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Analysis of Spatial and Temporal Variation in Sustainable Water Resources and Their Use Based on Improved Combination Weights

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Abstract: The sustainable use of water resources has become increasingly crucial given the present water supply and demand situation. In this study, the degree of sustainable water resource utilization in Harbin City from 2014 to 2021 was calculated using a fuzzy identification model with a combination of the "sequential relationship analysis method (G1) and coefficient of variation method (CVM)" and 18 evaluation indicators retrieved for water resources, reflecting social, economic, and ecological aspects. The study shows that (1) in terms of the research method, the combined weighting of "G1-CVM" is a feasible approach to avoid the shortcomings of single weighting and (2) in terms of the evaluation of water resources sustainable utilization, the spatial distribution of water resources in each district (county) of Harbin City has been stable over the past 8 years. The spatial distribution pattern is relatively stable, with the three regions of Binxian, Bayan, and Shuangcheng showing better sustainable water resource utilization and the three regions of Tonghe County, including the main urban area and Wuchang City, showing deteriorating sustainable water resource utilization. As a whole, the spatial distribution of sustainable water resources in the 13 districts (counties) of Harbin City from 2014 to 2021 shows a negative correlation, with the main urban area, Wuchang City, Hulan District, Bayan County, Shuangcheng District, and Yilan County showing a clustering type in the local spatial autocorrelation analysis. Based on the evaluation results, the spatial and temporal distribution characteristics of the sustainable use of water resources in Harbin are identified and found to be conducive to the timely adjustment of water resources allocation and the rational use of water resources in each district (county). Meanwhile, the research ideas and methods used in this paper can be applied to research on the sustainable use of water resources in other regions.

Keywords: sustainable utilization of water resources; fuzzy recognition model; "G1-CVM" weights; correlation analysis; Harbin City

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1. Introduction

Water is the source of life, a natural resource on which human beings depend, and the sustainable use of water resources occupies an important position in the sustainable development of regional economies. The United Nations [1] highlighted the importance of the sustainable use of resources for environmental and other forms of life conservation. Mishra Binaya Kumar et al. [2] remarked that water is essential for human beings, as the basis of life, and is extremely important for human societies and ecosystems. Nations, U. et al. [3] defined water sustainability as "the way to ensure that development meets the needs of the present without compromising the ability of future generations to meet their own needs". Weerasooriya, R. et al. [4] suggested that water is central to sustainable development and that sustainable water use is linked to all other sustainable development goals. Madias Konstantinos et al. [5] suggested that water is an essentially irreversible resource and that its sustainable management has important implications for future socio-economic and environmental aspects. Therefore, it is particularly important to analyze the sustainable use of water resources in order to provide guidance for its sustainable use and the sustainable development of society.

Research on the sustainable use of water resources has been conducted by domestic and foreign scholars using a variety of evaluation methods, and a wealth of results have been achieved. Li et al. [6] evaluated the sustainable use of water resources using the topologic evaluation method. Peng et al. [7] proposed a progressive operational scenario analysis (POSA) approach for water resource issues. Pan et al. [8] evaluated the trend of sustainable water resource use in Dongying City from 2005 to 2007 based on 21 indicators using the Driving Force-Pressure-State-Impact-Response (DPSIR) model. Fan et al. [9] used the SD model to evaluate the sustainable use of water resources in arid regions and predicted how the water resource situation in Xinjiang and its sub-regions would develop over the next 30 years. Liang et al. [10] used a three-dimensional water ecological footprint model to evaluate the sustainable use of water resources in the Wuhan metropolitan area, China, from 2010 to 2019. Liu et al. [11] assessed the sustainable use of water resources in Hunan Province, China, for the period of 2010–2019 in the context of water supply and demand. Song et al. [12] used descriptive statistics and spatial econometric models to analyze the spatial and temporal characteristics and influencing factors of water use efficiency in Chinese cities. Ouyang et al. [13] evaluated China's water resources from 2000 to 2017 based on an improved ecological footprint model of water resources and applied the system dynamics (SD) model to simulate the sustainable use control of water resources from 2018 to 2050 based on the evaluation. Tian et al. [14] developed a model for the sustainable use of water resources based on system dynamics and assessed the situation in Tianjin. Gulishengmu Anfuding et al. [15] analyzed the carrying capacity of water resources in the Manas River basin and the barrier factors based on the grey correlation method (GRA-TOPSIS) evaluation method. Based on the above analysis, it can be seen that the existing research can provide guidance for the construction of index systems for the sustainable utilization of water resources and options for evaluation methods, thus providing references for further research. However, there are certain problems and shortcomings: Firstly, most of the studies only used one method of research without combining it with other methods for comparison and analysis. Secondly, the previous studies only analyzed and compared the obtained values and did not perform a spatial trend analysis or spatial correlation analysis between neighboring regions. Thirdly, in determining the weight of evaluation indicators, most of the existing studies used objective determination methods and lacked subjective "quality".

