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COUPLING OF WATER-LAND RESOURCES AND WATER GOVERNANCE IN CHINA'S POYANG LAKE URBAN AGGLOMERATION

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Highlights:

- the utilization efficiency of land and water resources in the Poyang Lake Urban Agglomeration showed a fluctuating upward trend with significant spatial heterogeneity;
- the cities in the southwest and northeast directions of the Poyang Lake Urban Agglomeration have a faster growth rate of the coupling coordination degree of water and land resources, and there are alternating strong and weak phenomena;
- urbanization, land resource utilization efficiency, and foreign investment have a significant positive promoting effect on the improvement of water resource utilization efficiency;
- industrial structure, agricultural mechanization, and economic development level are significantly detrimental to the improvement of water resource utilization efficiency;
- the negative effect of R&D investment and the positive impact of graded highway construction have a lag effect.

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Abstract. The scientific and efficient use of water and land resources is an inevitable requirement for China's ecological civilization and achieve high-quality development. Investigating the spatiotemporal evolution of the utilisation efficiency of water and land resources in the Poyang Lake Urban Agglomeration, as well as the factors influencing water environment governance, can provide strategic support for the coordinated development of these resources in this urban agglomeration. This study examines the non-desired output Super-SBM model and the coupling coordination degree model to examine the spatiotemporal evolution of water and land resource utilization efficiency in the Poyang Lake Urban Agglomeration from 2009 to 2022. The results show that the efficiency of the utilization of water and land resources increased with spatial heterogeneity. The coupling coordination degree evolved from impending imbalance to medium-level coordination, with a spatial pattern of "high in the east and low in the west". Urbanization, land resource utilization efficiency, and foreign investment positively affect water resource utilization efficiency, while industrial structure, agricultural mechanization, and economic development level have negative impacts. The negative effect of R&D expenditure and the positive effect of grade highway construction have a lag effect. Overall, although the mean coupling-coordination degree improved, it remained between "marginal" and "primary" coordination, indicating modest rather than high-quality synergy. This study therefore propose efficiency-based zoning and cross-city spillover compensation as replicable tools for other lake-type urban agglomerations.

Keywords: Super-SBM model, coupling coordination degree, standard deviation ellipse, influencing factors, Poyang Lake Urban Agglomeration.

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1. Introduction

Land and water resources are essential for biodiversity, ecological balance, and human socio-economic development (Liu et al., 2026; Wang et al., 2025). Faced with increasingly strained water and land resource relationships, China has implemented the strictest water resource management system, including the "Three Red Lines" and emphasized the principle of determining urban development, land use, population size, and industrial output based on water availability (Ma et al., 2025b). This aims to shift from overexploitation and extensive use to moderate exploitation and intensive utilization of water resources. The 13th Five-Year Plan Outline for Land and Resources also calls for improving urban land use efficiency, proposing "dual control" measures for construction land use and setting basic constraints through the "Three Lines", which refers to arable land protection, ecological protection, and urban development boundaries. In response to these challenges, it is imperative to scientifically evaluate the utilization efficiency of land and water resources, clarify their coupling and coordination relationship, understand their spatiotemporal evolution, and enhance regional cooperation to achieve sustainable development (Bu et al., 2026; Wu et al., 2024).

Current research on the relationship between land and water resource utilization efficiency primarily focuses on three key areas. To begin with, regarding research units, early studies predominantly concentrated on national, provincial, and municipal levels, with limited attention to urban agglomerations. However, as new-type urbanization has progressed and the spatial layout of China's nineteen urban agglomerations has become clearer, research on these urban clusters has increased. For instance, Zhao et al. (2021) measured the land use efficiency of the Mid-Yangtze River Urban Agglomeration, while Qu et al. (2024) and Ma et al. (2024) analyzed the coupling relationship between the ecological environment and socio-economy in the Yellow River Basin Urban Agglomeration. Similarly, Xu and Jiao (2021) explored the relationship between urbanization level and water resource utilization efficiency in the Pearl River Delta Urban Agglomeration.

Moreover, methods of indicator construction and measurement, methods have evolved from single-factor indicators to comprehensive evaluation approaches that incorporate multiple factors and stochastic frontier analysis (Al-ossmi, 2024). With the advancement of ecological civilization and sustainable development concepts, Data Envelopment Analysis (DEA), a non-parametric method that allows for multiple inputs and outputs, has become the mainstream approach. DEA offers several advantages. It does not require assumptions about weights or uniformity of indicator units and can include undesirable outputs such as carbon emissions and waste in the evaluation system (Sun & Luo, 2026; Wang & Ma, 2024; Zhang et al., 2025). Various DEA models have been applied. For instance, Yan and Wang (2022) employed the Window-DEA model to analyze the spatiotemporal characteristics of land and water resource utilization efficiency in the Yellow River Basin. Tuoku and Men (2023) applied the non-desired output MinDS model to measure water use efficiency and its spatial pattern in the Yellow River Basin. He et al. (2023) combined the VRS-DEA model with the Malmquist index to assess land use efficiency in sixteen industrial parks in the Yangtze River Delta Urban Agglomeration. Cheng et al. (2023) applied the non-desired output SBM network DEA model to evaluate water resource efficiency in Chinese provinces. In addition, watershed-scale evidence shows that land-use/land-cover change significantly affects low-order stream water quality in southeastern Brazil (de Mello et al., 2018) and that urbanization and development exert measurable pressures on estuarine ecosystems and water quality worldwide (Freeman et al., 2019).

Besides, concerning influencing factors, existing studies have examined a range of variables, including environmental regulation, economic development level, industrial structure, technological level, industrial and agricultural structure, government intervention, and urbanization (Hua & Tong, 2025; Wang et al., 2025; Zou et al., 2024). For example, Anser et al. (2024) used dynamic panel GMM estimation and found that environmental regulation, economic development level, industrial structure optimization, and technological progress significantly promote water use efficiency. In contrast, farmland water conservancy facility construction and urbanization have a negative impact. Gu et al. (2024) used a Tobit model to reveal that regional economic development level, water resource abundance, industrial and agricultural industrial structure, and government intervention are significantly negatively correlated with water resource utilization efficiency. Fei and Lin (2016) proposed the Shephard water resource distance function, suggesting that economic development level is positively correlated with water resource utilization efficiency, while water resource endowment and urbanization level are negatively correlated. It is worth noting that the impact of these factors may vary depending on the specific research region (Van Vuuren et al., 2014). A comprehensive review further indicates that both natural and anthropogenic drivers contribute to water-quality degradation across basins (Akhtar et al., 2021), while land-use change in dryland regions can simultaneously alter ecosystem services and human well-being (Quintas-Soriano et al., 2016). Similarly, climate-induced land-use shifts in Kentucky were found to markedly affect water-related ecosystem services (Bai et al., 2019; Lei & He, 2025), and global assessments warn that future water scarcity will increasingly constrain agricultural land and food production (Fitton et al., 2019). Additionally, most studies agree that both land and water resource utilization efficiency generally show an increasing trend over time, but the overall level remains relatively low. Some research areas also exhibit convergence and spatial positive correlation (Yang et al., 2019; Paranina & Paranin, 2017). Overall, while existing research has largely focused on the efficiency evaluation of single elements of land or water resources or their coupling with other factors such as energy and economy, fewer studies have explored the interactive relationship between land and water resource utilization efficiency.

The Poyang Lake Urban Agglomeration, centered around China's largest freshwater lake—Poyang Lake, is the most urbanized and industrialized area in Jiangxi Province. It is characterized by intense land-use activities and complex conflicts between population and industrial development and the availability of land and water resources. There is an urgent need for new tools and perspectives to study the spatiotemporal evolution of land and water resources and water environment governance in this region. To meet this need, this study pioneers the integration of an undesirable-output Super-SBM model with a coupling-coordination-degree (CCD) framework that explicitly treats industrial wastewater, SO_2 and COD as undesirable outputs, thereby closing the gap between traditional CCD applications and water-quality feedbacks in lake-type urban agglomerations. Using the non-desired output Super-SBM model to measure the efficiency of land and water resource utilization in the Poyang Lake Urban Agglomeration from 2009 to 2022. It constructs a coupling coordination degree model to study the coupling coordination between land and water resource utilization efficiency. The spatial offset degree and speed of the coupling coordination are analyzed using the standard deviation ellipse. A two-way fixed-effects model is further employed to reveal how urbanisation, industrial structure and grade-highway density affect the improvement of water-environment governance. Beyond the local context, the revealed east-high vs. west-low CCD gradient and the efficiency–coordination quadrant map offer a replicable zoning template for river-basin management worldwide, demonstrating that "city-development dictated by water availability" can simultaneously raise economic efficiency and curb emission loads in other freshwater-lake regions. The aim is to provide policy recommendations for the coordinated development of land and water resources in this region.

2. Study area and data sources

2.1. Overview of the study area

The Poyang Lake Urban Agglomeration is located in the northern part of Jiangxi Province, spanning latitudes 26°57′N to 30°04′N and longitudes 113°34′E to 118°28′E. According to the "Poyang Lake Ecological Urban Agglomeration Plan (2015–2030)", its scope includes 42 counties (cities, districts), such as Nanchang, Jiujiang, and Jingdezhen. Based on the delineation of the Poyang Lake Urban Agglomeration's range according to the "Lake Effect" and considering the availability and comparability of research data, this study focuses on eight prefecture-level cities, namely Nanchang, Jiujiang, Jingdezhen, and Shangrao (Figure 1), with a total area of 9.85×104 km^2. The region features a subtropical humid climate, with abundant sunshine and rainfall. Its main topography consists of plains, hills, and mountains, and it is characterized by dense river networks and numerous lakes, all of which contribute to its favorable natural conditions. By the end of 2022, the regional gross domestic product (GDP) of the Poyang Lake Urban Agglomeration reached 2022.92 billions yuan, accounting for 63.07% of the province's total GDP. The total population within the region was 23.8877 million, among whom 13.5569 million were urban residents, indicating an urbanization level of 65.13%. As the most economically vibrant area in Jiangxi Province, the region also serves as an important ecological function protection zone in China. It is rich in natural resources and holds a significant geographical location. It plays a vital exemplary role in maintaining the ecological security pattern of the Yangtze River Basin and in promoting green and low-carbon development (Sun & Li, 2025; Wu et al., 2025; Ruan et al., 2025). With the implementation and advancement of regional development strategies such as the Rise of the Central Region and the Mid-Yangtze River Urban Agglomeration, the modernization process of the Poyang Lake Urban Agglomeration has been accelerating. This has led to continuous expansion of urban construction land and increased energy consumption intensity. Consequently, the coordinated development of land and water resources has become an increasingly pressing core issue that needs to be addressed for high- quality regional development.

