Sains Malaysiana 55(1)(2026): 61-75
http://doi.org/10.17576/jsm-2026-5501-05

Geospatial-Temporal Coupling of Urbanisation and Water Resources: Landscape Dynamics in Nanchang, China

(Penggandingan Georeruang-Temporal antara Urbanisasi dan Sumber Air: Dinamik Landskap di Nanchang, China)

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Received: 17 August 2025/Accepted: 12 January 2026

ABSTRACT

Rapid urbanisation necessitates an understanding of the coupling coordination between urban expansion and water resources to inform sustainable development strategies. However, research on this relationship remains limited in less economically developed regions. This study addresses the gap by examining Nanchang City, Jiangxi Province, China, using land use and socio-economic data (2000-2020) to analyse geospatial-temporal changes in land use and landscape patterns of construction land and water bodies. A coupling coordination model is applied to assess the relationship between urbanisation and water resources. Findings indicate that cultivated land, water bodies and forest land were major sources of new construction land. The expansion rate and intensity of construction land initially declined before increasing, peaking in 2000-2005. The fractal dimension exhibited a steady rise, while compactness remained relatively stable. Water body area, landscape shape index and edge density generally declined. Landscape fragmentation, separation and cohesion indices fluctuated between 2000 and 2015 but changed significantly in 2015-2020. Spatial overlap between the centroids of construction land and water bodies varied (1.8904-2.9465 km), following a positive-negative-positive cyclical pattern. The coupling coordination degree between urbanisation and water resources improved, progressing through stages from 'Moderately Unbalanced' to 'Highly Balanced'. To foster an urban-water symbiotic pattern, ecological corridors within the water system should be established and construction land boundaries delineated with caution. These findings offer valuable insights for urban planning and water resource management in Nanchang City and other rapidly developing regions.

Keywords: Coupling coordination; landscape pattern; sustainable development; urbanisation; water resources

ABSTRAK

Urbanisasi pesat memerlukan pemahaman tentang penggandingan dan koordinasi antara pengembangan bandar dan sumber air bagi memaklumkan strategi pembangunan lestari. Walau bagaimanapun, kajian mengenai hubungan ini masih terhad di wilayah yang kurang membangun dari segi ekonomi. Kajian ini menangani jurang tersebut dengan meneliti Bandar Nanchang, Wilayah Jiangxi, China dengan menggunakan data guna tanah dan sosio-ekonomi (2000-2020) untuk menganalisis perubahan georeruang-temporal dalam guna tanah dan corak landskap tanah binaan serta badan air. Model penggandingan koordinasi digunakan untuk menilai hubungan antara urbanisasi dan sumber air. Keputusan menunjukkan bahawa tanah pertanian, badan air dan hutan merupakan sumber utama kepada tanah binaan baharu. Kadar dan keamatan pengembangan tanah binaan pada awalnya menurun sebelum meningkat semula, dengan kemuncak pada tahun 2000-2005. Dimensi fraktal meningkat secara berterusan, manakala tahap kepadatan kekal agak stabil. Luas badan air, indeks bentuk landskap dan ketumpatan pinggir menurun secara umum. Fragmentasi, pemisahan dan indeks kohesi landskap berfluktuasi antara 2000 hingga 2015 tetapi berubah dengan ketara dalam tempoh 2015-2020. Pertindihan ruang antara pusat jisim tanah binaan dan badan air berbeza-beza (1.8904-2.9465 km) mengikuti corak kitaran positif-negatif-positif. Tahap penggandingan koordinasi antara urbanisasi dan sumber air bertambah baik, melalui tahap daripada 'Sederhana Tidak Seimbang' kepada 'Sangat Seimbang'. Bagi membentuk corak simbiotik bandar-air, koridor ekologi dalam sistem air perlu diwujudkan dan sempadan tanah binaan perlu ditentukan dengan berhati-hati. Penemuan ini memberikan pandangan berharga untuk perancangan bandar dan pengurusan sumber air di Bandar Nanchang serta wilayah lain yang sedang membangun dengan pesat.

Kata kunci: Corak landskap; koordinasi gandingan; pembangunan lestari; sumber air; urbanisasi

INTRODUCTION

Urbanisation is a key driver of socio-economic development and a fundamental pathway to national modernisation. By 2050, the global urbanisation rate is projected to reach 68% (Kundu & Pandey 2020). Since the reform and opening up of China, its urbanisation rate has surpassed the global average. Water resources are essential for human survival and development, as they play a crucial role in fulfilling human production and living needs, supporting socio-economic growth and maintaining ecological balance. However, the rapid pace of urbanisation has exacerbated the demand for water resources, posing significant challenges to water supply and environmental quality (Bian et al. 2022). Simultaneously, issues such as the fragmentation of water spaces and the degradation of aquatic ecosystems compromise the quality of urbanisation, thereby hindering sustainable urban development (Sun et al. 2019).

In response, China has introduced the concept of ecological civilisation, emphasising that economic and social development must be premised on the harmonious coexistence of humans and nature, thus promoting ecological protection and environmental governance. Ecosystem service value (ESV) quantifies the economic benefits provided by ecosystems to humans through their natural functions, including provisioning, regulating, supporting, and cultural services (Jiang, Wu & Fu 2021). In this context, a critical challenge is determining how to achieve coordinated symbiosis between construction land and water bodies during urban expansion, with particular attention to their contributions to ESV. This issue is especially pertinent in light of China's urbanisation transition and its ecological civilisation goals. Accurately quantifying the landscape patterns of construction land and water bodies, along with understanding their intrinsic relationships, is an essential prerequisite for addressing this challenge. Research in this area provides valuable references for the sustainable development of urbanisation and water bodies, as well as for national spatial planning (Ma et al. 2022).

Studies examining the relationship between urbanisation and water resources generally focus on three main aspects: the stress that urbanisation imposes on water resources, the constraints that water resources place on urbanisation and the interaction between urbanisation and water resources (Chen, Yu & Zhang 2024; Luo et al. 2018; Sanchez et al. 2020). In recent years, research on the coupling between urbanisation and water resources has gained increasing attention. The coupling coordination degree model is a widely used method for assessing the degree of coordination between two interacting systems. However, existing studies primarily focus on watersheds, arid regions and developed cities (Lyu 2018; Zhai et al. 2024; Zhao et al. 2021), with relatively little attention paid to underdeveloped regions experiencing rapid urbanisation. The rational utilisation and management of water resources during the urbanisation process may become a bottleneck for sustainable development in these regions. Therefore, studying the coupling coordination relationship between urbanisation levels and water resources can provide theoretical support for urban planning and management in the region. Furthermore, compared to traditional coupling analyses that rely exclusively on the coupling coordination degree model, incorporating the spatial centroid coupling model allows for a more comprehensive characterisation of the geospatial-temporal evolution of construction land expansion and water body patterns, thereby offering a clearer explanation of the spatial mechanisms underlying changes in the coupling coordination between urbanisation and water resources.

As the capital of Jiangxi Province and a typical example of rapid urbanisation, Nanchang reflects the urbanisation patterns of many second and third-tier cities in China, making it highly representative. Located adjacent to Poyang Lake, this lake-river network city features a distinctive hydrological setting within an urban-water system. Its accreditation as a Ramsar 'Wetland City' further underscores the policy significance of urban wetland co-management (Wang et al. 2024). This study focuses on Nanchang City, Jiangxi Province, China, intending to: (1) analyse the evolution of landscape patterns of construction land and water bodies from 2000 to 2020 by calculating landscape pattern indices and (2) employ the spatial centroid coupling model and the coupling coordination degree model to examine the coupling relationships between construction land and water bodies, as well as between urbanisation levels and water resources. The findings of this research can serve as a decision-making reference for promoting the coordinated development of construction land and water bodies in Nanchang City and other regions undergoing rapid urbanisation.

METHODS

STUDY AREA

Nanchang City is located in the southeastern part of Jiangxi Province, China, with geographical coordinates of 28°09' - 29°11'N and 115°27' -116°35'E. The primary topographic features include plains and hills, characterised by generally flat terrain that slopes gradually from northwest to southeast. The city lies within the subtropical East Asian monsoon region, experiencing an average annual temperature of 17.8 °C, with extreme maximum and minimum temperatures of 40.6 °C and -9.7°C, respectively. The average annual rainfall is 1,600 mm, accompanied by an average annual sunshine duration of 1,860.9 h and a frost-free period of 277.7 days. The predominant soil types are paddy soil and red soil and the vegetation belongs to the typical mid-subtropical evergreen broad-leaved forest zone (Lv et al. 2019).

