{\ln m}$, $\omega_j \in [0, 1]$.

Standardized standard matrix

Using the feature matrix as a guide, process the data row by row. To determine similarity using the dot product operation or other kernel operations, convert the sample vector into a unit vector. The eigenvalues are lowered to the interval $[0, 1]$ using boundary value information, to create a standard matrix that has been normalized. The following is the precise calculation formula:

$$R = (r_{ij})_{m \times n} \quad (6)$$

$$\text{Where } r_{ij} = W_{ij} \omega_j.$$

Positive and negative ideal solutions

Decision objectives and attribute features are taken into consideration when choosing positive and negative ideal solutions. The following is the calculation formula:

$$r_j^+ = [\max_{xy} |x = 1, 2, \dots, m] = [r_1^+, r_2^+, \dots, r_m^+] \quad (7)$$

And,

$$r_j^- = [\min_{xy} |x = 1, 2, \dots, m] = [r_1^-, r_2^-, \dots, r_m^-] \quad (8)$$

Among them, r_j^+ symbolizes each indicator's optimum positive solution, and r_j^- symbolizes each indicator's negative ideal solution.

Euclidean distance

To assess the water environment's ecological development in northern Xinjiang, we constructed a system that uses Euclidean geometry principles to calculate the distance between the optimal and worst solutions, and based on this, obtain the total score. Its precise mathematical expression is:

$$D^+ = \sqrt{\sum_{y=1}^m (r_{xy} - r_y^+)^2} \quad (x = 1, 2, \dots, n) \tag{9}$$

and.

$$D^- = \sqrt{\sum_{y=1}^m (r_{xy} - r_y^-)^2} \quad (x = 1, 2, \dots, n) \tag{10}$$

Among them, D^+ symbolizes the separation from the ideal (positive ideal) solution and D^- shows how far away the worst (negative ideal) answer is.

Value of proximity

Next, we determine how close every assessed object is to the best answer. The following is the precise formula:

$$T_i = \frac{D^-}{D^+ + D^-} \tag{11}$$

In the formula, T_i is a rough figure that indicates how near the optimal solution the evaluation object I 's water environment capacity for sustainability is, with a value range of $[0,1]$. When $T_i = 1$, it demonstrates that, for aquatic habitats, the location has the highest environmental carrying capacity; When $T_i = 0$, it demonstrates that the site's environmental capacity for water environments is the lowest.

Categorization of water environments' ecological carrying capacities

When establishing the threshold intervals for evaluating the ecological carrying capacity of the aquatic environment, we encountered several challenges, primarily due to the variability in classification methods used across different disciplines. To address this, our study followed the "technical guidelines for evaluation of aquatic biological carrying capacity" issued by the Chinese Society of Environmental Sciences, which provided a standardized reference for ecological classification. Building upon this, we applied the DPSIR model in combination with the entropy-weighted TOPSIS method to objectively evaluate the relative proximity of each unit to the ideal state. To facilitate interpretation and policy guidance, we categorized the normalized results into five levels: unsafe (0–0.2), relatively unsafe (0.2–0.4), critical (0.4–0.6), relatively safe (0.6–0.8), and safe (0.8–1.0). This equal-interval classification scheme is also consistent with practices in related environmental assessment studies and helps to clearly communicate risk levels in the context of water ecological security (Table 2).

Results analysis

Examination of the elements affecting the water environment's ecological improvement

The growth pattern of the water environment ecology in northern Xinjiang from 2014 to 2023 was examined using the DPSIR model. From high to low, the causal chain criteria layer system's spatial differentiation features had the following weight coefficients: S (0.671), D (0.577), I (0.469), S (0.671), and R (0.243) (Table 3). The indicator has a major influence on ecological governance and water resources in northern Xinjiang, as evidenced by the largest relative proximity between the state system and the driving system among them. The comparatively low degree of similarity among the pressure, impact, and reaction systems suggests that the natural ecology, water resource circumstances, and population and economic development in northern Xinjiang have little bearing on the implementation efforts.

There is a favorable growing tendency in the overall ecological mechanism of the aquatic environment in northern Xinjiang. The state system and drive system layers rank first and second in each subsystem layer, respectively, with weight coefficients of 0.671 and 0.577. Ranking from high to low as S6, S5, S4, S3, S2, and S1, the program layer weight coefficient values related to the state system are comparatively high, mostly due to the successful solutions put in place to address issues with the water ecology. The primary cause of the improvement in environmental water quality indicators is the extensive ecological construction improvements made in different parts of northern Xinjiang. The increase in the coefficients of relevant indicators such as total water resources, annual precipitation, and surface water resources reflects the protection of water resource management in northern Xinjiang. Intense water conservation systems, logical resource allocation, and the

Closeness	[0- 0.2)	[0.2–0.4)	[0.4–0.6)	[0.6–0.8)	[0.8- 1)
Ecological carrying capacity of the water environment	unsafe	Less secure	criticality safety	relatively safe	secure

Table 2. Standards for assessing Northern xinjiang's water environment's ecological carrying production level.

