Postprint: Analysis of Spatiotemporal Variations and Influencing Factors of Economic-Ecological Resilience of Water Resources in Xinjiang Based on the PSR Model

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Abstract

Taking the 14 prefectures in Xinjiang's arid region as an example, an evaluation index system was constructed based on the Pressure-State-Response (PSR) model, the entropy weight method was employed to calculate index weights, the comprehensive evaluation method and kernel density analysis were adopted to analyze the spatiotemporal distribution characteristics of pressure-state-response resilience in the 14 prefectures, and the geographical detector was utilized to detect the main influencing factors and factor interactions affecting water resources-economic-ecological resilience in Xinjiang. The results indicate: (1) From 2010 to 2020, the pressure resilience evaluation index in most prefectures of Xinjiang showed a declining trend, with the pressure resilience level of Kizilsu Kirghiz Autonomous Prefecture decreasing from high resilience to medium resilience. State resilience, response resilience, and comprehensive resilience all exhibited a continuously strengthening trend, with resilience levels also improving. (2) From 2010 to 2020, the kernel density of pressure-state-response resilience in Xinjiang's prefectures displayed a spatial pattern of alternating high and low values, with the southwestern region higher than the northeastern region. From the three-dimensional perspective, high-value areas of pressure resilience kernel density spread from the southwestern region toward the central region, with relatively concentrated distribution; high-value areas of state resilience and response resilience kernel density spread from the northern region to the southern region, with relatively dispersed distribution. In 2020, the differences in kernel density of comprehensive resilience, state resilience, and response resilience within the region showed a continuously narrowing trend, while spatial differences in pressure resilience kernel density were relatively significant. (3) The influence of industrial structure, per capita GDP, and ecological self-purification capacity factors on water resources-economic-ecological resilience strengthened, while factors such as anthropogenic disasters weakened. The interaction effects of factors such as industrial structure, ecological self-purification capacity, and social consumer goods retail sales were stronger than the influence of single factors on system resilience. Among the pairwise interactions of various influencing factors, the number of nonlinear enhancement relationships was greater than the number of dual-factor enhancements.

Full Text

Preamble

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Spatiotemporal Differences and Influencing Factors of Economic and Ecological Resilience of Water Resources in Xinjiang Based on the PSR Model

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Abstract: Taking 14 prefectures in the Xinjiang arid zone as examples, this study constructs an evaluation index system based on the Pressure-State-Response (PSR) model, employs the entropy weight method to calculate index weights, and utilizes the comprehensive evaluation method and kernel density analysis to examine the spatiotemporal distribution characteristics of pressure-state-response resilience. Geographic detectors are then applied to detect the main influencing factors and factor interactions affecting water resources' economic and ecological resilience in Xinjiang. The results show that: (1) From 2010 to 2020, the pressure resilience evaluation indices in most prefectures of Xinjiang exhibited a declining trend, with Kizilsu Kirgiz Autonomous Prefecture's pressure resilience level decreasing from high to moderate. In contrast, state resilience, response resilience, and comprehensive resilience all showed continuous enhancement trends, with resilience levels improving accordingly. (2) From 2010 to 2020, the kernel density of pressure-state-response resilience across Xinjiang prefectures displayed a spatially staggered distribution pattern, with higher values in the southwest than in the northeast. Analyzing the three dimensions reveals that high-value areas of pressure resilience kernel density spread from the southwest to the central region, showing relatively concentrated distribution. High-value areas of state resilience and response resilience kernel density spread from the north to the south, showing relatively dispersed distribution. From 2010 to 2020, differences in kernel density of comprehensive resilience, state resilience, and response resilience within the region showed a continuously narrowing trend, while spatial differences in pressure resilience kernel density remained significant. (3) The influence of industrial structure, per capita GDP, and ecological self-purification capacity on water resources' economic and ecological resilience has strengthened, while the impact of human-induced disasters and other factors has weakened. The interactive effects of industrial structure, ecological self-purification capacity, and retail sales of social consumer goods are stronger than the influence of single factors on system resilience. Among the pairwise interactions of various influencing factors, the number of nonlinear enhancement relationships exceeds the number of two-factor enhancements.

