Pol. J. Environ. Stud. Vol. 33, No. 4 (2024), 1-15
DOI: *10.15244/pjoes/183426* ONLINE PUBLICATION DATE:

Original Research

An Empirical Exploration of the Low-Carbon Economy- Water Resource Nexus in China

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Received: 22 September 2023
Accepted: 29 January 2024

Abstract

Utilizing an extensive dataset pertinent to the low-carbon economy and water resources extracted from 30 provinces across China, encompassing the period from 2004 to 2019, we have structured a synergistic model that explores the integrative interplay between the low-carbon economic framework and the water resource system. To assess the composite synergy effects, we employed Kernel density estimation in conjunction with Markov chain analysis, aiming to elucidate the temporal distribution dynamics and the spatial evolutionary patterns of provincial-level synergism within China's low-carbon economy-water resource nexus. Our findings reveal that, over the span from 2005 to 2019, the synergy effect within China's hybridized low-carbon economy-water resource system predominantly occupied a stage of moderate amalgamation, demonstrating a consistent upward trajectory since 2011. Notably, multilevel differentiation of composite system synergy is evident nationally, with pronounced trends of divergence manifesting in the eastern, western, and northeastern provinces. In contrast, the synergy effect exhibited in the central region is characterized by regional heterogeneity, yet the absolute disparities in synergy levels have diminished over time. Moreover, analysis of the synergy degree's rank order status within the composite system indicates a relative stability, punctuated by a 'club convergence' phenomenon. Against the backdrop of global climate change, the interactions between low-carbon economies and water resources have garnered significant attention within the realm of global sustainable development research. Exploring these synergistic relationships offers a potential avenue for identifying effective strategies to manage and harness resources, thereby facilitating economic growth and social advancement while mitigating the pace of global climate change. This paper employs data related to the low-carbon economy and water resources in 30 provinces of China from 2004 to 2019. It constructs a composite system model and an evaluation index system to investigate the synergistic effect between these two factors. The study employs the kernel density estimation method and Markov chain to analyze the distribution dynamics and spatial evolution of the synergy level in the composite system of the low-carbon economy and water resources across each province in China. The results indicate the following: [1] Between 2005 and 2019, the synergy effect of China's low-carbon economy-water resources complex system exhibited a mild level of synergy. Since 2011, the degree of synergy has steadily increased, with the synergy degrees of the low-carbon economy system, water resources system, and their complex systems reaching 0.256, 0.487, and 0.277, respectively, by 2019. [2] The absolute difference in the level of synergy between the low-carbon economy and water resources complex systems in the east, west, and northeast regions demonstrates a significant expansion. However, in the central region, regional differences in the synergy effect exist, although the absolute difference exhibits a narrowing trend. [3] The ranking status of the synergy in the low-carbon economy-

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water resources composite system is relatively stable, displaying the phenomenon of "club convergence." Nonetheless, when spatial effects are considered, the probability of "rank locking" decreases in the low-carbon economy-water resources composite system. The findings of this paper contribute to a deeper understanding of the synergistic relationship between China's low-carbon economy and water resources, providing a basis for decision-making aimed at achieving China's sustainable development.

Keywords: Low carbon economy; Water Resources; Synergy models; Kernel Density; Markov Chain

Introduction

In the context of globalization, numerous countries confront the concurrent challenges of natural resource scarcity and the imperative for sustained economic and social growth. This situation has exacerbated the prominence of climate warming. Climate directly impacts essential elements such as precipitation, evaporation, runoff, humidity, and soil moisture. Moreover, the scarcity of water resources can result in the emission of substantial quantities of greenhouse gases, posing a significant obstacle to a nation's sustainable development. Consequently, the effective management of the synergistic relationship between the low-carbon economy and water resources, while ensuring consistent economic growth, assumes paramount importance [1].

Severe climate change has far-reaching and significant implications for water resources, encompassing issues such as water supply and demand, water quality, the hydrological cycle, and sea-level rise [2]. Excessive rainfall can result in floods and mudslides, while prolonged drought can lead to an excessive concentration of water bodies. Pollution incidents further exacerbate water quality problems, posing serious health risks to those dependent on drinking water sources. Rising temperatures and glacier melt, driven by climate change, are gradually altering the hydrological cycle. Consequently, the contribution of snowmelt water to water resources is diminishing, and the overall hydrological dynamics are growing increasingly intricate, thereby intensifying the uncertainty surrounding water resources and jeopardizing watershed ecosystem stability [3]. Reducing greenhouse gas emissions represents a fundamental pillar of a low-carbon economy. Through targeted mitigation efforts, such as the reduction of various greenhouse gases (e.g., carbon dioxide, methane, and nitrous oxide), the adverse impacts of climate change can be directly attenuated [4]. In 2003, the concept of a low-carbon economy was introduced in the UK White Paper titled "Our Energy Future," which advocated for the reduction of natural resource consumption and environmental degradation through low energy consumption and limited pollution. Low-carbon economic development endeavors to curtail the environmental footprint of human activities, minimize energy consumption, enhance economic efficiency, and play a pivotal role in promoting ecological environmental improvement and fostering the construction of ecological civilization [5].

From the ratification of the United Nations Framework Convention on Climate Change in 1992 to the implementation of the Strictest Water Resources Management System in 2012 and the adoption of the Paris Agreement in 2015, China has consistently adhered to the development goal of resource conservation and environmental protection. The nation has integrated the synergistic management of the economy, environment, and resources, actively supported and participated in energy conservation and emission reduction strategies, and fostered high-quality development and ecological civilization. Additionally, the government has formulated a range of policies and regulations for water resource protection and utilization, including the implementation of three red lines for water resources proposed by the Ministry of Water Resources, which offer tangible guidance for unified water resource management.

There is an intrinsic link between the low-carbon economy and water resources, wherein the development of a low-carbon economy can significantly impact climate change and facilitate sustainable water resource conservation and utilization [6]. On the one hand, human activities result in significant carbon emissions, leading to elevated atmospheric concentrations of global greenhouse gases. This, in turn, causes severe environmental issues such as rising sea levels, shifts in vegetation, more frequent extreme weather events, and species extinction. The effective utilization and conservation of water resources can enhance carbon efficiency, leading to carbon reduction and neutrality. Furthermore, this approach is likely to be effective in reducing the impact of extreme weather disasters. Due to the heightened uncertainties associated with climate change, water resource vulnerability has emerged as a notable trend [7]. As the warming atmosphere increases the risk of extreme droughts in the global carbon cycle, positive anomalies in the carbon cycle, related to favorable environmental conditions, can help mitigate this risk [8]. Moving forward, it is crucial to establish institutional mechanisms for adaptive water resource management based on climate change scenarios, drawing on the analysis of water resource uncertainty in various Chinese basins [9]. By integrating water security and water resource research with social sciences, practical means and recommendations for ensuring water security and conservation, and facilitating sustainable water and human development have been developed [10]. Preserving lake ecosystems, maintaining high vegetation coverage, reducing human-induced damage to ecosystems, ensuring ecosystem stability, and developing ecosystem services are key to enhancing the carbon sink capacity of ecosystems in China [11].