Subsystem layer	P_i	Sort results	Indicator layer	G_i	Sort
D	0.577	2	D1	0.760	1
			D2	0.070	21
			D3	0.025	25
			D4	0.037	24
P	0.243	5	P1	0.094	18
			P2	0.104	17
			P3	0.115	16
			P4	0.125	15
			P5	0.135	14
S	0.671	1	S1	0.200	7
			S2	0.208	6
			S3	0.217	5
			S4	0.226	4
			S5	0.233	3
			S6	0.240	2
I	0.469	3	I1	0.048	23
			I2	0.060	22
			I3	0.071	20
			I4	0.083	19
R	0.243	4	R1	0.146	13
			R2	0.155	12
			R3	0.165	11
			R4	0.174	10
			R5	0.182	9
			R6	0.191	8

Table 3. Water environment impact factors in Northern Xinjiang from 2014 to 2023.

development of water conservation initiatives all support the ongoing improvement of state indicators. The slow rate of population growth, which reduces the demand on water resources and the natural environment, is the primary cause of the high weight coefficient value at the driving force level. The ecological security concerns of water resources have been successfully mitigated by the population factor, and the environment surrounding water supplies has been steadily improved.

Throughout the northern Xinjiang region, environmental stress placed on the water ecosystem is showing a constant and stable dynamic tendency. Specifically, the impact system layer, pressure system layer, and reaction system layer weight coefficients are 0.243, 0.469, and 0.243, respectively, and are marginally below the region's typical level of development. The environmental demands of social production and the daily life of the people are the main factors leading to high weight coefficients in the indicator layer of the stress system. From high to low, they are P5, P4, P3, P2, and P1. The main causes of this are the extensive development of water conservation projects that effectively solve the urban water supply issue, the fundamental resolution of the water for consumption and water supply challenges for the permanent population, and the rise in the rate of tap water penetration in rural areas, all of which lessen the strain on northern Xinjiang's water resources. The system layer is ranked in descending order as I4, I3, I2, and I1. This is due to the impact of ecological environmental factors in northern Xinjiang, where problems such as land desertification, soil erosion, and land salinization remain severe. The maintenance of ecological security in the water environment of northern Xinjiang is urgent. At the response system layer, in descending order, they are R1, R2, R3, R4, R5.

This indicates that there are insufficient sources of water because the region's water resource and environmental protection mechanisms are not flawless enough, and because there is little intensification of water resources and sustainable use of them. By reducing the ecological burden placed on the water environment, these factors affect the ecological environment of water resources.

Bearing capacity of the aquatic environment ecologically

Spatiotemporal deductive characteristics of ecological development in water environment

The spatiotemporal deduction characteristics of water environment ecology in northern Xinjiang show a trend of “growth decline rise”. Three phases can be distinguished in the overall shift in relative proximity: the initial phase, which lasted from 2014 to 2018, saw a slight increase in relative proximity; the second stage, which lasted from 2019 to 2021, saw a shift from unsafe to relatively safe relative proximity. But in the third stage of 2022–2023, it will begin to rebound again, and the ecological carrying capacity will gradually shift towards a relatively safe state. Even though northern Xinjiang's aquatic environment's ecological carrying capacity is trending in waves, it is generally growing slowly and continuously moving in the direction of relative safety (Table 4).

Year	D+	D-	Total relative proximity value	Ranking
2014	0.842	0.463	0.355	6
2015	0.805	0.416	0.341	10
2016	0.785	0.467	0.373	5
2017	0.733	0.553	0.430	2
2018	0.676	0.587	0.465	1
2019	0.783	0.425	0.352	7
2020	0.803	0.419	0.343	8
2021	0.823	0.428	0.342	9
2022	0.774	0.523	0.403	3
2023	0.765	0.486	0.388	4

Table 4. Relative closeness of water resources and environment in Northern Xinjiang from 2014 to 2023.