Keywords: PSR model; kernel density; geographic detector method; Xinjiang

1 Introduction

With rapid economic development, frequent water resource shortages and severe ecological pollution have emerged, posing challenges to the sustainable development of water resources, economic, and ecological systems. The natural environment forms the foundation for economic development, while economic demand for water resources constitutes a prerequisite for sustained economic growth. However, these systems are simultaneously subjected to disturbances and shocks from both internal and external risks. On one hand, there are natural disasters such as droughts and earthquakes; on the other hand, human-induced disasters arising from extensive development models have led to ecological and water system imbalances. In response to environmental damage from pollutants and imbalances between water supply and demand generated during economic development, regional water resources, economic, and ecological systems urgently need to enhance their resilience to limit system vulnerability and promote long-term sustainability. Against this backdrop, studying the interrelationships among water resources, economic, and ecological resilience is particularly important, providing theoretical foundations and empirical support for achieving coordinated development of the three systems' resilience.

Domestic and international scholars have conducted extensive research on water resources-economic-ecological system resilience. Regarding research perspectives, Zhao et al. [?] analyzed the resilience level of Zhengzhou's water resources system using a two-level fuzzy comprehensive evaluation method. Liu et al. [?] examined the resilience level of Qingdao's water supply system against flood and drought disasters. Yuan et al. [?] analyzed the resistance and recovery capacity of the economic system in the Yangtze River Economic Belt. Ma et al. [?] evaluated climate resilience levels of ecosystem communities based on sponge cities, community, and ecosystem adaptation theories. Regarding evaluation indicators, Tang et al. [?] constructed an indicator system for agricultural economic resilience from three dimensions: risk resistance, adaptive adjustment, and innovative transformation. Tao et al. [?] analyzed ecological resilience in the Yangtze River Delta region. Sun et al. [?] evaluated China's regional water resources system resilience from three aspects: economic factors, social factors, and resource-environment factors, selecting 23 indicators. Regarding research methods, scholars have employed spatial Markov chains [?], comprehensive evaluation methods [?], analytic hierarchy process [?], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [?], entropy method [?], and other approaches to analyze spatiotemporal evolution characteristics of urban resilience. Lü et al. [?] used the STIRPAT model to analyze influencing factors of ecological resilience in the Yangtze River Delta. Zhang et al. [?] identified main influencing factors of China's agricultural economic resilience using geographic detectors.

However, three primary gaps remain in existing research. First, correlation analysis of water resources-economic-ecological system resilience remains in its preliminary exploration stage, and resilience indicator system construction lacks theoretical model support. Second, there are few empirical studies on multi-system resilience influencing factors and their interactions. Third, as a typical arid and ecologically fragile region in northwest China, Xinjiang presents strong practical significance for studying water resources-economic-ecological resilience. In light of these gaps, this study draws on the Pressure-State-Response (PSR) model to deconstruct the entire process of system response to disturbances, constructs a water resources-economic-ecological resilience indicator system, employs comprehensive evaluation and kernel density analysis to examine spatiotemporal differences in pressure-state-response resilience across Xinjiang prefectures, and applies geographic detectors to analyze the main influencing factors and factor interactions affecting water resources-economic-ecological resilience, aiming to provide references for resilience construction.

1.1 Study Area Overview

Xinjiang Uygur Autonomous Region is located in northwest China between 73°40 –96°18 E and 34°25 –48°10 N, covering a total area of 1.66$×10^{6}$ km^{2}. The region comprises 14 prefectures and autonomous prefectures (Fig. [Figure 1: see original paper]). The area features a typical temperate continental arid climate with an average annual temperature of 4–13°C and precipitation of 89–208 mm. As an ecologically fragile zone, Xinjiang exhibits uneven spatiotemporal distribution of water resources with significant north-south differences, sparse surface vegetation, relatively harsh ecological conditions, severe desertification, and land salinization. In 2020, Xinjiang's GDP reached 1.38$×10^{12}$ yuan, a 6.12-fold increase from 2000. The contribution rates of the primary and secondary industries to economic growth were 18.0% and 79.0%, respectively, far exceeding the tertiary industry's economic contribution.

1.2 Data Sources

Statistical data primarily originate from government departments including the Xinjiang Water Resources Department and Xinjiang Statistical Bureau, as well as the *Xinjiang Statistical Yearbook (2011–2021)*, *Xinjiang Water Resources Bulletin (2010–2020)*, and statistical bulletins on national economic and social development and environmental status from various prefectures and cities. Missing data were supplemented through linear interpolation.