Therefore, in this paper, we take 13 districts (counties) of Harbin City as a research case-study, select the fuzzy identification model, and use subjective (sequential relationship analysis) and objective (coefficient of variation method) methods combined with GIS and GeoDa software (V1.18.0.0) to analyze and evaluate the level of sustainable water resource use in 13 districts (counties) of Harbin City over the last 8 years, from 2014 to 2021, in terms of time, space, and autocorrelation. We use the close value method and AHP method to verify the findings. Specifically, the innovations of this study are (1) the improvement of the weighting method by adopting the combination of "G1-CVM" to solve the shortcomings in the application of the objective weighting method and (2) the validation and comparative analysis of the results obtained by the improved method by combining the close value method and the AHP method, as well as the spatial trend analysis and spatial correlation analysis among neighboring regions to improve the deficiencies of the existing studies. Our objectives include (1) verifying the applicability of the improved combined weighting method in assessing the degree of sustainable utilization of water resources, by the "G1-CVM" combined weighting method to obtain indicator weight values and comparing the close value method and AHP method with the fuzzy identification model and (2) according to the improved method, analyzing the degree of sustainable utilization of water resources and the changes in water resources of 13 districts (counties) in Harbin in the last 8 years, the spatial distribution pattern among districts (counties), and their relevance according to provide references for water resources protection as well as the sustainable utilization of water resources of the 13 districts (counties) in Harbin City.

2. Materials and Methods

2.1. Study Area

Harbin, located between 125°42′ and 130°10′ E longitude and 44°04′ and 46°40′ N latitude, is one of the central cities in Northeastern China and the city with the third-largest household population and the largest land area under jurisdiction among Chinese provincial cities. In terms of administrative subdivisions, Harbin (Figure 1) includes four districts, namely the main urban area, Acheng District, Hulan District, Shuangcheng District, as well as nine counties, namely Wuchang City, Shangzhi City, Bin County, Founder County, Yanshou County, Bayan County, Mulan County, Tonghe County, and Yilan County, of which the main urban area includes six districts, namely, =Nangang District, Daoli District, Dawai District, Xiangfang District, Songbei District, and Pingfang District.