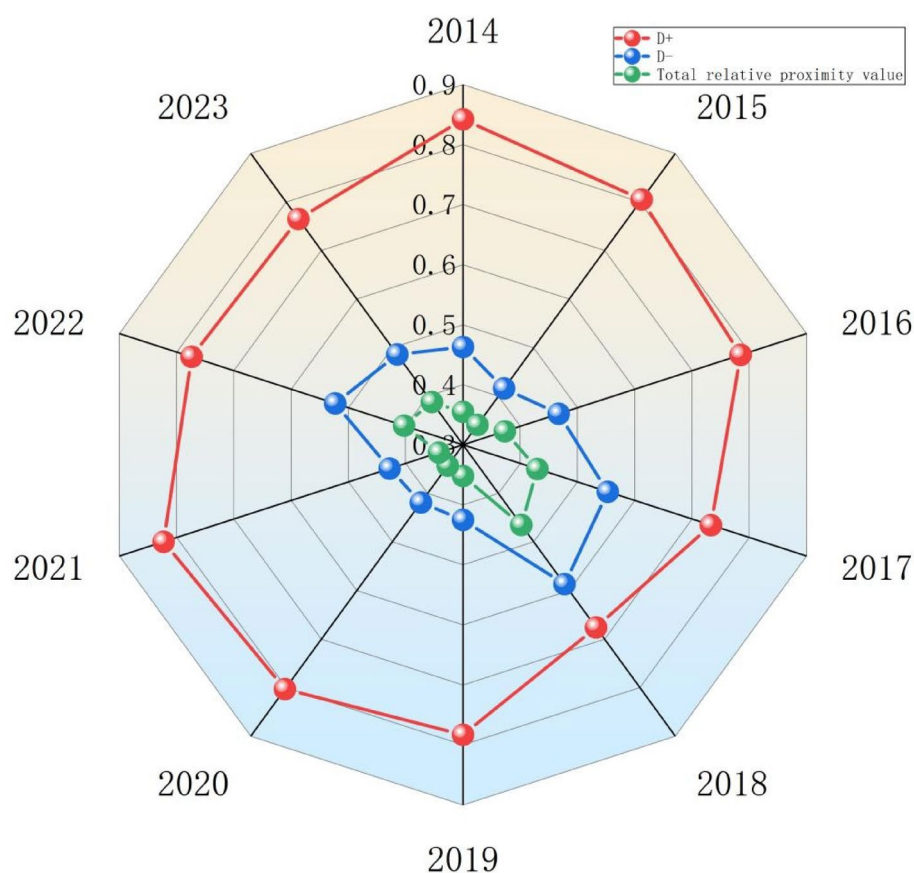


Fig. 3. Radar map of northern Xinjiang's water environment's environmental carrying capacity between 2014 and 2023.

Radar and box plots can visually and clearly display the characteristics of data distribution, and are commonly used for data distribution and rapid identification of outliers. Without being impacted by outliers, box plots provide an accurate way to show the discrete pattern of the data. Therefore, in northern Xinjiang, China, the use of box plots can intuitively reflect the water environment ecological carrying capacity index coefficients for different locations and years. The ecological carrying capacity curve displayed a consistent upward trend from 2014 to 2018, suggesting that ecological carrying capacity has been steadily rising in recent years. There has been a two-year decline since 2018, but it has continued to rise rapidly since 2020, indicating a steady upward trend in the spatiotemporal characteristics of various regions (Figs. 3 and 4). The improvement of the water environment in various regions over the years indicates that there is potential for further development of ecological security in the water environment of northern Xinjiang, and the ecological protection measures in northern Xinjiang have played a good role.

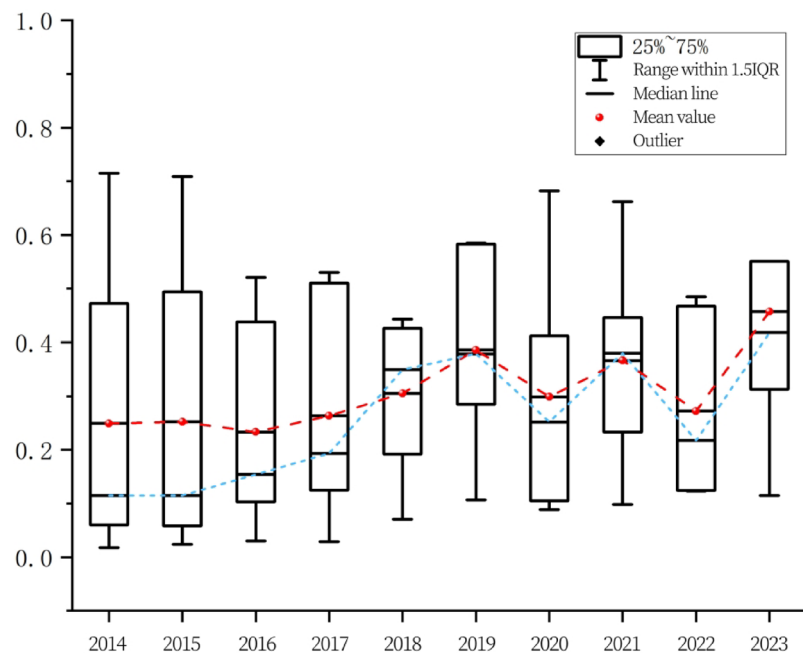


Fig. 4. Box map shows northern Xinjiang’s water environment’s ecological carrying capacity between 2014 and 2023.