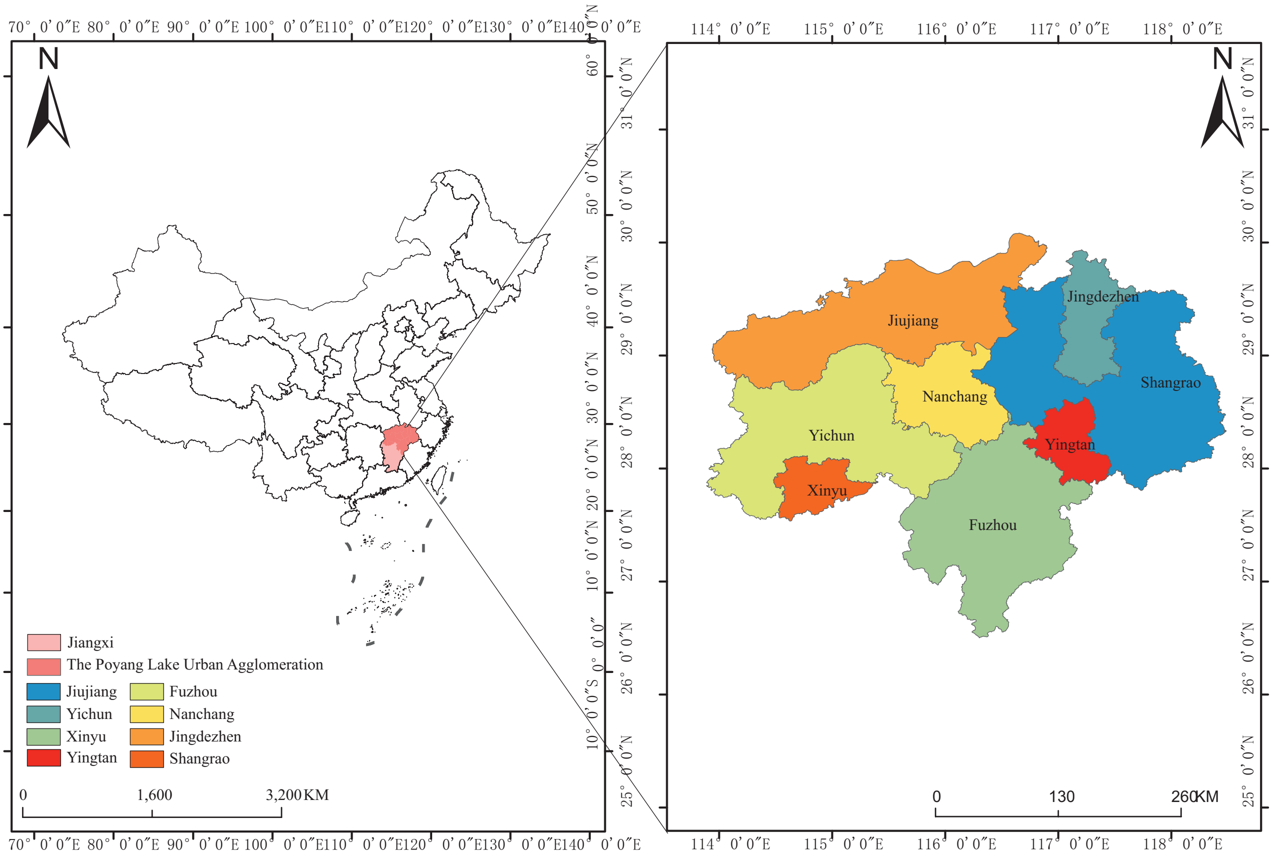

Figure 1. Geographical location map of the study area and study unit

2.2. Data sources

This paper takes the period from 2009 to 2022 as the research period. The Poyang Lake urban agglomeration includes 8 cities such as Nanchang, Jiujiang, Jingdezhen and Shangrao. The data used are derived from the China Urban Statistical Yearbook, Jiangxi Statistical Yearbook and the statistical yearbooks of each prefecture-level city of the corresponding years. Missing data were supplemented by using the linear interpolation method.

3. Research methods

3.1. Evaluation index system

In order to evaluate the efficiency of land and water resource use, it is necessary to consider input and output variables. Based on previous research and combining the specific circumstances of the Poyang Lake urban agglomeration (Lü et al., 2024), an input-output indicator system for land and water resource use efficiency was constructed, taking into account data availability and the scientific validity of the indicators (Table 1). In terms of inputs, the area of construction land is used as the material input for land resources, the total annual water is used as the material input for water resources, and the year-end employment population and the total fixed capital stock as the labor and capital inputs respectively. In terms of output, it includes both expected and unexpected outputs. Actual GDP is used as the expected output. Unexpected outputs include industrial wastewater and sulfur dioxide emissions are used for land resources, and wastewater emissions are used for water resources.

Table 1. Evaluation index system of land resources and water resources utilization efficiency in urban agglomeration around Poyang Lake

Target layer	Indicator classification	Indicator composition
Land Resource Use Efficiency	Input	Area of Construction Land (km^2)
		Year-End Employment Population (10,000 people)
		Fixed Capital Stock (10,000 yuan)
	Expected Output	Actual GDP (billion yuan)
	Non-Expected Output	Total Industrial Wastewater Emissions (10,000 tons)
		Total Industrial Sulfur Dioxide Emissions (tons)
Water Resource Use Efficiency	Input	Total Water Use (10^8 m^3)
		Year-End Employment Population (10,000 people)
		Fixed Capital Stock (10,000 yuan)
	Expected Output	Actual GDP (billion yuan)
	Non-Expected Output	Total Wastewater Emissions (10,000 tons)

3.2. Super-SBM model

The DEA method is widely used in multi-input, multi-output studies because it does not require a specific functional form to be defined in advance. Traditional DEA measurements include radial and non-radial methods. The radial method can produce a high efficiency value in actual measurements, whereas the non-radial method can only select one input or output angle, leading to biased results (Pan & Ying, 2013). Based on this, Tone proposed the SBM (Slack-Based Measure) model in 2001, which solved problems caused by slack variables and undesirable outputs (Tone, 2001). However, in practical applications, the SBM model often results in multiple decision-making units achieving an efficiency value of 1, making it difficult to compare and analyze these units further. In 2002, Tone also proposed that the radial method can only select one perspective of inputs or outputs, which leads to bias in the measurement results. In the same year, Tone also proposed a super-efficiency SBM (super-efficiency slack-based measure) model that combines the super-efficiency DEA and SBM models (Tone, 2002). The efficiency value can be greater than 1, providing a way to compare the efficiency of effective decision-making units (Li et al., 2013). This paper uses the super-efficiency SBM model, which considers non-desired outputs, to measure the efficiency of water and land resource utilization in the Poyang Lake Urban Agglomeration. The mathematical expression of the model is as follows:

$$\min\rho=\frac{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{\bar{x}}{x_{i0}}\right)}{\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{\overline{y^d}}{y^d_{r0}}+\sum_{q=1}^{s_2}\frac{\overline{y^u}}{y^u_{q0}}\right)}; \quad (1)$$

$$s.t.\begin{cases}\bar{x}\geq\sum\limits_{j=1,\neq 0}^{n}\varphi_j x_j\\ \overline{y^d}\leq\sum\limits_{j=1,\neq 0}^{n}\varphi_j y_j^d,\ \overline{y^u}\leq\sum\limits_{j=1,\neq 0}^{n}\varphi_j y_j^u,\\ \bar{x}\geq x_0;\ \overline{y^d}\leq y_0^d;\ \overline{y^u}\leq y_0^u;\ \varphi_j\geq 0\end{cases} \quad (2)$$

where ρ represents the efficiency value of the Decision Making Unit (DMU). When $\rho\geq 1$, it means that the evaluated decision-making unit reaches the effective state, and when $\rho<1$, it means that the evaluated decision-making unit is in the ineffective state. n is the number of decision-making units, and each decision-making unit contains m input indexes, s_1 desired output indexes, and s_2 undesired output indexes. x, y^d, and y^u denote the elements of the matrix of inputs, desired outputs, and undesired outputs, respectively.

3.3. Coupling coordination degree

Coupling generally refers to the relationship between two or more systems or the elements within the system that influence and interact with each other, and the coupling of water and land resources is a specific embodiment of coupled thinking in the field of natural resources (Zhao et al., 2016). Based on this, this study defines the coupling degree of land resource use efficiency and water resource use efficiency as follows:

$$C = \frac{\sqrt{U_1 \times U_2}}{U_1 + U_2}; \quad (3)$$

$$T = aU_1 + bU_2; \quad (4)$$

$$D = \sqrt{C \times T}, \quad (5)$$

where C stands for the coupling degree. U_1 and U_2 represent the land resource utilization efficiency and water resource utilization efficiency, respectively. T is the overall evaluation index. a and b represent the importance of the two systems, respectively. D is the coupling coordination degree.

Based on the general approach of existing studies (Yang et al., 2024; Xing & Jin, 2025) and considering the status of land and water resources in the Poyang Lake urban agglomeration, the coupling coordination degree between land resource utilization efficiency and water resource utilization efficiency is divided into 10 stages. Each stage is further categorized into 3 types based on the difference between the two efficiencies (Table 2).

3.4. Standard Deviational Ellipse

Standard Deviation Ellipse (SDE) is an intuitive method used in spatial statistics to show the spatial distribution characteristics of a point set. Compared with the traditional method of measuring the level of industrial agglomeration, the standard deviation ellipse spatially and intuitively reveals the directional deviation characteristics of the study elements in terms of geographical distribution (Zhao et al., 2014). The elements of the standard deviation ellipse are center, corner, standard deviation along the long axis and standard deviation along the short axis. The direction of maximum dispersion of points can be determined if the set of points exhibits a specific directional deviation. The standard deviation ellipse depicts the relevant spatial distribution characteristics of the object of study by forming a spatial distribution ellipse through the basic parameters of centre, angle of rotation, standard deviation along the long axis, standard deviation along the short axis, and azimuthal angle. The calculation formula is as follows:

$$(X,Y) = \left(\frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i} \right); \quad (6)$$

$$\tilde{x} = x_i - X, \quad \tilde{y} = y_i - Y; \quad (7)$$

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} \left(w_i \widetilde{x_i} \cos\theta - w_i \widetilde{y_i} \sin\theta \right)^2}{\sum_{i=1}^{n} w_i^2}}; \quad (8)$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n} \left(w_i \widetilde{x_i} \sin\theta - w_i \widetilde{y_i} \cos\theta \right)^2}{\sum_{i=1}^{n} w_i^2}}; \quad (9)$$

$$\theta = \frac{\arctan\left[\left(\sum_{i=1}^{n} w_i^2 \widetilde{x_i^2} - \sum_{i=1}^{n} w_i^2 \widetilde{y_i^2} \right) + \right.}{2 \sum_{i=1}^{n} w_i^2 \widetilde{x_i^2} \widetilde{y_i^2}} \frac{\left. \sqrt{\left(\sum_{i=1}^{n} w_i^2 \widetilde{x_i^2} - \sum_{i=1}^{n} w_i^2 \widetilde{y_i^2} \right)^2 + 4 \sum_{i=1}^{n} w_i^2 \widetilde{x_i^2} \widetilde{y_i^2}} \right]}{}; \quad (10)$$

$$S = \pi \sigma_x \sigma_y, \quad (11)$$

where (X,Y) is the weighted average centre of the research object. (x_i, y_i) refers to the spatial locations of the cities in the Poyang Lake urban agglomeration. ω_i represents the corresponding weights. $(\widetilde{x_i}, \widetilde{y_i})$ represents the coordinate deviations of each study object location from the centroid (X,Y). σ_x and σ_y denote the standard