1.3 Water Resources-Economic-Ecological Resilience Process in the PSR Model Context

The PSR model, jointly established by the Organisation for Economic Co-operation and Development (OECD) and the United Nations Environment Programme (UNEP), is a conceptual framework commonly used for environmental issues [**?**]. Resilience, also known as elasticity or recovery capacity, originally refers to an object's ability to return to its original state after external force application. In this process, when subjected to risk shocks, water resources, economic, and ecological systems maintain their stability and restore normal operational levels through material, information, and energy exchange. Through recovery and adaptive capacities, crises are transformed into opportunities, enabling innovative development and other stages [**?**]. Based on this understanding, resilience is divided into three stages: pre-disturbance, during disturbance, and post-disturbance, corresponding to pressure, state, and response elements. Therefore, combining the PSR model with the resilience operation process among systems, the process of water resources-economic-ecological system resilience can be deconstructed as follows: (1) **Pressure** refers to internal and external dual disasters (e.g., drought, earthquakes, water pollution, soil pollution, atmospheric pollution) that threaten normal system operation during urban development. (2) **State** refers to changes in each subsystem's status under pressure shocks and their coupling to present collective pressure resistance capacity, such as total water resources, primary industry proportion, secondary industry proportion, tertiary industry proportion, etc. (3) **Response** refers to human intervention and regulation of urban subsystems to restore them to equilibrium or generate new equilibrium, such as government management capacity and efficiency, pollution control investment, scientific and technological innovation input, and environmental supervision (Fig. [Figure 2: see original paper]).

1.4 Indicator System

Based on the PSR model, appropriate evaluation indicators must be selected for the three dimensions of pressure, state, and response while adhering to principles of objectivity, rationality, and feasibility [**?**]. Drawing on relevant research findings [**?**, **?**] and Xinjiang's actual development conditions, this study constructs a water resources-economic-ecological resilience evaluation indicator system (Table). The pressure dimension selects 7 indicators to measure natural and human-induced disaster threats facing water resources-economic-ecological systems. The state dimension selects 11 indicators: 4 indicators assess water resources status, 4 indicators assess economic status, and 3 indicators assess ecological status. The response dimension selects 10 indicators: 6 indicators evaluate the recovery capacity of water resources-economic-ecological resilience, and 4 indicators evaluate adaptive capacity.

1.5 Methods

1.5.1 Comprehensive Evaluation Method The entropy weight method is used to determine indicator weights, with relevant calculation formulas referenced in the literature [**?**]. The comprehensive evaluation method measures pressure-state-response resilience, with calculation formulas as follows:

$$Y_i = \sum_{j=1}^{N} \omega_j X'_{ij} \quad (i = 1, 2, 3)$$

where Y_i represents the pressure, state, and response resilience evaluation indices, respectively, with a value range of [0, 1]; X'_{ij} is the standardized indicator value; ω_j is the weight of each indicator; and N is the number of indicators.

$$T_j = \alpha Y_1 + \beta Y_2 + \gamma Y_3$$

where T_j is the pressure-state-response comprehensive resilience evaluation index; α, β, and γ are undetermined coefficients. Assuming the three systems are equally important, let $\alpha = \beta = \gamma = 1/3$.

Referencing relevant research [**?**], resilience levels are divided into 5 grades (Table). For kernel density estimation, resilience levels are redefined as shown in Table .

1.5.2 Kernel Density Estimation Kernel density estimation is a nonparametric statistical density estimation method that clearly reflects the spatial distribution density of research elements [**?**]. Based on this, this study employs kernel density estimation to reveal the spatial distribution characteristics and regional agglomeration patterns of pressure resilience, state resilience, response resilience, and comprehensive resilience across Xinjiang's 14 prefectures. Higher kernel density values indicate higher resilience levels. The calculation formula is:

$$f(y_i) = \frac{1}{nr} \sum_{i=1}^{n} k\left(\frac{y_i - y_j}{r}\right)$$

where $f(y_i)$ is the kernel density value at the valuation position; k is the kernel function; r is the search radius (bandwidth); n is the sample size; and d_i is the distance between points located between y_i and y_j.