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Driving force	0.586	0.449	0.460	0.356	0.311	0.338	0.286	0.378	0.429	0.530
Pressure	0.227	0.206	0.209	0.446	0.513	0.187	0.186	0.272	0.273	0.255
Status	0.231	0.430	0.660	0.468	0.493	0.555	0.505	0.530	0.536	0.505
Impact	0.208	0.238	0.178	0.239	0.360	0.430	0.445	0.444	0.764	0.538
Response	0.227	0.206	0.209	0.446	0.513	0.187	0.186	0.272	0.273	0.255
comprehensive	0.355	0.341	0.373	0.43	0.465	0.352	0.343	0.342	0.403	0.388

Table 5. Change index of closeness to ecological carrying capacity of water environment in Northern Xinjiang from 2014 to 2023.

Spatial deduction characteristics of water environment ecological development

To examine the spatiotemporal evolution of the features of the water surrounds’ ecological sustaining capacity in Northern Xinjiang, the trend of regional development differences was analyzed, and suggestions for improving overall development were made from a regional coordinating standpoint. According to the findings of the evaluation of the water environment’s capacity for sustainability in many northern Xinjiang regions between 2014 and 2023, we used a heat map presentation and ArcMap software platform, and classified the various regions in northern Xinjiang according to their development level thresholds. Low, alert, good, and exceptional are the classifications for these levels. Ranging from low to high. This creates a comparative differentiating chart that illustrates different types of regional development.

The spatial analysis coefficient of variation and relative proximity assessment indicators in the northern part of Xinjiang have demonstrated a slow upward trend over the last ten years from the standpoint of spatial inference (Table 5). We have produced a heatmap to visually represent the regional differences in the water environment’s ecological potential across the various northern Xinjiang regions. This heatmap can clearly highlight the differential characteristics of different regions and help us identify the distribution trends of high and poor ecological carrying capacity levels in the associated regions and water environment. In addition, heatmaps have significant advantages in displaying geographical change patterns, particularly when the particular data distribution patterns (such as normal distribution or other distributions) are unclear; heatmaps can more intuitively reveal these changes.

The findings indicate that the degree of ecological carrying capacity development in Northern Xinjiang in 2014 from high to low is: Urumqi City (0.523), Tacheng Prefecture (0.477), Hami City (0.474), Turpan City (0.387), Karamay City (0.325), Ili Kazakh Autonomous Prefecture (0.405), Changji Hui Autonomous Prefecture (0.463), Bortala Mongolian Autonomous Prefecture (0.44), and Altay Prefecture (0.318) (Table 6; Fig. 5). The ecological carrying capacity enhancement level in 2023 is Tacheng (0.527), which ranges from high to poor. Altay Prefecture (0.503), Ili Kazakh Autonomous Prefecture (0.5), Changji Hui Autonomous Prefecture (0.475), Hami

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ili Kazakh Autonomous Prefecture	0.405	0.466	0.466	0.542	0.511	0.431	0.420	0.474	0.484	0.500
Tacheng prefecture	0.477	0.512	0.566	0.464	0.410	0.459	0.488	0.446	0.438	0.527
Altay prefecture	0.318	0.342	0.399	0.404	0.549	0.403	0.463	0.455	0.446	0.503
Karamay city	0.325	0.425	0.381	0.339	0.450	0.330	0.345	0.389	0.386	0.436
Bortala Mongolian autonomous prefecture	0.440	0.390	0.490	0.377	0.333	0.462	0.479	0.501	0.452	0.454
Changji Hui autonomous prefecture	0.463	0.427	0.468	0.442	0.436	0.427	0.362	0.383	0.384	0.475
Urumqi city	0.523	0.508	0.545	0.494	0.441	0.412	0.452	0.408	0.444	0.448
Hami city	0.474	0.519	0.535	0.539	0.507	0.357	0.388	0.358	0.411	0.457
Turpan city	0.387	0.426	0.461	0.431	0.439	0.398	0.450	0.472	0.412	0.421

Table 6. Relative similarity index of water resources security in different regions of Northern Xinjiang from 2014 to 2023.

City (0.457), Bortala Mongolian Autonomous Prefecture (0.454), Urumqi City (0.448), Karamay City (0.436), Turpan City (0.421). These measurements are the main basis for evaluating the advantages and disadvantages of the environmental carrying capacity in northern Xinjiang. In Northern Xinjiang, the ecological resistance of the water environment is gradually convergent across regional inequalities, as indicated by the data presented by the coefficient of variation. They use relative proximity ratings to quantitatively rank the ecological resistance and level of development of the aquatic environment in various province regions. The biochemical carrying capability of the water surroundings varies in geographical arrangement in northern Xinjiang, with Urumqi, Hami, and Ili Kazakh Autonomous Prefecture exhibiting very good performance and comparatively high growth levels.