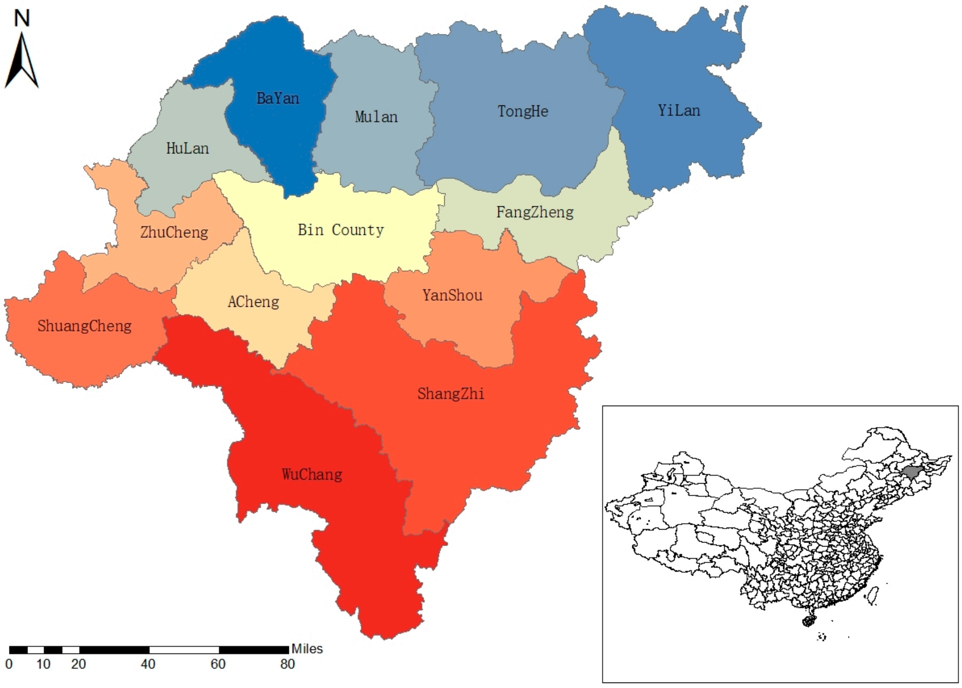


Figure 1. Location of Harbin City, China.

Harbin City has a long, cold, and dry winter, a rainy and hot summer, and a short, dry, and windy spring and autumn, reflecting a semi-humid, temperate, continental monsoon climate. In 2019, the city's annual average precipitation depth was 880.1 mm, ranking first in this regard since 1956. Its precipitation has the characteristics of an uneven spatial and temporal distribution, with rain and heat at the same time [16]. In 2019, the total water resources amounted to 25.489 billion m^3; the surface water resources amounted to 22.577 billion m^3; the annual runoff depth was 425.4 mm; the city's shallow underground water resources amounted to 6.700 billion m^3, of which 4.056 billion m^3 was in the plain area and 2.872 billion m^3 was in the hill area; and the combined groundwater resources in the hill area and the plain area amounted to 228 million m^3.

2.2. The Construction of the Evaluation Index System

The level of economic and social development directly reflects the demand for water resources, and generally speaking, the higher the level of economic development, the greater the demand for water resources, while the amount of water resources and the ecological environment situation are from different perspective constraints on the level of socio-economic development, thus affecting the sustainable use of water resources. Through a comprehensive analysis of impact indicators for water resources in Harbin City, based on the indicator system for the supply and demand analysis of national water resources [17–20] and based on the principles of strong target, wide scope of application, and operability, 18 indicators, including the water production modulus, total water resources, and underground water resources, were selected as representative indicators. For the index division criteria, based on the division criteria adopted by various scholars for other cities [21], we made appropriate adjustments in light of the socio-economic development characteristics of Harbin and divided the sustainable use of water resources into four levels: high-level sustainable use (level I), medium-level sustainable use (level II), low-level sustainable use (level III), and unsustainable use (level IV). The selected evaluation index system and its standard values for indicators at all levels are shown in Table 1.

Table 1. Evaluation Index and grade division of sustainable water resource utilization in Harbin.

Number	Evaluation Indicators	Unit	Calculation Formula	Type of Indicator	Level of Sustainable Use of Water Resources			
					Level I	Level II	Level III	Level IV
X1	Water production modulus	Million $m^3 \cdot km^{-2}$	Statistics	+	≥60	45	30	≤15
X2	Total water resources	Billion m^3	Statistics	+	≥5	20	30	≤45
X3	Groundwater resources	Billion m^3	Statistics	+	≥2	4	6	≤8
X4	Annual precipitation	Billion m^3	Statistics	+	≥15	35	55	≤75
X5	Water supply modulus	Million m^3/km^2	Water supply/Land area	−	≤6	10	25	≥35
X6	Combined water consumption per capita	m^3/per	Total water consumption/Total population	−	≤200	500	1000	≥2000
X7	Residential water consumption	Billion m^3	Statistics	−	≤0.05	0.5	1	≥2
X8	Population density	People/km^2	Statistics	−	≤150	300	500	≥800
X9	Natural population growth rate	‰	Statistics	−	≤0	3	5	≥7
X10	Urbanization rate	%	Urban population/Total population	−	≤20	40	50	≥60
X11	GDP per capita	USD	Regional GDP/Total population	+	≥1400	4200	7000	≤11,200
X12	Water consumption of USD 10,000 GDP	m^3/Million USD	Total water consumption/Regional GDP	−	≤710	2140	3570	≥5000
X13	Water consumption of USD 10,000 of industrial added value	m^3/Million	Industrial water consumption/Industrial added value	−	≤180	360	540	≥1070
X14	Water consumption for agricultural irrigation	Billion m^3	Statistics	−	≤2	5	7	≥10
X15	Water use rate for agricultural irrigation	%	Water consumption for agricultural irrigation/Total water consumption	−	≤30	50	70	≥90
X16	Industrial water rate	%	Industrial water consumption/Total water consumption	−	≤1	8	15	≥25
X17	The proportion of tertiary industry	%	Tertiary industry value/Regional GDP	+	≥35	50	60	≤75
X18	Ecological water use rate	%	Ecological water consumption/Total water consumption	+	≥0.1	1	3	≤4