DATA SOURCES

This study primarily employs land use and socio-economic data for Nanchang City from the years 2000, 2005, 2010, 2015, and 2020. The land use data were obtained from the Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (http://www.resdc.cn/), which were acquired through a combination of human-computer interactive visual interpretation and random sampling detection on Landsat series remote sensing images (Landsat-TM and Landsat 8; March acquisition) with a resolution of 30 metres. The interpretation accuracy is no less than 85%. The land use categories include water bodies, construction land, cultivated land, forest land, grassland, and unused land. The socioeconomic data were sourced from the Nanchang Statistical Yearbook, Nanchang National Economic and Social Development Bulletin, Jiangxi Statistical Yearbook and the Nanchang Water Resources Bulletin.

METHODS

LAND USE TRANSFER MATRIX

The land use transfer matrix quantitatively describes the area of conversion between different land use types over different periods. The calculation formula is as follows:

$$A_{ij} = \begin{bmatrix} A_{11} & A_{12} & L & A_{1n} \\ A_{21} & A_{n2} & L & A_{2n} \\ M & M & O & M \\ A_{n1} & A_{n2} & L & A_{nn} \end{bmatrix}$$

In the formula, A_{ij} represents the area of land type i at the beginning of the study period converting to land type j at the end of the study period; n is the total number of land use types; $i = (1, 2, ..., n)$, $j = (1, 2, ..., n)$.

CONSTRUCTION LAND LANDSCAPE PATTERN INDEX

This study shows the evolution characteristics of the construction land landscape pattern in Nanchang City through the scale and spatial morphology of urban spatial expansion. The indicators reflecting the scale of urban spatial expansion include the Compound Annual Growth Rate (CAGR) and the Expansion Intensity Index (EII), which represent the absolute and relative quantities of urban spatial expansion during a specific period, respectively. To assess the spatial form of urban expansion, the Fractal Dimension (D) and Compactness Index (CI) were employed. The specific calculation formulas are provided in Table 1 (Gen et al. 2019; Li, Shi & Wei 2015; Yu et al. 2021).

TABLE 1. Construction land landscape pattern index

Index number	Formula	Description
Annual expansion speed (*CAGR*)	$CAGR = \frac{S_2 - S_1}{S_1} \times \frac{1}{T} \times 100\%$ S_1 is the construction land area in the early stage of the study; S_2 is the construction land area at the end of the study; T is the study period and the value of T in this study is 5. Unit: %·a^{-1}	Reflect the amplitude of urban construction land area change within unit time. The larger the value indicates the faster the urban space expansion is
Annual expansion strength (*EII*)	$EII = \frac{S_2 - S_1}{TLA} \times \frac{1}{T} \times 100\%$ The TLA is the total area of the study area. Unit: %·a^{-1}	It reflects the strength of urban construction land expansion per unit of time relative to the research area. EII was divided into slow, low, medium, rapid and high expansion by natural break point classification
Fractal dimension (*D*)	$D = 2 \ln (P_t/4)/ \ln A_t$ *At* is the total area of urban construction land in period *t* period and *Pt* is the total perimeter of urban construction land in period *t* period	It reflects the degree of rule and the twists and turns of the boundary. D between 1 and 2, the larger the value, the more irregular the spatial form
Compactness (*CI*)	$CI = 2\sqrt{\pi A_t} / P_t$	It reflects the degree of dispersion and agglomeration of urban spatial form. *CI* between 0 and 1, the larger value indicates the higher compact degree of spatial morphology

WATER BODIES LANDSCAPE PATTERN INDEX

This study selects seven indices to analyse the evolutionary characteristics of the spatial pattern of water bodies in Nanchang City: gross area (CA), percentage of landscape (PLAND), landscape shape index (LSI), edge density (ED), splitting index (SPLIT), landscape division index (DIVISION) and cohesion index (COHESION). The specific calculation formulas are provided in Table 2 (Feng & Liu 2015; Zhu, Gan & Li 2024).

TABLE 2. Water bodies landscape pattern index

Index number	Formula	Description
Gross area (*CA*)	$CA = \sum_{j=1}^{n} a_{ij}(\frac{1}{1000})$ The a_{ij} is the area of the *j*-th patch in the class-i landscape. Unit: hm^2	Represents the total area of patches of a certain landscape type
Percentage of area (*PLAND*)	$PLAND = \frac{\sum_{j=1}^{n} a_{ij}}{A} \times 100$ and A is the total area of the landscape. Unit:%	Represents the percentage of patches of a landscape type as the total area, reflecting the proportional abundance of the landscape type
Landscape shape index (*LSI*)	$LSI = \frac{0.25\sum_{i=1}^{m} e_{ij}}{\sqrt{A}}$ m is the total number of patches in landscape category *i* and e_{ij} is the edge length between patches *i* and *j*	The complexity and irregularity of the plaque shape were characterised by calculating the average deviation between the patch shape and the regular shape of the same area. LSI = 1 when the plaque shape is square; *LSI* increases when the plaque shape is irregular or deviates from the square
Edge density (*ED*)	$ED = \frac{\sum_{i=1}^{m} e_{ij}}{A}(10000)$	It represents the ratio of the total circumference of a certain landscape type or all landscape patches to the total landscape area, reflecting the shape and edge effect of the landscape patches. Larger values indicate a more complex shape
Landscape fragmentation (*SPLIT*)	$SPLIT = \frac{N_i}{A_i}$ N_i is the number of patches in landscape *i* and A_i is the total area of landscape *i*	Reflects the degree of fragmentation of a certain landscape type is segmented. The larger the value, it indicates a higher degree of fragmentation
Landscape separation degree (*DIVISION*)	$DIVISION = \frac{D_{ij}}{A_{ij}}$ D_{ij} is the distance index of the *j* th patch in the class-i landscape and A_{ij} is the area index of the *j* th patch in the class-i landscape	Characterise the degree of separation of different patch distributions in a certain landscape type. Larger values indicate lower clustering of the landscape
Cohesion index (*COHESION*)	$COHESION = \left[1 - \frac{\sum_{j=1}^{m} p_{ij}}{\sum_{j=1}^{m} p_{ij}\sqrt{a_{ij}}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{-1} \times 100$ The p_{ij} represents the circumference of the *j* th patch in the class *i* landscape; the a_{ij} represents the area of the *j* th patch in the class *i* landscape type	It reflects the aggregation and dispersion state of landscape patches and can represent the connectivity of patches. Larger values indicate better connectivity

SPATIAL CENTROID COUPLING MODEL

First, the shape distribution direction of construction land and water bodies is analysed using the standard deviation ellipse method, which provides the centroids of both. The standard deviation ellipse analysis is a statistical technique commonly used in spatial pattern studies. It employs the mean and standard deviation of each variable to calculate the standard deviation ellipse for a set of variables, thereby showing correlations among the data. Then, the coupling degree between the centroids of construction land and water bodies is analysed using spatial overlap (SOA) and change consistency (CO). Spatial overlap represents the static perspective of spatial centroid coupling, while change consistency represents its dynamic perspective (Yang et al. 2023a). The specific calculation formulas are as follows:

$$SOA = K * \sqrt{(X_E - X_P)^2 + (Y_E - Y_P)^2}$$

$$CO = \cos w = \frac{\Delta X_E \Delta X_P + \Delta Y_E \Delta Y_P}{\sqrt{(\Delta X^2{}_E + \Delta Y^2{}_E)(\Delta X^2{}_P + \Delta Y^2{}_P)}}$$

In the formula, X_E is the longitude of the urban spatial centroid at a specific time period and Y_E is the latitude of the urban spatial centroid at that time. X_P is the longitude of the water body spatial centroid at that time and Y_P is the latitude of the water body spatial centroid at that time. w represents the angular displacement vector between the centroids of the two elements. ΔX_E represents the change in longitude of the urban spatial centroid from the beginning to the end of the study period. ΔY_E represents the change in latitude of the urban spatial centroid. ΔX_P represents the change in longitude of the water body spatial centroid. ΔY_P represents the change in latitude of the water body spatial centroid.