The aquatic environment’s ecological carrying capacity in northern Xinjiang exhibited a trend of development that was “high in the southwest and low in the northeast” between 2014 and 2023 (Fig. 6). With an average score of 0.478, Tacheng’s ecological strength quantitative evaluation comes in first, suggesting a high level of biological carrying capacity. Ili Kazakh Autonomous Prefecture and Urumqi rank second and third, respectively, with average values of 0.475 and 0.469, and they have also made significant progress in improving their ecological resilience in the watery environment. The water environment in the Northern Xinjiang watershed has an ecological load capacity that is at or above the leve. According to the quantitative computation results. This is a result of Northern Xinjiang’s efforts to enhance the unified leadership structure for water resources management and further reform the system^{15,16}. Strengthen the coordinated governance between local and corps, river basins and regions in northern Xinjiang, and provide institutional and mechanism guarantees for scientific allocation, precise scheduling, and intensive and economical utilization of water resources. The biological carrying potential of the water environment in northern Xinjiang has steadily increased as a result of the management system’s ongoing standardization and implementation¹⁴.

Discussion

This article focuses on the creation of water supply protection index methods and level standards in nine regions of northern Xinjiang. Use the The topsis team fuzzy assessment approach to evaluate the security of water supplies. Studied how the security of water resources has changed throughout time and space in terms of driving, pressure, status, influencing, and response factors.

In this study, a total of twenty-five influencing factors were used. The population that has the biggest influence on water resources is the registered dwelling population (D1), indicating that the population has a major influence on the ecological security of water resources. Indicators such as per capita usage of water (P1), residential water demand (P2), and others demonstrate how human activity affects water resources., rural centralized water supply amount (R2), and water-saving irrigation area (R6) (Fig. 7). The impact of humans on nature is steadily growing as society develops. As the economy grows, we should increase the rate at which water resources are used and make the most of them to safeguard the ecological environment. To increase water resources’ recycling and sustainable usage, as well as to use them wisely¹⁷. The state indicator, which comprises indicators like total water supply (S1), yearly precipitation (S2), and aquatic product production (S4), has the greatest impact on water resources’ ecological security. This suggests that the primary factor limiting the maximum capacity of the water supply in northern Xinjiang is water shortage. The water resources in northern Xinjiang have a distinct spatial distribution pattern that is limited by the natural geographical context^{18,19}. Its geographical distribution is extremely uneven, with poor matching with land resources, which in turn affects the ecological security of water supply²⁰.

This study employs the DPSIR paradigm to construct an ecological assessment index system for evaluating the water environment in northern Xinjiang. The weighted TOPSIS model is applied to organize and analyze data samples, thereby providing a systematic explanation of the “driving force–pressure–state–impact–response” chain reaction within the region’s water ecosystem. Furthermore, ArcMap was used to examine the spatial distribution, spatial inference characteristics, and developmental trends of ecological water environment carrying capacity. This approach helps to overcome the limitations of single-method data representation and enhances the comprehensiveness of comparative analyses across different regions.

The results indicate that the ecological water quality carrying capacity in northern Xinjiang is significantly lower than the national average²¹. Although the region possesses relatively abundant water resources and a high

