Coordination and order risk assessment of water and land resource system based on periphery and synergetics theories

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Abstract: Coordinated and orderly water and land resource system is vital to ensure the economic and social development of a region. Grain production in Heilongjiang Province has increased consecutively every year since 2003, and numerous water and land resource-related problems have become increasingly prominent and have had significant adverse effects on social and economic development and stability in the region. In this study, Heilongjiang Province and its 13 prefecture-level cities were selected as the study area, and the degrees of coordination of the social, economic and ecological subsystems were evaluated using periphery theory and the theory of synergetics. To ensure that the assessment was objective and accurate, weights were calculated using the projection pursuit technique, and similarity degrees were calculated using a modified (by introducing the chi-square distance) order of preference by similarity to ideal solution (TOPSIS) technique. Moreover, to reflect the variations in the overall degree of coordination in Heilongjiang Province, the risk level of the coordination of the water and land resource system was predicted through the year 2020 using a dynamic neural network. This study provides a reference for establishing effective and balanced coordination between society and water and land resources.

Keywords: water and land resources, periphery theory, coordination, particle swarm optimization, neural network
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1 Introduction

Water and land resources support social and economic development and are the basic components of ecological environments. Moreover, they constitute a large, complex dynamic system containing numerous complex and uncertain factors[1]. Restricted by such factors like the regional economy and human and ecological activities, combinations of water and land resources vary on a regional scale, leading to various levels and types of risk.

The purpose of assessing the risk in a water and land resource system is to formulate effective risk aversion techniques and measures by quantifying the known and unknown risks in the system being assessed to allow the water and land resource system to develop sustainably[2]. Risk assessments of water and land resource systems have received attention from researchers around the globe, and fruitful results have been achieved in various areas, such as the climatological and ecological benefits of water and land resources[3,4] and managing risks related to the quantity of water and land resources[5,6].

The theory of synergetics is applicable to analyze the relationships between the elements of a dissipative system as well as the overall evolutionary state of a system and can reflect cyclic trends and processes that control interactions between the subsystems of a system[7]. However, the theory of synergetics ignores the role of the periphery of a system when describing the generation and development of systemic risk, resulting in a lack of restrictions on the exchange (of matter, energy and information) between the system and the environment. In reality, a system can be formed only when its periphery controls the import of sufficient amounts of matter and energy. By contrast, periphery theory can be used to describe exchanges between the periphery of the system and the environment and protective activities. Therefore, periphery theory complements the theory of synergetics. Periphery theory supplements the theory of synergetics with a theoretical basis for finding solutions and, in contrast, the theory of synergetics quantifies the solution-finding process of periphery theory. Both the theory of synergetics and periphery theory have been extensively used in earthquake preparedness[8]. Moreover, the combination of these two theories provides a new approach for research in system risk assessment[9].

Periphery theory has been previously applied in risk assessments related to water resources. For example, it has been used to assess the risk of a multidimensional regulation and control plan for water resources[10] and a sustainable water resource development plan[11]. In comparison, the theory of synergetics has rarely been used in risk assessment. In this study, periphery theory is integrated with the theory of synergetics to address this research gap. The existing problems facing water and land resource systems are analyzed from a coordinated risk perspective based on periphery theory. Weights are calculated using a particle swarm optimization (PSO)-based projection pursuit algorithm. Additionally, the degree of order in a system is calculated by introducing the chi-square distance. Order parameters are predicted using a dynamic neural network time series over five years. This study provides a reference for the efficient

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coordinated development of water and land resource systems.

2 Research methods

2.1 Periphery theory and the theory of synergetics

The periphery theory proposed by Chinese researcher Hongxing Cao is a general system theory that addresses common laws in the peripheries of systems[12]. According to periphery theory, a system is composed of two parts named a periphery and an inside, and the exchange of matter between a system and the external environment is controlled by its periphery. Consequently, the periphery plays a pivotal role in the survival and development of the system[13]. The periphery of a system is composed of a wall and gates. The wall keeps the system relatively stable, and the gates determine the efficiency of the exchange of matter and energy[14]. During the exchange of matter and energy, a self-organizing structure with certain functions is generated between the subsystems as a result of their coordinated actions. At the macroscopic scale, this structure is orderly but varies in space and time. This self-organizing structure can be studied based on the theory of synergetics first proposed by German physicist Hermann Haken[7].