Table 2. Classification criteria of coupling coordination degree of land and water resources use efficiency

$0.0 \le D < 0.4$				$0.4 \le D < 0.7$			$0.7 \le D < 1.0$		
Discoordination period				Transition period			Coordination period		
$[0.0, 0.1)$	$[0.1, 0.2)$	$[0.2, 0.3)$	$[0.3, 0.4)$	$[0.4, 0.5)$	$[0.5, 0.6)$	$[0.6, 0.7)$	$[0.7, 0.8)$	$[0.8, 0.9)$	$[0.9, 1.0)$
Extreme Discoordination	Severe Discoordination	Moderate Discoordination	Mild Discoordination	On the Verge of Discoordination	Marginal Coordination	Primary Coordination	Intermediate Coordination	Benign Coordination	High-Quality Coordination
$U_2 - U_1 > 0.1$ Land Resource Utilization Efficiency Lag				$\lvert U_2 - U_1 \rvert \le 0.1$ Synchronization			$U_1 - U_2 < 0.1$ Water Resource Efficiency Lag		

deviations along the x-axis and y-axis, respectively. θ stands for the orientation angle of the ellipse; S represents the area of the standard deviation ellipse.

3.5. Model specification and control variables

3.5.1. Model specification

Based on the analysis of the coupling coordination degree of land and water resource use efficiency in the Poyang Lake urban agglomeration, this study further explores the factors influencing water environment governance in the region by constructing the following regression model:

$$Water_{it} = \beta_0 + \beta_1 Land_{it} + \sum_{k=1}^{n} \beta_k Control_{it} + \mu_i + \theta_t + \varepsilon_{it}. \quad (12)$$

In the model, i represents the city, and t the year. $Water_{it}$ is the water resource use efficiency, and $Land_{it}$ is the land resource use efficiency of city i in year t. $Control_{it}$ includes factors affecting water efficiency. Fixed effects μ_i and θ_t control for city-specific and time-related variations. ε_{it} is the error term. β_0 is the constant. β_k represents the coefficients of the control variables, and $\sum_{k=1}^{n} \beta_k Control_{it}$ denotes the cumulative effect of all control variables on water resource use efficiency. β_1, the focal coefficient, measures the impact of land resource use efficiency on water resource use efficiency in the Poyang Lake urban agglomeration.

3.5.2. SDM

To investigate the spatial spillover effects of land and water resources in the Poyang Lake Urban Agglomeration, we specify the following spatial Durbin model (SDM):

$$Water_{it} = \beta_0 + \rho \boldsymbol{W} Water_{it} + \tau Land_{it} + \sum_{k=1}^{n} \beta_k Control_{it} + \mu_2 \boldsymbol{W} Land_{it} + \sum_{k=1}^{n} \omega_k \boldsymbol{W} Control_{it} + \mu_i + \theta_t + \varepsilon_{it}. \quad (13)$$

In the model, ρ denotes the spatial autoregressive coefficient, $\boldsymbol{W}$ represents the spatial weight matrix, β and τ are the coefficients attached to the control and explanatory variables, respectively, and μ_2 and ω_k correspond to the spatial interaction terms of the explanatory and control variables; all remaining variables are defined as in Equation (13).

For the spatial-weight matrix, adjacency implies shorter geographic distances and more diversified transport links, thereby facilitating labor mobility and resource sharing. Moreover, regions with similar income levels absorb and utilize economic resources more effectively, moving closer to increasing-returns-to-scale outcomes. Consequently, an economic-geographic weight matrix is adopted as the baseline, with a contiguity matrix employed for robustness checks.

3.5.3. Control variables

Most scholars explore the factors influencing environmental governance from the perspectives of economic and social development (Ma et al., 2025a). In this regard, based on the "13th Five-Year Plan" for Ecological and Environmental Protection and the "Water Pollution Prevention and Control Action Plan" ("Water Ten Articles"), and in combination with existing research results, the following control variables are selected: agricultural mechanization (InAgrM) (Belton et al., 2021), openness to foreign investment (FDI) (Kim et al., 2013), industrial output value (IndO) (Chen & Yang, 2019), grade of highway mileage (Inroad) (Liu et al., 2019), R&D expenditure (InRDsup) (Sun & Li Y, 2025; Sokolov-Mladenović et al., 2016), industrial structure (IndA) (Jin, 2012), economic development level (Eco) (Guo et al., 2023), population density (InPeop) (Rahman & Alam, 2021), and urbanization level (Urban) (Yu, 2021).

Table 3. Descriptive statistics of variables

Variables	Unit	Mean	SD	Min	Max
FDI	10^8yuan	67.12	67.11	6.78	286.80
IndO	10^8yuan	695.10	487.10	153.20	2511.00
IndA	%	0.39	0.07	0.24	0.52
Eco	10^{12}yuan	5.03	2.54	1.07	11.30
InAgrM	10^4kw/h	11.15	0.84	8.99	12.62
Inroad	km	9.08	0.75	7.79	11.57
InRDsup	10^8yuan	2.66	0.94	0.62	4.39
Urban	%	0.57	0.11	0.36	0.79
InPeop	10^3people/km^2	5.78	0.36	4.80	6.69

Foreign investment (FDI) can have ambiguous environmental effects, presenting either a "pollution halo" or "pollution haven" phenomenon, which is represented by "actual foreign investment used". As urbanisation accelerates, a series of ecological and environmental problems such as ecological imbalance and functional degradation will arise. However, urbanization is irreversible. Since 2010, the Chinese government has launched a new type of urbanization strategy, and its impact on the water environment is worth exploring, represented by "urban population/total population". As the industries with the largest gray water footprint, the optimization of the patterns and structures of agriculture and industry is conducive to improving the quality of the water ecological environment. Therefore, relevant indicators such as IndA, IndO, and InAgrM are selected as influencing factors for further analysis, represented by "the added value of the secondary industry or the added value of the tertiary industry", "industrial output value", and "rural electricity consumption", respectively. The role of economic development level (Eco) in protecting the water environment should be viewed dialectically. Due to the existence of the "Environmental Kuznets Curve", the direction of Eco's impact is difficult to predict and is represented by "per capita GDP". Research and development (R&D) expenditure (InRDsup) has significant impacts on environmental governance and development. This study represents it by "R&D funding". Population density (InPeop) often has a negative environmental impact. Whether this phenomenon still exists under the coordination of land and water resources in this region is represented by "total population or land area". While the construction of grade highways has certain negative environmental impacts, it plays an irreplaceable role in promoting urban development. Since 2009, China's Ministry of Transport has issued the "Policy on Developing Resource-Saving and Environment-Friendly Highway and Waterway Transportation", proposing the acceleration of industrial restructuring and the transformation of China's highway and other transportation departments' development model, in order to follow a resource-saving, environmentally friendly development path. The impact of this new development mode on water environment governance is worth exploring, as represented by "the mileage of grade highways". For further details, please refer to Table 3.

4. Results and analysis

4.1. Measurement and analysis of land and water resource use efficiency in the Poyang Lake urban agglomeration

To explore the spatio-temporal evolution characteristics of land and water resource use efficiency in the Poyang Lake urban agglomeration, the non-radial super-efficiency SBM model with variable returns to scale in DEA-Solver 5.0 was used to measure the land and water resource use efficiency of the urban agglomeration in the Poyang Lake Basin. The results are shown in Figure 2. During the study period, the overall level of land use efficiency in the cities of the Poyang Lake Basin was not high, with an average level of only 0.641, indicating significant room for improvement. From 2009 to 2022, the average land use efficiency of each city was ranked as follows: Nanchang (0.757) > Xinyu (0.727) > Shangrao (0.672) > Yingtan (0.653) > Jiujiang (0.634) > Fuzhou (0.604) > Jingdezhen (0.572) > Yichun (0.509). Among them, Nanchang had the largest increase in land use efficiency, reaching 50.17%, followed by Xinyu with an increase of 49.88%, while Shangrao had the lowest growth rate of land use efficiency, with an increase of only 19.59%. The land use efficiency of Jingdezhen increased by 26.10%, Jiujiang by 38.35%, Yingtan by 43.96%, and Yichun by 23.32%, all showing an upward trend.

As shown in Figure 2, the overall water resource use efficiency in the Poyang Lake urban agglomeration showed a fluctuating upward trend, with an overall level lower than that of land use efficiency in each region. From 2009 to 2016, the water resource use efficiency of each city fluctuated relatively gently, and from 2017 to 2022, a more significant upward trend was observed, with an average efficiency of 0.582, gradually approaching the effective state. From 2009 to 2022, Nanchang had the largest increase in water resource use efficiency, reaching 70.56%, which was higher than the average level of the Poyang Lake urban agglomeration. Specifically, in 2009, Nanchang had the lowest water resource use efficiency among the eight cities, with only 0.207, while Yingtan's water resource use efficiency had already reached 0.50 at that time. By 2022, half of the eight cities in the Poyang Lake urban agglomeration had reached the effective level of water resource use efficiency.