On the other hand, there are direct and indirect connections between energy for a low-carbon economy and water resources. Directly, water plays a fundamental role in energy extraction and electricity production. Moreover, significant energy consumption occurs during water production, transportation, treatment, and wastewater recycling, resulting in carbon emissions throughout the entire process of interaction between these two elements. For energy development, water resources are essential for hydropower, tidal power, solar energy, and wind energy, and rational planning and management can maximize their potential [12]. Transitioning to a low-carbon economy necessitates the promotion of clean and renewable energy sources to reduce environmental pollution. Thermal and water resources hold substantial potential for emission reduction [13]. High levels of carbon emissions are positively correlated with water resources, energy consumption intensity, and energy consumption structure. Therefore, water resources should steer away from high-emission and high-consumption patterns, guiding economic and social development towards a clean, low-carbon, green, and circular direction [14]. As for water resource usage, reducing water consumption and improving water pollution treatment capacity require substantial energy inputs, urging a focus on environmentally friendly and clean energy usage [15]. Indirectly, scholars examine the interaction between energy and water resources, particularly in terms of carbon emissions, within systems such as food or land. Exploitation and interplay among the three resources of water, land, and energy give rise to significant carbon emissions [16]. The synergy and comprehensive evaluation index levels of China's inter-provincial water-energy-food subsystem are currently low but exhibit an increasing trend [17]. Future urban development should proactively optimize land use and industrial structure, promoting low-carbon and green development in industries while considering the constraints imposed by the water resources threshold [18]. Based on the principle of synergy, water-food synergy slightly surpasses energy-food synergy and water-energy synergy [19]. Heat and electricity consumption on campuses constitute the

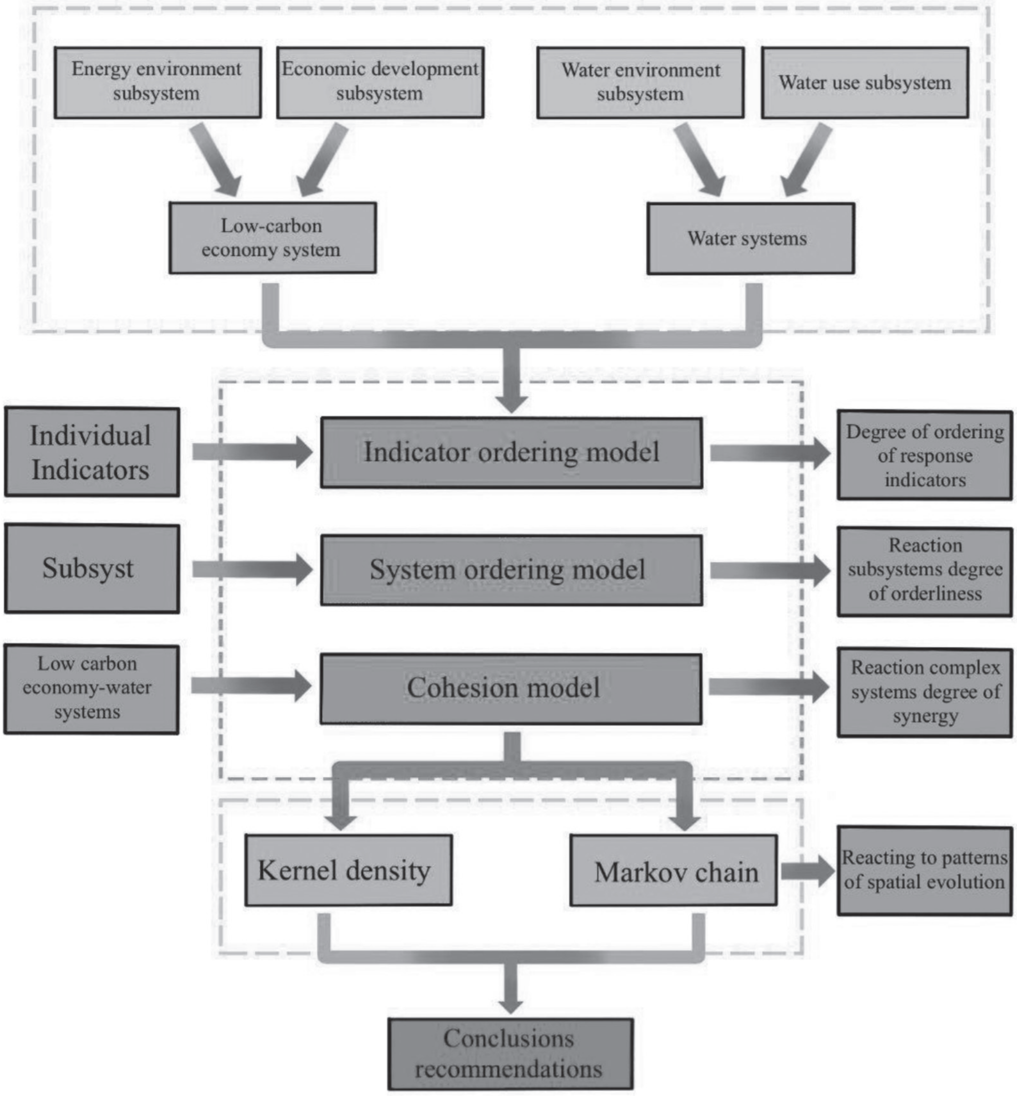


Fig. 1. Flowchart of the study on the relationship between low-carbon economy and water resources in China.

primary sources of carbon emissions, and the relationship among water, energy, and carbon varies depending on functional areas, mainly determined by the nature of buildings, energy mix, population density, and human behavior [20].

This paper aims to explore the synergistic relationship between the low-carbon economy and water resources, while analyzing its spatial and temporal trends in the context of climate change. The objective is to provide a reference for the development of low-carbon economy, as well as the protection and utilization of water resources in China. The novelty of this paper lies in several aspects. Firstly, previous literature primarily focused on studying the synergistic effect or coupling degree between water resources and energy, water resources and land, or the low-carbon economy and energy. Few studies have directly addressed the synergistic relationship between the low-carbon economy and water resources. Therefore, this paper attempts to investigate this aspect, aiming to enhance the research theory and expand the knowledge base regarding the relationship between the low-carbon economy and water resources. Secondly, by constructing a low-carbon economy-water resources composite system comprising four major subsystems (energy environment, low-carbon economy, water resources environment, and water resources use), this paper places the low-carbon economy and water resources on the same dimension. Theoretical and empirical research is conducted to analyze the synergistic effect and theoretical mechanism between these two factors. Thirdly, Kernel Density and Markov Chain Models are utilized to examine the overall distribution pattern, temporal and spatial distribution characteristics, and dynamic evolution of the synergistic effect between the low-carbon economy and water resources across 30 provinces. These analytical tools enable the revelation of the temporal and spatial dynamic evolution law of the low-carbon economy-water resources composite system's synergy (Fig. 1).