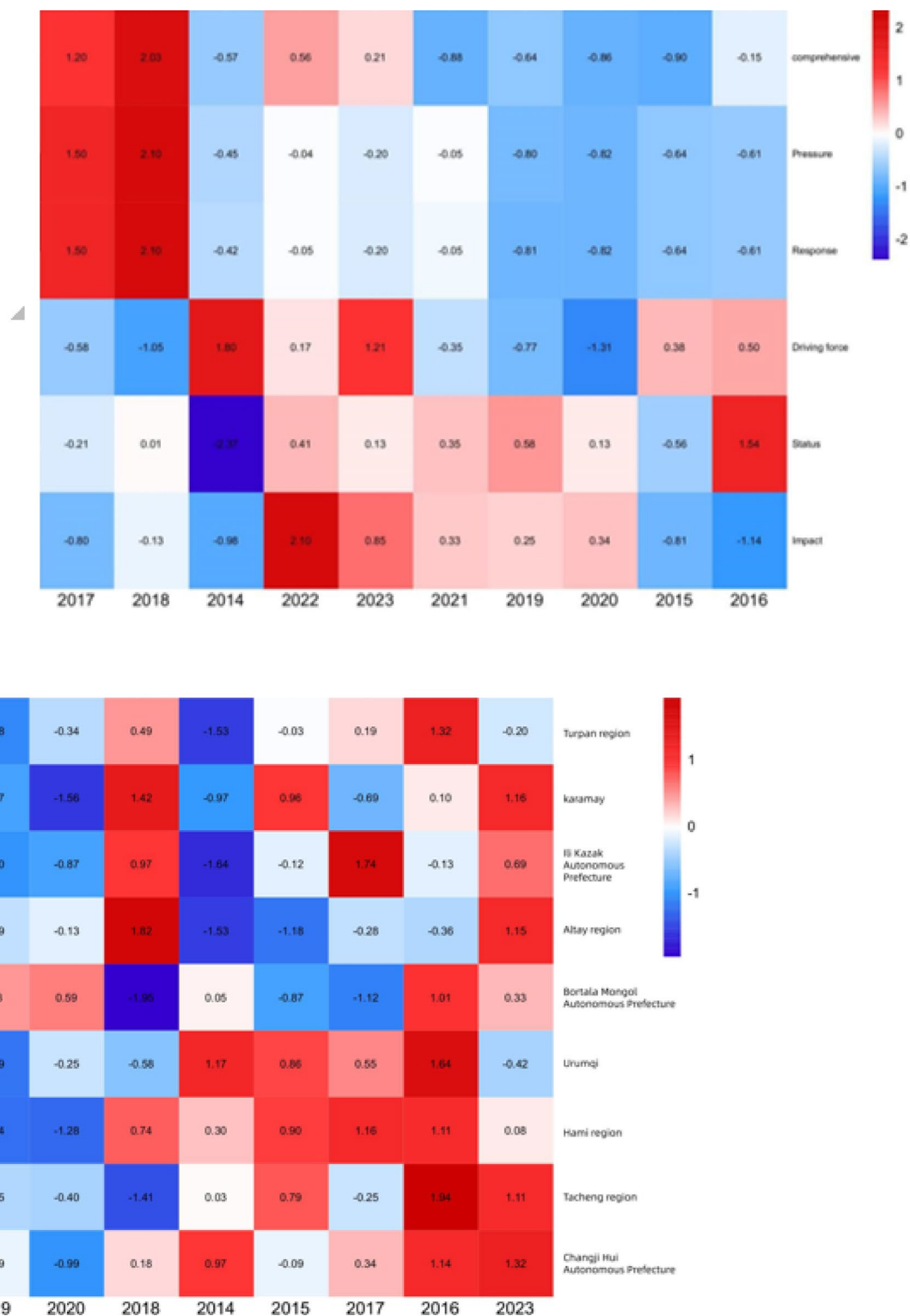


Fig. 5. An environmental carrying capacity map depicting the water environment's thermal correlation in the northern Xinjiang area.

per capita water resource availability^{22,23}, its natural environment is constrained by arid climatic conditions and low precipitation^{24,25}.

To address these challenges, northern Xinjiang should adhere to the principle of rational water resource allocation, work to mitigate regional ecological pressures, improve residents living conditions and environmental quality, and pursue a path of more comprehensive and coordinated development.