4.2. Analysis of coupling coordination degree of land and water resource use efficiency

4.2.1. Spatio-temporal evolution

The coupling coordination degree of land and water resource use efficiency was calculated using Equations (3)–(5), and the coupling coordination types of each region were classified according to Table 2. As shown in Table 3, from 2009 to 2013, the coupling coordination degree of water and land resource use efficiency in the Poyang Lake Basin was generally in the barely coordinated stage. From 2014 to 2017, it was basically in the transition from barely coordinated to primary coordinated stage, with the mutual influence between land and water resource use efficiency gradually deepening. From 2018 to 2022, the number of cities with good coordination increased, and the degree of coordination between water and land resources further deepened. By 2022, several cities in the Poyang Lake urban agglomeration had achieved high coordination. In the early stage of the study, the Poyang Lake urban agglom-

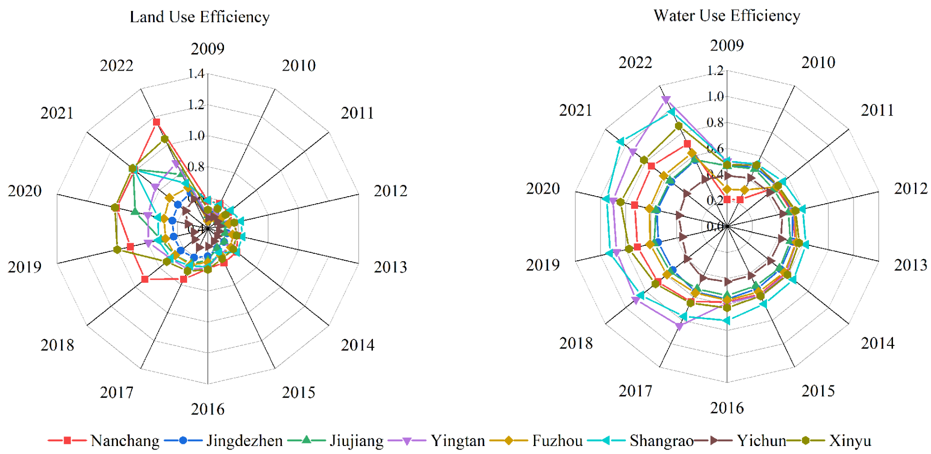

Figure 2. Utilization efficiency of land and water resources in urban agglomeration around Poyang Lake from 2009 to 2022

eration was in a stage of extensive development, with low water resource use efficiency. With the proposal of the "new type of urbanization strategy" and "innovation-driven development strategy" in 2014, the land market gradually warmed up, and water resources gradually achieved multi-level utilization (Ma & Appolloni, 2025). In 2019, China entered a period of prioritizing ecological protection, and various ecological construction projects were launched successively, leading to continuous improvement in the efficiency of water and land resource use.

4.2.2. Spatial pattern evolution and identification of problematic areas

In order to analyze the spatio-temporal pattern of the coupling coordination degree of land and water resource use efficiency in the Poyang Lake urban agglomeration more intuitively, this study combines the coupling coordination degree with spatial analysis methods and uses ArcGIS 10.8 to visualize the results of the coupling coordination degree of land and water resource use efficiency in the Poyang Lake urban agglomeration in 2009, 2013, 2017, and 2022 (Figure 3). The differences in land and water resource use efficiency from 2009 to 2022 reveal the lagging types in each city.

As shown in Table 4 and Figure 3, the average coupling-coordination degree (CCD) of land- and water-use efficiency in the Poyang Lake urban agglomeration rose from 2009 to 2022. However, the mean value remained between "marginal coordination" and "rimary coordination" throughout the study period, indicating that the

Table 4. Statistical results of coupling coordination degree of land and water resources use efficiency in Poyang Lake urban agglomeration from 2009 to 2022

Coordination level	2009		2013		2017		2022	
	Number	Proportion (%)	Number	Proportion (%)	Number	Proportion (%)	Number	Proportion (%)
Mild Discoordination	2	25	0	0.0	0	0.0	0	0.0
On the Verge of Discoordination	5	62.5	1	12.5	1	12.5	0	0.0
Marginal Coordination	1	12.5	6	75	2	25	1	12.5
Primary Coordination	0	0.0	1	12.5	2	25	3	37.5
Intermediate Coordination	0	0.0	0	0.0	3	37.5	0	0.0
Benign Coordination	0	0.0	0	0.0	0	0.0	1	12.5
High-Quality Coordination	0	0.0	0	0.0	0	0.0	3	37.5

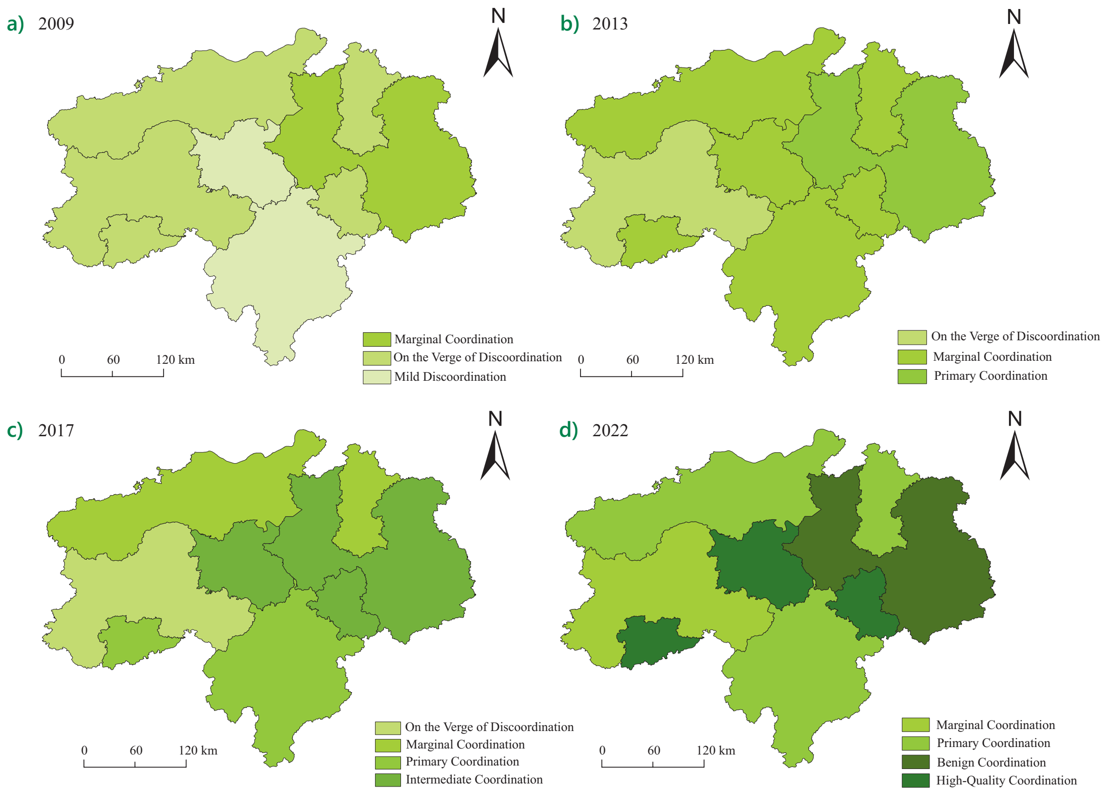

Figure 3. Spatial distribution of coupling coordination degree of land and water resources use efficiency in urban agglomeration around Poyang Lake

overall level was still low. Although the spatial extent of nominally coordinated counties expanded, the improvement represents only a preliminary step toward balanced development rather than evidence of high-quality synergy between land and water systems. The specific characteristics are as follows: (1) In 2009, the coupling coordination degree of land and water resource use efficiency in the Poyang Lake urban agglomeration showed significant regional differences. Shangrao was in the barely coordinated stage, while other cities except Nanchang and Fuzhou were in the near-discoordination stage. Nanchang and Fuzhou were in the mild discoordination stage, with the most prominent imbalance. (2) In 2013, the overall coupling coordination degree of the cities improved, and the coordinated spatial range gradually expanded. Seven cities had a coupling coordination degree above 0.50, entering the coordinated stage, while Yichun had a coupling coordination degree below 0.50, remaining in the mild discoordination stage. (3) In 2017, the coupling coordination degree of land and water resources further increased, with five cities having a coupling coordination degree above 0.60. For the first time, three cities reached the medium coordinated stage, and the coupling coordination degree of the urban agglomeration showed a strip-like spatial layout. (4) In 2022, Nanchang, Yingtan, and Xinyu maintained a balanced development trend and entered the excellent coordination stage. Shangrao showed good coordination, and Yichun also shifted from near-discoordination to coordination for the first time. The coupling coordination degree of the remaining cities also improved synchronously, and the Poyang Lake urban agglomeration showed spatial equilibrium development in land and water resource use efficiency.

4.3. Spatial analysis of coupling coordination degree of land and water resources in the Poyang Lake Basin

To further explore the spatial differentiation pattern of the coupling coordination degree of land and water resource use efficiency in the Poyang Lake urban agglomeration, accurately interpret the multidimensional characteristics of the spatial distribution of coupling coordination, and clarify its spatial evolution trajectory, the standard deviation ellipse was drawn for the coupling coordination degree of land and water resources in the Poyang Lake urban agglomeration in 2009, 2013, 2017, and 2022 using ArcGIS 10.8. The coupling coordination degree was used as the weight (Figure 4), and the ellipse parameters are shown in Table 5.

Table 5. Elliptic parameters of standard deviation of coupling coordination degree of land resources and water resources utilization efficiency in urban agglomeration around Poyang Lake from 2009 to 2022

Standard Deviation Ellipse						
Year	Centroid coordinates		Area (10^4 km^2)	Major axis (km)	Minor axis (km)	Azimuth (°)
	Longitude E	Latitude N				
2009	116° 13′ 48.112″	28° 31′ 10.603″	3.591	116.230	28.519	76.039
2013	116° 14′ 24.546″	28° 28′ 57.639″	3.552	116.240	28.483	75.617
2017	116° 15′ 29.545″	28° 28′ 48.576″	3.485	116.258	28.480	76.572
2022	116° 13′ 58.361″	28° 27′ 51.252″	3.408	116.233	28.464	76.512

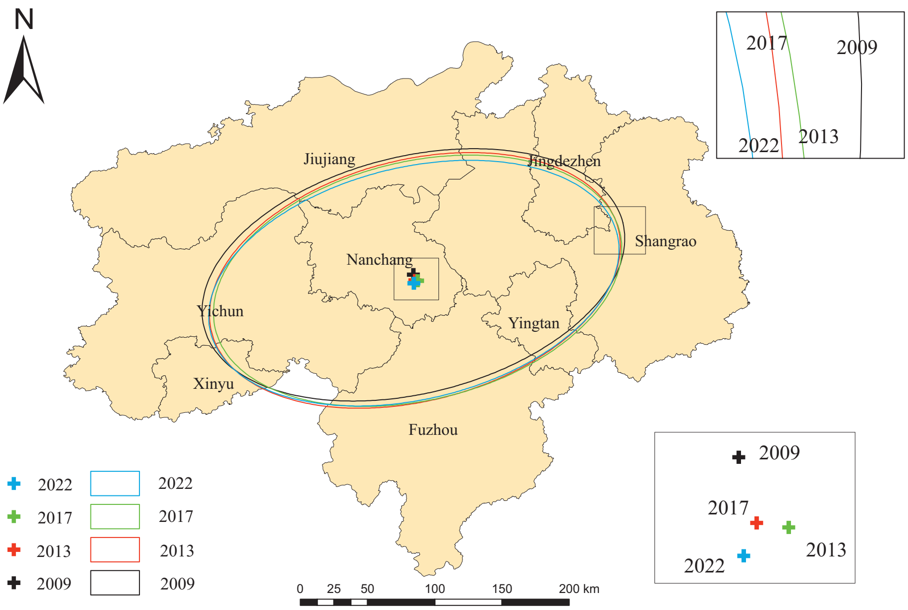

Figure 4. Ellipse of standard deviation of coupling coordination degree of land resource and water resource use efficiency in Poyang Lake urban Agglomeration from 2009 to 2022

From the perspective of the spatial distribution centroid changes, the spatial distribution centroid of the coupling coordination degree of land and water resources in the Poyang Lake urban agglomeration is located in Nanchang, and it moves within the range of 116°13′48.112″E to 116°15′29.545″E and 28°27′51.252″N to 28°31′10.603″N. Specifically, from 2009 to 2022, it showed a "southeast → northwest → southwest" movement trend, indicating that from 2009 to 2013, the growth rate of coupling coordination degree in the northern region was higher than that in the southern cities. From 2013 to 2017 and from 2017 to 2022, the growth rate of coupling coordination degree in the southern region was higher than that in the northern region, with alternating patterns of strong and weak growth in the southeast and southwest regions. Overall, from 2009 to 2022, the centroid moved southeastward, with the largest movement distance from 2009 to 2013, breaking the initial pattern of "strong north and weak south". The reason is that the southeastern cities, influenced by the radiation effect of the eastern coastal cities, developed by optimizing the industrial structure, intensively and efficiently using water resources, and deepening land use reform, achieving a significant increase in the coupling coordination degree.