In this study, water and land resources are viewed as a large complex system composed of social, economic and ecological levels. When the system exchanges matter and energy with the external environment, the water and land resource system will undoubtedly be at risk if the periphery wall, as the medium, is unable to maintain stability. To determine whether the periphery wall of the water and the land resource system is able to maintain stability, it is necessary to evaluate the degree of coordinated order of the social, economic and ecological levels. Through this evaluation, the risk level of the water and land resource system is analyzed. Figure 1 shows the basic form of the periphery of a water and land resource system.

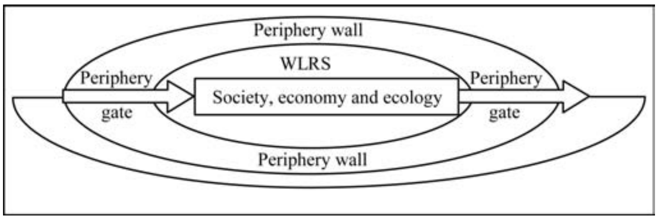

Figure 1 Schematic diagram of the periphery wall structure

2.2 Calculation of the degree of order in the system

The finitude of water and land resources and the uncertainty of human disturbances lead to a competitive relationship between society, economy, ecology and water and land resources. To determine the trend in the coordinated evolution of subsystems within the periphery of a water and land resource system, the degree of order is introduced to measure the coordination between the water and land resource system and the environment. The overall degree of order in the system is determined not only by the magnitude of the degree of order in each subsystem, but also by the way that the degrees of order in the subsystems combined[15]. To allow the degree of order to be able to accurately reflect the degree of similarity between the system's current and ideal states, a distance coordination model based on the idea of the technique for order of preference by similarity to ideal solution (TOPSIS)[16] is selected for the calculations.

2.2.1 Determination and normalization of the order parameters of the system

According to the theory of synergetics, the order parameters of a system control the direction of evolution of the system as a whole and determine the coordinated and orderly state of the system. Based on the principle that the order parameters control the evolutionary process as well as the behavior of the fast variables, order parameters that fully reflect changes in the system are selected[17]. The value of order parameter j (j = 1,…,n) of evaluation object i (i = 1,…,m) is set as x_{ij} ($x_{ij\min}$ (minimum critical threshold)< x_{ij} <$x_{ij\max}$ (maximum critical threshold)). The greater x_{ij} is, the higher the degree of order in the system is, in which case the normalized value of order parameter j of evaluation object i (x_{ij}^*) is calculated using Equation (1). Otherwise, x_{ij}^* is calculated using Equation (2). The closer to a certain value (e) x_{ij} is, the higher the degree of order in the system is, in which case x_{ij}^* is calculated using Equation (3):

$$r_{ij}^* = \frac{x_{ij} - x_{ij\min}}{x_{ij\max} - x_{ij\min}} \tag{1}$$

$$r_{ij}^* = \frac{x_{ij\max} - x_{ij}}{x_{ij\max} - x_{ij\min}} \tag{2}$$

$$r_{ij}^* = 1 - \frac{|x_{ij} - e|}{x_{ij\max} - x_{ij\min}} \tag{3}$$

2.2.2 Determination of weights and weighted decision values

In this study, the weight of each order parameter is calculated using the projection pursuit (PP) model. The idea of the PP model is to transform high-dimensional data into low-dimensional data by projecting them, and then calculate the contribution of each order parameter[18]. For the projection direction optimization problem pertaining to the PP model, a PSO algorithm is employed to provide high-dimensional global optimization[19]. The weights (w_j) determined using the PP-PSO algorithm reflects the structural characteristics of the objective data and do not contain the errors caused by interference when they are subjectively determined. Details of the solution process are available elsewhere[20,21]. The weighted decision value of each order parameter (r_{ij}) is determined based on its weight:

$$r_{ij}=w_j \times r_{ij}^* \tag{4}$$

2.2.3 Determination of the distance between each order parameter and its critical threshold

The TOPSIS method can be used to determine the quality of an evaluation object by comparing the distances between the value of each parameter and the maximum/minimum critical thresholds[22]. The chi-square distance measures the difference between a random variable and its expected value. The use of the chi-square distance ensures that the result is reliable[23]. Let $R^+=(r_{i1}^+, r_{i2}^+,\ldots, r_{in}^+)$ is set as the maximum critical thresholds and $R^-=(r_{i1}^-, r_{i2}^-,\ldots, r_{in}^-)$ is set as the minimum critical thresholds. The following equations are used to calculate the chi-square distances between a weighted decision value (r_{ij}) and its maximum (d_{ij}^+) and minimum thresholds (d_{ij}^-), respectively[24]:

$$\begin{cases} d_{ij}^+ = \dfrac{(r_{ij}-k_{ij})^2}{k_{ij}} + \dfrac{(r_{ij}^+ - k_{ij}^+)^2}{k_{ij}^+} \\ k_{ij} = \dfrac{r_{ij} \times \sum_{i=1}^{m} r_{ij}}{\sum_{j=1}^{n} r_{ij} + \sum_{j=1}^{n} r_{ij}^+} \\ k_{ij}^+ = \dfrac{r_{ij}^+ \times \sum_{i=1}^{m} r_{ij}}{\sum_{j=1}^{n} r_{ij} + \sum_{j=1}^{n} r_{ij}^+} \end{cases} \tag{5}$$

$$\begin{cases} d_{ij}^- = \dfrac{(r_{ij} - k'_{ij})^2}{k'_{ij}} + \dfrac{(r_{ij}^- - k_{ij}^-)^2}{k_{ij}^-} \\ k'_{ij} = \dfrac{r_{ij} \times \sum_{i=1}^{m} r_{ij}}{\sum_{j=1}^{n} r_{ij} + \sum_{j=1}^{n} r_{ij}^-} \\ k_{ij}^- = \dfrac{r_{ij}^- \times \sum_{i=1}^{m} r_{ij}}{\sum_{j=1}^{n} r_{ij} + \sum_{j=1}^{n} r_{ij}^-} \end{cases} \quad (6)$$

2.2.4 Calculation of the degree of order

The degree of order in a subsystem (c_{ij}) is calculated using the following equation[8]:

$$c_{ij} = \frac{d_{ij}^-}{d_{ij}^- + d_{ij}^+} \quad (7)$$

The comprehensive degree of order (c_i) is calculated using the following equation:

$$c_i = \sum_{j=1}^{n} w_j \times c_{ij} \quad (8)$$

Based on Equation (7), it is know that $0 \leq c_{ij} \leq 1$; the closer to unity c_{ij} is, the higher the degree of order is and vice versa[25]. The comprehensive degree of order reflects the level of development of the system. When $0 < c_i \leq 0.3$, the periphery has a relatively low capacity to maintain the stability of the water and land resource system, which means the system has a relatively low overall level of development and a high level of risk. When $0.3 < c_i \leq 0.5$, the periphery can maintain the development of the system. However, the degree of order in the system is relatively low and its risk level is moderate. When $0.5 < c_i \leq 0.8$, the degree of order in the system is at a good level, and the system is at a relatively high level of development and a low level of risk. When $0.8 < c_i \leq 1$, the degree of order in the system is high, an exceptional balance is reached, and coordinated development is underway inside the system. Thus, the risk in the system can be ignored[26].

2.3 Calculation of the degree of coordination in the system

The degree of coordination can be used to describe the harmonious and synchronous relationships among the subsystems. During the exchange of matter and energy across the periphery, the exchange efficiency of the periphery is affected by each subsystem. Therefore, it is necessary to determine the driving factor for this type of impact of the subsystems to calculate the ideal degree of order in the system and, eventually, determine the degree of coordination in the system.

2.3.1 Correlation

The correlation between each subsystem and the ideal value was calculated using gray relational analysis (GRA). On this basis, the main driving factor of the degree of coordination in the water and land resource system was determined. The GRA method is as follows[27].

The absolute value of the difference (Δ_{ij}) is calculated using the following equation:

$$\Delta_{ij} = \left| \frac{r_i^+ \times m}{\sum_{i=1}^{m} r_i^+} - \frac{r_{ij}^* \times m}{\sum_{i=1}^{m} r_{ij}^*} \right| \quad (9)$$

The correlation coefficient (u_{ij}) is calculated using the following equation:

$$u_{ij} = \frac{\min \Delta_{ij} + 0.5 \max \Delta_{ij}}{\Delta_{ij} + 0.5 \max \Delta_{ij}} \quad (10)$$

Finally, the correlation (u_j) is calculated using the following equation:

$$u_j = \frac{\sum_{i=1}^{m} u_{ij}}{m} \quad (11)$$

2.3.2 Comprehensive degree of coordination

The comprehensive degree of coordination (o_i) reflects the interactions between the subsystems or elements within the periphery and is calculated using the following equation[15]:

$$\begin{cases} o_i = \sqrt[m]{\prod_{j=1}^{m} o_{ij}} \\ o_{ij} = \dfrac{c_{ij}}{c_{ij} + |c_{ij} - c'_{ij}|} \\ c'_{ij} = w_j \times u_{ij} \times c_{ij} \end{cases} \quad (12)$$

where o_{ij} represents the degree of coordination in each subsystem and c'_{ij} represents the ideal degree of development of each evaluation object. The classification standard and its meaning for the comprehensive degree of coordination (o_i) are the same as those for the comprehensive degree of order (c_i).