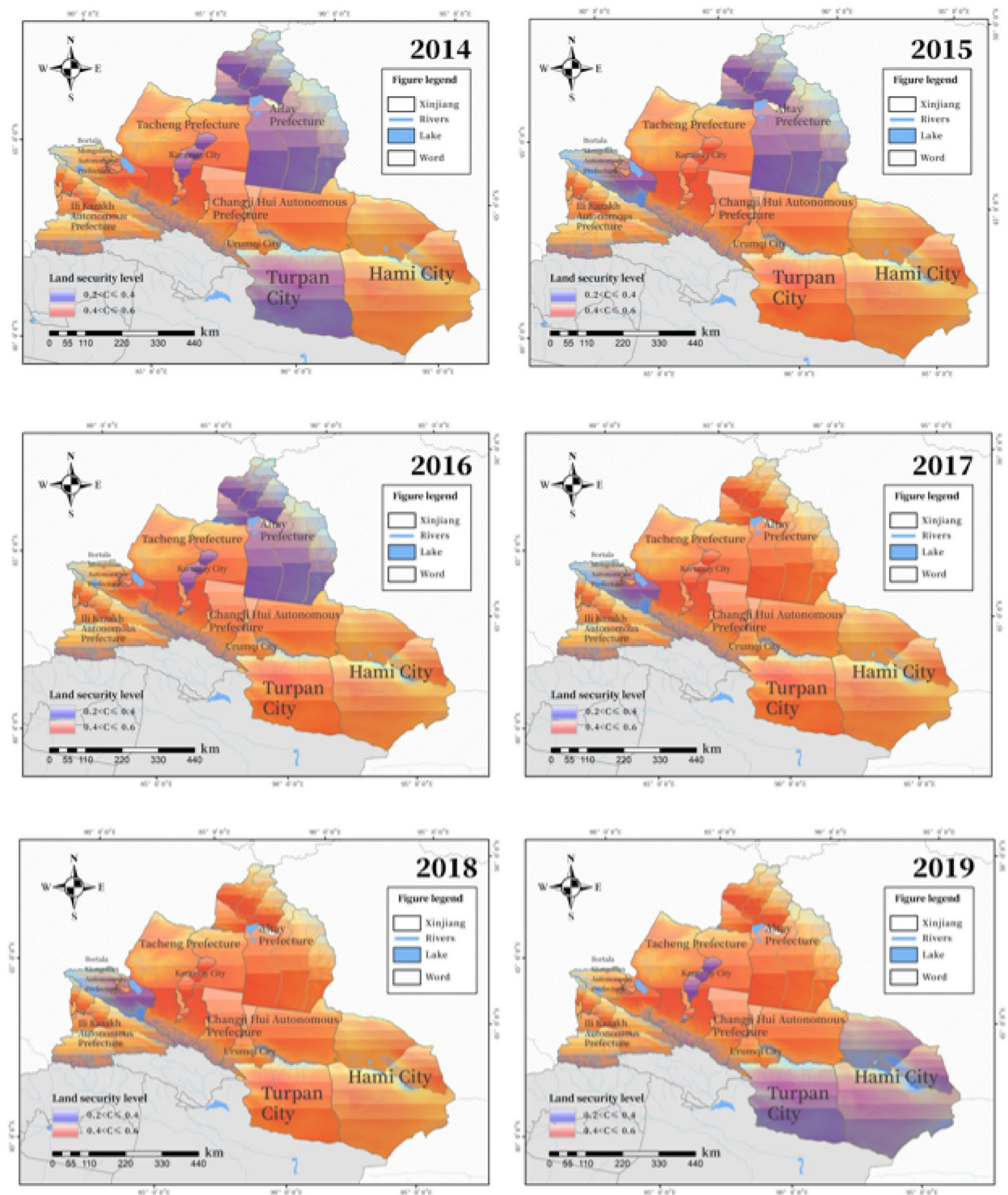


Fig. 6. Changes in spatial and temporal water environment ecological security in various counties and cities. Maps were drawn by authors, using ArcGIS 10.8 (Environmental Systems Research Institute, USA. <https://www.esri.com/>), created based on China's 2022 prefecture and city administrative boundaries (<http://www.resdc.cn/>), Gaode map data, based on traditional village point data ((<https://www.gov.cn/> & <https://www.ah.gov.cn/>)).

Conclusions

Using the TOPSIS and DPSIR theoretical frameworks, this study assessed the carrying capacity of water resources in northern Xinjiang in the context of rapid urban expansion. It constructed a comprehensive evaluation system integrating water, economy, society, and environment, offering a scientific basis for sustainable water resource management and planning in the region.