From the perspective of the spatial distribution area, during the study period, the spatial distribution range of the coupling coordination degree of land and water resources in the Poyang Lake urban agglomeration showed a slow shrinking trend, increasing from 3.591×10^4 km^2 in 2009 to 3.408×10^4 km^2 in 2022. The major axis of the standard deviation ellipse of the coupling coordination degree of land and water resources in the Poyang Lake urban agglomeration increased from 116.230 km to 116.233 km from 2009 to 2022, while the minor axis decreased from 28.519 km to 28.464 km. The major axis of the ellipse in the "east-west" direction was always greater than the minor axis in the "south-north" direction, showing a clear "east-west" distribution pattern. This indicates that during the study period, the coupling coordination degree of land and water resource use efficiency in the Poyang Lake urban agglomeration increased in the east-west direction and decreased in the north-south direction, with the increasing trend being greater than the decreasing trend.

From the perspective of the spatial distribution direction changes, during the study period, the azimuth angle of the coupling coordination degree of land and water resources in the Poyang Lake urban agglomeration did not change significantly, maintaining a continuous shrinking trend, decreasing from 0.422° in 2009–2013 to 0.06° in 2017–2022. The spatial distribution ellipse showed a slight clockwise rotation overall, meaning that cities in the southwest or southeast inside the ellipse had a relatively faster increase in the coupling coordination degree of land and water resources. In other words, the growth rate of the coupling coordination degree of land and water resources in the southern and eastern cities such as Shangrao, Jingdezhen, Yingtan, and Fuzhou was faster than that in the northern and western cities such as Jiujiang and Yichun. The main reason is that the southeastern cities such as Shangrao and Yingtan, as well as the southwestern city of Xinyu, vigorously developed their economies, actively researched and introduced water-saving and pollution control technologies and concepts, improved transportation infrastructure, and enhanced the marketization level of land to improve the efficiency of land and water resource use.

5. Analysis of influencing factors

5.1. Regression results

To ensure the scientific nature of the model (11) specification, we first verified the variance inflation factors (VIF) of each variable, and the results were all within 10, indicating no multicollinearity problem. Subsequently, we conducted a serial correlation test (Wooldridge test), and the test results rejected the null hypothesis at the 1% level ($F(1,7) = 59.856$, $Prob > F = 0.0001$). In addition, targeting the common heteroscedasticity issue in economic problems, we performed a heteroscedasticity test (Wald test), and the test results rejected the null hypothesis at the 1% level ($chi2(8) = 590.44$, $Prob > chi2 = 0$). Finally, we tested for cross-sectional correlation (Breusch-Pagan LM test), and the test results rejected the null hypothesis at the 1% level ($chi2(28) = 95.603$, $Prob > chi2 = 0$). Therefore, in the regression process, it is necessary to consider issues such as variable autocorrelation, heteroscedasticity, and cross-sectional correlation. Based on this, we used the Hausman test to select the model and found that the null hypothesis was rejected at the 1% level ($chi2(7) = 121.32$, $Prob > chi2 = 0$), indicating that a fixed-effects model should be used in the regression. Taking all factors into account, we employed feasible generalized least squares (FGLS) to analyze the influencing factors (Table 6). Columns (1)–(10) show the regression results obtained by sequentially adding control variables. Future work could exploit quasi-experimental settings (e.g., water-rights pilot reforms) to construct instruments and further disentangle causal pathways. Until such data become available, our fixed-effects results should be interpreted as conditional correlations.

From the empirical results, different factors have different impacts on water environment governance in the study area. In terms of the magnitude of the impact, land resource use efficiency, urbanization, and industrial structure have a greater impact on water environment governance.

(1) The impact coefficient of land resource use efficiency (Land) on water environment governance is 0.1208, which is significantly positive at the 1% level. This indicates that land resources can serve as a carrier to provide storage, processing, and transportation activities for water resources. Changes in the hydrological cycle process and form also interact with land use. The improvement in land resource use efficiency has, to some extent, enhanced

Table 6. FGLS regression results of influencing factors of water use efficiency in urban agglomeration around Poyang Lake

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Variables	Water	Water	Water	Water	Water	Water	Water	Water	Water	Water
Land	0.2853^{***}	0.2851^{***}	0.2349^{***}	0.2004^{***}	0.1620^{***}	0.1329^{***}	0.1399^{***}	0.1460^{***}	0.1252^{***}	0.1208^{***}
	(0.0179)	(0.0313)	(0.0317)	(0.0336)	(0.0358)	(0.0416)	(0.0455)	(0.0467)	(0.0455)	(0.0463)
FDI		0.0004^{***}	0.0011^{***}	0.0007^{***}	0.0009^{***}	0.0009^{***}	0.0011^{***}	0.0011^{***}	0.0012^{***}	0.0013^{***}
		(0.0001)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
IndO			-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}
			(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
IndA				-0.7495^{***}	-0.8430^{***}	-0.8381^{***}	-0.8481^{***}	-0.8306^{***}	-0.8442^{***}	-0.8094^{***}
				(0.1601)	(0.1739)	(0.1754)	(0.1808)	(0.1875)	(0.1736)	(0.1818)
Eco					-0.0113^{**}	-0.0107^{**}	-0.0146^{***}	-0.0155^{***}	-0.0267^{***}	-0.0276^{***}
					(0.0051)	(0.0050)	(0.0054)	(0.0059)	(0.0058)	(0.0060)
lnAgrM						−0.0210	-0.0247^{*}	−0.0240	-0.0263^{*}	-0.0283^{**}
						(0.0160)	(0.0148)	(0.0154)	(0.0141)	(0.0143)
lnRDsup							0.0105	0.0094	−0.0105	−0.0104
							(0.0105)	(0.0107)	(0.0105)	(0.0105)
lnroad								0.0081	0.0104	0.0119
								(0.0108)	(0.0088)	(0.0098)
Urban									0.5446^{***}	0.5540^{***}
									(0.1351)	(0.1355)
lnPeop										−0.0204
										(0.0192)
_cons	0.5426^{***}	0.4953^{***}	0.5454^{***}	0.9907^{***}	1.1656^{***}	1.4129^{***}	1.4336^{***}	1.3555^{***}	1.1266^{***}	1.2393^{***}
	(0.0197)	(0.0282)	(0.0329)	(0.1001)	(0.1161)	(0.2182)	(0.2206)	(0.2379)	(0.2373)	(0.2664)
N	112	112	112	112	112	112	112	112	112	112
year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
area	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

water resource use efficiency, with land and water resources exhibiting synergistic effects in the "production-living-ecology" system.

(2) The impact coefficient of outward investment (FDI) is 0.0013, which is significantly positive at the 1% level. There is a divergence in the environmental effects of FDI between the "pollution haven" hypothesis and the "pollution halo" hypothesis. In this study, FDI in the Poyang Lake urban agglomeration has a positive impact on water environment governance, consistent with Peng et al. (2020). Looking at the data on FDI investment, the growth rate of foreign investment in the Poyang Lake cities has shown a gradual slowdown within the time span of this study, indicating that the threshold for inflows of foreign investment is continuously increasing, and the government is focusing on the transformation of FDI towards green and innovative industries.

(3) The impact coefficient of industrial structure is –0.8094, which is significantly negative at the 1% level. This suggests that the optimization and upgrading of the industrial structure in the Poyang Lake urban agglomeration are insufficient, with traditional industries dominating and a focus on heavy industry. This leads to relatively extensive resource use, characterized by high energy consumption, high pollution, and high emissions, causing significant damage to the ecological environment of the region. This finding partially confirms the existence of the "pollution haven" effect. Therefore, it is necessary to accelerate the transformation of the economic development system and build a modern industrial system dominated by low-carbon, intelligent manufacturing, and modern service industries. Accelerating the construction of resource-saving and environmentally friendly cities is essential.

(4) The impact coefficient of urbanization (Urban) is 0.5540, which is significantly positive at the 1% level. This indicates that a higher level of urbanization is associated with higher water resource use efficiency, consistent with the findings of (Wang, 2020). On the one hand, as urbanization increases, the surplus rural labor force moves to cities, where they are influenced by urban civilization and their quality is significantly improved. This leads to greater efforts to protect the urban water ecological environment. On the other hand, high-quality labor can reduce the environmental destruction caused by urban life in the region, alleviate the conflict between humans and nature, and promote the coordinated development of water and land resources (Xie et al., 2021).

(5) The impact coefficient of the economic development level (Eco) is –0.0266, which is significantly negative at the 1% level. This indicates that the relationship between the current economic development of the Poyang Lake urban agglomeration and the water ecological environment conforms to the left side of the Environmental Kuznets Curve, meaning that as per capita income increases, environmental pollution tends to rise. However, once economic development reaches a certain critical point, the degree of environmental pollution will gradually slow down. Therefore, further promotion of economic development in this urban agglomeration is necessary, and structural and technological effects should be used to improve the water ecological environment in the region.

(6) The impact coefficient of industrial output value (IndO) is –0.0001, which is significantly negative at the 1% level. This indicates that as industrial output value increases, water resource use efficiency decreases, although the impact is small. Compared to the tertiary industry, industrial manufacturing requires more water resources and generates a larger amount of wastewater. The proportion of high-tech industries in the current study area is not high, and the industrial structure is dominated by heavy industry. This cannot effectively resolve the contradiction between industrial production and environmental governance. Industrial production technology and effective governance measures are urgently needed for improvement.