1.5.3 Geographic Detector Model Geographic detector is a statistical method for detecting spatial differentiation and revealing its underlying driving factors, capable of analyzing both numerical and qualitative data [**?**]. It includes factor detection and interaction detection.

Factor detection examines the spatial differentiation of attribute Y and the extent to which a factor X explains the spatial differentiation of attribute Y, measured by the q-value with a range of [0, 1]. A larger q-value indicates stronger explanatory power of X on Y. The calculation formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where $h = 1, 2, \dots, L$ represents the stratification of variable Y (resilience) or factor X (influencing factor), i.e., classification or zoning; N_h and N are the unit numbers in layer h and the entire region, respectively; and σ_h^2 and σ^2 are the variances of Y values in layer h and the entire region, respectively.

Interaction detection identifies whether the interaction between two influencing factors X_1 and X_2 increases or decreases the explanatory power on dependent variable Y, or whether these factors independently affect Y. This is primarily determined by comparing $q(X_1) + q(X_2)$ with $q(X_1 \cap X_2)$. The interaction types are defined in Table .

2 Results and Analysis

2.1 Temporal Difference Analysis

2.1.1 Temporal Variation Characteristics From 2010 to 2020, pressure resilience indices in most Xinjiang prefectures showed a declining trend (Table), while a few areas improved. Karamay City's pressure resilience index growth rate was 14.78%, increasing from 0.229 in 2010 to 0.263 in 2020. As an industrial city rich in petroleum resources, Karamay's oil extraction and refining scales have continuously expanded, leading to significant increases in two negative indicators: industrial solid waste discharge and fertilizer application intensity. Consequently, the pressure resilience index rose rapidly, negatively impacting system development. Kizilsu Kirgiz Autonomous Prefecture's pressure resilience index decreased from 0.407 (2010) to 0.360 (2020), with its resilience level dropping from high to moderate, indicating that while human-induced disaster impacts on Kizilsu's development have weakened, sharp precipitation reductions have also exerted pressure on its development.

From 2010 to 2020, state resilience indices across Xinjiang prefectures generally increased, with some areas showing significant growth. Aksu Prefecture's state resilience index rose from 0.264 in 2010 to 0.414 in 2020, representing the largest increase. Its resilience level upgraded from lower to higher resilience, indicating that Aksu's ecosystem status is relatively optimal. Its high forest coverage rate, per capita park green area, and soil erosion control area demonstrate that the ecological status is less susceptible to external disturbances breaking its internal balance, with a relatively stable ecological structure. Additionally, sufficient agricultural water use, industrial water use, and water supply indicate favorable water resources status in Aksu, with water use degree and structure conducive to enhancing water resources state resilience. Furthermore, steady increases in per capita GDP, fixed asset investment, total import-export trade, and tertiary industry proportion have boosted regional economic capital stock and economic vitality, which are also fundamental elements for enhancing water resources state resilience and ecological state resilience.

From 2010 to 2020, response resilience indices in Xinjiang prefectures increased substantially, indicating that all prefectures have implemented active response measures and strategies to cope with pressure shocks, changing current states to better adapt to urban development. Urumqi City's response resilience index grew from 0.314 (2010) to 0.356 (2020), a 13.35% increase, with its resilience level jumping from lower to high resilience. This demonstrates that in the recovery capacity subsystem, government management capacity and efficiency are relatively high, pollution control investment is substantial, and the system exhibits strong positive feedback on environmental governance, thereby enhancing response resilience. Moreover, Urumqi's significant expenditure on research and development has strengthened its development capacity, enabling it to recover more quickly from unbalanced states and even elevate to a new high-level equilibrium.

Comprehensive resilience indices across Xinjiang prefectures from 2010 to 2020 showed an upward trend. Ranking from highest to lowest in 2020: Hotan Prefecture (0.383), Kizilsu Kirgiz Autonomous Prefecture (0.376), Aksu Prefecture (0.369), Urumqi City (0.356), Altay Prefecture (0.352), Karamay City (0.350), Bortala Mongol Autonomous Prefecture (0.345), Bayingolin Mongol Autonomous Prefecture (0.340), Kashgar Prefecture (0.336), Turpan City (0.332), Hami City (0.330), Tacheng Prefecture (0.328), Changji Hui Autonomous Prefecture (0.326), and Ili Kazakh Autonomous Prefecture (0.324). Hotan Prefecture ranked first in comprehensive resilience, indicating strong self-resistance capacity of water resources status, economic status, and ecological status under natural and human-induced disaster shocks, coupled with active responses from government, enterprises, and residents, substantial environmental governance investment, and enhanced scientific and technological innovation capacity, all contributing to restoring water resources-economic-ecological system resilience.