The comprehensive degree of coordinated order (oc_i) is defined as follows:

$$oc_i = \sqrt{o_i \times c_i} \quad (13)$$

When $0 < oc_i \leq 0.25$, the degree of coordinated order of the system is relatively low, and the level of risk is high. When $0.25 < oc_i \leq 0.45$, the stability of the periphery is slightly weak. The degree of coordinated order in the system is moderate, and the level of risk is moderate. When $0.45 < oc_i \leq 0.75$, the degree of coordinated order in the system is at a good level, and the level of risk is low. When $0.75 < oc_i \leq 1$, the degree of coordinated order in the system is at a high level, and the exchange of matter and energy between the system and the environment reaches the optimal state. Thus, the risk in the system can be ignored[26].

3 Risk analysis of the coordination and order of water and land resources in Heilongjiang Province

3.1 General information on the study area

Situated at the middle latitudes of the Eurasian Continent eastern part, Heilongjiang Province is the northernmost province in China and is one of three well-known black earth regions in the world. The administrative region of Heilongjiang Province, which consists of 13 prefectural-level cities, encompasses a total area of 473,000 km^2, makes it the 6th largest province in China. Figure 2 shows the location of Heilongjiang Province. The terrain of Heilongjiang Province mainly consists of mountains, plateaus, plains and water, is generally high in the northwest, north and southeast and low in the northeast and southwest. The average annual precipitation in Heilongjiang Province is relatively low, mainly ranging at 400-650 mm, and the precipitation during the growing season (May through September) accounts for 80%-90% of the total annual precipitation[28]. Heilongjiang Province has abundant reserve land resources, 83.53% of which are farmland. The majority of the farmland soil is black earth. In recent years, the government of Heilongjiang Province has integrated cultural and ecological construction to improve the livelihoods of residents. In addition, the government of Heilongjiang Province is pursuing comprehensive supportive reform to modernize agricultural production in the two great plain areas within the province. This reform has been promoted to a major national development strategy, which has accelerated the transformation of Heilongjiang Province from a large agricultural province to a strong economic province. However, with rapid economic development, industrial water consumption in the province has continuously increased. In addition, the construction land area, which accounts for 31.7% of the total land area of the province and of which nearly 13.3% are usable land, has not been effectively utilized. Industrial and urban development in Heilongjiang Province has encroached on agricultural water and land resources. This process cannot be easily reversed, and the conflict between social and agricultural development and water and land resources is becoming more severe[28]. Therefore, risk assessments of the water and land resource system in Heilongjiang Province must be performed to determine the existing problems related to water and land resources, identify the optimal solution and improve the agricultural production efficiency and the social and economic support capacities.

3.2 Establishment of an assessment index system

A good assessment index system should reflect the characteristics of the region in question while being both hierarchical and discrete. The indices within the system should also be computable and comparable[29]. Based on this principle, the actual situation in Heilongjiang Province and relevant results obtained by other researchers[30,31], the 15 assessment indices that have the most significant impact on the exchange of matter and energy through the periphery of the water and land resource system were selected as order parameters to establish a risk assessment index system for the coordination and order of water and land resources in Heilongjiang Province (Table 1).

Figure 2 Location of Heilongjiang Province

Table 1 Risk assessment index system for the coordination and order of water and land resources in Heilongjiang Province