EVALUATION INDEX SYSTEM AND COMPREHENSIVE INDEX CALCULATION

Following the principles of scientific rigour and representativeness and referring to related studies (Qu et al. 2024; Zhai et al. 2024; Zou et al. 2022), this study constructs an evaluation index system for urbanisation level and water resources in Nanchang City. Twelve indicators from four dimensions, i.e., population urbanisation, economic urbanisation, social urbanisation and spatial urbanisation are selected to reflect the level of urbanisation. Meanwhile, eight indicators from four dimensions, i.e., water resource availability, water resource utilisation, water resource pressure and water resource protection, are chosen to assess the comprehensive development of water resources (Table 3). To eliminate dimensional and attribute differences among the indicators, the range method is used for standardisation. The entropy weight method, which calculates indicator weights based on the degree of dispersion of evaluation data, is employed to minimise subjective bias (Liao 2020). Consequently, the entropy weight method is applied to determine the indicator weights and the comprehensive indices for urbanisation and water resources are calculated based on the standardised values of the indicators and their respective weight coefficients. To assess the impact of different weighting schemes on the composite indices, a comparative analysis was performed using the equal-weight method. The Spearman rank correlation coefficient between the composite indices obtained from the entropy-weight and equal-weight methods was 0.88 ($P < 0.01$), suggesting that the composite evaluation results are insensitive to the choice of weighting method and thus robust.

COUPLING COORDINATION DEGREE MODEL

The Coupling Coordination Degree (CD) model is adopted to further analyse the interactive relationship between urbanisation level and water resources. The coupling coordination degree measures the degree of coordinated development between systems, reflecting the extent to which the systems mutually promote or antagonise one another (Wang et al. 2021). The specific calculation formulas are as follows:

$$C = \frac{2\sqrt{UW}}{U + W}$$

$$T = \alpha U + \beta W$$

$$CD = \sqrt{CT}$$

where C represents the coupling degree between two systems, U and W represent the comprehensive indices of urbanisation and water resources, respectively. T represents the comprehensive coordination degree, while α and β are coefficients such that $\alpha+\beta=1$, representing the relative importance of urbanisation and water resources. In this study, urbanisation and water resources are considered equally important, thus $\alpha=\beta=0.5$. Based on relevant research and actual conditions, the coupling state between urbanisation and water resources is classified into 5 levels: Severely Unbalanced (SU) ($0 \leq CD \leq 0.2$), Moderately Unbalanced (MU) ($0.2 < CD \leq 0.4$), Basically Balanced (BB) ($0.4 < CD \leq 0.6$), Moderately Balanced (MB) ($0.6 < CD \leq 0.8$), and Highly Balanced (HB) ($0.8 < CD \leq 1.0$).

STATISTICAL ANALYSIS

Landscape pattern indices, centroid coordinates and the land use transition matrix were derived from statistical analyses conducted in ArcGIS 10.2. The coupling coordination degree was calculated using Microsoft Excel 2010.

RESULTS

SPATIOTEMPORAL EVOLUTION OF LAND USE IN NANCHANG CITY

Table 4 and Figure 1 present the land use transfer matrix and spatial distribution map of Nanchang City from 2000 to 2020, whereby land use transition in Nanchang City mainly involved the conversion of cultivated land, forest land and water bodies into construction land, with areas of 349.68 km², 58.13 km² and 39.11 km², respectively. In terms of water body changes, cultivated land and construction land were the most converted land types, with areas of 105.63 km² and 39.11 km², respectively. It is evident that, as urbanisation progresses, a significant portion of non-construction land types has been converted into construction land.

As illustrated in Figure 2, cultivated land, water bodies and forest land are major sources of conversion to newly added construction land across all four periods. The proportion of water bodies converted to newly added construction land shows an overall declining trend, peaking at 16.90% during 2000-2005. This indicates that the unregulated occupation of water bodies has been a key driver of urban spatial expansion over the past two decades. Additionally, construction land served as a significant source of conversion for water bodies only during the 2005-2010 period, with the area of construction land converted to water bodies (12.16 km²) exceeding that of water bodies converted to construction land (9.43 km²) during this period.

EVOLUTION OF LANDSCAPE PATTERNS OF CONSTRUCTION LAND AND WATER BODIES

Between 2000 and 2020, the area of urban construction land in Nanchang City exhibited a consistent increase, with expansion characterised primarily by central infilling and, to a lesser extent, edge sprawl. This suggests that Nanchang City's urban space has been in a prolonged stage of expansion over the past two decades, with continuous improvements in urbanisation levels (Figure 3). As indicated in Table 4, the area of newly added construction land, along with the compound annual growth rate (CAGR) and expansion intensity index (EII), shows an initial decrease followed by an increase. The maximum values

TABLE 3. Evaluation index system of urbanisation level and water resources in Nanchang city

Target layer	The standard layer	Index layer	Unit	Weight (%)
Urbanisation level (*U*)	Population urbanisation (18.48%)	Density of population	Person / km^2	6.55
		The proportion of the urban population	%	6.64
		Natural population growth rate	‰	5.29
	Economic urbanisation (27.09%)	per capita GDP	first	8.78
		Per capita disposable income of urban residents	first	9.78
		The proportion of the output value of the tertiary industry in the GDP	%	8.53
	Social urbanisation (35.40%)	Number of hospital beds in medical and health institutions	fix	13.17
		Total retail sales of social consumer goods	100 million	11.17
		Investment in fixed assets	100 million	11.06
	Space urbanisation (19.03%)	Construction land area	km^2	5.52
		Road area per capita	m^2	6.99
		Per capita park green space area	m^2	6.52
Water resource (*W*)	Water resources level (30.13%)	Per capita water resources	Person / m^3	19.69
		Amount of water resources per unit area	m^3/km^2	10.44
	Water resources utilisation (17.15%)	Water consumption per capita	m^3	8.81
		Water consumption in ten thousand yuan of GDP	m^3	8.34
	Water pressure (21.23%)	Domestic sewage discharge amount	Ten thousand tons	10.63
		Total wastewater discharge	Ten thousand tons	10.60
	Protection of water resources (31.49%)	Sewage treatment rate	%	9.46
		Length of drainage pipe	km	22.03

for these indicators were recorded during the period from 2000 to 2005 (211.24 km², 13.80 %·a⁻¹ and 0.59 %·a⁻¹, respectively), while the minimum values occurred from 2005 to 2010 (20.82 km², 0.80 %·a⁻¹ and 0.06 %·a⁻¹, respectively). This trend indicates a significant deceleration in the average annual expansion rate of urban space after 2005. Moreover, the trend observed in the EII suggests a shift in the type of urban spatial expansion, transitioning from medium-speed expansion to slow and finally low-speed expansion. Both the periods of 2005-2010 and 2010-2015 were characterised by slow expansion.

Analysis of the urban spatial form indices (Figure 4) shows that, as the scale of urban space expanded, the fractal dimension (D) gradually decreased from 1.414 to 1.382. This decline indicates that the boundary contours of urban space have become simpler and more regular over time. From 2000 to 2005, the compactness index (CI) increased slightly from 0.016 to 0.018 but remained stable thereafter. This suggests that the internal connectivity within Nanchang's urban space has remained weak over the past two decades, indicating a trend towards greater land use compactness.