2.1.2 Spatial Difference Analysis To further analyze spatial differences in Xinjiang prefectures' resilience, data from 2010, 2015, and 2020 were selected. Using ArcGIS 10.2, kernel density analysis was applied to examine the spatial distribution of pressure-state-response resilience comprehensive indices across Xinjiang prefectures. The spatial patterns exhibit the following characteristics:

Pressure Resilience: From 2010 to 2020, pressure resilience kernel density values across prefectures ranged from 0 to 0.435$×10^{{-4}, 0to0.418×10}{-4}, and 0to0.450×10^{-4}$, respectively, indicating moderate resilience levels and strong impacts from natural and human-induced disasters on system development in some prefectures. The distribution pattern shows high density in the southwest and low density in the northeast, with high-density areas primarily located in Kizilsu Kirgiz Autonomous Prefecture and Kashgar Prefecture, where drought, water pollution, and soil pollution impacts are strong, breaking the inherent balance of water resources, economic, and ecological systems and causing system disorder. From 2010 to 2020, high-density pressure resilience areas spread from the southwest to Tacheng Prefecture and Turpan City in the northeast. These regions are characterized by severe drought, low environmental efficiency, and large pollution discharge, thus developing from low-density to high-density pressure areas.

State Resilience: From 2010 to 2020, state resilience kernel density values ranged from 0 to 0.324\$$\times10^{\{-4\},0to0.414\times10}\{-4\},and0to0.447\times10^{\{-4\},respectively,withresiliencelevelsshiftingfromlower}$ 4}–0.299×10^{-4}\$ to 0.191\$$\times10^{\{-4\}-0.447\times10}$\{-4\}\$, indicating enhanced shock resistance capacity.

Response Resilience: From 2010 to 2020, response resilience kernel density values ranged from 0 to 0.263\$$\times10^{\{-4\},0to0.457\times10}\{-4\},and0to0.693\times10$^{-4}\$, respectively, with resilience levels jumping from lower to higher, demonstrating strengthened capacity to restore resilient operation levels. The distribution pattern shows high density in the central region and low density in the north and south, with Karamay City and Changji Hui Autonomous Prefecture at high-value levels, Aksu Prefecture, Bayingolin Mongol Autonomous Prefecture, and Altay Prefecture at medium-value levels, and Kashgar and Hotan prefectures at low-value levels, showing significant spatial differences. From 2010 to 2020, high-density response resilience areas were relatively dispersed, with Tacheng Prefecture, Karamay City, Changji Hui Autonomous Prefecture, and Urumqi City at leading levels. Kizilsu Kirgiz Autonomous Prefecture, Kashgar Prefecture, and Hotan Prefecture were at medium levels, while Hami City and Bayingolin Mongol Autonomous Prefecture were at low levels. However, all prefectures showed increased response resilience kernel density compared to 2010, indicating that enhanced economic development, resource conditions, and environmental quality have improved system anti-interference capacity. In 2020, the spatial pattern of response resilience kernel density showed high density in the northeast and low density in the southwest, with overall improvement across prefectures. Kizilsu Kirgiz Autonomous Prefecture, Kashgar Prefecture, and Hotan Prefecture showed slight growth trends, indicating that increased pollution control investment and enhanced scientific and technological innovation capacity have promoted improved recovery and adaptive capacities after system disturbances, enabling system resilience to reach original or even higher adaptive operation levels.

Comprehensive Resilience: From 2010 to 2020, comprehensive resilience kernel density values ranged from 0 to 0.263\$$\times10^{\{-4\},0to0.457\times10}$\{-4\}, $and0to0.383\times10$^{-4}\$, respectively, with resilience levels shifting from lower to moderate, indicating overall improvement. Kizilsu Kirgiz Autonomous Prefecture, Kashgar Prefecture, and Ili Kazakh Autonomous Prefecture counties and cities belong to high-value areas of comprehensive resilience kernel density, with spatial distribution weakening from southwest to northeast.