Rule layer	Index layer	Index type	Unit	Threshold	Weight	Correlation
A. Social subsystem	A_1 Population density	-	people/km^2	0–800	0.0737	0.67
	A_2 Registered urban unemployment rate	-	%	1.84–4.6	0.0741	0.60
	A_3 Water supply rate	-	%	0–100	0.0739	0.56
	A_4 Proportion of irrigation performed using water-saving techniques	+	%	0–100	0.0739	0.71
	A_5 Grain yield per unit area	+	kg/hm^2	500–8000	0.0413	0.44
B. Economic subsystem	B_6 Gross domestic product (GDP) per capita	+	10^4 yuan/person	0–25	0.0741	0.81
	B_7 Economic density	+	10^4 yuan/km^2	0–2000	0.0724	0.87
	B_8 Average rural disposable income	+	Yuan	0–35000	0.0023	0.55
	B_9 Percentage of GDP from the tertiary industry	+	%	0–75	0.0739	0.70
	B_{10} Water consumption per 10,000-yuan GDP	-	m^3/10^4yuan	0–1000	0.0716	0.70
C. Ecological subsystem	C_{11} Percentage of water consumed by the ecological environment	-	%	0–5	0.0741	0.60
	C_{12} Degree of coordination in the water and land resources	+	10^8/km^2	0–100	0.0737	0.65
	C_{13} Surface drainage rate	+	%	0–100	0.0737	0.72
	C_{14} Wastewater discharge per unit area	-	wt/km^2	0–40	0.0741	0.53
	C_{15} Amount of fertilizer (effective component) per unit area of agricultural land	-	kg/hm^2	0–700	0.0732	0.68

Notes: "+" signifies that the greater the index is, the greater the degree of coordinated order in the system is and the lower the risk in the system; "-" signifies that the smaller the value of the index is, the greater the degree of coordinated order in the system is and the lower the risk in the system.

3.3 Risk assessment of the coordination and order in the water and land resource system in Heilongjiang Province

3.3.1 Risk assessment of the order in the water and land resource system

Based on the values of the assessment indices for the coordinated development of water and land resources in Heilongjiang Province in 2014[28], a PSO-based PP program was created using MATLAB 2014. After the program was debugged, the parameters were set as follows: number of particles (N), 400; acceleration constants (C_1 and C_2), 1.49445; inertia weight (w), 0.9965; and maximum number of iterations (D_{max}), 50. In the MATLAB 2014 environment, the weights of the 15 indices were calculated. By running the program, the following optimal projection values (a*) were obtained: a*=(2.8376, 2.8533, 2.8450, 2.8451, 1.6331, 2.8534, 2.7875, 0.0062, 2.8462, 2.7564, 2.8542, 2.8378, 2.8376, 2.8542, 2.8378). Based on a*, the weight of each assessment index was calculated (Table 1). Figure 3 shows the optimization process of the PSO algorithm. Based on Equations (1)-(8), the degree of order in each of the social, economic and ecological subsystems of the water and land resource system and the comprehensive degree of order in the water and land resource system as a whole were obtained (Table 2).

Table 2 shows that the overall order of the water and land resource system in Heilongjiang Province was at a moderate risk level. The periphery could maintain the development of the system but that the system's stability was slightly low. Moreover, there was an imbalance between different areas in terms of the degree of order. Only the degree of order in Jiamusi was associated with a relatively low risk level due to the relatively high degree of order in its ecological subsystem. Notably, Jiamusi improved its efficiency in treating and discharging water used for ecological purposes and wastewater in recent years[32]. The degree of order in Qiqihar, Jixi, Hegang, Shuangyashan, Qitaihe and Suihua reflected a moderate risk level, and the degree of order in the economic subsystem in each of these cities was low. The degree of order in Harbin, Daqing, Yichun, Mudanjiang, Heihe and Daxing'anling was relatively high. Notably, the economy restricted the degree of order in Daxing'anling and Yichun, and social development restricted the degree of order in all the other cities.

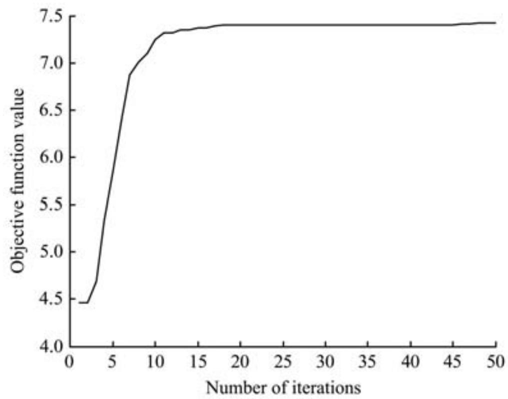

Figure 3 Optimization process of the PSO algorithm

Table 2 Degree of coordinated order of water and land resources in various regions of Heilongjiang Province in 2014