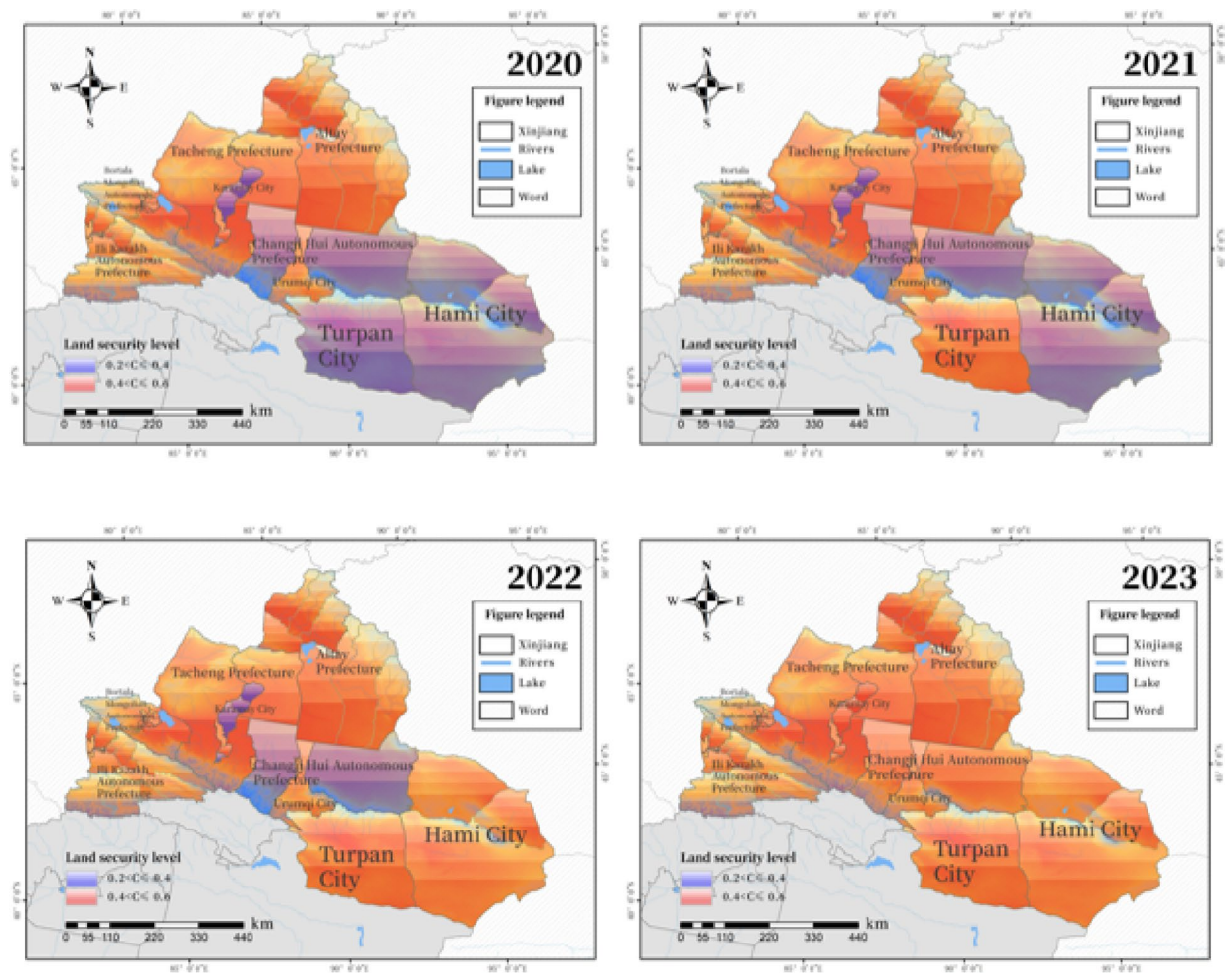


Fig. 6. (continued)

The study yields the following key findings:

- (1) Weight differentiation in DPSIR indicators revealed a clear stratification: State (S) factors carried the highest importance, followed by Driving force (D), Impact (I), Response (R), and Pressure (P). Water scarcity, identified as a key status indicator, poses the most significant threat to the ecological security of the region. The spatial mismatch between water and land resources, shaped by the region's natural geography, also limits carrying capacity.
- (2) Temporal analysis (2014–2023) revealed a 'rise–decline–rebound' trajectory in ecological carrying capacity. Recent recovery, particularly after 2022, can be attributed to reforms such as the unified management of the 'six rivers and one lake,' water-saving initiatives, and improvements in water-related infrastructure.
- (3) Spatially, the southwest (e.g., Tacheng, Ili, Urumqi) performed better due to stronger governance and investment. However, areas such as Karamay continue to face high ecological pressure due to overexploitation and concentrated human activity.

Despite some improvements in recent years, the region still faces severe challenges. In the future, priority should be given to promoting water-saving measures, developing adaptive infrastructure, and optimizing spatial planning. Meanwhile, integrating multi-scale spatial analysis and dynamic monitoring will help further strengthen the scientific foundation of ecological water management in northern Xinjiang.

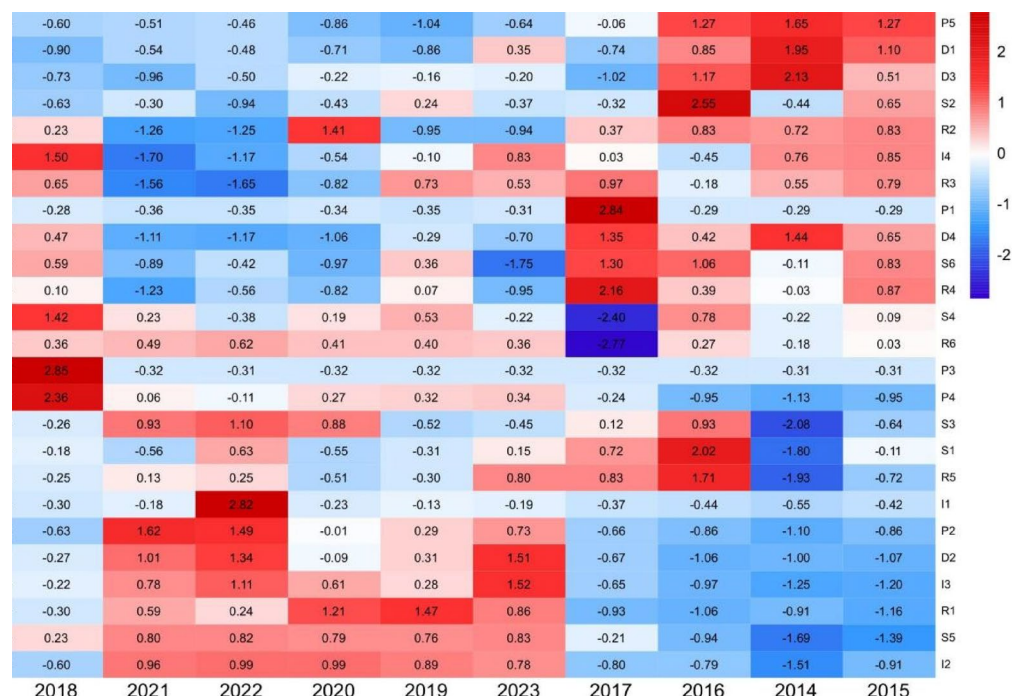


Fig. 7. Thermal map of water environment impact factors in Northern Xinjiang.

Data availability

The experimental data used to support the findings of this study are included in the article.

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Author contributions

Conceptualization, H.G. and H.Z.; methodology, H.Z. and J.H.; software, H.G.; validation, H.G. and Y.G.; formal analysis, Y.G.; investigation, J.H. and Y.G.; resources, J.H.; data curation, H.G.; writing—original draft preparation, Y.G. and J.H.; writing—review J.H. and Y.G.; visualization, H.Z.; supervision, Y.G.; project administration, Y.G. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Y.G.

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