(7) (lnAgrM) is –0.0281, which is significantly negative at the 5% level. This indicates that agricultural mechanization has a negative effect on water resource use efficiency. Agricultural mechanization can not only change the agricultural planting structure but also promote the transfer of rural labor to non-agricultural industries. This, in turn, changes the behavior of farmers in using polluting input factors and disposing of agricultural production waste, thereby affecting the regional ecological environment.

(8) The impact coefficients of population density (lnPeop), grade of highway mileage (lnroad), and R&D expenditure (lnRDsup) all show negative effects but are not significant. As population density increases, the construction of grade highways and the investment in R&D funding indicate more frequent population movement and economic activities. This not only increases the pressure on the water ecological environment but also leads to an increase in pollution sources such as industrial wastewater,

Table 7. Robustness test results based on one lag period of independent variables

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Variables	Water	Water	Water	Water	Water	Water	Water	Water	Water	Water
L.Land	0.2380***	0.1491***	0.1010***	0.0374	0.0350	0.0880**	0.0851**	0.1016***	0.0799*	0.0837**
	(0.0399)	(0.0425)	(0.0365)	(0.0238)	(0.0241)	(0.0359)	(0.0334)	(0.0328)	(0.0410)	(0.0418)
L.FDI		0.0008***	0.0013***	0.0012***	0.0013***	0.0014***	0.0013***	0.0013***	0.0013***	0.0013***
		(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
L.IndO			–0.0001***	–0.0002***	–0.0002***	–0.0001***	–0.0001***	–0.0001***	–0.0001***	–0.0001***
			(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
L.IndA				–0.9715***	–0.9699***	–0.9153***	–0.8173***	–0.8148***	–0.8436***	–0.7781***
				(0.1034)	(0.1038)	(0.1019)	(0.1050)	(0.1021)	(0.1014)	(0.1102)
L.Eco					–0.0078**	–0.0092**	–0.0077**	–0.0096**	–0.0117***	–0.0117***
					(0.0040)	(0.0038)	(0.0038)	(0.0037)	(0.0039)	(0.0040)
L.lnAgrM						0.0332**	0.0356***	0.0348***	0.0256*	0.0286*
						(0.0132)	(0.0124)	(0.0121)	(0.0147)	(0.0149)
L.lnRDsup							–0.0114	–0.0112	–0.0150**	–0.0174**
							(0.0076)	(0.0074)	(0.0076)	(0.0079)
L.lnroad								0.0115*	0.0143**	0.0125*
								(0.0064)	(0.0067)	(0.0070)
L.Urban									0.1479	0.1400
									(0.1167)	(0.1189)
L.lnPeop										–0.0276
										(0.0183)
_cons	0.5802***	0.5787***	0.6504***	1.2172***	1.2834***	0.8583***	0.8048***	0.7188***	0.7471***	0.8695***
	(0.0397)	(0.0379)	(0.0351)	(0.0653)	(0.0756)	(0.1794)	(0.1650)	(0.1660)	(0.1698)	(0.1931)
N	104	104	104	104	104	104	104	104	104	104
year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
area	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

domestic sewage, and agricultural non-point source pollution. This makes water environment governance more difficult and reduces water resource use efficiency. The short panel (2009–2022, 14 years) is insufficient to capture the long gestation periods typical for these investments. Because the dataset contains only one additional pre-period (2008) and no reliable instrumental variables, distributed-lag or Granger tests would be under-powered and potentially misleading.

5.2. Robustness test

Considering that the impact of independent variables on the water resource use efficiency of the Poyang Lake urban agglomeration may have a lag effect, this study uses a one-period lag method to lag each variable and tests the robustness of the model (Table 7). Columns (1)–(10) show the regression results obtained by sequentially adding the control variables lagged by one period.

Compared with the results in Table 6, two characteristics are worth noting: First, the test results obtained after lagging the independent variables by one period show no significant changes in the direction and significance of the impact, indicating that the empirical test results obtained above are robust and credible. Second, the test results of L.InRDsup and L.Inroad are significant, indicating that the negative effect of R&D expenditure and the positive effect of grade highway construction on the water resource use efficiency of the Poyang Lake urban agglomeration have a lag effect.

5.3. Heterogeneity analysis

Given the extensive spatial scope of the cities influenced by Poyang Lake and the varying geographical positions of each city relative to the lake, the water and soil resources and water environment conditions are inevitably distinct across these regions. Consequently, it is pertinent to investigate whether the water and soil resources and water environment within the study area exhibit differential outcomes based on the geographical proximity to Poyang Lake. To this end, this study categorizes the eight prefecture-level cities into two groups, using adjacency to Poyang Lake as the classification criterion. The first group consists of cities bordering Poyang Lake, namely Nanchang, Shangrao, and Jiujiang. The second group includes cities that do not border Poyang Lake, such as Jingdezhen, Yingtan, Fuzhou, Yichun, and Xinyu.

The results of the heterogeneity analysis based on geographical location, as shown in Columns 1 and 2 of Table 8, reveal significant differences in the impact of IndO, InRDsup, and Urban on water resource utilization efficiency among the cities bordering Poyang Lake and those that do not. This discrepancy can be attributed to the distinct characteristics in water resource acquisition, utilization patterns, and management strategies between the bordering and non-bordering cities. Cities adjacent to Poyang Lake are more reliant on the lake's

Table 8. Heterogeneity test results

Variables	(1)	(2)
	Water	Water
Land	0.3415**	0.1229**
	(0.1672)	(0.0602)
FDI	0.0016*	0.0015*
	(0.0009)	(0.0008)
IndO	0.0001***	–0.0001***
	(0.0000)	(0.0000)
IndA	–0.8277***	–1.7580*
	(0.2374)	(1.0617)
Eco	0.0100	0.0015
	(0.0111)	(0.0393)
InAgrM	0.0425**	0.2878*
	(0.0186)	(0.1541)
InRDsup	0.0042*	0.0571
	(0.0024)	(0.0976)
Inroad	0.0147**	0.0090
	(0.0072)	(0.0109)
Urban	1.0721***	–2.9149***
	(0.2172)	(0.4702)
InPeop	–0.2312*	0.0945
	(0.1231)	(0.1521)
_cons	0.8663*	0.8023***
	(0.4438)	(0.2686)
N	69	42
year	Yes	Yes
area	Yes	Yes

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

water resources and tend to develop water-intensive industries in their economic structures. In contrast, non-bordering cities are more dependent on other types of industries. Moreover, in terms of InRDsup, bordering cities tend to focus more on the development and innovation of water resource recycling technologies. This focus directly promotes the application and dissemination of these technologies, thereby enhancing water resource utilization efficiency. Conversely, non-bordering cities allocate a larger proportion of their R&D investments to other sectors, which results in a less pronounced effect on improving water resource utilization efficiency. Lastly, the increase in urbanization level in bordering cities is accompanied by more comprehensive infrastructure and more efficient water resource management practices. For instance, these cities are more likely to establish additional wastewater treatment plants and deploy water-saving devices. In contrast, the rise in urbanization rate in non-bordering cities primarily leads to industrial expansion and population growth, which in turn increases the demand for water resources. However, the lack of corresponding water resource management measures in these non-bordering cities results in a decline in water resource utilization efficiency.

5.4. Spatial econometric model estimation

5.4.1. Spatial dependence diagnostics

Spatial-dependence diagnostics (global Moran's I = 0.339, $p < 0.01$; local Moran's I = 0.253, $p < 0.05$) reveal significant positive spatial autocorrelation in land and water resources across the Poyang Lake Urban Agglomeration, with LM-Error (17.005, $p < 0.01$) and LM-Lag (23.477, $p < 0.01$) reinforcing this finding.

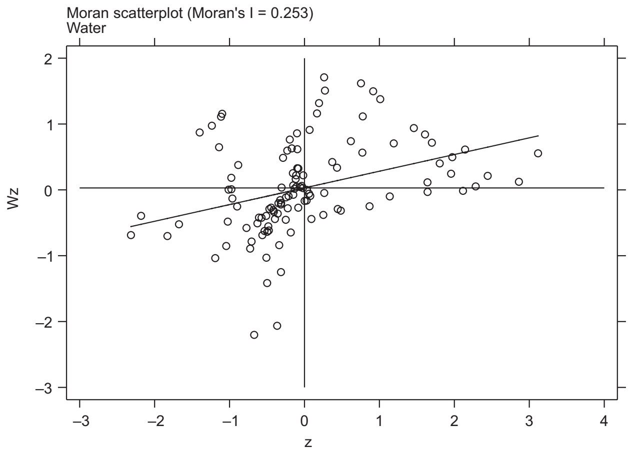

Figure 5. Local Moran's I Scatter Plot

As shown in Figure 5, the local Moran scatterplot for water-use efficiency is dominated by high-high (HH) and low-low (LL) clusters, confirming a pronounced "like-with-like" spatial regime. HH counties are concentrated around the core city of Nanchang, whereas LL counties are mainly located in the peripheral uplands, revealing a core–periphery gradient rather than random outliers.

5.4.2. Spatial Durbin model regression results

The estimation results of the spatial Durbin model, specified to examine the land-use efficiency effects on water-resource utilization in the Poyang Lake Urban Agglomeration, are presented in Table 9. First, the short-run main effects in all three specifications are positive and significant at the 1%, indicating that an immediate improvement in local land-use efficiency translates into higher water-resource utilization efficiency. The spatial Durbin model (SDM) yields the largest coefficient (0.239), implying that the local land-water effect is strongest once both spatial lags and spatial errors are accounted for. With respect to long-run total effects, the SDM and SAR estimates are 0.218 and 0.185, respectively, and both are significant at the 5% level, confirming that the water-saving dividend generated by higher land efficiency remains stable within the regional system.

Second, the estimated spatial parameters show that the ñ coefficients in the SDM and SAR are 0.247 and 0.189, respectively. They are both significant at the 5% level, demonstrating a significant positive spatial spillover of land-use efficiency. The ë coefficient in the SEM is 0.211 and is also significant and positive, indicating that unobserved water-saving factors are spatially clustered as well.

In summary, the land-water system in the Poyang Lake Urban Agglomeration exhibits a dual mechanism of "local efficiency gains and neighbour spillovers". The spatial Durbin model is the most appropriate specification for capturing such spatial interactions and provides an empirical basis for designing cross-regional water-saving policies.