Synergistic Mechanisms between Low-Carbon Economy and Water Resources

As human socioeconomic development and the demand for water increase, the configuration of water resources in socioeconomic systems undergoes changes that alter the characteristics of carbon emissions [21]. The dynamic interplay between a low-carbon economy and sustainable water resource management, driven by energy flows, is continually evolving, and its synergistic effects warrant growing attention in the holistic response to climate change [22]. From a logical standpoint, water resources play a crucial role in the development of a low-carbon economy as they are involved in the energy production and consumption chain (e.g., thermal power and nuclear power plants require a significant amount of water for cooling purposes). Given that the components of the low-carbon economy-water resources complex system are intertwined, inseparable, interdependent, and mutually constrained, it becomes imperative to elucidate the mechanisms operating between the low-carbon economy system and the water resources system in order to investigate the synergistic effects present in their interaction.

On one side, socioeconomic development has resulted in an increase in carbon emissions, while simultaneously leading to an escalation in water consumption for various purposes, such as industry, agriculture, and domestic use [23]. For instance, in the agricultural sector, the utilization of water for crop irrigation to enhance food production may diminish river flow and the potential for hydropower generation, thereby affecting the progress of a low-carbon economy. In the industrial sector, substantial amounts of

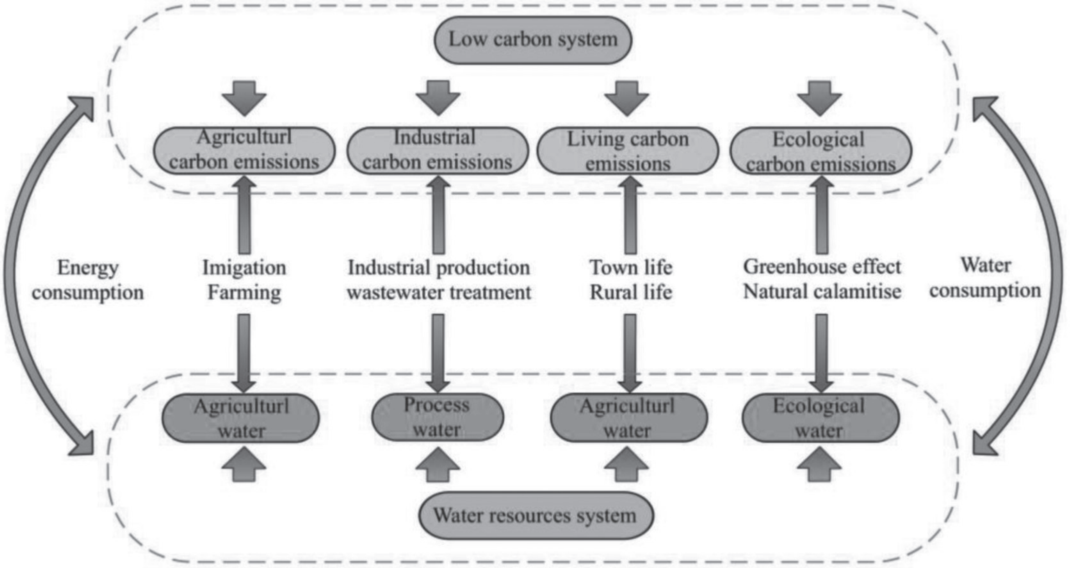


Fig. 2. Low-carbon system- water system cycle diagram.

energy are consumed for the deep treatment of industrial wastewater during discharge, consequently generating carbon emissions. Additionally, in the realm of urban life, the implementation of the "14th Five-Year Plan for the Implementation of New Urbanization" in July 2022 has spurred an influx of rural populations into cities and towns, leading to a substantial rise in water demand and consequent carbon dioxide emissions.

Another aspect to consider is the continuous encroachment upon ecological water, resulting in the inability to meet ecological water requirements in a timely manner. This situation leads to ecosystem degradation and an increase in net carbon emissions [24]. For example, the eutrophication of water bodies can disrupt the distribution of ecosystem species, leading to the excessive growth of a single species and the subsequent collapse of the ecosystem [25]. Consequently, the ecosystem fails to realize its full potential as a natural carbon sink, including forests, grasslands, croplands, and soils, and is unable to effectively contribute to water conservation in promoting a low-carbon economy [26]. Furthermore, soil erosion contributes to the loss and destruction of the soil cultivation layer, depletes land fertility, accelerates the process of desertification, and diminishes natural forest resources [27]. In the absence of vegetation protection, the ecological environment suffers further damage and adverse impacts, while inefficient water use leads to additional carbon emissions [28] (Fig. 2).

Research Methods and Data Sources

Synergetic Model

Based on the method of Wu Caixia, this paper uses the synergy model to measure the synergy effect of low-carbon economy and water resources complex system and defines low-carbon economy system as W_1 and water resources system as W_2, which interact to form a complex system W (wu,2021). A composite system $W = (W_1, W_2)$ is defined and the parameters of the system are set as $F_{ji} = (F_{j1}, F_{j2}, F_{j3}, \ldots, F_{jn})$, where n is the number of indexes affecting the operation of the system, $n \geq 1$; $\theta_{ji} \leq F_{ji} \leq \varphi_{ji}$ $(i = 1,2,3,\cdots\cdots,n)$, θ_{ji} and φ_{ji} are the upper limit and lower limit of order parameters to ensure the stable operation F_{ji} of the system, that is, φ_{ji} is the maximum value of all data in the corresponding indexes during the study period and θ_{ji} is the minimum value of all data in the corresponding indexes. Assuming F_{j1}, F_{j2}, ..., the larger the value of F_{j1}, the higher the order degree of the system, otherwise the lower the order degree of the system; Assuming the larger the F_{j1+1}, ..., F_{jn} the lower the order degree of the system, and the higher the order degree of the system.

Index Order Model

The degree of order reflects the degree of order of the system. When $i \in (1, k)$, F_{ji} is positive index; When $i \in (k+1, n)$, F_{ji} is negative index. In this paper, the following equation is adopted to calculate the degree of order:

$$\phi_j(F_{ji}) = \begin{cases} \dfrac{F_{ji} - \theta_{ji}}{\varphi_{ji} - \theta_{ji}}, i \in (1, k) \\ \dfrac{\varphi_{ji} - F_{ji}}{\varphi_{ji} - \theta_{ji}}, i \in (k+1, n) \end{cases} \tag{1}$$

From equation (1), the order degree of each index of each subsystem in different time periods can be obtained. The value of order degree satisfies, and its value is positively correlated with the order degree of the system. $\phi_j(F_{ji}) \in [0,1]$.