TABLE 4. Land use transfer matrix (km^2) of Nanchang city from 2000 to 2020

Land use type	Cultivated land	Forest land	Grassland	Water body	Construction land	Unutilised land	Total in 2000
Cultivated land	3579.49	55.55	2.68	80.11	349.68	0.01	4067.53
Forest land	77.76	1070.60	4.06	4.60	58.13	/	1215.15
Grassland	8.24	15.65	67.09	1.92	3.78	/	96.67
Water body	105.63	7.03	1.50	1351.45	39.11	/	1504.73
Construction land	28.43	1.25	0.07	14.46	261.89	/	306.11
Unutilised land	/	0.02	/	/	/	0.10	0.12
Total in 2020	3799.55	1150.10	75.40	1452.54	712.60	0.11	7190.30

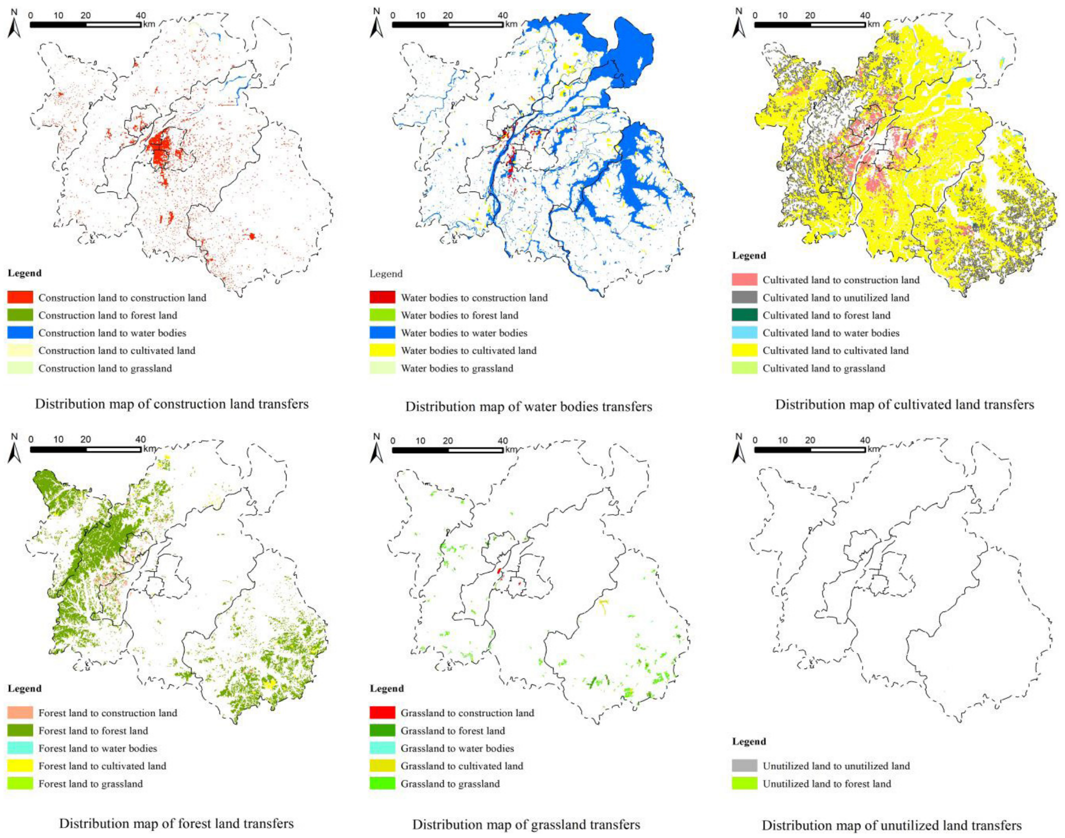

FIGURE 1. Spatial distribution of land use transitions in Nanchang city from 2000 to 2020

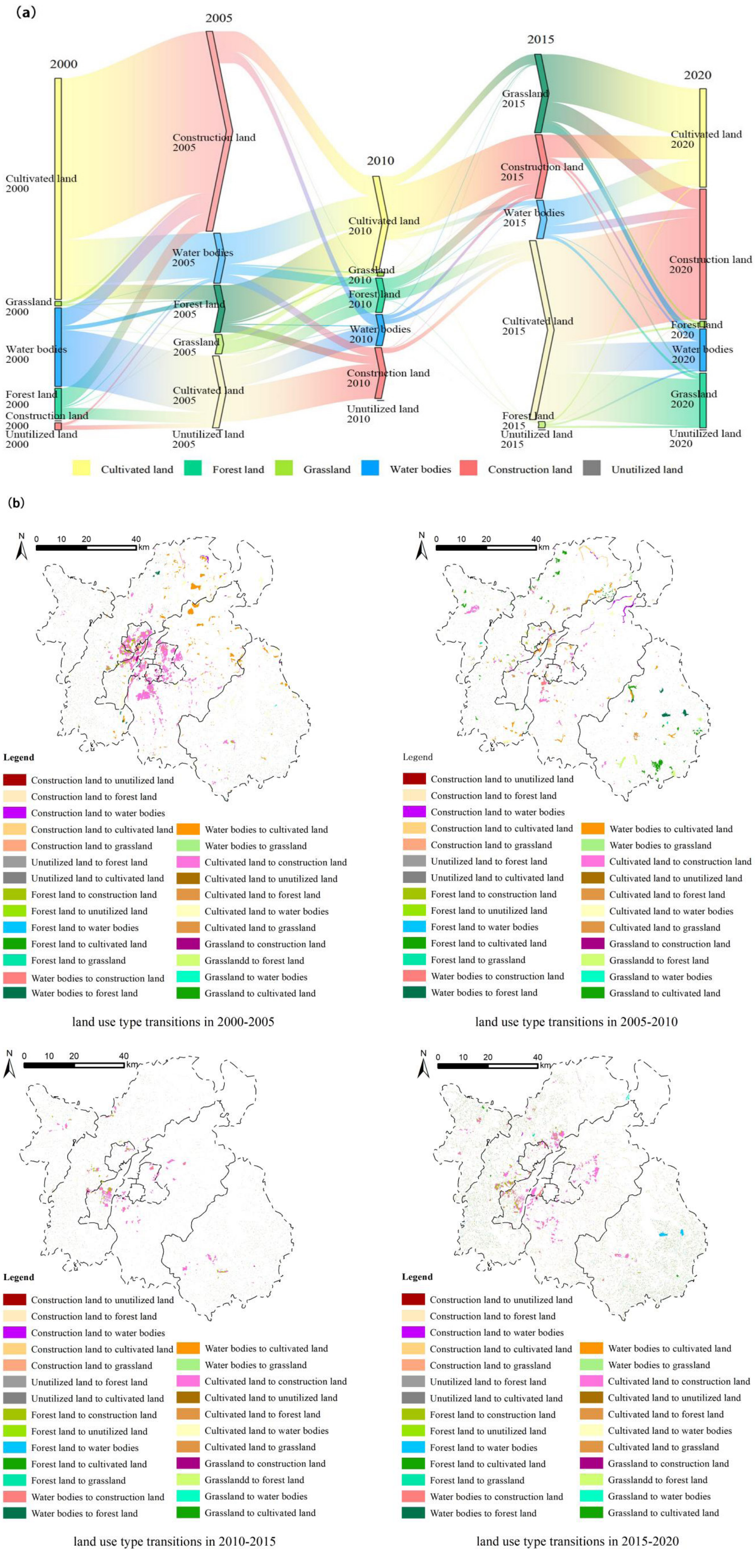

FIGURE 2. (a) Sankey diagram and (b) land use type transitions in Nanchang city for different periods

