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Carrying Capacity and Coupling Coordination of Water and Land Resources Systems in Arid and Semi-arid Areas: A Case Study of Yulin City, China

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Abstract: Quantitatively assessing the carrying capacity of water and land resources systems in arid and semi-arid areas is crucial for achieving the 2030 Sustainable Development Goals. In this work, taking Yulin City in China as a case study and employing the Criteria Importance Through Intercriteria Correlation (CRITIC) method, a modified model of coupling degree was developed to evaluate the carrying capacity of water and land resources systems endowment and utilization, as well as their coupling coordination degree from 2013 to 2020. Our findings indicate that the water and land resources of Yulin are diminishing due to declines in agriculture, higher industrial water use, and wetland shrinkage. However, reallocating domestic water for ecological sustainability and reducing sloping farmland can mitigate this trend of decline. Temporally, as the coupling coordination between water and land resources system endowment in Yulin continuously improved, the coupling coordination between water and land resources system utilization first decreased and then increased with 2016 as the turning point. Spatially, the carrying capacity of water and land resources systems, the coupling coordination degree between water and land resources system endowment, and the coupling coordination degree between water and land resources system utilization in Yulin exhibited the same pattern of being higher in the six northern counties than in the six southern counties. Improving the water resources endowment is vital for the highly efficient use of water and land resources.

Keywords: water and land resources systems; carrying capacity; coupling coordination; human-earth system; sustainable development; Yulin City, China

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1 Introduction

The management, protection, and sustainable use of water and land resources form the cornerstone of human survival and economic and social advancement, playing a pivotal role in achieving the 2030 Sustainable Development Goals (Fu et al., 2021). Arid and semi-arid areas occupy approximately 47% of the world's land surface (Koutroulis, 2019) and are home to 40% (Fu et al., 2021) of its population. These regions are particularly susceptible to the impacts of water scarcity and severe desertification (Reynolds et al., 2007). The situation in arid and semi-arid areas is further aggravated by frequent extreme weather events driven by ongoing global climate change, heightening the risks to human health and food security (Safriel and Adeel, 2008). China is one of the major drought-affected nations, and 42% of its land is arid and semi-arid areas (Lü et al., 2009); as such, it

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must contend with the degradation of its water and land resources as a consequence of rapid urbanization and industrialization, and this poses a substantial barrier to its sustainable development (Mao et al., 2018).

The carrying capacity of water and land resources systems refers to the ability of water and land resources in a specific area to support the sustainable development of the regional economy, society, and environment (Ahmed et al., 2019; Chen et al., 2022). In the context of sustainable development, the concept of carrying capacity serves as a key tool for evaluating how human activities may impact the environment. If the utilization of water and land resources exceeds their carrying capacity, this can lead to ecological degradation and a decline in the quality of life for residents (Long et al., 2020). Conversely, underutilization can lead to resource wastage, impeding regional development (Graymore et al., 2010; Ren et al., 2011). Thus, assessing the carrying capacity of water and land resources systems is essential for sustainable development, particularly in arid and semi-arid areas. This requires an in-depth analysis of the interactions among various subsystems, their internal dynamics, and their overall integration within the resource systems. This comprehensive approach underpins sustainable development strategies and promotes the well-being of the community.

Initial assessments of the carrying capacity of land resources systems focused on estimating biological or vegetation productivity through approaches such as the Wageningen model, the Miami model, the agroecological zone method, the post-build model, and remote sensing measurements, primarily accounting for natural factors such as sunlight, temperature, and moisture (Lieth, 1975; Higgins et al., 1982; Abdul-Jabbar et al., 1984; Hou and You, 1990; Rudorff and Batista, 1991). Slesser (1990) constructed the Enhancement of Carrying Capacity Options model, which integrated complex relations among natural environmental, economic, and demographic factors to estimate the carrying capacity of land resources system; this is commonly used to simulate and predict the carrying capacity of land resources system under different development strategies in China (Chen et al., 1999; Harris and Kennedy, 1999; Hasbagen et al., 2008).

The literature on the carrying capacity of land resources system mainly analyses the food supply of farmland but does not sufficiently explore other land types such as construction land, ecological land, and industrial and mining land. Simultaneously, research examining the carrying capacity of water resources system tends to select indicators that can portray the quantity and quality of water resources supporting regional development to establish a comprehensive evaluation-index system (Haddadin, 2000; Yang et al., 2001; Zhu et al., 2003). These approaches use fuzzy comprehensive evaluation, grey correlation evaluation, projection tracing models, and other methods to quantitatively evaluate the carrying capacity of water resources system (Friedman and Tukey, 1974; Song and Cai, 2004; Xia et al., 2004). In addition, artificial neural network models, multi-objective decision analysis, and autoregressive integrated moving average models have been used to predict the future carrying capacity of water resources system (Yeh and Labadie, 1997; Zhang et al., 2013). Nonetheless, no systematic study has evaluated the carrying capacity of water resources system by considering both water resources system endowment and utilization or the balance of supply and demand. In general, water and land resources systems are interpenetrating (Qu et al., 2021), but some studies take water resources system evaluation indicators such as per capita water resources and wastewater discharge as part of the evaluation of the carrying capacity of land resources system (Chen et al., 2011; Yang et al., 2019). Alternatively, evaluation indicators for the carrying capacity of water and land resources utilization and endowment may be placed in the same evaluation system, which makes it hard to explain whether the water and land resources systems are mainly determined by endowment or utilization (Ren et al., 2010).

Various conceptual frameworks have been proposed to systematically examine the interactions between humans and the natural environment, including the coupled human-environment system (Turner et al., 2003) and the social-ecological system (Berkes and Folke, 1998). In China, the human-earth system was proposed as a dynamic structure formed by human interaction with the natural environment (Li et al., 2019). Studies based on the human-earth system theory combine qualitative and quantitative analysis, natural and human indicators, and partial and overall changes to reveal the relationship between regional human activities and the natural environment (Li et al., 2019). As such, they can provide a systematic perspective for the evaluation of the carrying capacity of regional water and land resources systems.

Located on the southern edge of the Mu Us Desert of China, Yulin City is a typical arid/semi-arid area known as the 'New Granary' of Shaanxi Province. Recently, Yulin has made significant strides in modern agricultural development (Yang and Shi, 2021). However, rapid urbanization, industrialization, and climate change have posed challenges, such as water scarcity, local over-extraction of groundwater, and low efficiency in farmland reclamation and utilization, hampering the green and high-quality development of modern agriculture in the region (Dong et al., 2017; Li et al., 2021; Wen et al., 2022). The delicate ecological balance in Yulin underscores its growing conflict between agricultural expansion and environmental preservation. While land-reclamation projects in sandy grasslands and hilly and gully areas have provided essential farmland resources for modern agriculture, the increasing demand for agricultural water and the inadequacy of water-saving agricultural practices have made water-resources constraints a key limiting factor in Yulin's agricultural development.

Aiming to reveal the spatiotemporal evolution of the carrying capacity and coupling coordination of the water and land resources systems in Yulin, this study innovatively proposes a three-dimension (social, economic, and environmental), two-aspect (supply and demand) system for evaluating the carrying capacity of water and land resources systems from the human-earth system perspective, and quantitative methods such as the modified model of coupling degree are applied, so as to hold significant importance for reinforcing Yulin's status as the New Granary of Shaanxi and for increasing the quality of modern agricultural development and protection of the ecological environment in the city.