Table 9. Two-way fixed-effects spatial Durbin model regression results

Variable / diagnostic	SDM	SEM	SAR
Short-run Main effect (x)	0.239^{***} (0.051)	0.158^{***} (0.059)	0.161^{***} (0.059)
Long-run Total effect (x)	0.218^{**} (0.131)	—	0.185^{**} (0.073)
Spatial parameter	$\rho = 0.247^{**}$ (0.118)	$\lambda = 0.211^{**}$ (0.102)	$\rho = 0.189^{**}$ (0.087)
R^2	0.529	0.364	0.275
LM-Error	17.01^{***}	—	17.01^{***}
LM-Lag	23.48^{***}	23.48^{***}	—
LR Test	—	61.48^{***}	77.68^{***}
Wald Test	—	—	62.31^{***}
Hausman	96.78^{***}		
Number of area	8	8	8
Observations	112	112	112
Controls	Yes	Yes	Yes

Note: Standard errors in parentheses. ** $p < 0.05$, *** $p < 0.01$.

6. Conclusions and recommendations

6.1. Conclusions

(1) During the study period, the overall level of water and land resource use efficiency in the Poyang Lake urban agglomeration was not high, showing a fluctuating upward trend with significant spatial heterogeneity. The top three cities in land resource use efficiency were Nanchang, Yingtan, and Xinyu, while the top three in water resource use efficiency were Yingtan, Shangrao, and Xinyu.

(2) From 2009 to 2013, the coupling coordination degree of water and land resource use efficiency in the Poyang Lake urban agglomeration was generally in the near-discoordination stage. From 2014 to 2017, it was basically in the transition from barely coordinated to primary coordinated stage. From 2018 to 2022, it was mainly in the medium coordinated stage. Throughout the study period, the lag of water resource use efficiency dominated, with significant spatial differences in the coupling coordination degree, gradually evolving into a spatial pattern of "high in the east and low in the west".

(3) From the results of the standard deviation ellipse, the increase in the coupling coordination degree of water and land resources in the "east-west" direction was greater than the decrease in the "south-north" direction.

Cities in the northeast and southwest directions had a faster growth rate in coupling coordination degree, with alternating patterns of strong and weak growth.

(4) The empirical results of the factors influencing water resource use efficiency show that urbanization, land resource use efficiency, and outward investment have a significantly positive promoting effect on the improvement of water resource efficiency in the Poyang Lake urban agglomeration. In contrast, industrial structure, agricultural mechanization, and economic development level are significantly unfavorable for the improvement of water resource use efficiency. The negative effect of R&D expenditure and the positive effect of grade highway construction have a lag effect.

(5) Spatial Durbin estimates for the Poyang Lake Urban Agglomeration reveal an immediate, statistically robust synergy between land-use and water-resource efficiency: every 1-unit local gain in land productivity raises on-site water efficiency by 0.24 units and spills over to increase neighbours' water efficiency by 0.25 units, with the combined dividend persisting at 0.22 units in the long run. This simultaneous "local gain plus neighbour spillover" demonstrates that land-water coupling is not only a municipal phenomenon but also a regional process driven by observable spatial externalities.

6.2. Recommendations

(1) The Poyang Lake urban agglomeration should adapt measures to local conditions and innovate or learn the latest technologies for land and water resource use. It should be also rely on technological innovation, and improve the comprehensive efficiency of land and water resource use through multiple channels. A reasonable and moderate water resource planning strategy should be developed to optimize the spatial development pattern of the urban agglomeration. The strictest water resource management system must be implemented to uphold the "three red lines". Advanced water-saving technologies must be adopted to ensure the intensive and efficient use of urban water and land resources, and to achieve the goals of green, recycle, and low-carbon development.

(2) As the coupling and coordination of land and water resources varies across the cities surrounding Poyang Lake, with cities such as Jiujiang and Fuzhou having relatively low levels of both, it is important to learn from cities such as Nanchang, Shangrao and Yingtan. These cities should actively learn from those cities such as Nanchang, Shangrao and Yingtan, breaking free from the traditional "point-based policy" mindset. The radiating and leading role of central cities should be fully utilized to facilitate the flow of basic elements such as knowledge and technology for intensive and efficient water and land use between regions, and an efficient inter-city communication mechanism should be established.

(3) Carefully manage and strictly control the use of water and land resources. Under the premise of ensuring food production security, improve the irrigation methods of agriculture to avoid extensive use of agricultural water, reduce the input of polluting factors, and eliminate high-energy-consuming, high-polluting, and high-emission industrial enterprises. Optimize the use of water and land by industries and establish incentive mechanisms to encourage water saving between enterprises. Urban construction plans should be coordinated with land use planning and water resource use planning. In ecologically fragile areas, the input of construction land should be reduced, more ecological land should be developed, and the construction of ecological urban agglomerations should be gradually implemented. The blind expansion of land production for arable and forested land should be eliminated, and the principle of "determining urban development, land use, population size, and industrial output based on water availability" should be firmly implemented to ensure the safe and efficient use of water and strengthen water environment governance.

(4) Moderately reducing the scale of secondary industry development and encourage the development of the tertiary industry in the Poyang Lake urban agglomeration. This will help to build a modern industrial system dominated by low-carbon, intelligent manufacturing, and modern service industries. Drive the improvement of local economic and water and land resource use efficiency by relying on the development of the tertiary industry, and enhance the coordinated degree of water and land resource use efficiency in all cities within the region by focusing on the overall industrial structure transformation and upgrading of the urban agglomeration. Attract talent and encourage innovative, technology-based enterprises to settle in the Poyang Lake urban agglomeration, achieving the coordinated and efficient use of water and land resources and ensuring ecological security and high-quality economic development.

(5) Encourage basin-level managers establish a cross-city "efficiency-credit" trading platform. It allows high-performing municipalities to sell saved water quotas to neighbours, prioritise grade-highway and industrial-park investment along the demonstrated Nanchang–Yingtan–Xinyu HH-core corridor to amplify demonstration effects. Besides, introduce performance-based fiscal transfers that reward peripheral LL counties for annual improvements in land-use efficiency, thereby gradually closing the core-periphery gap in water productivity while safeguarding regional water security.

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No potential conflict of interest was reported by the author(s).

Data availability

Data and materials are available from the authors upon request.

References

Akhtar, N., Syakir Ishak, M. I., Bhawani, S. A., & Umar, K. (2021). Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water*, *13*(19), Article 2660. https://doi.org/10.3390/w13192660

Al-ossmi, L. H. (2024). Land tenure administration in Iraq: Quantitative analysis and a comprehensive evaluation. *Land Use Policy*, *141*, Article 107092. https://doi.org/10.1016/j.landusepol.2024.107092

Anser, M. K., Ali, S., Umair, M., Javid, R., & Mirzaliev, S. (2024). Energy consumption, technological innovation, and economic growth in BRICS: A GMM panel VAR framework analysis. *Energy Strategy Reviews*, *56*, Article 101587. https://doi.org/10.1016/j.esr.2024.101587

Bai, Y., Ochuodho, T. O., & Yang, J. (2019). Impact of land use and climate change on water-related ecosystem services in Kentucky, USA. *Ecological Indicators*, *102*, 51–64. https://doi.org/10.1016/j.ecolind.2019.01.079

Belton, B., Win, M. T., Zhang, X., & Filipski, M. (2021). The rapid rise of agricultural mechanization in Myanmar. *Food Policy*, *101*, Article 102095. https://doi.org/10.1016/j.foodpol.2021.102095

Bu, Z., Mo, D., Sun, Y., Zhang, L., Zhu, Y., Duan, X., Nian, L., Tang, Y., Ye, C., & Cao, J. (2026). Dynamic accumulation and co-occurrence of phthalates and squalene in settled dust: Implications for assessing indoor phthalate homology and exposures. *Environmental Science*: *Processes* & *Impacts*, *28*(6), 1721–1732. https://doi.org/10.1039/D6EM00265J

Chen, X., & Yang, L. (2019). Temperature and industrial output: Firm-level evidence from China. *Journal of Environmental Economics and Management*, *95*, 257–274. https://doi.org/10.1016/j.jeem.2017.07.009

Cheng, Z., He, J., Liu, Y., Zhang, Q., & Deng, Y. (2023). Exploring the spatial structure and impact factors of water use efficiency in China. *Environmental Impact Assessment Review*, *103*, Article 107258. https://doi.org/10.1016/j.eiar.2023.107258

de Mello, K., Valente, R. A., Randhir, T. O., dos Santos, A. C., & Vettorazzi, C. A. (2018). Effects of land use and land cover on water quality of low-order streams in Southeastern Brazil: Watershed versus riparian zone. *Catena*, *167*, 130–138. https://doi.org/10.1016/j.catena.2018.04.027

Fei, R., & Lin, B. (2016). Energy efficiency and production technology heterogeneity in China's agricultural sector: A meta-frontier approach. *Technological Forecasting and Social Change*, *109*, 25–34. https://doi.org/10.1016/j.techfore.2016.05.012

Fitton, N., Alexander, P., Arnell, N., Bajzelj, B., Calvin, K., Doelman, J., Gerber, J. S., Havlik, P., Hasegawa, T., Herrero, M., Krisztin, T., van Meijl, H., Powell, T., Sands, R., Stehfest, E., West, P. C., & Smith, P. (2019). The vulnerabilities of agricultural land and food production to future water scarcity. *Global Environmental Change*, *58*, Article 101944. https://doi.org/10.1016/j.gloenvcha.2019.101944

Freeman, L. A., Corbett, D. R., Fitzgerald, A. M., Lemley, D. A., Quigg, A., & Steppe, C. N. (2019). Impacts of urbanization and development on estuarine ecosystems and water quality. *Estuaries and Coasts*, *42*(7), 1821–1838. https://doi.org/10.1007/s12237-019-00597-z

Gu, Y., Chen, J., Ji, J., & Deng, M. (2024). The impacts of water ecological carrying capacity on green total factor productivity: The case of chemical industry in Jiangsu, China. *SAGE Open*, *14*(2), 1–17. https://doi.org/10.1177/21582440241242665

Guo, B., Wang, Y., Zhang, H., Liang, C., Feng, Y., & Hu, F. (2023). Impact of the digital economy on high-quality urban economic development: Evidence from Chinese cities. *Economic Modelling*, *120*, Article 106194. https://doi.org/10.1016/j.econmod.2023.106194

He, Y., Zhu, Z., Xie, H., Zhang, X., & Sheng, M. (2023). A case study in China of the influence mechanism of industrial park efficiency using DEA. *Environment*, *Development and Sustainability*, *25*(7), 7261–7280. https://doi.org/10.1007/s10668-022-02290-x

Hua, Y., & Tong, T. (2025). Renewable energy integration in the Belt and Road Initiative: Government expenditure, green finance, and economic growth. *Renewable Energy*, 123980. https://doi.org/10.1016/j.renene.2025.123980

Jin, K. (2012). Industrial structure and capital flows. *American Economic Review*, *102*(5), 2111–2146. https://doi.org/10.1257/aer.102.5.2111

Kim, D. H., Lin, S. C., & Suen, Y. B. (2013). Investment, trade openness and foreign direct investment: Social capability matters. *International Review of Economics* & *Finance*, *26*, 56–69. https://doi.org/10.1016/j.iref.2012.08.008