Region	Degree of order in the subsystems			Degree of order	Degree of coordination	Degree of coordinated order
	Social	Economic	Ecological			
Heilongjiang Province	0.0355	0.0365	0.2346	0.3066	0.5140	0.3970
Harbin	0.0393	0.0524	0.1631	0.2548	0.5080	0.3598
Qiqihar	0.0438	0.0341	0.3340	0.4119	0.5107	0.4586
Jixi	0.0434	0.0375	0.2729	0.3538	0.5099	0.4248
Hegang	0.0510	0.0311	0.3391	0.4212	0.5100	0.4635
Shuangyashan	0.0456	0.0341	0.2899	0.3696	0.5117	0.4349
Daqing	0.0422	0.0692	0.1790	0.2904	0.5076	0.3840
Yichun	0.0339	0.0331	0.1638	0.2308	0.5108	0.3433
Jiamusi	0.0754	0.0341	0.5053	0.6149	0.5105	0.5603
Qitaihe	0.0369	0.0339	0.2460	0.3168	0.5102	0.4020
Mudanjiang	0.0434	0.0459	0.1361	0.2255	0.5100	0.3391
Heihe	0.0422	0.0336	0.1794	0.2551	0.5081	0.3600
Suihua	0.0429	0.0343	0.2691	0.3463	0.5093	0.4199
Daxing'anling	0.0427	0.0316	0.1198	0.1940	0.5069	0.3136

3.3.2 Risk assessment of the coordination of the water and land resource system

A GRA program was created using MATLAB 2014. The program was then used to calculate the correlation between each index and its ideal value (Table 1) as well as the comprehensive degrees of coordination and coordinated order in each city in Heilongjiang Province (Table 2). In addition, the differences between the comprehensive degrees of coordinated order of the cities of Heilongjiang Province were added into the map (Figure 4).

As demonstrated in Table 2, the comprehensive risk level of water and land resources was determined based on the degree of order and the degree of coordination. In 2014, the comprehensive degrees of coordination of water and land resources in Heilongjiang Province and its 13 cities were at moderate risk levels. Water and land resources could mutually promote one another and maintain a balance. In the same period, the comprehensive degree of coordinated order in the entire water and land resource system in Heilongjiang Province was at a moderate level. Notably, the development of water and land resources in the province was relatively lacking, and the water and land resource system was at a moderate risk level. As demonstrated in Figure 4, the water and land resources in the cities in the southern and northern regions of Heilongjiang Province exhibited a relatively low comprehensive degree of coordinated order, whereas those cities in the eastern and western regions of the province displayed a relatively high comprehensive degree of coordinated order. The cause of risk associated with the water and land resource system in each city is as follows. In Jiamusi, the cause of risk was the relatively low degree of order in the water and land resource system. In Harbin, Daqing, Yichun, Mudanjiang, Heihe and Daxing'anling, the cause of risk was the relatively low degree of coordination in the water and land resource system. In Qiqihar, Jixi, Hegang, Shuangyashan, Qitaihe and Suihua, the difference between the degree of order and the degree of coordination in the water and land resource system was relatively small. However, they exhibited varying results. Consequently, water and land resources did not develop in a coordinated manner.

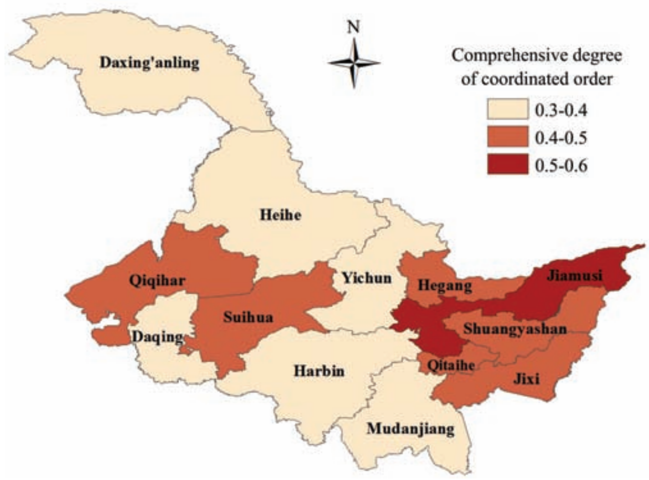

Figure 4 Spatial distribution of the comprehensive degree of coordinated order of water and land resources

3.3.3 Risk assessment of the degree of coordinated order in the water and land resource system

Heilongjiang Province exhibited rapid social and economic development from 2003 to 2014, during which there was an increase in grain production. Thus, assessing the risk level of the coordinated order in Heilongjiang Province in 2014 alone cannot fully reveal the overall trend[28]. Moreover, the calculations showed that the degree of coordination in the water and land resources in Heilongjiang Province was extremely unstable during the time period between 2011 and 2014 and could not be qualitatively analyzed. Therefore, the values of the order parameters of the water and land resource system of Heilongjiang Province in future years (through 2020) were obtained using rolling predictions based on a dynamic neural network time series. Through a long-term analysis of the risk level of the coordination and order in the water and land resource system in Heilongjiang Province between 2003 and 2020, problems in the water and land resource system were identified and solutions to these problems were formulated.