2 Materials and Methods

2.1 Study area

Yulin City (36°57′N–39°34′N, 107°28′E–111°15′E), encompasses an area of 43 400 km^2 in northern Shaanxi Province, China. The area consists of 12 counties (Fig. 1): Yuyang, Shenmu, Fugu, Hengshan, Jingbian, Dingbian, Suide, Mizhi, Jiaxian, Wubu, Qingjian, and Zizhou. Western Yulin has higher terrain than eastern Yulin; the northern sandy grass area (42%) features continuous dunes and degraded vegetation, while the southern loess hilly and gully area (58%) has serious land erosion, ravines, and crisscrossing gullies. Yulin experiences a temperate semi-arid continental monsoon climate, with an annual precipitation of 414 mm and an average temperature of 9 °C. As a significant energy hub in China, Yulin is endowed with abundant coal, oil, and natural gas reserves, mainly concentrated in Fugu County and Shenmu County. However, extensive mining and other

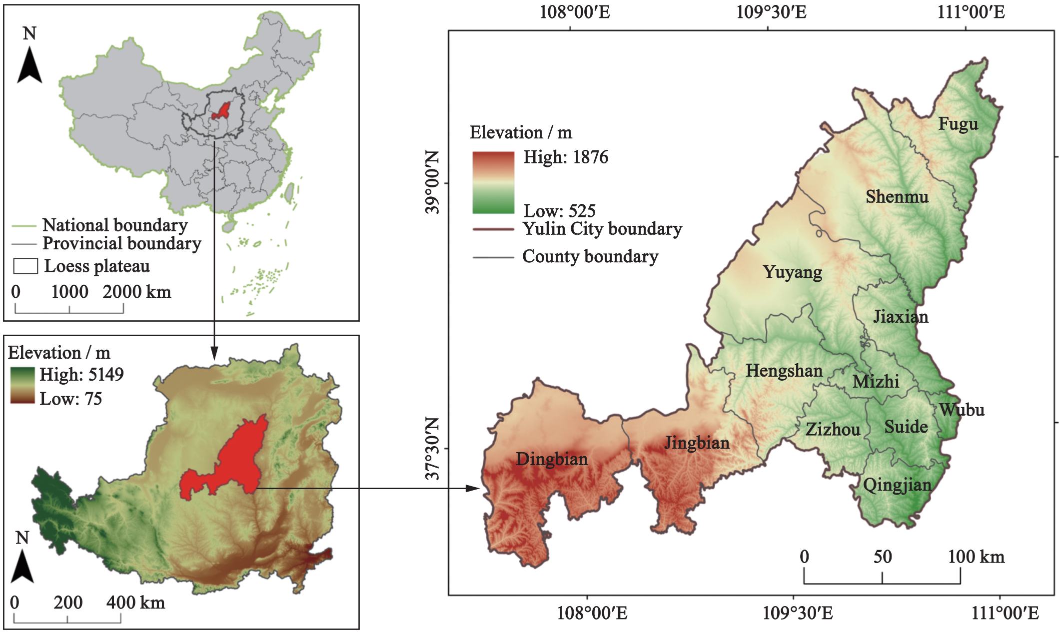

Fig. 1 Location and digital elevation model (DEM) of Yulin City, China. Based on the standard map service website of the Ministry of Natural Resources (http://bzdt.ch.mnr.gov.cn) with the approval number GS (2019) 1822, and the boundary of the base map has not been modified

unsustainable human activities since the 1980s have led to the degradation of its water and land resources systems (Dang et al., 2014).

2.2 Data sources

Since 2013, China has embarked on a comprehensive initiative to advance its ecological civilization (Li, 2013), with its arid and semi-arid areas, including Yulin, being pivotal in this endeavor. Additionally, 2013 is also the earliest year for which detailed water resources data for Yulin can be obtained. In 2016, the Chinese government released the 13th Five-Year Plan for Protecting the Ecological Environment, which focuses on enhancing environmental quality, strengthening comprehensive management of the ecological environment, and urgently addressing deficiencies in ecological environmental areas; 2020 was the target year for this plan. Consequently, this study evaluated the carrying capacity and coupling coordination between water and land resources system in Yulin based on data in 2013, 2016, and 2020, aiming to comprehensively understand China's overall process of coordinated and balanced ecological, economic, and social construction.

Population, economy, industry, and crop data were collected from the 2013, 2016, and 2020 statistical yearbooks of Yulin (https://data.cnki.net/yearBook/single?id=N2015110267), and missing county data were supplemented using data from the county's statistical bulletin. The village land area and sub-slope land area were obtained from the Yulin Sub-district County 2020 Change Survey Base Library (Yulin Water Conservancy Bureau), while the water resources data were obtained from the 2016 and 2020 Yulin Water Resources Bulletin (http://slj.yl.gov.cn/xxgk-19-0.html). The water resources data for 2013 came from the Yulin City Water Resources Carrying Capacity Study Report, which was provided by the Henan Yellow River Hydrological Survey and Design Institute. Normalized Difference Vegetation Index (NDVI) and Digital Elevation Model (DEM) data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/).

2.3 Methods

2.3.1 Construction of indicator system

Drawing on the perspective of the human-earth system theory (Li et al., 2019), it is understood that regional water and land resources systems are intertwined entities, impacting each other. Based on this understanding, we integrated three concepts—carrying capacity, coupling, and coupling coordination—to construct our theoretical framework (Fig. 2). The carrying capacity of water and land resources systems reflects the sustainability threshold of these resources within an ecosystem, determining the extent to which they can support societal and economic development without ecological degradation (Cheng et al., 2016). Intrinsically linked to this is water and land resources coupling, which highlights the mutual dependence and interaction between water and land resources, and the fact that the management of one inevitably impacts the other (Cui and Li, 2022). Building upon these concepts, coupling coordination emphasizes the harmonization and balance between water and land resources, advocating for their synergistic and sustainable use to support social progress, economic growth, and ecological stability (Yin et al., 2023). The concepts involved in the theoretical framework are defined as follows.

Coupling degree between water and land resources system endowment reflects the degree of compatibility between water and land resources conditions. A higher value indicates better matching of water and land resources system, while a lower value suggests poor compatibility; it is difficult to distinguish whether the water and land resources system endowment represents a high level of mutual promotion or a low level of mutual constraint. Coupling degree between water and land resources system utilization indicates the balance in the development and utilization of water and land resources. A higher value denotes more balanced intensity in the

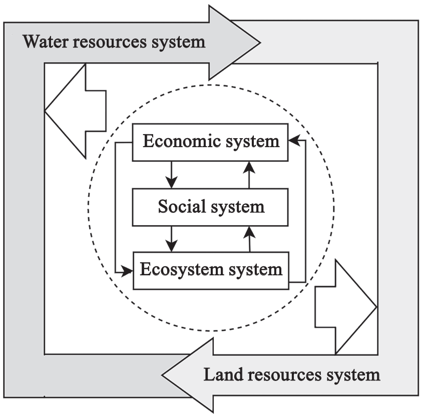

Fig. 2 Theoretical framework for the construction of the indicator system for carrying capacity of water and land resources systems

development and utilization of water and land resources, whereas a lower value indicates an imbalance; it is difficult to discern whether the water and land resources system utilization represents a high level of mutual promotion or a low level of mutual constraint.

The coupling coordination degree between water and land resources system endowment and utilization are calculated based on relevant indicators of Yulin's districts and counties. High endowment coordination levels indicate superior water and land resources conditions across districts and counties, while high utilization coordination levels suggest more intensive use of these resources in the areas. Comparing the size and temporal changes of these degrees can reflect the pressure on water and land resources in each district and county to some extent. If the endowment coupling coordination degree is greater than the utilization coupling coordination degree, this implies that the water and land resources conditions are better than the development intensity in the districts and counties, indicating the potential for further development. Conversely, if the endowment coupling coordination degree is less than the utilization coupling coordination degree, this suggests that the development intensity of water and land resources exceeds their conditions, indicating limited potential for further development.