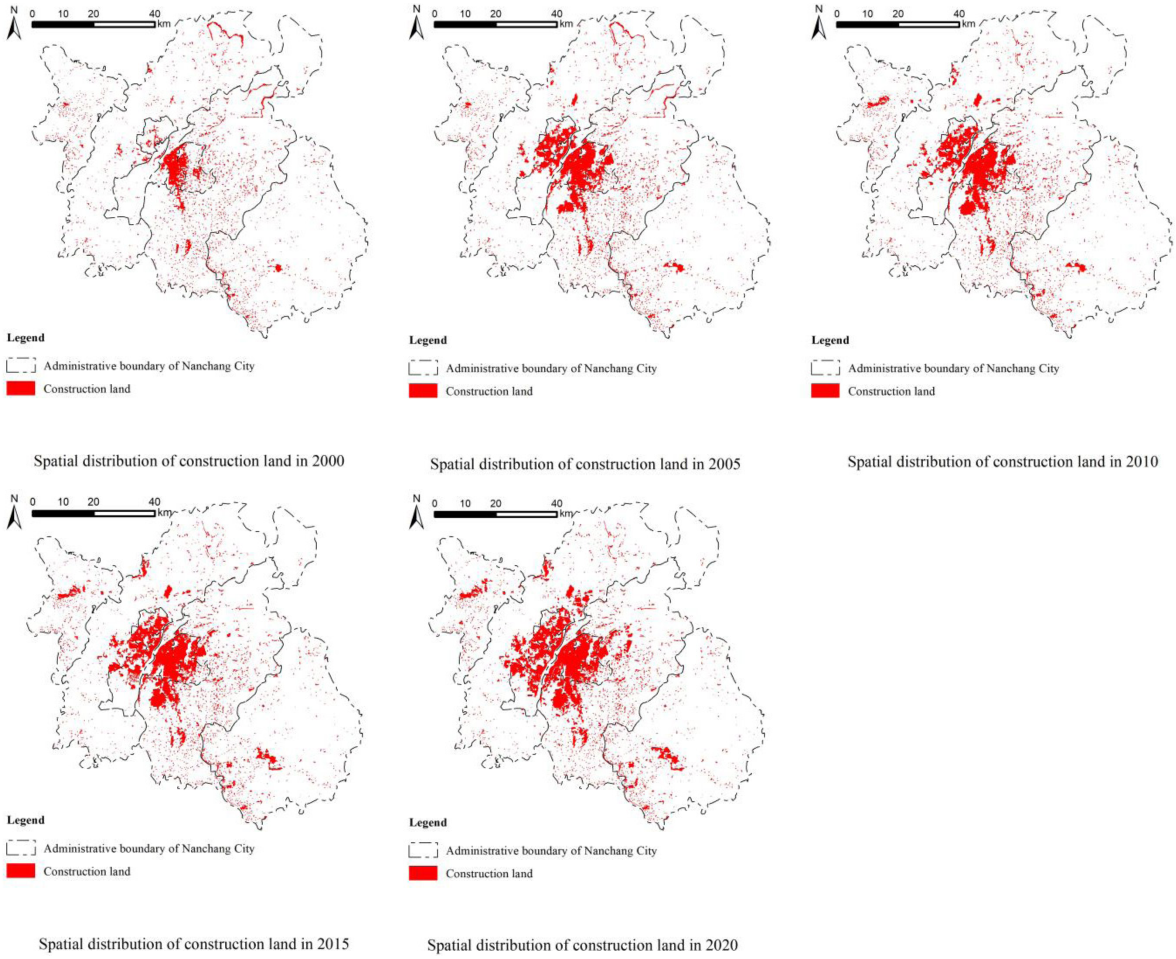

FIGURE 3. Spatial distribution of construction land in Nanchang city from 2000 to 2020

TABLE 5. Changes in urban spatial expansion index of Nanchang city from 2000 to 2020

Period	Area of new construction land (km^2)	CAGR (%·a^{-1})	EII (%·a^{-1})	Expansion type
2000-2005	211.24	13.80	0.59	Medium speed expansion
2005-2010	20.82	0.80	0.06	Slow expansion
2010-2015	63.60	2.36	0.18	Slow expansion
2015-2020	110.83	3.68	0.31	Low speed expansion

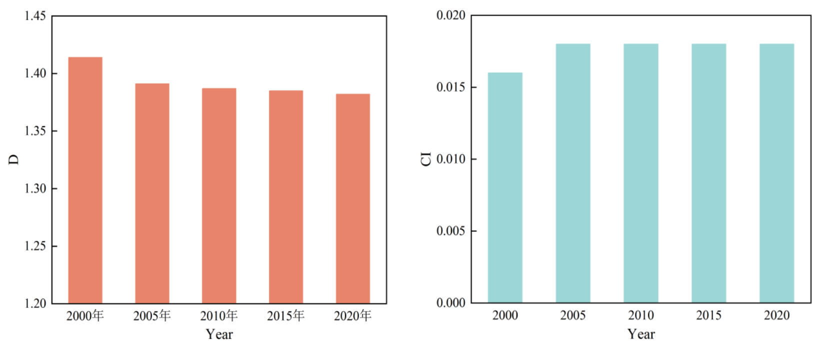

FIGURE 4. Changes in the form index of construction land in Nanchang city from 2000 to 2020

The analysis of the water body landscape pattern index indicated (Figure 5) that both the gross area (CA) and percentage of landscape (PLAND) decreased from 150,473.88 hm² and 20.93% to 144,816.21 hm² and 20.14%, respectively, from 2000 to 2015, with the magnitude of change gradually declining, followed by a slight increase from 2015 to 2020. The landscape shape index (LSI) and edge density (ED) exhibit similar trends to the scale indices. The splitting index (SPLIT) and landscape division index (DIVISION) show minor changes from 2000 to 2015 but experienced significant increases between 2015 and 2020, rising from 51.73 to 84.29 and from 0.98 to 0.99, respectively. The connectivity index (COHESION) gradually increased slightly from 2000 to 2015 but decreased from 99.82 to 99.74 between 2015 and 2020. These results suggest that the overall spatial pattern of water bodies in Nanchang City from 2000 to 2020 has evolved, demonstrating a significant reduction in scale, marked simplification of shape, increased fragmentation and decreased connectivity. Additionally, the trends of various indices suggest that 2015-2020 marks an important turning point in the evolution of the spatial pattern of water bodies in Nanchang City over the past two decades, which aligns with changes in the expansion rate and intensity of urban space, albeit with a certain lag effect.

ANALYSIS OF THE SPATIAL CENTROID COUPLING RELATIONSHIP BETWEEN CONSTRUCTION LAND AND WATER BODIES

As shown in Table 6, the centroid coordinates of construction land range from 115.9739°E to 115.9770°E and 28.5853°N to 28.5902°N, with a general trend of development towards the southeast. The centroid coordinates of water bodies 28.5741°N, showing a general trend of development towards the southwest. A comparison of the movement trajectories of the centroids of construction land and water bodies reveals that the trajectory of the water bodies exhibits greater variation. Additionally, over time, SOA generally shows an increasing trend but remains within a small range (1.8904-2.9465 km), while CO exhibits a positive-negative-positive cyclical change. This suggests that the coupling of urban and water spatial morphology in Nanchang City has remained strong in the past 20 years, but with a gradual tendency towards separation (Figure 6).

ANALYSIS OF COUPLING COORDINATION DEGREE BETWEEN URBANISATION LEVEL AND WATER RESOURCES

As shown in ally from 2000 to 2020, with a larger increase in urbanisation development after 2010. Although the comprehensive index of water resources in 2015 (0.55) is slightly lower than in 2010 (0.57), the overall trend remains upward. The coupling coordination degree between the comprehensive urbanisation index and the comprehensive water resource index increased annually from 2000 to 2020, rising from 0.40 in 2000 to 0.92 in 2020. This suggests that Nanchang City has progressed through developmental stages of 'moderate imbalance - basic coordination - moderate coordination - high coordination', entering the coordination stage in 2005 and achieving high coordination by 2020.

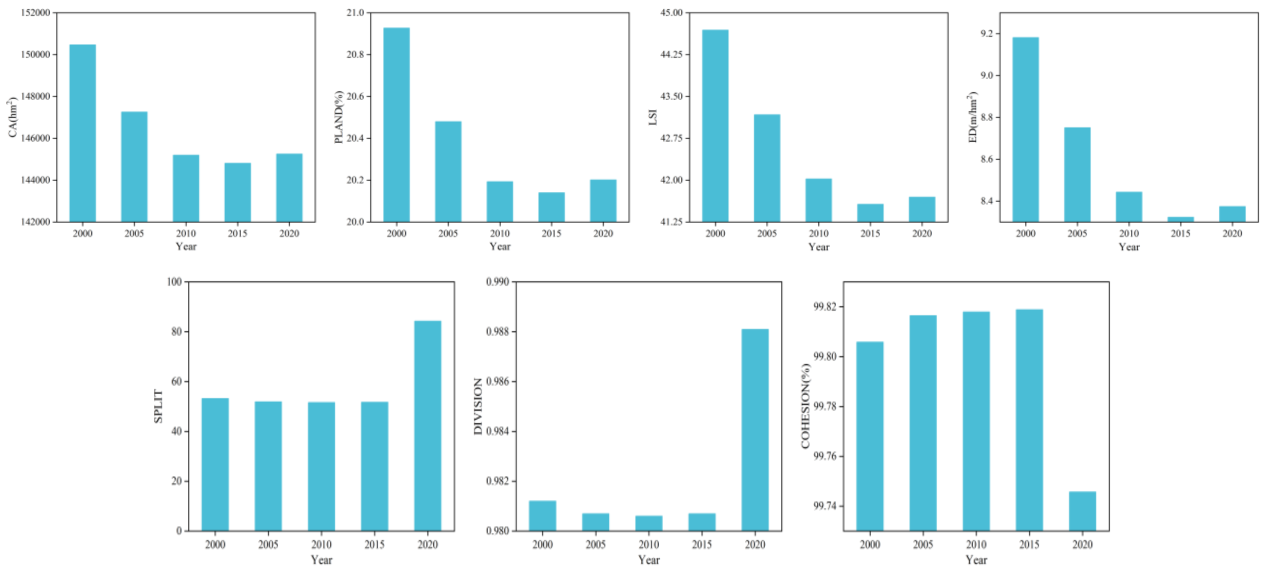

FIGURE 5. Changes in water body landscape pattern index in Nanchang city from 2000 to 2020