System Order Model

After obtaining the order degree values of each index in different periods, the order degree values of each subsystem index are integrated by the geometric average method, thus obtaining the order degree measurement index of the subsystem. The equation is defined as follows:

$$\phi_j(F_j) = \sqrt[n]{\prod_{i=1}^{n} \phi_j\left(F_{ji}\right)} \tag{2}$$

Synergy Model of the System

Considering that the stability of the composite system will not only be affected by the interaction between the systems, but also by the interaction between various indexes within the system, this paper obtains the synergy degree cw of the composite system of low-carbon economy and water resources by geometric average method. Assuming that the change value of order degree of subsystem at the initial time t_0, the change value of order degree of subsystem is $\phi_j^0(F_j)$, (j=1,2,3, · · · · · , k), At time t_1, the order degree of the subsystem is $\phi_j^1(F_j)$ and $(j = 1,2,3,\cdots\cdots,k)$, and the synergy degree of the low-carbon economy and water resources complex system is obtained, then the coefficient η is used to reflect the action direction of the subsystem to the synergy degree of the complex system. The calculation equation is as follows:

$$cw = \eta \sqrt[n]{\left| \prod_{j=1}^{n} \left[\phi_j^1(F_j) - \phi_j^0(F_j)\right] \right|} \tag{3}$$

Among them $\eta = \min\left[\phi_j^1(F_j) - \phi_j^0(F_j)\right] / \left|\min\left[\phi_j^1(F_j) - \phi_j^0(F_j)\right]\right|$, the value of synergy degree is based on the change value of order degree of each subsystem. The synergy degree of the composite system is obtained by calculating the geometric mean value of the order degree of each subsystem. The value range is [–1,1], and the larger the value, the higher the synergy degree of the system, and vice versa (Table 1).

Table 1. Division table of cooperation level of composite system

Synergy degree	**Synergy level**
$\in [-1, -0.66)$	High dyssynergy
$\in [-0.66, -0.33)$	Moderate dyssynergy
$\in [-0.33, 0)$	Mild dyssynergy
$\in [0, 0.33)$	Low-level synergy
$\in [0.33, 0.66)$	Middle-level synergy
$\in [0.66, 1)$	High-level synergy

Kernel Density Estimation

Kernel density estimation is a very important nonparametric estimation program, which estimates the probability density function of random variables from data samples and produces a continuous density curve representing the distribution pattern of random variables, which reflects the position, shape, and distribution characteristics of variable distribution. The kernel density estimation method has been widely used in spatial disequilibrium analysis. In this paper, the Gaussian kernel function is selected to estimate the distribution of compound synergy level between the low-carbon economic system and water resources system, as shown in Equations (4) and (5):

$$f(x) = \frac{1}{n\hbar}\sum_{i=1}^{n} K\left(\frac{D_i - d}{\hbar}\right) \tag{4}$$

$$K(d) = \frac{1}{\sqrt{2\pi}} exp\left(-\frac{d^2}{2}\right) \tag{5}$$

Markov Chain Analysis

Markov chain is a sequence of random variables presenting different states in a given state space. Any Markov modeling process must satisfy that the probability distribution of the next state only depends on the current state and has nothing to do with the previous state, that is, the whole system is “amnesia”.

Traditional Markov Chain

The traditional Markov chain in the application process needs to discretize the synergy index of low-carbon economy-water resources composite system into k types and approximate the whole process of synergy evolution of low-carbon economy-water resources composite system by calculating the transition probability distribution of each type. The matrix elements are calculated as follows:

$$P_{ij}^{t,t+d} = \frac{\sum_{t=2010}^{2019-d} n_{ij}^{t,t+d}}{\sum_{t=2010}^{2019-d} n_i^t} \tag{6}$$

In Equation (6), $n_{ij}^{t,t+d}$ indicates the number of areas belonging to the i type in the t year transferred to the j type in the $t+d$ year, and n_{ti} indicates the number of areas belonging to the i type in the t year. For specific i and d, there is $\sum_j P_{ij}^{t,t+d} = 1$. If the compound synergy degree of a low-carbon economy and water resources remains unchanged after years, it shows that the state is stable; If the type of level becomes higher after t years, it is considered that upward transfer occurs, otherwise it is downward transfer.

Spatial Markov Chain

The traditional Markov chain can only capture the surface information of data, but cannot more accurately reveal the substantive characteristics of spatial clusters within the region and their changes with time. To better understand this phenomenon, this paper adds a spatial Markov chain to study the spatial and temporal evolution law of the synergistic effect of low-carbon economy-water resources complex system and its spatial convergence effect. Assuming that the state of random variable X is i at time t and X is arbitrary at time $t+1$, X is only related to the state at time t, and has nothing to do with the states at other times.

$$\begin{gathered} P(X_{t+1} = j | X_t = i, X_{t-1} = i_{k-1}, \cdots, X_0 = i_0) = \\ P(X_{t+1} = j | X_t = i) = P(X_1 = j | X_0 = i), i_0, i_{k-1}, i, j \in I \end{gathered} \tag{7}$$

Where $P_{ij} = P(X_1 = j | X_0 = i)(i, j \in I)$ presents the probability of the state transition from $\{X_t\}$ to j at the next time when the current state is i. If the synergy degree of the low-carbon economy-water resources composite system is divided into n grades, a state transition matrix $n \times n$ composed of $\boldsymbol{P}$ state transition probabilities can be obtained.

$$\boldsymbol{P} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \tag{8}$$

Among them, any element P_{ij} in $\boldsymbol{P}$ represents the probability of transition from state i to state j. The spatial dynamic evolution trend of each level in the compound synergy degree of low-carbon economy and water resources is grasped by the state transition matrix, and then the state transition probability between each level is obtained by the maximum likelihood estimation method, which is expressed as equation (9).

$$P_{ij} = \frac{n_{ij}}{n_i} \tag{9}$$

Among them, n_{ij} is the number of times that the i state changes to the j state during the sample study period, and n_{ij} is the total number of times that the first state appears.

Selection of Indicators

This paper constructs data related to the low-carbon economic system and water resources system for 30 provinces in China from 2004 to 2019, as presented in Table 2, utilizing data from the China Statistical Yearbook, China Energy Statistical Yearbook, and China Environmental Statistical Yearbook for the corresponding years. To classify China into four major regions (eastern, central, western, and northeastern), the regional classification criteria proposed by the Development Research Centre of the State Council were employed. From 2005 to 2019, the synergy values of the low-carbon economic system, water resources system, and the low-carbon economic-water resources composite system were calculated, using the 2004 data as the benchmark. Notably, the positive and negative directions of each indicator were initially determined, and subsequently, the data were substituted into equation (1) to calculate the orderliness values of each subsystem and obtain the orderliness of all assessed indicators. By integrating the orderliness values of these indicators, the orderliness values of the energy environment subsystem, low-carbon economy subsystem, water resources environment subsystem, and water resources utilization subsystem can be obtained by substituting them into equation (2). Equation (3) was then used to calculate the internal synergy of the low-carbon economy system and water resources system, thereby verifying their internal synergy. Finally, the difference between the orderliness values of each subsystem was substituted into equation (3) to determine the synergy of the low-carbon economy-water resources composite system. The final results of this paper are presented in Table 3.