Because the fundamental driving force for the development and utilization of water and land resources is the production and living demands of people, the evaluation indicators involve both their supply (endowment) and demand (utilization). Taking into consideration the actual situation and the availability of data, the index system for evaluating the carrying capacity of water and land resources systems in Yulin was constructed as described in Table 1.

2.3.2 CRITIC method

The Criteria Importance Through Intercriteria Correlation (CRITIC) method was chosen for assigning weights to our indicator system due to its robustness and precision. The CRITIC excels in harnessing the objective attributes of data for assessment, surpassing traditional techniques such as the coefficient-of-variation method and the entropy weighting method (Diakoulaki et al., 1995).

One of the method's strengths lies in its ability to gauge the comparison strength. An indicator having a larger standard deviation indicates that it has more pronounced fluctuations, highlighting greater disparities in values among different entities and thereby resulting in that indicator being assigned a higher weight (Mishra et al., 2022). This feature is particularly useful for pinpointing the drivers behind regional disparities in the carrying capacity of water and land resources systems. Additionally, the CRITIC method evaluates the conflicts among indicators. Indicators with higher correlation coefficients have less conflict, leading to them being assigned lower weights. This unique aspect of the CRITIC method not only ensures a thorough and balanced evaluation but also validates the judiciousness of the selected indicators by verifying their capacity to encompass comprehensive information (Mishra et al., 2022).

The raw data are normalized (Dong et al., 2017), whereby scores of indicators are calculated for different years and regions, again normalized to ensure that the carrying capacity levels are both horizontally and vertically comparable.

$$S_j = \sqrt{\frac{\sum_{i=1}^{n}(x_{ij} - \overline{x}_j)^2}{n-1}} \tag{1}$$

$$R_j = \sum_{i=1}^{m}(1 - r_{ij}) \tag{2}$$

where n, m, i, j, x_{ij}, $\overline{x}_j$ refer to the number of samples, the number of indicators, the ith sample, the jth indicator, the jth indicator value of the ith sample, and the average value of the jth index of all samples, respectively. S_j is the standard deviation of the jth indicator for different indicators. The correlation coefficient r_{ij} is used to indicate the conflict (R_j) between the values of the jth indicator for different samples.

The amount of information is represented by C_j:

$$C_j = S_j \times R_j \tag{3}$$

Finally, from Eqs. (1)–(3), the weight of the jth indicator (W_j) is represented as:

$$W_j = C_j / \left(\sum_{j=1}^{m} C_j \right) \tag{4}$$

The evaluation indexes for the carrying capacity of water and land resources systems in Yulin, as obtained using the CRITIC method, are shown in Table 2. In this The indicators corresponding to the social, economic, and ecological subsystems are used to compute scores for the carrying capacity of water and land resources of each subsystem. The overall score for the carrying capacity of water and land resources of the regional system is the sum of the scores of these three subsystems. A higher score indicates that the water and land resources in a system have a higher level of carrying capacity.

$$P_i = \sum_{j=1}^{m} W_j x_{ij} \tag{5}$$

where P_i is the carrying capacity of water and land resources systems. Besides, the carrying capacity of water and land resources for the economic, social, and ecological subsystem is the weighted sum of their corresponding indicators in Table 2, respectively.

Carrying capacity of water resources system endowment/utilization is the weighted sum of the supply/demand indicators corresponding to the coupling systems containing 'water system' in Table 2, respectively. The land resources system endowment/utilization is calculated in the same way.

Table 1 Index system for evaluating the carrying capacity of water and land resources of Yulin City, China

System	Coupling system	Criterion	Indicator	Calculation	Content	Selection basis
Social system	Social-water system	Water resources utilization (demand)	Population density / (person/km^2)	Resident population/Administrative district area	Pressure on water resources to meet the demands of the region's population	Dang et al., 2014
			Natural population growth rate / ‰	–	Capacity of water resources in response to changes in population demand	Qu et al., 2021
			Water supply per capita / (m^3/person)	Total water supply/Resident population	Water resources support residents in their aspirations for higher living standards	Yang et al., 2019
			Social-ecological eater resources allocation factor	(Total water utilization−ecological water utilization)/Ecological water utilization	Coordination of Production-living water and domestic water	Yin et al., 2023
		Water resources endowment (supply)	Water supply module / (m^3/m^2)	Total water supply/Regional land area	Abundance and scarcity of water resources supplied per unit of land area	Pan et al., 2007
			Water resources per capita / (m^3/person)	Total water resources/Resident population	Abundance and scarcity of water resources supplied to each inhabitant	Qu et al., 2021
	Social-land system	Land resources utilization (demand)	Yield per unit area of grain crops / (kg/ha)	Total grain crop yields/Total planted area	The capacity of land resources to meet food demand	Qu et al., 2021
			Proportion of village area / %	Rural settlements area/Administrative area	The capacity of land resources to meet housing demand	Dong et al., 2023
		Land resources endowment (supply)	Farmland suitability (i.e.farmland availability)	Farmland area with slopes over 25°/Total farmland area	The quality of land resources available to each resident population	Dong et al., 2021.
			Farmland per capita / (ha/person)	Total farmland area/Resident population	Abundance and scarcity of water resources available to each resident population	Yang et al., 2019
			Building land area per capita / (km^2/person)	Building land area/Resident population	Abundance and scarcity of land resources to underpin regional construction	Wu et al., 2022

Continued Table 1

System	Coupling system	Criterion	Indicator	Calculation	Content	Selection basis
Economic system	Economic-water system	Water resources utilization (demand)	Proportion of primary sector / %	Value-added of the primary industry/GDP	Water utilization for primary production	Yin et al., 2023
			Irrigation rate of farmland / %	(Paddy field area+Wetland area)/Total area	Water utilization for irrigating farmland	Xiao et al., 2020
			Industrial water use rate / %	Industrial water utilization/Total water utilization	Water utilization for industrial production	Dong et al., 2023
		Water resources endowment (supply)	Investment rate in water projects / %	Agroforestry water expenditure/Total water expenditure	Safeguarding of regional water supply	Bai et al., 2022
			Human and livestock water supply rate / %	(Domestic water utilization+Forestry, livestock, and fishery water utilization)/Total water utilization	Safeguarding regional domestic, forestry, livestock, and fishery water supply	Xiao et al., 2020
			Water consumption per unit of GDP / ($m^3/10^4$ yuan RMB)	Total water utilization/Regional GDP	Supply of water consumed by regional economic growth	Yang et al., 2019
	Economic-land system	Land resources utilization (demand)	Farmland output benefits / (10^4 yuan/ha)	Total agricultural output/Farmland area	Economic benefits per unit area of farmland	Yin et al., 2023
			Industrial building land output efficiency / (10^4 yuan/ha)	Total industrial output/Industrial building land area	Industrial production efficiency per unit area of building land	Qu et al., 2021
		Land resources endowment (supply)	Production value per unit area of land / (10^4 yuan/ha)	Regional GDP/Total area	Regional land supply to economic development	Cheng et al., 2016
			Land construction utilization / %	Building land area/Total area	Regional land supply to resident living, industry, transport construction, *etc.*	Wu et al., 2022
Ecological system	Ecological-water system	Water resources utilization (demand)	Ecological water use rate / %	Ecological water utilization/Total water utilization	Ecosystem demand for water resources	Qu et al., 2021
		Water resources endowment (supply)	Surface water factor	Precipitation/Surface water amount	The ratio of precipitation to surface water in regional water resources supply	Yin et al., 2023
	Ecological-land system	Land resources utilization (demand)	Proportion of mine area / %	Mine area/Total area	The proportion of regional land used for fossil-energy exploitation and economic development	Li et al., 2022
			Ecological land allocation factor	(Total area−Ecological land area)/Ecological land area	Coordination of the allocation of productive and ecological land use	Dong et al., 2021
		Land resources endowment (supply)	Vegetation cover / %	Max NDVI/Mean NDVI	Afforestation of land supplied by the region	Dong et al., 2017
			Proportion of wetland area / %	Wetland area/Total area	Regional capacity to provide ecological wetlands	Wen et al., 2022