The 2020 comprehensive resilience high-density distribution differs from 2010, showing a pattern of high density in the northeast and low density in the southwest. In 2020, high-density areas are more dispersed, with more regions at high-density levels, indicating that strengthened pollution prevention efforts and enhanced environmental awareness have effectively increased system capacity to resist pressure shocks and restore normal operation levels.

2.2 Analysis of Influencing Factors

2.2.1 Construction of Detection Factors Using geographic detector factor detection, this study compares and analyzes influencing factors of spatial differences in pressure, state, and response resilience across Xinjiang prefectures from 2010 to 2020. Based on existing research and following scientific and operational data principles, 15 representative indicators were selected as detection factors for geographic detector analysis [**?**, **?**]. Natural disasters are represented by precipitation (X_1), which regulates soil moisture and temperature to improve crop growth conditions, but scarce rainfall restricts agricultural economic development. Human-induced disasters primarily include industrial wastewater discharge (X_2), domestic sewage discharge (X_3), industrial solid waste production (X_4), and fertilizer application intensity (X_5). Excessive pollutant discharge causes water, soil, and air pollution, breaking the inherent balance of ecosystems. Water use structure includes agricultural water proportion (X_6), industrial water proportion (X_7), and ecological water proportion (X_8). A rational water use structure can ensure sustainable economic and social development. Industrial structure reflects the development level and vitality of various industrial sectors, with indicators selected as primary industry proportion (X_9), secondary industry proportion (X_{10}), and tertiary industry proportion (X_{11}). Per capita GDP (X_{12}) reflects a region's economic wealth and development level; higher per capita GDP indicates greater economic development and living standards. Retail sales of social consumer goods (X_{13}) reflect the impact of consumption demand on economic operation; higher values indicate stronger consumption demand, stimulating investment, increasing output, improving corporate benefits, and raising resident incomes. Ecological self-purification capacity refers to a system's ability to achieve environmental self-purification without structural changes, with indicators selected as wetland area (X_{14}), per capita park green area (X_{15}), and built-up area green coverage rate (X_{16}). Environmental regulation intensity is represented by environmental governance investment (X_{17}); stronger environmental regulation improves industrial and agricultural production environments. Scientific and technological innovation capacity is represented by R&D expenditure proportion (X_{18}); high-level scientific and technological innovation can optimize traditional agriculture, improve production efficiency, and effectively reduce pollutant emissions through energy-saving and environmental protection technology development, maintaining the balance between ecological environment and economic development.

2.2.2 Factor Detection Fifteen influencing factors were selected to detect their explanatory power on water resources-economic-ecological resilience (Fig. [Figure 4: see original paper]). A larger q-value indicates stronger explanatory power. In 2010, the q-values for dominant factors affecting the three-system resilience ranked from largest to smallest as: X_{14} (wetland area) > X_{13} (retail sales of social consumer goods) > X_2 (industrial wastewater discharge) > X_{12} (per capita GDP) > X_{17} (environmental governance investment). Among these, wetland area, retail sales of social consumer goods, and industrial wastewater discharge were the main influencing factors of Xinjiang's three-system resilience.

In 2020, the q-values for dominant factors ranked from largest to smallest as: X_{10} (secondary industry proportion) > X_{11} (tertiary industry proportion) > X_{12} (per capita GDP) > X_{14} (wetland area) > X_{15} (per capita park green area). Secondary industry proportion, tertiary industry proportion, and per capita GDP became the main influencing factors of Xinjiang's three-system resilience. In summary, the influence of industrial structure, ecological self-purification capacity, and retail sales of social consumer goods has strengthened, while the impact of human-induced disasters has weakened.

2.2.3 Interaction Detection Interaction detection was conducted on 15 influencing factors of water resources-economic-ecological resilience (Fig. [Figure 4: see original paper]). Results show that pairwise interactions among influencing factors are primarily two-factor enhancement and nonlinear enhancement types, with nonlinear enhancement effects exceeding two-factor enhancement. Specifically, in 2010, the most explanatory factor pairs in the two-factor enhancement type were X_6 X_{10}, X_6 X_{11}, and X_6 X_{12}. The most explanatory factor pairs in the nonlinear enhancement type were X_2 X_{14}, X_2 X_{15}, and X_2 X_{16}.