Drawing upon the inherent characteristics of the low-carbon economy and the development status of water resources, the evaluation index system for the low-carbon economy and water resources was constructed in accordance with the principles governing the construction of such systems (Fig. 3). This comprehensive evaluation index system comprises three levels: sub-system, system, and composite system. The composite system, which encompassed the low-carbon economy system and water resources system, was further divided into four sub-systems: energy environment, low-carbon economy, water resources environment, and water resources utilization. Thus, the low-carbon economy-water resources composite system was established, consisting of 21 indicators as presented in Table 2.

Empirical Results

Synergism

Synergistic Calculation Results

Based on the above algorithm, the synergetic theory model was used to derive the changes in the mean values of the low-carbon economic system synergy, water resource system synergy, and composite system synergy for 30 Chinese provinces from 2005 to 2019 as shown in Table 3.

From 2005 to 2019, both China's low-carbon economy and water resources systems demonstrated positive development and exhibited a complementary relationship, ultimately achieving a state of synergy. By 2019, the low-carbon economy system, the water resources system, and their composite systems had reached synergy degrees of 0.256, 0.487, and 0.277, respectively. The water resources system displayed a progression towards a high level of synergy, while the low-carbon economy system and composite systems showed a moderate level of synergy. The above results show that from 2005 to 2019, China's water resources efficiency was improved in an orderly manner, which promoted the development of a low-carbon economy and gradually embarked on a new path of low-carbon economy-water resources development synergy. In addition, China's practical experience also shows that the various subsystems are interlinked and mutually reinforcing development relationships, and the

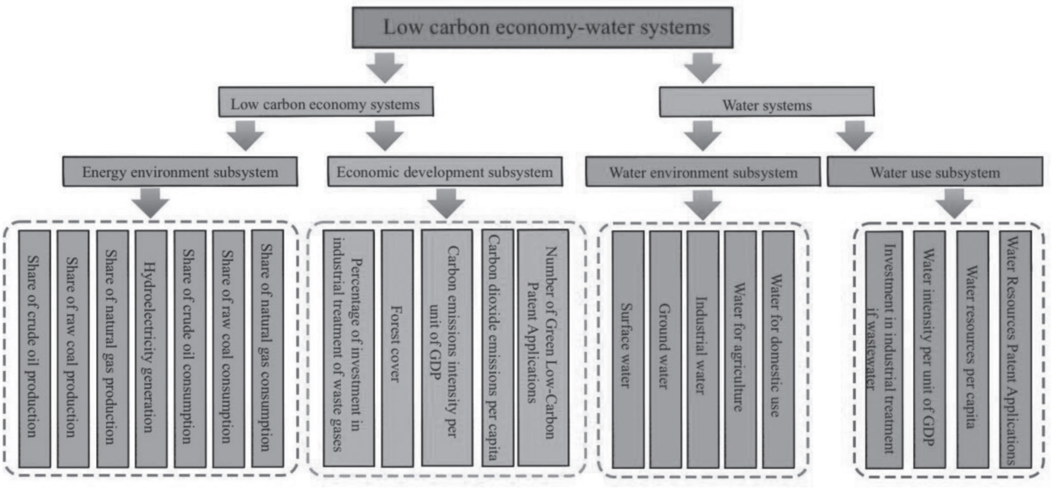


Fig. 3. Low-carbon economy- water system synergy assessment indicator system.

Table 2. Selection of indicators for the low-carbon economy- water resources system.

Systems	Subsystems	Indicators	Unit	Indicator meaning	Indicator attributes
Low carbon economy system	Energy Environment Subsystem	Share of crude oil production	%	Reflects the share of crude oil in total energy production	Negative
		Share of raw coal production	%	Reflects the share of raw coal in total energy production	Negative
		Share of natural gas production	%	Reflects the share of natural gas in total energy production	Positive
		Hydroelectricity generation	billion kWh	Reflecting clean energy capacity	Positive
		Share of crude oil consumption	%	Reflects the share of crude oil in total energy consumption	Negative
		Share of raw coal consumption	%	Reflects the proportion of total energy consumption accounted for by raw coal	Negative
		Share of natural gas consumption	%	Reflects the share of natural gas in total energy consumption	Positive
	Economic Development Subsystem	Percentage of investment in industrial treatment of waste gases	%	Reflects the level of environmental pollution	Positive
		Forest cover	%	Reflects the extent of reforestation progress in the area	Positive
		Carbon emissions intensity per unit of GDP		Reflects the relationship between the national economy and carbon emissions	Negative
		Carbon dioxide emissions per capita		Reflects the level of carbon emissions per capita in a region	Negative
		Number of Green Low Carbon Patent Applications	Pieces	Ability to respond to innovation	Positive
Water Systems	Water Environment Subsystem	Surface water	%	Reflects natural river runoff	Positive
		Groundwater	%	Reflects the quality and quantity of groundwater	Positive
		Industrial water	%	Reflects the amount of water used for production in industrial processes and for domestic use by employees within the plant	Negative
		Water for agriculture	%	Reflects irrigation of agricultural land, irrigation of fruit fields, irrigation of grassland and recharge of fish ponds	Negative
		Water for domestic use	%	Reflects the amount of water used for urban domestic use and rural domestic use	Negative
	Water Use Subsystem	Investment in industrial treatment of wastewater	%	Reflects the level of environmental pollution	Positive
		Water intensity per unit of GDP	%	Reflects the efficiency of integrated water resources use	Negative
		Water resources per capita		Reflects the harmony between population and water resources	Negative
		Water Resources Patent Applications	Pieces	Reflecting innovation capacity	Positive

synergistic development of the composite system can become a new driving force for the low-carbon economy and water resources utilization. In the new era, actively responding to climate change and building a green, low-carbon, and recycling-focused development system will be conducive to achieving synergy and win-win results among multiple systems [29].