Notes：NDVI, Normalized Difference Vegetation Index; GDP, Gross Domestic Product

Table 2 Evaluation-index weightings for the carrying capacity of water and land resources systems of Yulin City, China

System	Coupling system	Criterion	Indicator	Indicator weight	Coupling system weight	Subsystem weight
Social system	Social-water system	Water resources utilization (demand)	Population density / (person/km^2)	0.0445	0.1458	0.4091
			Natural population growth rate / ‰	0.0296		
			Water supply per capita / (m^3/person)	0.0393		
			Social-ecological water resources allocation factor	0.0324		
		Water resources endowment (supply)	Water supply module / (m^3/ha)	0.0399	0.0723	
			Water resources per capita / (m^3/person)	0.0319		
	Social-land system	Land resources utilization (demand)	Yield per unit area of grain crops / (kg/ha)	0.0413	0.0751	
			Proportion of village area / %	0.0338		
		Land resources endowment (supply)	Farmland suitability/availability	0.0462	0.1159	
			Farmland per capita / (km^2/person)	0.0393		
			Building land area per capita / (km^2/person)	0.0304		
Economic system	Economic-water system	Water resources utilization (demand)	Proportion of primary sector / %	0.042	0.1106	0.3624
			Irrigation rate of farmland / %	0.0339		
			Industrial water use rate / %	0.0347		
		Water resources endowment (supply)	Investment rate in water projects / %	0.0411	0.1144	
			Human and livestock water supply rate / %	0.0396		
			Water consumption per unit of GDP / (m^3/10^4 yuan)	0.0337		
	Economic-land system	Land resources utilization (demand)	Farmland output benefits / (10^4 yuan/ha)	0.0323	0.0646	
			Industrial building land output efficiency / (10^4 yuan/ha)	0.0323		
		Land resources endowment (supply)	Production value per unit area of land / (10^4 yuan/ha)	0.0348	0.0728	
			Land construction utilization / %	0.038		
Ecological system	Ecological-water system	Water resources utilization (demand)	Ecological water use rate / %	0.0398	0.0690	0.2288
		Water resources endowment (supply)	Surface water amount	0.0292		
	Ecological-land system	Land resources utilization (demand)	Proportion of mine area / %	0.0471	0.0878	
			Ecological land allocation factor	0.0407		
		Land resources endowment (supply)	Vegetation cover / %	0.0355	0.0720	
			Proportion of wetland area / %	0.0365		

2.3.3 Modified model of coupling degree

In the context of our study, the application of the modified model of coupling degree serves as an important methodological advancement. This model facilitates an in-depth understanding of the interactions and levels of harmony between different systems, such as the economic and environmental systems. Conventional coupling coordination models evaluate the strength of an interaction (the coupling degree, *C*) and the extent of harmonious coexistence (the coordination degree, *D*) between systems. However, these traditional models have limitations, particularly in their approach to measuring interactions.

Typically, the range of the *C* value is confined to intervals of [0, 1/2] or [0, 1/3], constraining comprehension of the actual interplays between different systems. The modified model of coupling degree addresses this limitation by expanding the range of *C* to be uniformly distributed across the interval [0, 1]. This modification allows for a more precise evaluation of the interactions and coordination levels between various domains (Wang et al., 2021). The modified model of coupling degree is:

$$D = \sqrt{C \times T} \tag{6}$$

$$C = \sqrt{\left[1 - \frac{\sum_{g>k,\, k=1}^{s} \sqrt{(U_g - U_k)^2}}{\sum_{m=1}^{s-1} m}\right] \times \left(\prod_{g=1}^{s} \frac{U_g}{\max U_g}\right)^{\frac{1}{s-1}}} \tag{7}$$

$$T = \sum_{g=1}^{s} \alpha_g \times U_g, \sum_{g=1}^{s} \alpha_g = 1 \tag{8}$$

where s is the total number of subsystems, g (k) is the g-th (k-th) subsystem, U_g (U_k) is the value of the g-th (k-th) subsystem, α_g represents the weight of the g-th subsystem, and T represents the coordinated development degree and is calculated using an arithmetic weighting method. A low value of C indicates that the subsystems are relatively discrete, while a higher value of C indicates the interactions between subsystems are stronger.

Since the water resources system and the land resources system are equally important in this study, their weighting values are both 1/2. This study divided the coupling coordination degree in the [0, 1.00] interval into ten equally spaced intervals, as shown in Table 3.

While U_g and U_k are both the water and land resources system endowments, C-E (the coupling degree between water and land resources system endowment) refers to the extent and nature of interaction or interdependence between water and land resources, focusing particularly on their natural availability and distribution. D-E (the coupling coordination degree between water and land resources system endowment) evaluates the consistency or synchronicity in the availability, distribution, and quality of water and land resources. Practically, it is essential to avoid scenarios in which an overabundance or scarcity of one resource adversely impacts another. If U_g and U_k are both the water and land resources system utilization, C-U and D-U are defined similarly to above, with only endowments replaced with utilizations.

3 Results

3.1 Evaluation of carrying capacity

From 2013 to 2020, the carrying capacity of Yulin's water and land resources systems exhibited a continuous decline. The changes in the carrying capacity in the economic subsystem were consistent with the overall changes (Table 4). Concurrently, the carrying capacity in the social subsystem showed a consistent rise, whereas the ecological subsystem's capacity initially decreased from 2013 to 2016 before increasing from 2016 to 2020. Throughout the study period, the shifts in the economic subsystem's carrying capacity surpassed those in both the social and ecological subsystems, thereby critically influencing the overall carrying capacity of Yulin's water and land resources systems.

The computational results indicate that during the study period, the peak carrying capacity of water and land resources systems in Yulin registered at 0.47. Aligning with prior research (Pan et al., 2007) and employing a [0, 1.00] scale for classification, in this study, the carrying capacity was divided into five distinct levels. However, 97% of the computed results were con-

Table 3 Evaluation criteria for the regional system's state of coupling coordination of Yulin City, China

Coupling degree (C)	Coupling coordination degree (D)	Level	System state
[0, 0.10)	[0, 0.10)	1	Extremely uncoordinated
[0.10, 0.20)	[0.10, 0.20)	2	Severely uncoordinated
[0.20, 0.30)	[0.20, 0.30)	3	Moderately uncoordinated
[0.30, 0.40)	[0.30, 0.40)	4	Slightly uncoordinated
[0.40, 0.50)	[0.40, 0.50)	5	Borderline uncoordinated
[0.50, 0.60)	[0.50, 0.60)	6	Barely coordinated
[0.60, 0.70)	[0.60, 0.70)	7	Initially coordinated
[0.70, 0.80)	[0.70, 0.80)	8	Moderately coordinated
[0.80, 0.90)	[0.80, 0.90)	9	Well coordinated
[0.90, 1.00]	[0.90, 1.00]	10	High-quality coordinated

Table 4 Carrying capacity of water and land resources systems of Yulin City, China in 2013, 2016 and 2020