In 2020, among interaction types between influencing factors, the number of nonlinear enhancement relationships exceeded two-factor enhancements. The most explanatory factor pairs in the two-factor enhancement type were X_9 X_{10}, X_9 X_{11}, and X_{10} X_{11}. The most explanatory factor pairs in the nonlinear enhancement type were X_{14} X_{15}, X_{14} X_{16}, and X_{15} X_{16}. In summary, the interactive influence of industrial structure, ecological self-purification capacity, and retail sales of social consumer goods is stronger than single-factor influence, indicating that factor superposition can enhance impacts on system resilience. Therefore, Xinjiang should emphasize fertilizer pollution prevention in agricultural development, promote green agriculture, reduce soil pollution and ecological damage during oil and coal mining and processing, and aim for low-pollution discharge and low environmental costs to enhance ecosystem self-purification capacity and achieve sustainable resource, economic, and ecological development.

3 Discussion

This study investigates spatiotemporal differences and influencing factors of water resources-economic-ecological resilience in Xinjiang using the PSR model.

Research findings show that Chu et al. [?] and Zhang et al. [?] studied urban resilience and agricultural economic resilience, respectively, both concluding that market economic scale and retail sales of social consumer goods significantly influence urban or agricultural economic resilience. Market scale and technology input levels are important factors in interactions, partially consistent with this study's conclusion that these are dominant influencing factors. Zhang et al. [?] analyzed spatiotemporal differences in China's agricultural economic resilience from resistance and reconstruction dimensions, with research content and dimensions representing part of this study. Lü et al. [?] analyzed spatiotemporal changes in urban ecological resilience in the Yangtze River Delta but did not conduct detailed multi-system resilience research. The above literature lacks theoretical model support for resilience indicator system construction, with scholars focusing on single-system resilience. This study introduces the PSR model to construct a multi-system resilience indicator system, quantitatively measuring from multi-angle and interconnected factor layers, which is more scientific and specific than previous subjective evaluation methods and better characterizes resilience performance. Using kernel density estimation to analyze multi-system resilience evaluation indices under the PSR model can reveal spatial distribution characteristics and regional agglomeration patterns of multi-system resilience.

This study has limitations: Resilience is dynamically changing, and any element change affects the whole system. However, this study only considers resilience changes under pressure shocks without quantifying impacts caused by post-shock element changes. Therefore, future research should deeply investigate dynamically changing resilience.

4 Conclusions

This study takes 14 Xinjiang prefectures as the research area, establishing a water resources-economic-ecological resilience indicator system using the PSR model. First, the entropy weight method calculates indicator weights, and the comprehensive evaluation method measures pressure-state-response resilience evaluation indices from 2010 to 2020. Second, kernel density estimation analyzes spatial differences in pressure, state, and response resilience across prefectures. Finally, geographic detectors effectively identify influencing factors of water resources-economic-ecological resilience. Research conclusions are as follows:

1. From 2010 to 2020, pressure resilience evaluation indices in most Xinjiang prefectures showed a declining trend, with Kizilsu Kirgiz Autonomous Prefecture's pressure resilience level decreasing from high to moderate. In contrast, state resilience, response resilience, and comprehensive resilience exhibited continuous enhancement trends, with overall resilience levels improving.
2. From 2010 to 2020, the spatial distribution of pressure-state-response resilience kernel density across Xinjiang prefectures displayed a staggered

pattern, with higher values in the southwest than in the northeast. Analyzing the three dimensions reveals that high-value pressure resilience kernel density areas spread from the southwest to the central region with relatively concentrated distribution. High-value state resilience and response resilience kernel density areas spread from the north to the south with relatively dispersed distribution. From 2010 to 2020, differences in comprehensive resilience, state resilience, and response resilience kernel densities showed a continuously narrowing trend, while spatial differences in pressure resilience kernel density remained significant, with resilience levels improving across all dimensions.

3. The influence of industrial structure, per capita GDP, and ecological self-purification capacity on water resources-economic-ecological resilience has strengthened, while the impact of human-induced disasters has weakened. Interactive effects among industrial structure, ecological self-purification capacity, and retail sales of social consumer goods are stronger than single-factor influences on system resilience. Among pairwise interactions of different influencing factors, the number of nonlinear enhancement relationships exceeds the number of two-factor enhancements.

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