From a single system perspective, the low-carbon economic system and the composite system exhibited a light level of synergy from 2005 to 2019. However, since 2011, the level of synergy has consistently increased. This trend suggests that the implementation of various policy measures, including energy conservation and emission reduction initiatives in China, has yielded substantial results and has accelerated the economic and social transformation towards high-quality and low-carbon development. On the other hand, the water resources system demonstrated a light level of synergy

Table 3. Synergy of low-carbon economic systems, water resources systems and their composite systems in China, 2005-2019.

year	Low-carbon economy system synergies	Degree of synergy in water systems	Complex system synergy
2004	——	——	——
2005	0.006	0.018	0.003
2006	0.034	0.080	0.025
2007	0.050	0.094	0.045
2008	0.065	0.120	0.068
2009	0.099	0.163	0.106
2010	0.093	0.158	0.100
2011	0.061	0.216	0.064
2012	0.097	0.223	0.121
2013	0.153	0.282	0.190
2014	0.189	0.335	0.236
2015	0.216	0.386	0.273
2016	0.196	0.377	0.253
2017	0.209	0.463	0.283
2018	0.255	0.451	0.273
2019	0.256	0.487	0.277

from 2005 to 2013. However, from 2014 onwards, it has progressed to a medium level of synergy and has continued to improve annually. In recent years, China has continuously increased the protection of water resources. Guaranteeing the sustainable use of water resources has become an important element of the national strategic resource guarantee system, which has promoted the orderly development of the water resources subsystem.

Analysis of Synergistic Results

The synergy of water resources has substantially increased (Fig. 4), indicating notable progress in the protection and utilization of water resources in China. With the escalating issues of water shortages and pollution, China has shifted its focus from water supply management to water demand management, from inefficient water use to efficient water use, and from overexploitation to proactive conservation. Since the revised Water Law of the People's Republic of China took effect in October 2002, which explicitly stated the implementation of a system combining total water use control and quota management, the management of China's water resources protection and use has become progressively more stringent [30]. In January 2012, the State Council issued the Opinions on Implementing the Strictest Water Resources Management System, which established the "three red lines" comprising total water use control, water use efficiency control, and water function zone pollution limitation, along with the "four systems" of total water use control, water use efficiency control, water function zone pollution limitation, and water resources management. Subsequently, the management of water resources protection and use became more rigorous [31]. In 2015, the State Council issued the "Notice on the issuance of the Action Plan for the Prevention and Control of Water Pollution" known as the "Ten Articles of Water," which adopted robust measures to address compound pollution problems, effectively halting the deterioration of water environments and enhancing the quality of water environments in river basins and regions [32]. Over the past two decades, water resources management has undergone a transition

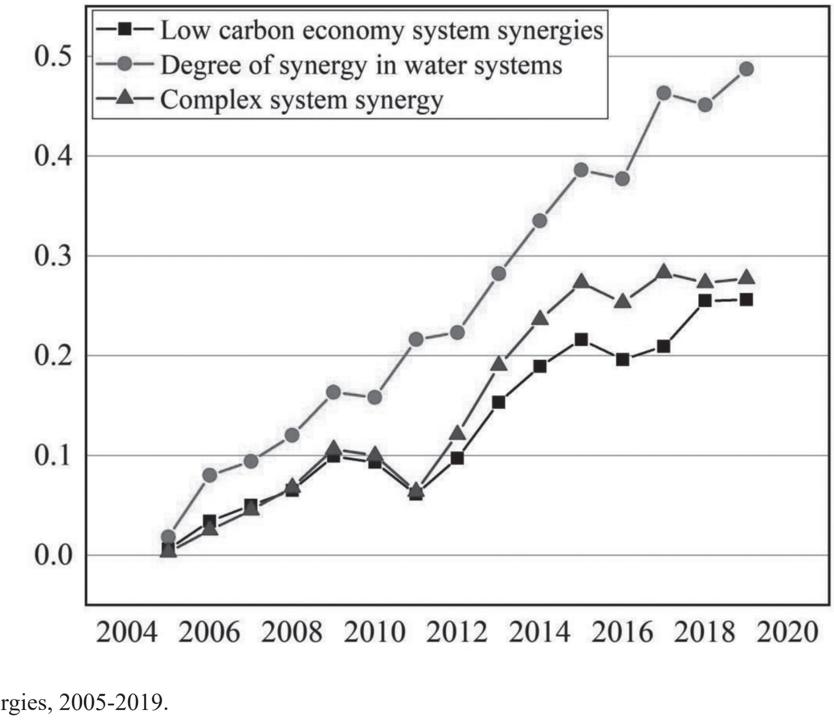


Fig. 4. Trends in synergies, 2005-2019.

from rudimentary to refined approaches, shifting from empirical to intelligent management systems [33]. This has fundamentally fostered the harmonious relationship between people and water, and facilitated high-quality economic and social development [34]. Consequently, the synergy effect within the water resources system has consistently increased year by year, reaching a moderate level of synergy at present.

The synergy of the low-carbon economy system has remained at a low level for a span of 16 years (Fig. 4), although recent trends indicate a shift towards a medium level of synergy. China has demonstrated a long-standing commitment to the development of a low-carbon economy [35]. This commitment is exemplified by the inclusion of low-carbon economic development in the 14th Five-Year Plan and the discussion during the 75th General Debate of the United Nations General Assembly [36]. The plan emphasizes the adherence to the notion of "green water and green mountains are golden mountains" and advocates for clean, low-carbon, safe, and efficient energy utilization [37]. Aligned with national conditions and driven by a sense of responsibility as a major global player, China has set ambitious goals, aiming to reach the peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. As part of these efforts, the "Carbon Neutral Energy System" was launched in October 2021 [38]. Additionally, the "Opinions on the Complete and Accurate Implementation of the New Development Concept for Carbon Neutrality" was issued, which calls for a comprehensive review and revision of existing laws and regulations incompatible with the dual-carbon goal, enhanced coordination between legislation, and improved relevance and effectiveness of relevant policies [39]. Moreover, China has made unprecedented strides in promoting ecological civilization by implementing various strategies, measures, and actions to address climate change, actively participating in global climate governance, and achieving notable progress in the development of a low-carbon economy in recent years [40].

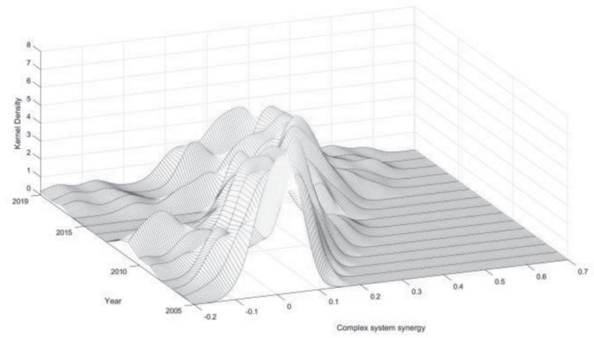
The synergy between the low-carbon economy and water resources exhibits a similar trend to that of the low-carbon economy alone (Fig. 4), wherein it has experienced low-level synergy for 16 years and has shown an upward trajectory in recent years, moving towards medium-level synergy. The recent increase in synergies between the low-carbon economy and water resources can possibly be attributed to several factors. Firstly, hydropower, serving as a clean energy source, plays a pivotal role in promoting the optimization of the energy mix and the development of an "efficient, clean, low-carbon, and safe" energy system. Secondly, water resources are indispensable for production, and their rational utilization and effective protection contribute to the restoration and reconstruction of ecosystems, as well as the maintenance of ecosystem equilibrium, thereby facilitating carbon sequestration by ecosystems. In order to fully comprehend the complex interconnections between the low-carbon economy and water resources, it is imperative to undertake a scientific and systematic exploration, taking into account their interrelationships and multiple interactions, while examining the complementarities and potential synergies between the two domains. Consequently, it becomes possible to integrate low-carbon economy and water resources planning and optimize policies to minimize inefficiencies, maximize synergistic effects, and reduce negative impacts. It shows that over the years, the country has made significant achievements in promoting low-carbon economic and social development and in promoting the conservation and intensive use of water resources, which is one of the major reasons why the 18th World Water Conference was chosen to be held in China [41]. China will also work with the international community to promote the reform and development of the global low-carbon economy, and promote the construction of a new chapter of water governance for the community of human destiny [42]. Thus, fostering research on strategies for the synergistic development of water resources and the low-carbon economy assumes significant policy implications for designing pathways to advance low-carbon economic development in China under the present circumstances [43].