County	Regional capacity			Economic subsystem			Social subsystem			Ecological subsystem		
	2013	2016	2020	2013	2016	2020	2013	2016	2020	2013	2016	2020
Yuyang	0.40	0.35	0.36	0.26	0.16	0.20	0.11	0.09	0.12	0.10	0.10	0.11
Hengshan	0.30	0.21	0.27	0.16	0.10	0.15	0.08	0.06	0.07	0.06	0.05	0.08
Shenmu	0.35	0.29	0.25	0.18	0.08	0.08	0.08	0.13	0.10	0.09	0.07	0.08
Fugu	0.36	0.27	0.30	0.20	0.13	0.14	0.09	0.07	0.11	0.07	0.08	0.09
Jingbian	0.34	0.29	0.28	0.18	0.12	0.15	0.06	0.07	0.07	0.10	0.10	0.06
Dingbian	0.28	0.21	0.21	0.18	0.12	0.10	0.05	0.07	0.09	0.05	0.03	0.05
Suide	0.36	0.23	0.20	0.24	0.11	0.08	0.08	0.08	0.10	0.04	0.04	0.08
Mizhi	0.37	0.24	0.22	0.23	0.13	0.10	0.05	0.06	0.09	0.09	0.05	0.05
Jiaxian	0.35	0.24	0.24	0.18	0.09	0.04	0.09	0.11	0.18	0.08	0.03	0.09
Wubu	0.36	0.30	0.24	0.21	0.11	0.09	0.06	0.13	0.09	0.09	0.07	0.06
Qingjian	0.31	0.25	0.20	0.14	0.10	0.08	0.10	0.14	0.11	0.07	0.02	0.10
Zizhou	0.35	0.29	0.26	0.15	0.12	0.09	0.11	0.09	0.10	0.09	0.08	0.11
Average	0.34	0.26	0.25	0.19	0.11	0.11	0.08	0.09	0.10	0.08	0.06	0.08

centrated within the intervals [0, 0.20) and [0.20, 0.40), yielding limited differentiation. To enhance the spatial distinction of the carrying capacity across Yulin's counties and to accurately portray the temporal evolution of each county's carrying capacity, the interval [0.45, 1.00], encompassing the system's maximum val-ue (0.47), was identified as the uppermost carrying capacity range. Similarly, the [0, 0.25] interval, capturing the system's minimum value (0.20), served as the lower-most range. Consequently, the carrying capacity of water and land resources systems in Yulin was divided into five intervals, and analogous logic was applied for subdividing the subsystems' carrying capacity (Table 5).

Spatially, the carrying capacity of water and land resources in the six northern counties (Shenmu, Fugu, Yuyang, Dingbian, Jingbian and Hengshan, *Territorial Spatial Master Planning of Yulin (2021–2035)*) was higher than that of the six southern counties (Jiaxian, Mizhi, Zizhou, Wubu, Suide and Qiangjian) in different periods (Fig. 3). Between 2013 and 2020, Yuyang and Hengshan districts uniquely exhibited an initial decrease followed by an increase in the carrying capacity of water and land resources, whereas Dingbian consistently ranked at the lowest level. In contrast, the remaining counties experienced a continuous decline in their carrying capacity of water and land resources; this was especially notable in northern Fugu and the southern counties of Suide, Wubu, and Qingjian (Fig. 3).

Between 2013 and 2020, there was a persistent decline in the carrying capacity of water and land resources in the economic subsystem. Jiaxian specifically experienced a significant decrease, moving from the highest to the lowest carrying capacity level. In contrast, Hengshan, Zizhou, and Qingjian maintained stable capacities (Fig. 4). Notably, after an initial drop, Yuyang's carrying capacity showed a rebound, marking a positive shift toward recovery in the latter part of the period.

The carrying capacity in the social subsystem was generally higher in the east and south, but it was lower in the west and north (Fig. 4). The six northern counties experienced minimal fluctuation in social subsystem's

Table 5 Classification criteria for the carrying capacity of water and land resources systems

Grade	Carrying capacity	Regional system score	Economic subsystem score	Social subsystem score	Ecological subsystem score
I	Worst	[0, 0.25)	[0, 0.06)	[0, 0.06)	[0, 0.02)
II	Poor	[0.25, 0.30)	[0.06, 0.08)	[0.06, 0.08)	[0.02, 0.04)
III	Moderate	[0.30, 0.35)	[0.08, 0.12)	[0.08, 0.10)	[0.04, 0.06)
IV	Strong	[0.35, 0.45)	[0.12, 0.16)	[0.10, 0.12)	[0.06, 0.08)
V	Strongest	[0.45, 1.00]	[0.16, 1.00]	[0.12, 1.00]	[0.08, 1.00]

Fig. 3 Spatial distribution of the carrying capacity of water and land resources systems in Yulin City, China in 2013, 2016 and 2020

a. Economic subsystem

b. Social subsystem

c. Ecological subsystem

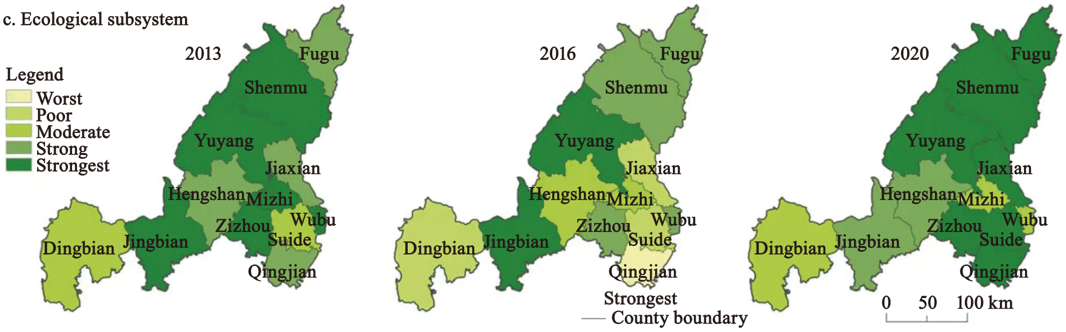

Fig. 4 Spatial distribution of the carrying capacity of economic (a), social (b), and ecological (c) subsystems of water and land resources systems in Yulin City, China in 2013, 2016 and 2020

carrying capacity. In Fugu and Yuyang, the carrying capacity in the social subsystem first decreased and then increased, whereas Shenmu exhibited the opposite pattern. Meanwhile, the carrying capacity of Dingbian's social subsystem steadily increased (Fig. 4). From 2013 to 2016, the carrying capacity in the social subsystem declined across all northern counties. Simultaneously, the overall carrying capacity in the six southern counties experienced a reduction during this timeframe.

3.2 Coupling coordination analysis

3.2.1 Coupling degree between water and land resources system endowment

From 2013 to 2020, Yulin experienced an increasing trend in the coupling degree between water and land resources system endowments (Table 6). The coupling degree between water and land resources system endowment notably improved, rising from 0.57 in 2013 to 0.94 in 2016 and then to 0.90 by 2020, demonstrating a significant interaction and mutual influence between the water and land resources system endowment (Table 6). The overall coordination degree D value fell below the coupling degree C. Although there were significant disparities in the water resources endowments and land resources endowments, they remain closely coupled.

In 2013, 2016, and 2020, Yulin's water and land resources system endowment exhibited average coupling coordination degrees of 0.54, 0.58, and 0.73, respectively, indicating a progression from minimal to moderate levels of coordination (Table 6). Despite Yulin demonstrating a robust interaction between its water and land resources endowment, significant potential for developmental enhancement remains. Most counties and districts had gradually achieved coordinated development, transitioning overall from initial to moderate levels.