Lei, X., & He, S. (2025). Climate shocks and innovation persistence: Evidence from extreme precipitation. *Humanities and Social Sciences Communications*, *12*(1), 1–14. https://doi.org/10.1057/s41599-025-05229-5

Li, H., Fang, K., Yang, W., Wang, D., & Hong, X. (2013). Regional environmental efficiency evaluation in China: Analysis based on the Super-SBM model with undesirable outputs. *Mathematical and Computer Modelling*, *58*(5–6), 1018–1031. https://doi.org/10.1016/j.mcm.2012.09.007

Liu, H., Cong, R., Liu, L., Li, P., & Ma, S. (2026). The impact of digital transformation on innovation efficiency in construction enterprises under the dual carbon background. *Journal of Asian Architecture and Building Engineering*, *25*(3), 2358–2375. https://doi.org/10.1080/13467581.2025.2499723

Liu, H., Rodgers, M. O., & Guensler, R. (2019). The impact of road grade on vehicle accelerations behavior, PM2. 5 emissions, and dispersion modeling. *Transportation Research Part D*: *Transport and Environment*, *75*, 297–319. https://doi.org/10.1016/j.trd.2019.09.006

Lü, S., Lü, C., Liu, P., Zhao, H., & Wang, F. (2024). Regional water cycle health evaluation and obstacle factor analysis: A case study of the Yellow River basin in Henan Province, China. *Ecological Indicators*, *166*, Article 112500. https://doi.org/10.1016/j.ecolind.2024.112500

Ma, S., & Appolloni, A. (2025). Can financial flexibility enhance corporate green innovation performance? Evidence from an ESG approach in China. *Journal of Environmental Management*, *387*, Article 125869. https://doi.org/10.1016/j.jenvman.2025.125869

Ma, S., Benkraiem, R., Abedin, M. Z., & Zeng, H. (2025a). Climate anomalies and corporate environmental governance: Empirical evidence from ENSO events. *Finance Research Letters*, *85*, Article 107970. https://doi.org/10.1016/j.frl.2025.107970

Ma, S., Wen, L., & Yuan, Y. (2024). Study on the coupled and coordinated development of tourism, urbanization and ecological environment in Shanxi Province. *Global NEST Journal*, *26*(4), 1–9. https://doi.org/10.30955/gnj.005907

Ma, S., Zeng, H., & Abedin, M. Z. (2025b). The impact of the reforms in the Chinese equities exchange and quotations on innovation in cross-border e-commerce enterprises. *Asia Pacific Business Review*, 1–41. https://doi.org/10.1080/13602381.2025.2510509

Pan, D., & Ying, R. Y. (2013). Evaluation methods and empirical analysis of China's agricultural ecological efficiency: A nondesirable output SBM model analysis. *Acta Ecologica Sinica*, *33*(12), 3837–3845. https://doi.org/10.5846/stxb201207080953

Paranina, A. N., & Paranin, R. V. (2017). Information in geographical space as the basis of cross-disciplinary researches in culture geography. *European Journal of Geography*, *8*(3), 67–77.

Peng, B., Chen, H., Elahi, E., & Wei, G. (2020). Study on the spatial differentiation of environmental governance performance of Yangtze river urban agglomeration in Jiangsu province of China. *Land Use Policy*, *99*, Article 105063. https://doi.org/10.1016/j.landusepol.2020.105063

Qu, B., Jiang, E., Li, J., Liu, Y., & Liu, C. (2024). Coupling coordination relationship of water resources, eco-environment and socio-economy in the water-receiving area of the Lower Yellow River. *Ecological Indicators*, *160*, Article 111766. https://doi.org/10.1016/j.ecolind.2024.111766

Quintas-Soriano, C., Castro, A. J., Castro, H., & Garcia-Llorente, M. (2016). Impacts of land use change on ecosystem services and implications for human well-being in Spanish drylands. *Land Use Policy*, *54*, 534–548. https://doi.org/10.1016/j.landusepol.2016.03.011

Rahman, M. M., & Alam, K. (2021). Clean energy, population density, urbanization and environmental pollution nexus: Evidence from Bangladesh. *Renewable Energy*, *172*, 1063–1072. https://doi.org/10.1016/j.renene.2021.03.103

Ruan, Y., Wang, W., Abubakar, M., & Ahmad, N. (2025). Global economic resilience: Developing green growth strategies, renewable energy integration, and environmental economics for sustainability. *Renewable Energy*, *251*, Article 123341. https://doi.org/10.1016/j.renene.2025.123341

Sokolov-Mladenović, S., Cvetanović, S., & Mladenović, I. (2016). R&D expenditure and economic growth: EU28 evidence for the period 2002–2012. *Economic Research-Ekonomska Istraživanja*, *29*(1), 1005–1020. https://doi.org/10.1080/1331677X.2016.1211948

Sun, D., & Luo, Q. (2026). Green transition under carbon peak pressure: beyond greenwashing. *Applied Economics*, 1–17. https://doi.org/10.1080/00036846.2026.2635633

Sun, D., & Li, J. (2025). Carbon peaking pressure and corporate earnings management. *International Review of Economics & Finance*, *103*, Article 104503. https://doi.org/10.1016/j.iref.2025.104503

Sun, D., & Li, Y. (2025). Carbon peaking pressure and corporate R&D investment. *Economics Letters*, *251*, Article 112328. https://doi.org/10.1016/j.econlet.2025.112328

Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. *European Journal of Operational Research*, *130*, 498–509. https://doi.org/10.1016/S0377-2217(99)00407-5

Tone, K. (2002). A slacks-based measure of super-efficiency in data envelopment analysis. *European Journal of Operational Research*, *143*(1), 32–41. https://doi.org/10.1016/S0377-2217(01)00324-1

Tuoku, L., & Men, B. (2023). Evaluation of water resource use efficiency in Beijing-Tianjin-Hebei based on three-dimensional water ecological footprint. *Ecological Indicators*, *154*, Article 110884. https://doi.org/10.1016/j.ecolind.2023.110884

Van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., & Winkler, H. (2014). A new scenario framework for climate change research: Scenario matrix architecture. *Climatic Change*, *122*, 373–386. https://doi.org/10.1007/s10584-013-0906-1

Wang, M., Wang, C., Ali, S., Nazar, R., & Meo, M. S. (2025). Budgeting for bio-resilience: Unraveling the asymmetric impact of bioenergy technology budgets on environmental quality. *Renewable Energy*, *239*, Article 122074. https://doi.org/10.1016/j.renene.2024.122074

Wang, Y. (2020). Urban land and sustainable resource use: Unpacking the countervailing effects of urbanization on water use in China, 1990–2014. *Land Use Policy*, *90*, Article 104307. https://doi.org/10.1016/j.landusepol.2019.104307

Wang, Y., Zhao, J., Jeibo, L., & Yungho, C. (2025). Total quality management and hydrogen finance: Strengthening organizational legitimacy through procurement and innovation. *Journal of Energy Storage*, *128*, Article 116901. https://doi.org/10.1016/j.est.2025.116901

Wang, Z., & Ma, S. (2024). Research on the impact of digital inclusive finance development on carbon emissions—Based on the double fixed effects model. *Global NEST Journal*, *26*(7), 1–10. https://doi.org/10.30955/gnj.06227

Wu, Q., Jin, Y., & Ma, S. (2024). Impact of dual pilot policies for low-carbon and innovative cities on the high-quality development of urban economies. *Global NEST Journal*, *26*(9), Article 06307.

Wu, Y., Wang, X., Xie, H., & Ma, S. (2025). How digital trade can reshape the trajectory of green and low-carbon development under the leadership of "dual-control" objectives. *Global NEST Journal*, *27*(7), 1–16.

Xie, X., Fang, B., Xu, H., He, S., & Li, X. (2021). Study on the coordinated relationship between urban land use efficiency and ecosystem health in China. *Land Use Policy*, *102*, Article 105235. https://doi.org/10.1016/j.landusepol.2020.105235

Xing, Y., & Jin, Y. Q. (2025). Evolutionary characteristics and identification of driving factors of the coupling coordination degree between the dual circulation development pattern and new-quality productive forces. *Statistics and Decision*, *41*(7), 135–140.

Xu, H., & Jiao, M. (2021). City size, industrial structure and urbanization quality—A case study of the Yangtze River Delta urban agglomeration in China. *Land Use Policy*, *111*, Article 105735. https://doi.org/10.1016/j.landusepol.2021.105735

Yan, S., & Wang, J. (2022). Does polycentric development improve green utilization efficiency of urban land? An empirical study based on panel threshold model approach. *Land*, *11*(1), Article 124. https://doi.org/10.3390/land11010124

Yang, X., Fang, Z., Yin, L., Li, J., Lu, S., & Zhao, Z. (2019). Revealing the relationship of human convergence–divergence patterns and land use: A case study on Shenzhen City, China. *Cities*, *95*, Article 102384. https://doi.org/10.1016/j.cities.2019.06.015

Yang, Z., Chen, H., Ma, C., Gao, X., Yang, C., Sun, W., & Wang, Y. (2024). A novel framework reveals anthropogenic stressors of phosphorus polluted river-lake connection water system in Poyang lake basin of China. *Journal of Environmental Management*, *370*, Article 122794. https://doi.org/10.1016/j.jenvman.2024.122794

Yu, B. (2021). Ecological effects of new-type urbanization in China. *Renewable and Sustainable Energy Reviews*, *135*, Article 110239. https://doi.org/10.1016/j.rser.2020.110239

Zhang, X., Li, G., Wu, R., Zeng, H., & Ma, S. (2025). Impact of carbon emissions, green energy, artificial intelligence and high-tech policy uncertainty on China's financial market. *Finance Research Letters*, *82*, Article 107599. https://doi.org/10.1016/j.frl.2025.107599

Zhao, J., Zhu, D., Cheng, J., Jiang, X., Lun, F., & Zhang, Q. (2021). Does regional economic integration promote urban land use efficiency? Evidence from the Yangtze River Delta, China. *Habitat International*, *116*, Article 102404. https://doi.org/10.1016/j.habitatint.2021.102404

Zhao, L., Zhao, Z. Q., & Wang, W. (2014). Changes in the economic spatial pattern of the eastern coastal region of China. *Economic Geography*, *34*(2), 14–18+27.

Zhao, R. Q., Li, Z. P., Han, Y. P., Kandlikar, M., Zhang, Z. P., & Ding, M. L. (2016). Analysis of the coupling mechanism of water-soil-energy-carbon in the region. *Journal of Geography*, *71*(9), 1613–1628.

Zou, F., Ma, S., Liu, H., Gao, T., & Li, W. (2024). Do technological innovation and environmental regulation reduce carbon dioxide emissions? Evidence from China. *Global NEST Journal*, *26*(7), 1–15. https://doi.org/10.30955/gnj.06291