The dynamic neural network time series method has high predictive accuracy and is suitable for situations in which there is no data output[33]. In this method, the time series can comprise a small number of years, and the data can be relatively irregular. However, this prediction method requires a relatively large amount of data. The period (from 2003) during which grain production in Heilongjiang Province increased was relatively short. To avoid inaccurate predictions, the values of the order parameters were only predicted until the year 2020. The prediction program was created using MATLAB 2014, and the initial values were set as follows: number of samples (N), 12; number of learning samples (N_u), 8; and number of test samples (N_t), 4. Based on the prediction results, the level of risk in the coordination and order of the water and land resources in Heilongjiang Province between 2003 and 2020 was calculated (Figure 5).

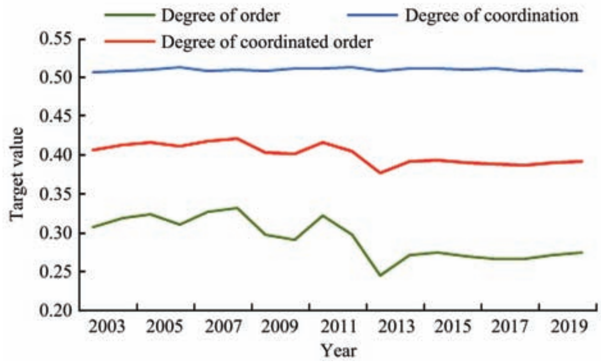

Figure 5 Degree of coordinated order of the water and land resources in Heilongjiang Province between 2003 and 2020

Figure 5 illustrates that between 2003 and 2020, the coordination and order of the water and land resources in Heilongjiang Province was at a moderate risk level and the degree of coordination of the water and land resources in the province was stable at a relatively high level. The characteristics of the degree of coordinated order in the water and land resource system in Heilongjiang Province are as follows: the degree of coordinated order fluctuated between 2003 and 2009, and on average, a cycle occurred every three years during this period. the degree of coordinated order reached its maximum in 2008,then decreased overall between 2010 and 2013, and specifically the degree of order in 2013 was less than 0.25, which resulted in an extremely high level of risk. Although the overall risk levels of the coordination and order decreased to some extent and became stable between 2014 and 2020, the degree of coordinated order in each year was lower than it was between 2003 and 2012. In the five years after 2015, the degree of coordinated order of water and land resources in Heilongjiang Province was predicted to remain at a medium to low level. This result significantly constrains development in the region. Moreover, as a result of the medium to low degree of coordinated order, the risk in the water and land resource system in Heilongjiang Province is moderate and exhibits a potential tendency to transition to a medium to low level. The large extent to which the degree of order varies is the main factor affecting the risk level of the system.

4 Discussion

The aforementioned analysis reveals relatively large differences in the risk levels of the coordinated order in the water and land resource systems of different cities in Heilongjiang Province. This result is mainly due to regressive planning concepts, unstable and independent economic growth mechanisms and unreasonable industrial structures[34]. Therefore, it is necessary to focus on industrial development and actively develop tertiary industry while maintaining the agricultural industry. In cities that have a low degree of economic order (Yichun, Heihe, Daxing'anling, Qiqihar, Jixi, Hegang, Shuangyashan, Qitaihe and Suihua), there is a need to vigorously advocate for a circular economy, regulate construction land, increase the fiscal revenue per unit area and increase the industrial water consumption efficiency. In cities that have a low degree of social order (Harbin, Daqing and Mudanjiang), the focus should be on the people-oriented, comprehensive, coordinated, sustainable development of the water and land planning and the establishment of utilization policies while actively improving water and land resource development and use. In Daxing'anling, Yichun and Heihe, where ecological resources (e.g., water and land) are relatively abundant but social and economic development lagged, it is necessary to focus on the exchange and allocation of resources while strengthening regional development, which should create balanced development in Heilongjiang Province. Moreover, according to the above assessment, the ecological level is the driving factor of the overall water and land resource system. On this basis, it is necessary to strengthen the construction and protection of ecological environmental functional zones, reduce soil erosion and fundamentally improve the ecological level.