Table 6 Coupling degree between water and land resources system endowment (C-E) and coupling coordination degree between water and land resources system endowment (D-E) in Yulin City, China

County	2013		2016		2020	
	C-E	D-E	C-E	D-E	C-E	D-E
Yuyang	0.58	0.76	0.79	0.68	0.84	0.87
Hengshan	0.46	0.44	1.00	0.33	0.94	0.81
Shenmu	0.58	0.62	0.95	0.68	0.50	0.50
Fugu	0.57	0.56	0.99	0.79	0.88	0.91
Jingbian	0.28	0.35	0.82	0.55	0.76	0.70
Dingbian	0.35	0.39	0.92	0.45	0.99	0.71
Suide	0.63	0.50	0.99	0.46	0.98	0.69
Mizhi	0.74	0.61	1.00	0.34	0.99	0.78
Jiaxian	0.56	0.54	0.95	0.63	0.99	0.72
Wubu	0.86	0.62	0.97	0.77	0.99	0.66
Qingjian	0.65	0.50	0.96	0.66	0.97	0.65
Zizhou	0.63	0.59	0.98	0.66	0.92	0.81
Average	0.57	0.54	0.94	0.58	0.90	0.73

Spatially, Yuyang district consistently demonstrated the highest level of coupling coordination between water and land resources system endowment in Yulin. From 2013 to 2020, the areas with high coupling coordination expanded from the central region to the northeast, southeast, and then to the west, contributing to an overall enhancement in the coupling coordination across Yulin (Fig. 5). The primary driver for the improvement in water and land resources system endowment since 2016, relative to 2013, was the increase in the coupling degree (C), which enabled Hengshan, Suide, and Mizhi to maintain their levels of coordination and coupling in their original states, despite significant decreases in their levels of coordinated development (T) (Fig. 5).

The main driver behind the improvement in the coupling degree between water and land resources system endowment from 2013 to 2020 was the increase in the water resources system endowment (Fig. 6). In 2013, the overall coupling degree between water and land resources system endowment of Yulin was relatively low, indicating weak interaction. Although Zizhou had modest endowment scores for both water and land resources system, their levels were similar, exhibiting strong interdependence. However, in Shenmu and Yuyang, high land resources system endowment did not translate into a high regional coupling degree due to the inadequate water resources system endowment, which restricted the development and utilization of land resources. In 2016, the improvement in Yulin's water resources system endowment enhanced the coupling degree across all counties (Fig. 6). The increase in the coupling degree between the water and land resources system in Jingbian arose not from a higher water resources system but from a reduced land resources. By 2020, despite an improvement in Hengshan's land resources system endowment, a decline in water resources system endowment resulted in a reduced coupling degree between them.

3.2.2 Coupling degree between water and land resources system utilization

During 2013–2020, the coupling degree between water and land resources system utilization remained at a high-quality level. The significant demands from development and construction activities in Yulin fostered the concurrent development and utilization of these re-

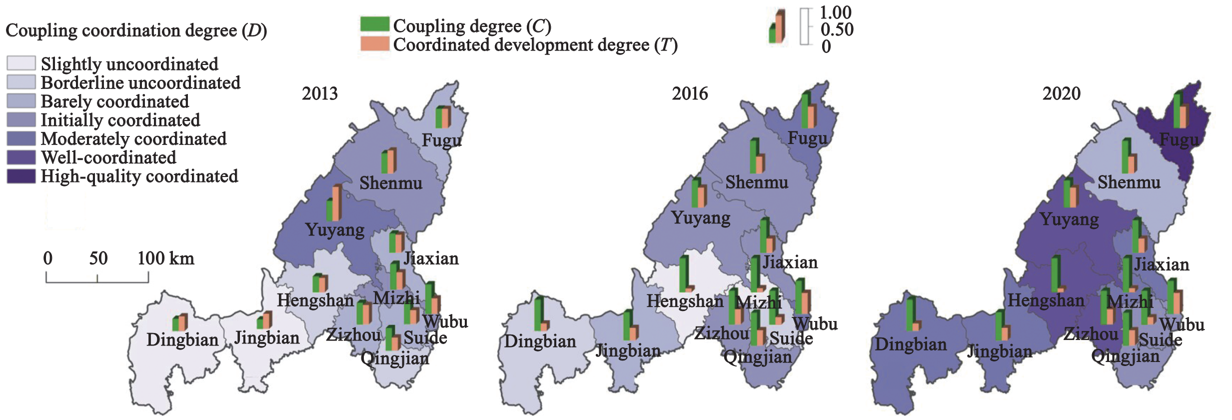

Fig. 5 Spatial distribution of the coupling coordination degree (*D*), coupling degree (*C*), and the coordinated development degree (*T*) between the carrying capacity of water and land resources system endowment in Yulin City, China in 2013, 2016 and 2020

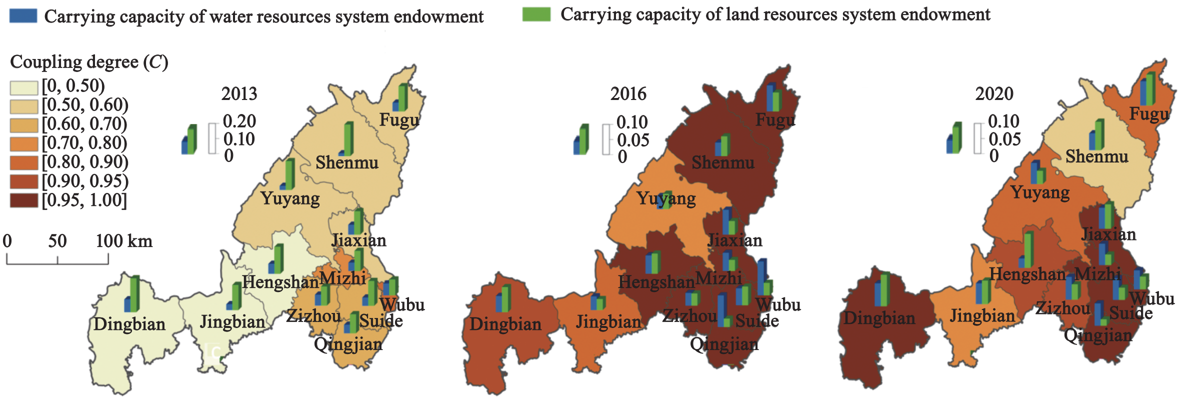

Fig. 6 Spatial distribution of the coupling degree between water and land resources system endowment and the carrying capacity of water resources system endowment and land resources system endowment in Yulin City, China in 2013, 2016 and 2020

sources, mutually propelling their advancement (Table 7). In 2013, 2016, and 2020, the coordination degrees between water and land resources utilization were 0.72, 0.58, and 0.62, respectively. The utilization levels of water and land resources system in each of these years were moderately coordinated, barely coordinated, and initially coordinated, respectively (Table 7). Overall, Yulin's water and land resources system utilization level remained modest, with coordination between water and land resources system utilization at a moderate to low level.