TABLE 6. Spatial centroid coupling of construction land and water bodies in Nanchang city from 2000 to 2020

Time	Centre of gravity of construction land		Centre of gravity of water body		SOA	CO
	Longitude/°E	Latitude/°N	Longitude/°E	Latitude/°N		
2000	115.9739	28.5902	115.9684	28.5741	1.8904	/
2005	115.9747	28.5853	115.9632	28.5711	2.0303	0.3536
2010	115.9745	28.5877	115.9622	28.5681	2.5711	-0.9191
2015	115.9746	28.5875	115.9678	28.5683	2.2632	0.4150
2020	115.9770	28.5870	115.9603	28.5664	2.9465	-0.8989

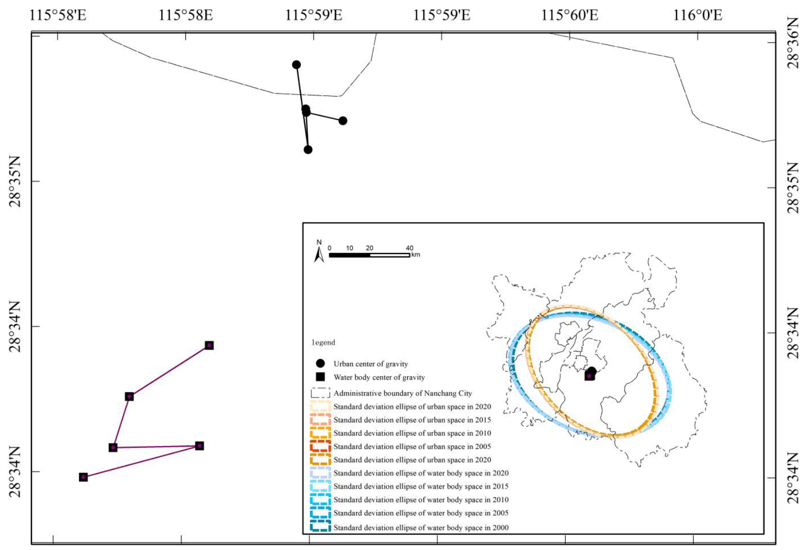

FIGURE 6. Trajectory of centroid changes between construction land and water bodies in Nanchang city

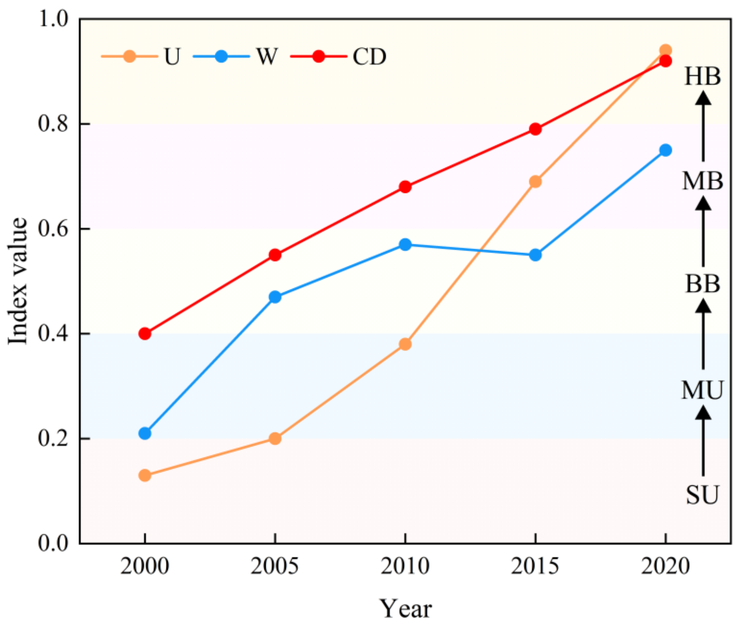

FIGURE 7. Urbanisation level and water resources coupling coordination in Nanchang city from 2000 to 2020

where *U* represents the comprehensive index of urbanisation level; *W* represents the comprehensive index of water resources; and *CD* represents the coupling coordination degree between urbanisation level and water resources. SU indicates Severely Unbalanced, MU indicates Moderately Unbalanced, BB indicates Basically Balanced, MB indicates Moderately Balanced and HB indicates Highly Balanced.

DISCUSSIONS

CHANGES IN THE LANDSCAPE PATTERNS OF CONSTRUCTION LAND AND WATER BODIES

This study found that Nanchang's urban space has continuously expanded between 2000 and 2020, indicating a consistent increase in urbanisation and socioeconomic development. The results also show that, after 2005, the average annual expansion rate and intensity of construction land significantly decreased. This is mainly due to the fact that many administrative districts, especially the newly established Honggutan District, were in the early stages of development from 2000 to 2005, resulting in a strong demand for construction land. As the scale of urban space expands, this study finds that urban form tends to become more compact, which aligns with findings from various scholars (Lemoine-Rodríguez, Inostroza & Zepp 2020; Yan et al. 2024). This trend can be primarily attributed to Nanchang's rapid economic growth, sustained population inflows and accelerating industrialisation. Specifically, substantial GDP growth and broader socio-economic development from 2000 to 2020 emerged as primary drivers of land-use change, resulting in peaks in construction land expansion and greater regularisation of urban boundaries (Duo et al. 2022). Furthermore, national regional development policies, such as the 'Rise of Central China' strategy initiated in 2004 and the establishment of the Ganjiang New Area in 2016, have further accelerated Nanchang's urbanisation by promoting infrastructure investment and intensive land use, thereby reinforcing the observed trend towards compactness (An, Peng & Geng 2024). These policy interventions partly account for the slight increase in compactness observed from 2000 to 2005 and its subsequent stabilisation. A compact urban form is generally regarded as effective in mitigating the decline in population density, which is especially significant for densely populated areas undergoing rapid urbanisation (Chai & Seto 2019; Xu et al. 2020). Given that Nanchang City fits this profile, future planning of construction land layout should prioritise maintaining a certain degree of spatial compactness.

Due to the limited nature of land resources, urban expansion inevitably involves the conversion of other land types into construction land, with cultivated land, water bodies and forest land typically serving as important sources of conversion for newly added construction land (Chu, Lu & Sun 2022; Dadashpoor, Azizi & Moghadasi 2019; Niu et al. 2023), as this study well illustrates. Consistent with many previous research findings (Akubia & Bruns 2019; Lei et al. 2022; Zhang et al. 2023), the water bodies landscape patterns in this study also showed a significant reduction in scale, simplification of shape, increased fragmentation and decreased connectivity during urban expansion. Changes in water bodies' landscape patterns may, to some extent, directly affect the ecosystem service value (ESV) of water bodies, particularly in ecological protection areas (Ouyang et al. 2021; Yushanjiang et al. 2024). Some studies have indicated that in cities with developed water systems, water bodies contribute significantly to regional ESV (Rahman & Szabó 2021; Sharma et al. 2021). Therefore, for Nanchang City, which has already developed a complex water system network, it is crucial to coordinate the relationship between urban construction land and water bodies to maximise urban ESV, making an understanding of the coupling relationship between the two a primary condition.