In regard to the overall comprehensive level of Heilongjiang Province, although the risk of the coordination and order in the water and land resource system was moderate during the period in which grain production increased, the degree of coordinated order is expected to decrease to a medium to low level and did not exhibit a significant increasing trend in the eight years after 2013. Additionally, the subsystems are relatively highly coordinated. However, the degree of order of water and land resources is extremely low, which affects the overall trend of the water and land resource system. Economic development is the main restricting factor and is a potential safety risk. Table 1 suggests that the following factors have the most significant impacts on the coordinated development of the system (correlation>0.65): A_1 (the population density), A_4 (the proportion of irrigation performed using water-saving techniques), B_6 (the GDP per capita), B_7 (the economic density), B_9 (the proportion of GDP from tertiary industry), B_{10} (the water consumption per 10,000 yuan of GDP), C_{12} (the degree of coordination of water and land resources), C_{13} (the surface drainage rate) and C_{15} (the amount of fertilizer (effective component) per unit area of agricultural land). Particular consideration should be given to these factors if the degree of coordinated order of water and land resources increases. Between 2003 and 2012, on average, the economic indices B_6, B_7, B_8 and B_{10} in Heilongjiang Province increased by 13.64%, 13.70%, 14.51% and -8.27%, respectively. However, between 2013 and 2020[28], these indices increase by 2.53%, 3.44%, 7.75% and 0.22%, respectively. Therefore, each economic index is expected to develop at a slower pace. Moreover, the water supply rate is expected to decrease, and the amount of wastewater and fertilizer discharged is expected to increase annually between 2013 and 2020. Therefore, the future degree of coordinated order of the water and land resources in Heilongjiang Province is not entirely optimistic[28]. Focusing on accelerating economic development, increasing the water consumption efficiency, increasing the area irrigated using water-saving techniques, increasing the efficiency of waste-processing plants, decreasing the discharge of harmful substances (e.g., fertilizer), addressing issues relating to the employment of the urban population and constructing a new industrial structure while continuously optimizing the current development structure are effective measures for mitigating the risk in the coordination and order of the water and land resource system in Heilongjiang Province.

5 Conclusions

In this study, the current problems facing water and land resources are analyzed from social, economic and ecological perspectives based on periphery theory and the theory of synergetics. The following conclusions are derived from this study.

(1) The theory of synergetics only addresses the generation and development of a self-organizing system; it does not control the input of matter and energy into and the output of matter and energy from the system. In comparison, periphery theory supplements the theory of synergetics by including the key role of the periphery in the exchange of matter and energy. The risk assessment system for the coordination and order of water and land resources established on the basis of periphery theory and the theory of synergetics, as well as relevant research results in combination with the actual situation in Heilongjiang Province, may reflect the level of coordinated development within the system relatively well. In addition, the results obtained using the proposed risk assessment method are consistent with the actual situation in Heilongjiang Province. This study provides a reference for maintaining the balanced and orderly development of water and land resources in Heilongjiang Province. Moreover, periphery theory and the theory of synergetics provide an effective approach for analyzing the risk in water and land resource systems.

(2) A PP-PSO algorithm was employed to calculate the weights of the order parameters. The dimensionality was reduced to allow the projected indices to better match the actual application background and thereby reflect the level of importance of the variables. The TOPSIS method was used to calculate and analyze the degree of order in the water and land resources. The TOPSIS method reflects the difference between an order parameter and the ideal threshold. In addition, the chi-square distance was introduced to improve the TOPSIS method and reflect the relationship between a random variable and its expected value. The introduction of the chi-square distance helped avoid artificial interference while simultaneously considering expert experience.

(3) Based on the degree of coordination model, the influence of each order parameter on the system was calculated with GRA and used to calculate the ideal degree of development. As a result, the final assessment results were in better agreement with the actual situation. The variation in each order parameter in the period leading up to 2020 was obtained by rolling prediction using a dynamic neural network time series. Due to the relatively short time series of the data, the results were not comprehensive. In future research, long time series of data should be collected, and more suitable prediction methods should be adopted. Due to limited space, this paper only focuses on analyzing the degree of order and the comprehensive degree of coordinated order. For the degree of coordination, only the final results are provided, and no in-depth analysis is performed due to the relatively insignificant difference between the results. Therefore, the mechanism of generation of the degree of coordination should be further analyzed in future research.

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