Between 2013 and 2020, the coupling coordination degree between water and land resources system utilization in Yulin displayed notable spatiotemporal fluctuations, with a pronounced increase in the north and a steady decline in the south. Annually, the coupling coordination degree was high in the north and east and low in the south and west (Fig. 7). In 2013, the north overall exhibited a higher level of coupling coordination than the south, with high-value areas predominantly located in the north. The six northern counties experienced more intense water and land resources development and utilization, generally maintaining a state of synchronized development (Fig. 8). During 2013–2016, due to the irrational utilization of the regional water and land resources system, the coordinated development degree of water and land resources system utilization decreased significantly. Fugu was the county with the largest reduction in the level of coupling coordination among the six northern counties, with the relationship between water and land resources system utilization being extremely uncoordinated and struggling to achieve mutual promotion (Fig. 8). In 2020, Yulin's coupling degree between water and land resources system utilization showed further improvements from 2016. However, there was a decline in their levels of water and land resources system utilization in Shenmu and Fugu, with a more significant reduction in the intensity in the devel-

Table 7 Coupling degree between water and land resources system utilization (*C*-U) and coupling coordination degree between water and land resources system utilization (*D*-U) in Yulin City, China

County	2013		2016		2020	
	C-U	*D*-U	*C*-U	*D*-U	*C*-U	*D*-U
Yuyang	0.99	0.97	0.99	0.93	0.97	0.94
Hengshan	0.98	0.50	0.98	0.47	0.96	0.60
Shenmu	0.98	0.62	0.95	0.75	0.99	0.60
Fugu	0.98	0.74	0.97	0.47	0.98	0.65
Jingbian	0.83	0.64	0.91	0.68	1.00	0.73
Dingbian	0.87	0.28	0.96	0.38	0.97	0.43
Suide	0.98	0.86	0.97	0.53	0.97	0.43
Mizhi	1.00	0.89	0.98	0.62	0.98	0.42
Jiaxian	0.92	0.76	0.98	0.36	0.95	0.71
Wubu	0.97	0.91	0.98	0.64	0.97	0.69
Qingjian	0.99	0.69	0.98	0.37	0.99	0.60
Zizhou	0.86	0.72	0.97	0.72	0.99	0.60
Average	0.95	0.72	0.97	0.58	0.98	0.62

opment and utilization of water resources compared to land resources. Nevertheless, the coupling degree improved (Fig. 8). There was overall an increase in water and land resources utilization coordination, but land resources utilization in Mizhi and Suide decreased by 15.70% and 26.20%, respectively, leading them to a shift from well coordinated to borderline uncoordinated in Yulin (Fig. 8).

4 Discussion

4.1 Reasons for changes in the carrying capacity of water and land resources systems

From 2013 to 2020, the carrying capacity of Yulin's water and land resources systems declined by approximately 24.00%. Yulin faces increasing pressures on its water and land resources systems due to increasing population density and per capita water demand, as well as the impacts of global climate change (Wang et al.,

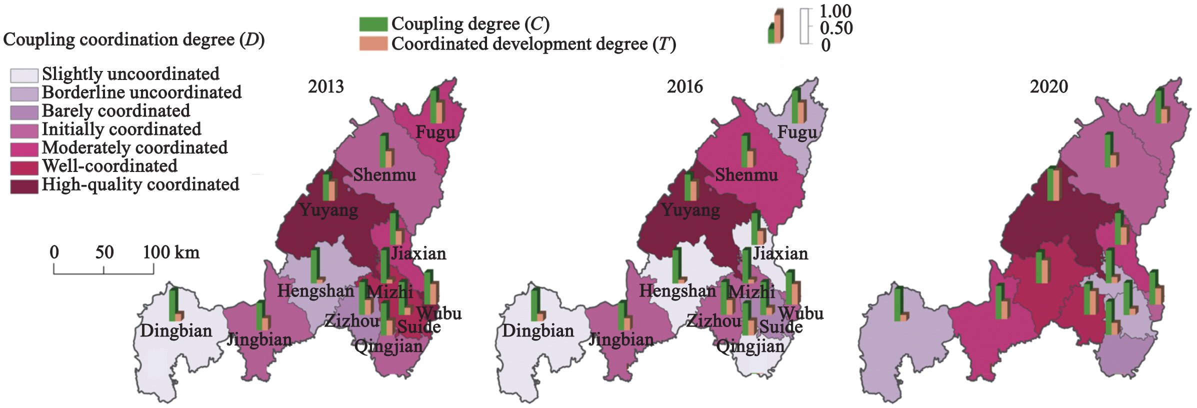

Fig. 7 Spatial distribution of the coupling coordination degree (*D*), coupling degree (*C*), and the degree of coordinated development (*T*) between water and land resources system utilization in Yulin City, China in 2013, 2016 and 2020

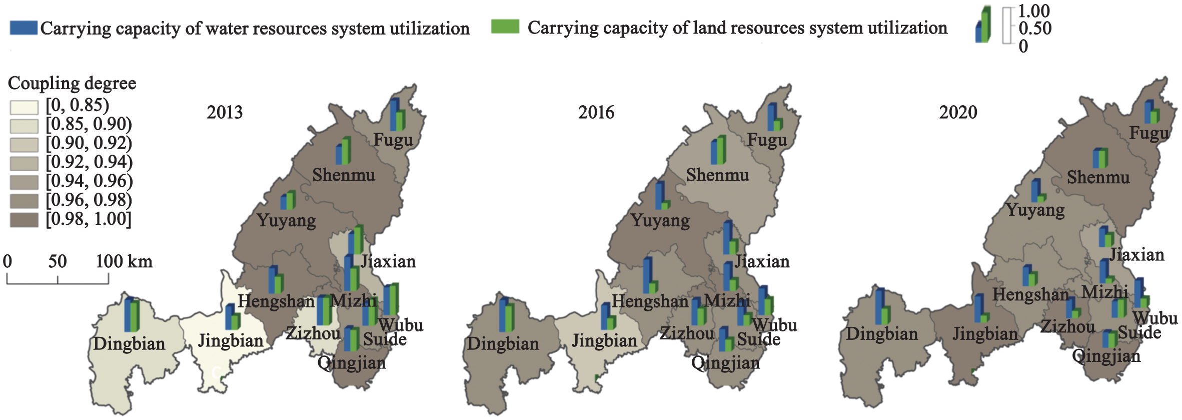

Fig. 8 Spatial distribution of the coupling degree between water and land resources system utilization and the carrying capacity of water resources system utilization and land resources system utilization in Yulin City, China in 2013, 2016 and 2020

2004). The social and industrial water use rates for residents increased by approximately 9.00% and 11.00%, respectively, from 2013 to 2020. However, the available regional water resources decreased by 17% during this period, indicating excessive exploitation of natural resources for human production and life, resulting in the water and land resources systems imbalance. The growing water demand that accompanies population expansion intensifies water scarcity in arid and semi-arid areas (Postel et al., 1996), making the challenges of surface water reduction, wetland shrinkage, and the decline in natural reservoirs even more daunting (Mitsch et al., 2009).

Against the backdrop of global climate change, Yulin' s annual average temperature is showing a fluctuating upward trend, increasing by 0.37°C/10yr (Yang and Shi, 2021). This is fostering high evaporation rates and variable precipitation (Pachauri et al., 2014) and consequently diminishing surface-water availability and causing wetland reduction (Abayomi and Wright, 1999; Hasan et al., 2022). The desert freshwater lakes heavily depend on precipitation for their replenishment (Jiang et al., 2021). In China, the largest desert freshwater lake, Hongjiannao, located in northwest Yulin, experienced an average water-level decrease of 30–60 cm from 2013 to 2016, losing about 1 km^2 of surface area annually. Additionally, rising temperatures are accelerating the loss of soil moisture (Bao et al., 2023), reducing soil fertility and stability (Yang et al., 2021), and sporadic and intense precipitation events are exacerbating soil erosion, stripping away nutrient-rich topsoil and reducing the land's agricultural viability.

With decreases in the carrying capacity of water and land resources system, meeting the demands of production and life will require more intensive exploitation of these resources. However, while this may temporarily boost productivity to fulfill development needs, it risks long-term depletion of resources and soil degradation (Lal, 2001), trapping the water and land resources systems in a 'vicious cycle' in which increased utilization further diminishes carrying capacity. For instance, water-conservancy investment in Jiaxian county of Yulin increased by 4.34 times from 2013 to 2020, but the water used for agricultural production also increased by 1.50 times, ultimately resulting in a 33.00% decrease in the carrying capacity of its water and land resources systems.