Kernel Density Estimation

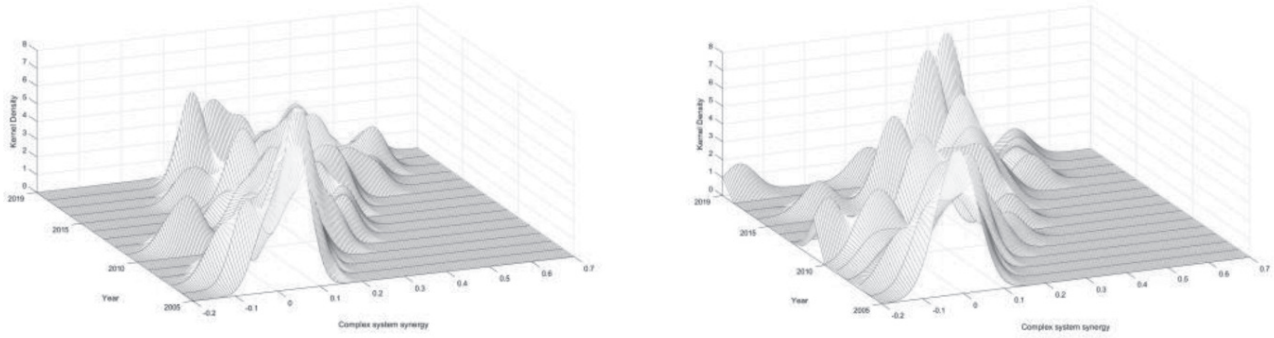
This paper uses Matlab2023A software to estimate the kernel density of the synergy of the low-carbon economy-water resources complex system and to portray the overall shape of its distribution and the dynamic evolution pattern.

Fig. 5 (a) illustrates the dynamic evolutionary characteristics of the average low-carbon economy-water resources composite system synergy level distribution in the 30 provinces of China from 2005 to 2019. In terms of the spatial distribution, the wave peak of the low-carbon economy-water resources composite system synergy level has steadily shifted towards the right, indicating an increasing level of composite system synergy. Furthermore, the height of the wave peak has decreased while the width has widened, suggesting a decrease in concentration and a broader distribution of the synergy levels. This distribution trend is reflected in the kernel density curve, which exhibits a pronounced right-skewed pattern, indicating the existence of provinces with a high level of composite system synergy. Additionally, there is evidence of polarization in the distribution curve of the composite system synergy levels, characterized by a prominent main peak accompanied by several smaller peaks. This suggests the presence of multi-level differentiation in the synergy levels.

The analysis of the images reveals a notable similarity in nucleus densities among the eastern, central, and western regions. Concerning distribution patterns, all four regions display distribution curves featuring multiple small side peaks, indicating a trend of multi-level differentiation. The effect of multi-level differentiation leads to the concentration of synergistic elements of the composite system at several central points. Regarding distribution

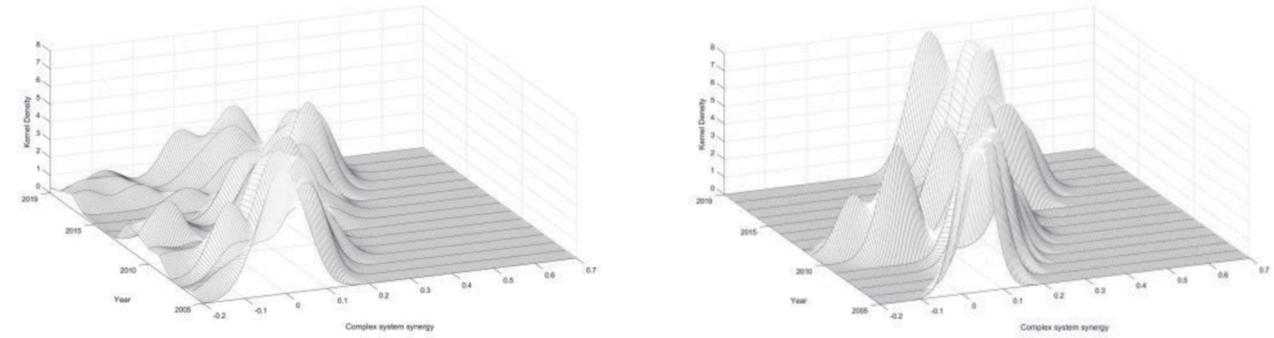


(a) National



(b) Eastern Region

(c) Central Region



(d) Western Region

(e) Northeast China

Fig. 5. Estimated kernel density of synergies for the low-carbon economy-water resources complex system in China.

Table 4. Characteristics of the dynamic evolution of the distribution of composite synergies

Region	Distribution position	Distribution pattern	Distribution ductility	Polarization trends
National	Right shift	Main peak shortens, width increases	Right trailing, extended and broadened	Multipolar trends
East	Right shift	Main peak shortens, width increases	Right trailing, extended and broadened	Multipolar trends
Central	Right shift	Main peak shortens, width increases	Right trailing, extended and broadened	Multipolar trends
West	Right shift	Main peak shortens, width increases	Right trailing, extended and broadened	Multipolar trends
Northeast	Right shift	Main peak shortens, width increases	Right trailing, extended and broadened	Multipolar trends

Table 5. Traditional Markov chain transfer probability matrix.

t/(t+1)	Low level	Lower level	Higher level	High level	n
Low level	0.615	0.303	0.083	0.000	109
Lower level	0.110	0.486	0.349	0.055	109
Higher level	0.039	0.184	0.476	0.301	103
High level	0.020	0.051	0.172	0.758	99

positions, the main peaks in the eastern, central, western, and northeastern regions consistently shift towards the right. Furthermore, the peak patterns of the synergistic levels in the composite system in the eastern, western, and northeastern regions have transitioned from a "sharp and narrow" shape to a "flat and broad" shape in terms of peak height and width. This change signifies a decrease in peak height and an increase in peak width, suggesting a substantial increase in the absolute difference in the synoptic level of the composite system. In contrast, the central region exhibits a peak height trend of "rising-declining-rising," with an overall increase in wave height and widening width. This indicates regional variations in the synergistic effect of the composite system, yet the absolute differences are diminishing. This trend is likely attributed to increased financial, political, and technical support from the government to the central provinces, leading to significant advancements in the development of both the low-carbon economy and water resources system in the central region, thereby narrowing the internal gap between the two [44].