COUPLING RELATIONSHIP BETWEEN URBANISATION LEVEL AND WATER RESOURCES

The analysis of the spatial overlap and consistency of changes in the centroids of construction land and water bodies indicates that, although there is strong coupling between the two land uses, their spatial centroids may gradually become more separated over time. This reflects the conflict between the decreasing availability of water resources and the expansion of construction land during the urbanisation process. Future urban planning should prioritise the protection and rational use of water resources to ensure that urbanisation progresses while maintaining a balance between ecological preservation and urban development. In this regard, this study further developed an evaluation index system for urbanisation level and water resources and calculated the coupling coordination degree between the urbanisation comprehensive index and the water resources comprehensive index. The results indicate that Nanchang has experienced a developmental trajectory of 'Moderately Unbalanced, Basically Balanced, Moderately Balanced and Highly Balanced'. This suggests that Nanchang has progressively achieved more effective regulation and optimisation in water resource management, significantly alleviating the conflict between sustainable water use and urban development. These findings provide valuable insights for the planning and management of rapidly developing second- and third-tier cities. Many studies on the coupling coordination relationship between urbanisation level and water resources have reported similar developmental trends (Bi et al. 2023; Qu et al. 2024). However, some studies, influenced by factors, such as time span, evaluation indicators and their weightings, have produced results that differ from those of this study (Huang et al. 2023; Wang et al. 2023).

Based on the results and discussion, this study attempts to propose targeted optimisation strategies from the perspectives of water bodies' spatial protection and urban space control, in order to further promote the formation of a symbiotic relationship between urban areas and water bodies in Nanchang City. These strategies also provide policy-relevant insights for local urban water governance in Nanchang, as they can be directly operationalised through existing planning instruments, including ecological civilisation-oriented spatial zoning and the wetland protection red line. First, efforts should be made to ensure that the existing scale of water bodies remains stable and the integrity of shorelines is preserved. Concurrently, measures such as establishing water system ecological corridors and green ecological corridors (Wei et al. 2024) can be implemented to enhance the connectivity of water body spaces. In practice, this entails prioritising the protection and restoration of corridors and shorelines in fragmentation hotspots, while integrating these ecological corridors into statutory territorial spatial plans to enhance enforceability. Second, improving the land resource management system and reasonably delineating the boundaries of construction land and growth boundaries can effectively curb the disorderly expansion of urban space, thereby constructing a stable water ecological security pattern (Paiva et al. 2020; Yang et al. 2023b). This study is primarily based on analysis at the municipal scale and future research could explore the urban-water coupling relationship across various administrative districts within Nanchang City to implement differentiated control and governance strategies. Additionally, although this study has strictly screened the evaluation indicators, the construction of the index system still has room for optimisation due to data availability limitations. Future research should incorporate more representative indicators and further explore the main driving factors of coupling coordination.

CONCLUSION AND LIMITATIONS

Focusing on Nanchang City in Jiangxi Province, China, this study analysed land use changes and the evolution of construction land and water bodies landscape patterns between 2000 and 2020 and uses the coupling coordination degree model to elucidate the coupling relationship between urbanisation level and water resources. The results indicated that from 2000 to 2020, land use transition in Nanchang primarily involved the conversion of cultivated land, forest land and water bodies into construction land. Nanchang City's urban space has been in a continuous expansion stage, characterised by trends of boundary contour simplification and land use compactness. The spatial pattern of water bodies generally shows characteristics of significant scale reduction, clear shape simplification, increased fragmentation and decreased connectivity. The gravity centres of construction land and water bodies exhibit trends of development towards the southeast and southwest, respectively. While the coupling between the two centroids is strong, there is a trend of gradual separation. The coupling coordination relationship between urbanisation levels and water resources in Nanchang City has progressed through developmental stages of 'moderate imbalance - basic coordination - moderate coordination - high coordination', entering the high coordination stage in 2020. This study shows the spatiotemporal evolution characteristics of the urban-water relationship in Nanchang during rapid development, providing new insights and valuable experience for decision-making on sustainable development in other rapidly urbanising regions. Although the evaluation indicators in this study were rigorously selected, the construction of the index system remains subject to improvement owing to limitations in data availability. Future studies should incorporate additional representative indicators to further explore the main driving factors in influencing coupling coordination.

ACKNOWLEDGEMENTS

We would like to thank the financial support provided by the National Natural Science Foundation of China (32260418).

REFERENCES

Akubia, J.E.K. & Bruns, A. 2019. Unravelling the frontiers of urban growth: Spatio-temporal dynamics of land-use change and urban expansion in greater Accra metropolitan area, Ghana. *Land* 8(9): 131. https://doi.org/10.3390/land8090131

An, Y., Peng, L. & Geng, L. 2024. Spatio-temporal evolution and driving factors of new urbanization in central China based on multi-source data[J]. *PLoS ONE* 19(3): e0298099. https://doi.org/10.1371/journal.pone.0298099

Bi, Y., Zheng, L., Wang, Y., Li, J., Yang, H. & Zhang, B. 2023. Coupling relationship between urbanization and water-related ecosystem services in China's Yangtze River economic Belt and its socio-ecological driving forces: A county-level perspective. *Ecological Indicators* 146: 109871. https://doi.org/10.1016/j.ecolind.2023.109871

Bian, D., Yang, X., Wu, F., Babuna, P., Luo, Y., Wang, B. & Chen, Y. 2022. A three-stage hybrid model investigating regional evaluation, pattern analysis and obstruction factor analysis for water resource spatial equilibrium in China. *Journal of Cleaner Production* 331: 129940. https://doi.org/10.1016/j.jclepro.2021.129940

Chai, B. & Seto, K.C. 2019. Conceptualizing and characterizing micro-urbanization: A new perspective applied to Africa. *Landscape and Urban Planning* 190: 103595. https://doi.org/10.1016/j.landurbplan.2019.103595

Chen, L., Yu, W. & Zhang, X. 2024. Spatio-temporal patterns of high-quality urbanization development under water resource constraints and their key drivers: A case study in the Yellow River Basin, China. *Ecological Indicators* 166: 112441. https://doi.org/10.1016/j.ecolind.2024.112441

Chu, M., Lu, J. & Sun, D. 2022. Influence of urban agglomeration expansion on fragmentation of green space: A case study of Beijing-Tianjin-Hebei urban agglomeration. *Land* 11(2): 275. https://doi.org/10.3390/land11020275

Dadashpoor, H., Azizi, P. & Moghadasi, M. 2019. Land use change, urbanization, and change in landscape pattern in a metropolitan area. *Science of The Total Environment* 655: 707-719. https://doi.org/10.1016/j.scitotenv.2018.11.267

Duo, L., Li, Y., Zhang, M., Zhao, Y., Wu, Z. & Zhao, D. 2022. Spatiotemporal pattern evolution of urban ecosystem resilience based on "resistance-adaptation-vitality": A case study of Nanchang City. *Frontiers in Earth Science* 10: 902444. https://doi.org/10.3389/feart.2022.902444

Feng, Y. & Liu, Y. 2015. Fractal dimension as an indicator for quantifying the effects of changing spatial scales on landscape metrics. *Ecological Indicators* 53: 18-27. https://doi.org/10.1016/j.ecolind.2015.01.020

Gen, T., Mao, Y., Li, J. & Chen, H. 2019. Spatio-temporal characteristics and driving mechanism of Xi'an urban expansion. *Economic Geography* 39(10): 62-70. https://doi.org/10.15957/j.cnki.jjdl.2019.10.009

Huang, X., Shen, J., Sun, F., Wang, L., Zhang, P. & Wan, Y. 2023. Study on the spatial and temporal distribution of the high–quality development of urbanization and water resource coupling in the Yellow River Basin. *Sustainability* 15(16): 12270. https://doi.org/10.3390/su151612270

Jiang, W., Wu, T. & Fu, B. 2021. The value of ecosystem services in China: A systematic review for twenty years. *Ecosystem Services* 52: 101365. https://doi.org/10.1016/j.ecoser.2021.101365

Kundu, D. & Pandey, A.K. 2020. World urbanisation: Trends and patterns. In *Developing National Urban Policies: Ways Forward to Green and Smart Cities*, edited by Kundu, D., Sietchiping, R. & Kinyanjui, M. Singapore: Springer Singapore. pp. 13-49.