The expansion of construction land is often cited as a major factor in reducing the carrying capacity of water and land resources systems (Xie et al., 2019; Zou et al., 2019; Fang et al., 2021). However, in arid and semi-arid areas, the expansion of construction land is predicated on the successful control of soil erosion and land leveling (Song et al., 2021; Wu et al., 2022), improving the water-retention and sand-resistance capabilities of the land (Jiang et al., 2017; Long et al., 2020), meeting the requirements for agricultural irrigation and mechanized farming (Graymore et al., 2010; Ren et al., 2011). In Yulin, from 2013 to 2020, the conversion of farmland back to forests and grasslands and water- and soil-conservation projects have progressed, particularly in Yuyang district. Between 2016 and 2020, although the land construction utilization rate in Yuyang district was approximately 1.20 times higher than the city average, the carrying capacity of water and land resources systems in its economic subsystem improved from the moderate level to the stronger level. Amidst a 25.00% overall decline in the carrying capacity of Yulin's water and land resources systems, Yuyang stands out as the only area in which the level has improved.

In summary, the degradation of the carrying capacity of water and land resources in arid and semi-arid areas, exemplified by Yulin, affects water regulation, soil health, and human life, and it exacerbates the negative impacts of climate change. Therefore, adaptive strategies to mitigate these impacts is essential.

4.2 Reasons for changes in the coupling coordination degree between water and land resources system

As validated by Xiao et al. (2020), in arid and semi-arid areas, water scarcity leads to land desertification, while inadequate soil water-retention capacity worsens moisture and nutrient loss, a phenomenon emphasized by Ioanna et al. (2021). Compared to 2013, the precipitation in 2020 decreased by 162.70 mm. From 2013 to 2020, the total amount of water resources continued to decline, nearing a 20.00% reduction. In Yulin, from 2013 to 2020, the coupling degree between water and land resources system endowment was 1.3 times higher than the coupling coordination degree, indicating a disparity in the development levels of water and land resources system; water resources system endowment thus emerges as a major factor in the lower coordination degree of the city's water and land resources system.

During the study period, Yulin’s water resources system endowment significantly increased, by nearly 60.00%, and the coupling coordination degree of water and land resources system increased by 36.00%. This improvement largely resulted from increases in water-conservancy projects and more efficient ecological water use. From 2013 to 2020, Yulin boosted its water-conservancy project investment, implementing projects such as the Eastern Yellow River Diversion Project in Mazhen, the Suide-Mizhi-Zichang County Water Supply Project, water ecology management projects, and erosion-control projects closely related to water and land resources, including the Beijing-Tianjin Sand Source Control, Comprehensive Control of Sloping Farmland Soil Erosion, and the Hazardous and Silted Dam Removal and Reinforcement projects. By 2020, Yulin’s investment in water-conservancy projects had doubled compared to 2013. To improve water-use efficiency, especially for ecological water, Yulin implemented major river-water discharge plans based on ecological flow guarantees, scientifically guiding the ecological release flow of the Wuding and Tuwei rivers, annually providing cross-provincial ecological water replenishment to Hongjiannao, controlling the total amount of groundwater extraction and the groundwater level. Concurrent efforts have been made to reduce groundwater extraction through efficient water saving, industrial structure adjustment, reclaimed water reuse, well sealing, and other measures. These initiatives not only improve the effectiveness of the management of water resources but also bridge the gap between the water and land resources endowments.

As pointed out by Li et al. (2021) and Wang et al. (2012), water resources endowment critically influences the coupling coordination degree between water and land resources system in arid and semi-arid areas. The optimization of water resources system has alleviated Yulin’s severe challenges, reducing the risk of desertification and enhancing the soil’s water-retention capacity, promoting sustainable and balanced development of water and land resources. Investments in water infrastructure and the adoption of more efficient water-use practices not only improve the supply and quality of water but also support sustainable management and utilization of land resources.

Yulin’s economic development is highly dependent on coal resources (Li et al., 2022; Wen et al., 2022). However, extensive coal-mining activities significantly threaten the land resources system (Hangen-Brodersen et al., 2005), reducing its carrying capacity and consequently leading to a decline in the coupling coordination degree between water and land resources system utilization. In Fugu, which has the largest coal reserves in Yulin, the carrying capacity of the land resources system significantly decreased from 2013 to 2020, by approximately 40%. This decrease can be attributed to a 37.00% expansion of its mining area during the study period, damaging surface vegetation and landforms (Sonwalkar et al., 2010; Gallagher et al., 2008) and exacerbating issues such as soil erosion, desertification, and ground subsidence (Bian et al., 2009; Xie et al., 2010; Dang et al., 2014). This environmental degradation compromises the land’s agricultural and ecological capabilities, thereby reducing the overall coupling coordination degree between water and land resources system utilization.

Among the six northern counties of Yulin, which have relatively higher economic development levels, Fugu experienced the most significant decrease in the coupling coordination degree between water and land resources system utilization during the study period, with a decline of 13%. This indicates that the intensity of coal mining and related industrial activities were particularly detrimental to the balance and sustainability of the water and land resources. The efficiency of farmland use is another reason for distinguishing the coupling coordination levels between water and land resources utilization among the northern and southern counties. During the study period, the yield per unit area of grain crops in the north was approximately double that in the south. The rugged, hilly terrain in the south impedes mechanized farming, limits land use, and poses water supply and land-management challenges.

4.3 Limitations

This study has several limitations. First, given the limited availability of data, particularly at the county level, the evaluation-index system for the carrying capacity of water and land resources system developed in this study has a slightly inadequate number of indicators. Second, while the study quantitatively assessed the carrying capacity of water and land resources systems, the coupling coordination degree between the water and land resources system endowment, and the coupling coordination degree obetween the water and land resources system utilization, there was no quantification of the relationship between the system's carrying capacity and the coordination degrees. Finally, the index evaluation method can only quantify the past and current carrying capacity of water and land resources systems; simulating and predicting future the carrying capacity of the water and land resources systems remains an area for further exploration.

5 Conclusions

Based on a human-earth system perspective, in this study, an evaluative index system to assess the carrying capacity of water and land resources systems in Yulin City, China was devised, which was used to quantitatively analyze the carrying capacity and coupling coordination degrees of both the endowment and utilization of these resources, examining their spatiotemporal evolution from 2013 to 2020. This has led to several key conclusions.

Firstly, from 2013 to 2020, the carrying capacity of water and land resources systems in the six northern counties of Yulin showed an increasing trend; this was in contrast to a decrease in the six southern counties. The primary factors contributing to this decline were heightened agricultural water consumption and the reduction of ecological land. Conversely, shifting domestic water usage to ecological purposes and reducing sloping farmland significantly enhanced the area's carrying capacity.

Secondly, mining activities significantly impacted the carrying capacity, with the coupling coordination between water and land resources utilization being predominantly influenced by the utilization of land resources. Mining activities damage vegetation and the land surface, adversely affecting the carrying capacity of land resources. This degradation has a cascading effect on the overall carrying capacity of water and land resources systems, challenging the ecological balance and sustainability of arid and semi-arid areas.

Finally, the spatial distribution in the carrying capacity of water and land resources systems in Yulin and the coupling coordination degree between the water and land resources system endowment and utilization varies significantly. The counties with high carrying capacity and coupling coordination degree are mainly concentrated in the north, which is attributable to their more advanced technological level and greater environmental awareness. These factors facilitated synchronized and efficient management and utilization of water and land resources, improving the carrying capacity of water and land resources systems.

Conflict of Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by ZHANG Qianxi and CAO Zhi, reviewed by WANG Yongsheng and HUANG Yijia. The first draft of the manuscript was written by ZHANG Qianxi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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