Markov Chain Analysis

Traditional Markov Chain Analysis

In this paper, the synergy of the low-carbon economy-water resources complex system is classified into four levels: low level, lower level, higher level and high level, and the Markov transfer probability matrix is obtained using MATLAB2023a software (Table 5).

In Table 5, firstly, the diagonal elements are always larger than the non-diagonal elements, where the probability of provinces at low, lower, higher, and high levels maintaining their original levels after one year is 61.5%, 48.6%, 47.6%, and 75.8% respectively, indicating different levels of synergy in the low-carbon economy-water resources complex system. This, in turn, indicates that the different levels of synergy in the low-carbon economy-water resources complex are stable and there is a "club convergence" phenomenon, i.e., there is a certain path dependency in the low-carbon economy-water resources complex. In addition, the elements at the back end of the diagonal are larger than the front end, indicating that the clubbing phenomenon is more evident at higher levels and convergence. Secondly, the shift in rank occurs between types, suggesting a 'jump' in synergy in the complex system. Thirdly, the probability of moving up one level after one year is 30.3%, 34.9%, and 30.1% for low, lower, and higher levels respectively; 8.3% and 5.1% for moving up two levels after one year for low and lower levels respectively; 11%, 18.4% and 17.2% for moving down one level after one year for lower, higher, and high levels respectively; and 17.2% for moving down one level after one year for higher and high levels respectively. The probability of moving down two levels after one year is 3.9% and 5.1% for higher and high levels respectively, and 2% for higher levels after one year.

Table 6. Spatial Markov chain transfer probability matrix

Spatial lag	t/t+1	Low level	Lower level	Higher level	High level	n
Low level	Low level	0.574	0.407	0.019	0.000	54
	Lower level	0.075	0.600	0.300	0.025	40
	Higher level	0.050	0.350	0.400	0.200	20
	High level	0.000	0.000	0.500	0.500	2
Lower level	Low level	0.600	0.257	0.143	0.000	35
	Lower level	0.149	0.511	0.319	0.021	47
	Higher level	0.033	0.233	0.567	0.167	30
	High level	0.000	0.000	0.333	0.667	6
Higher level	Low level	0.714	0.143	0.143	0.000	14
	Lower level	0.111	0.278	0.556	0.056	18
	Higher level	0.000	0.056	0.528	0.417	36
	High level	0.000	0.079	0.211	0.711	38
High level	Low level	0.833	0.000	0.167	0.000	6
	Lower level	0.000	0.000	0.250	0.750	4
	Higher level	0.118	0.176	0.294	0.412	17
	High level	0.038	0.038	0.113	0.811	53

Spatial Markov Chain Analysis

After considering the spatial factors in Table 6, it can be seen that, first, the probability of the transfer matrix under different types of spatial lags is not the same, indicating that the probability of the transfer of the synergy of the composite system of low-carbon economy and water resources in this province is not the same under the difference of the synergy of the composite system of low-carbon economy and water resources in the neighboring provinces; second, the diagonal elements of the transfer matrix are not exactly larger than the off-diagonal elements for different types of spatial lags. Second, for different types of spatial lags, the diagonal elements of the transfer probability matrix are not exactly larger than the non-diagonal elements, indicating that the probability of "class-locking" of composite system synergies decreases under consideration of the spatial effect, and it is especially obvious under the condition of "high" lags; third, the effect of the same type of lag on different classes is not the same, but the probability of transferring is not the same. Fourth, the impact of the same lag type on different levels is not the same, for example, under the condition of higher lag type, the probability of upward transfer of low level, lower level, and higher level is 0, 25%, and 41.2% respectively, showing an increasing trend, indicating that the probability of transfer is not only related to the type of lag type, but also related to the initial state of the composite system of low-carbon economy and water resources, and neighboring the high level region will be conducive to promoting the development of low and high level regions, which will help to promote the development of low-carbon economy and water resources. It shows that the transfer probability is not only related to the type of lag, but also to the initial state of the low-carbon economy-water resources complex system, and that neighboring high-level regions will be conducive to the development of low-carbon economy-water resources complex system synergies in lower and higher-level regions [45].

Conclusions and Policy Recommendations

Based on data collected from 30 Chinese provinces (including autonomous regions and municipalities) between 2004 and 2019, this study employs a synergy model to assess the synergy among the low-carbon economy, water resources, and the combined synergy of the low-carbon economy and water resources. The analysis utilizes the Kernel density estimation method and the Markov chain to investigate spatial and temporal patterns of evolution in China and its four regions. The findings indicate the following:

1. Between 2005 and 2019, the synergy effect of China's low-carbon economy-water resources complex system exhibited a moderate level of synergy. Since 2011, the degree of synergy has steadily increased, with the synergy degrees of the low-carbon economy system, water resources system, and their complex systems reaching 0.256, 0.487, and 0.277, respectively, by 2019.

2. The absolute difference in the level of synergy between the low-carbon economy and water resources complex systems in the eastern, western, and northeastern regions demonstrates a significant expansion. However, in the central region, regional differences in the synergy effect exist, although the absolute difference shows a narrowing trend.

3. The ranking status of the synergy in the low-carbon economy-water resources composite system is relatively stable, displaying the phenomenon of "club convergence." Nonetheless, when spatial effects are considered, the probability of "rank locking" decreases in the low-carbon economy-water resources composite system.

To summarize, the recommendations based on the conclusions are as follows:

1. Policy formulation should consider the coordinated development between the low-carbon economy and water resources, employing a cross-system integrated assessment paradigm; 2. Provinces and cities should prioritize their unique circumstances and undertake technological transformations and upgrades of energy and water-intensive industries. They should also focus on promoting efficient water-saving irrigation, limiting high water consumption energy projects, developing new energy projects with low water consumption, and stimulating the utilization of wastewater for energy production; 3. Future research should consider new data and directions to enhance our understanding of the synergistic effects between the low-carbon economy and water resources; 4. Further research should explore the theory of the low-carbon economy, analyze the concepts, principles, and practical experiences, and establish a more solid theoretical foundation for subsequent studies.

By implementing these recommendations, policymakers and researchers can work towards achieving a more sustainable and synergistic relationship between the low-carbon economy and water resources, leading to long-term environmental and economic benefits.

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