Lei, Z., Fu, J., Luo, J. & Cao, L. 2022. Attribution analysis of runoff changes in the Sanchuan River Basin of Shanxi Province from the perspective of landscape patterns. *Acta Ecologica Sinica* 42(12): 4946-4958. https://doi.org/10.5846/stxb202105131259

Lemoine-Rodríguez, R., Inostroza, L. & Zepp, H. 2020. The global homogenization of urban form. An assessment of 194 cities across time. *Landscape and Urban Planning* 204: 103949. https://doi.org/10.1016/j.landurbplan.2020.103949

Li, J., Shi, P. & Wei, W. 2015. Research on urban expansion and drive mechanism in an oasis town of Arid region. *Arid Zone Research* 32(3): 598-605. https://doi.org/10.13866/j.azr.2015.03.26

Liao, S. 2020. Provincial perspective analysis on the coordination between urbanization growth and resource environment carrying capacity (RECC) in China. *Science of the Total Environment* 730: 138964. https://doi.org/10.1016/j.scitotenv.2020.138964

Luo, K., Hu, X., He, Q., Wu, Z., Cheng, H., Hu, Z. & Mazumder, A. 2018. Impacts of rapid urbanization on the water quality and macroinvertebrate communities of streams: A case study in Liangjiang New Area, China. *Science of The Total Environment* 621: 1601-1614. https://doi.org/10.1016/j.scitotenv.2017.10.068

Lv, T., Wang, L., Zhang, X., Xie, H., Lu, H., Li, H., Liu, W. & Zhang, Y. 2019. Coupling coordinated development and exploring its influencing factors in Nanchang, China: From the perspectives of land urbanization and population urbanization. *Land* 8(12): 178. https://doi.org/10.3390/land8120178

Lyu, R. 2018. Impacts of urbanization on ecosystem services and their temporal relations: A case study in Northern Ningxia, China. *Land Use Policy* 77: 163-173. https://doi.org/10.1016/j.landusepol.2018.05.022

Ma, X., Li, N., Yang, H. & Li, Y. 2022. Exploring the relationship between urbanization and water environment based on coupling analysis in Nanjing, East China. *Environmental Science and Pollution Research* 29(3): 4654-4667. https://doi.org/10.1007/s11356-021-15161-1

Niu, W., Shen, Q., Xu, Z. & Shang, W. 2023. Evaluation of the land use benefit of rapidly expanding cities based on coupling coordination and a transfer matrix. *Journal of Resources and Ecology* 14(3): 542-555. https://doi.org/10.5814/j.issn.1674-764x.2023.03.010

Ouyang, X., Tang, L., Wei, X. & Li, Y. 2021. Spatial interaction between urbanization and ecosystem services in Chinese urban agglomerations. *Land Use Policy* 109: 105587. https://doi.org/10.1016/j.landusepol.2021.105587

Paiva, A.C.D.E., Nascimento, N., Rodriguez, D.A., Tomasella, J., Carriello, F. & Rezende, F.S. 2020. Urban expansion and its impact on water security: The case of the Paraíba do Sul River Basin, São Paulo, Brazil. *Science of The Total Environment* 720: 137509. https://doi.org/10.1016/j.scitotenv.2020.137509

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: 111766. https://doi.org/10.1016/j.ecolind.2024.111766

Rahman, Md. & Szabó, G. 2021. Impact of land use and land cover changes on urban ecosystem service value in Dhaka, Bangladesh. *Land* 10(8): 793. https://doi.org/10.3390/land10080793

Sanchez, G.M., Terando, A., Smith, J.W., García, A.M., Wagner, C.R. & Meentemeyer, R.K. 2020. Forecasting water demand across a rapidly urbanizing region. *Science of the Total Environment* 730: 139050. https://doi.org/10.1016/j.scitotenv.2020.139050

Sharma, S., Anees, M.M., Sharma, M. & Joshi, P.K. 2021. Longitudinal study of changes in ecosystem services in a city of lakes, Bhopal, India. *Energy, Ecology and Environment* 6(5): 408-424. https://doi.org/10.1007/s40974-020-00199-7

Sun, Y., Liu, S., Dong, Y., An, Y., Shi, F., Dong, S. & Liu, G. 2019. Spatio-temporal evolution scenarios and the coupling analysis of ecosystem services with land use change in China. *Science of the Total Environment* 681: 211-225. https://doi.org/10.1016/j.scitotenv.2019.05.136

Wang, A., Wang, S., Liang, S., Yang, R., Yang, M. & Yang, J. 2023. Research on ecological protection and high-quality development of the lower Yellow River based on system dynamics. *Water* 15(17): 3046. https://doi.org/10.3390/w15173046

Wang, L., Zheng, H., Chen, Y. & Huang, B. 2024. Ecological redline policy strengthens sustainable development goals through the strict protection of multiple ecosystem services. *Global Ecology and Conservation* 56: e03306. https://doi.org/10.1016/j.gecco.2024.e03306

Wang, S., Sun, W., Ren, L., Ye, D. & Dai, B. 2021. Research on misuses and modification of coupling coordination degree model in China. *Journal of Natural Resources* 36(3): 793-810. https://doi.org/10.31497/zrzyxb.20210319

Wei, W., Liu, C., Ma, L., Xie, B., Zhou, J. & Nan, S. 2024. Optimization strategies of ecological security patterns through importance of ecosystem services and ecological sensitivity - A case study in the Yellow River Basin. *Land Degradation & Development* 35(3): 985-1001. https://doi.org/10.1002/ldr.4965

Xu, G., Zhou, Z., Jiao, L. & Zhao, R. 2020. Compact urban form and expansion pattern slow down the decline in urban densities: A global perspective. *Land Use Policy* 94: 104563. https://doi.org/10.1016/j.landusepol.2020.104563

Yan, J., Wang, J., Su, F. & Liu, B. 2024. Morphology changes and the expansion of major port cities in the Philippines from 1990 to 2020. *Cities* 147: 104818. https://doi.org/10.1016/j.cities.2024.104818

Yang, H., Ning, Q., Zhou, H., Lai, N., Song, Q., Ji, Q. & Zeng, Z. 2023a. Digital research on the resilience control of water ecological space under the concept of urban-water coupling. *Frontiers in Environmental Science* 11: 1270921. https://doi.org/10.3389/fenvs.2023.1270921

Yang, Z., Wu, Y., Wang, F., Chen, A. & Wang, Y. 2023b. Spatial-temporal differences and influencing factors of coupling coordination between urban quality and technology innovation in the Guangdong-Hong Kong-Macao Greater Bay Area. *PLoS ONE* 18(9): e0289988. https://doi.org/ 10.1371/journal.pone.0289988

Yu, Z., Chen, L., Li, L., Zhang, T., Yuan, L., Liu, R., Wang, Z., Zang, J. & Shi, S. 2021. Spatiotemporal characterization of the urban expansion patterns in the Yangtze River delta region. *Remote Sensing* 13(21): 4484. https://doi.org/10.3390/rs13214484

Yushanjiang, A., Zhou, W., Wang, J. & Wang, J. 2024. Impact of urbanization on regional ecosystem services - A case study in Guangdong-Hong Kong-Macao greater bay area. *Ecological Indicators* 159: 111633. https://doi.org/10.1016/j.ecolind.2024.111633

Zhai, Y., Zhai, G., Yu, Z., Lu, Z., Chen, Y. & Liu, J. 2024. Coupling coordination between urbanization and ecosystem services value in the Beijing-Tianjin-Hebei urban agglomeration. *Sustainable Cities and Society* 113: 105715. https://doi.org/10.1016/j.scs.2024.105715

Zhang, A., Zhao, X., He, J., Huang, X., Zhao, X. & Zhao, Y. 2023. Characteristics of hydrogen and oxygen isotope composition in precipitation, rivers, and lakes in Wuhan and the ecological environmental effects of lakes. *Water* 15(16): 2996. https://doi.org/10.3390/w15162996

Zhao, G., Liang, R., Li, K., Wang, Y. & Pu, X. 2021. Study on the coupling model of urbanization and water environment with basin as a unit: A study on the Hanjiang Basin in China. *Ecological Indicators* 131: 108130. https://doi.org/10.1016/j.ecolind.2021.108130

Zhu, R., Gan, X. & Li, Z. 2024. Spatio-temporal changes of ecological resilience and ecological risk and construction of ecological zones in Sichuan province. *Resources and Environment in the Yangtze Basin* 33(1): 175-188. https://doi.org/10.11870/cjlyzyyhj202401015

Zou, C., Zhu, J., Lou, K. & Yang, L. 2022. Coupling coordination and spatiotemporal heterogeneity between urbanization and ecological environment in Shaanxi Province, China. *Ecological Indicators* 141: 109152. https://doi.org/10.1016/j.ecolind.2022.109152

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