Note: Evaluation indexes X1, X2, X3, X4, X7, and X14, reflecting water supply, total water consumption, industrial water consumption, agricultural irrigation water consumption, and ecological environment water consumption come from Harbin City's water resources bulletin for previous years; the data on X8, X9, land area, total population, urban population, regional GDP, industrial added value, and tertiary industry value come from Harbin City's statistical yearbook for previous years.

2.3. Methods

2.3.1. Weighting

1. Sequential relationship analysis method (G1 method)

First, we selected 15 experts from the research direction of hydrology and water resources of Heilongjiang University and the water resources of Heilongjiang Provincial Institute of Water Resources Science to carry out the assessment. In this method, the experts ranked all evaluation indicators of the evaluated object in a uniform order of importance, and then they calculated the G1 subjective weights of the evaluation indicators according to the following steps [22–24]:

① Expert ranking of importance of evaluation indicators.

② Rational assignment r_k of the ratio for the degree of importance of adjacent indicators X_{k-1} and determination of X_k by the experts:

$$r_k = \frac{X_{k-1}}{X_k} \tag{1}$$

③ Based on the rational assignment r_k determined by the experts, the G1 method weight Wm of the indicator m can be calculated as:

$$W_m = \frac{1}{1 + \sum\limits_{k=2}^{m} \prod\limits_{i=k}^{m} r_i} \tag{2}$$

④ From the weight W_m, the weights of indicator $m-1$, indicator $m-2, \ldots$, indicator 3, and indicator 2 are calculated as:

$$W_{k-1} = r_k \cdot W_k \tag{3}$$

where W_{k-1} is the G1 method weight of indicator $k-1$, r_k is the rational assignment assigned by the experts, and W_k is the G1 method weight of indicator k.

2. Coefficient of Variation Method (CVM)

The core aim of the coefficient of variation method is to obtain the corresponding weights of different indicators in the system through the mathematical calculation of each indicator and to then calculate the aggregation of the indicators' given weights [25,26]. Let W_i be the value of the given weight of indicator i. Then, the steps for calculating the variation coefficient weight W_i of the evaluation indicators are as follows:

① The value of the coefficient of variation is calculated as:

$$V_i = \frac{\sqrt{\frac{1}{n-1} \sum\limits_{i=1}^{n} (r_i - \overline{r_i})^2}}{\overline{r_i}} \tag{4}$$

where r_i is the eigenvalue of indicator i. $\overline{r}_i$ is the average of the eigenvalues of indicator i.

② The weights of each evaluation index are calculated as:

$$W_i = \frac{V_i}{\sum\limits_{i=1}^{n} V_i} \tag{5}$$

where V_i is the coefficient of variation of indicator i. W_i is the weight of indicator i:$i = 1, 2, 3, \ldots, n$.

3. Portfolio weights

In this study, the sequential relationship analysis method is combined with the coefficient of variation method, i.e., the subjective and objective methods are used in combination to determine the index weights through the comprehensive index calculation formula. The formula for calculating the composite index is as follows:

$$W_i = \frac{\sqrt{a_n b_i}}{\sum_{i=1}^{n} \sqrt{a_i b_i}} \tag{6}$$

where W_i is the combined weight of indicator i. a_i is the weight of indicator i calculated using the G1 method. b_i is the weight of indicator i calculated using the coefficient of variation method.

2.3.2. Method Introduction

1. Fuzzy recognition model

When evaluating the sustainable use of water resources under certain spatial and temporal conditions, the model is often fuzzy and complex. The main components of the fuzzy identification model [27–29] are the calculation and analysis of the relative affiliation degree, difference degree, and fuzzy variable set, and the specific process is as follows:

Step 1: Obtain the relative affiliation function of the indicator. Let n samples of water resources for sustainable use be the object to be identified; each sample constitutes a set expressed as: $X = (x_{ij})_{m \times n}$. In this formula, x_{ij} is the Dth factor of sample j, $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$. According to the criteria of the n samples for sustainable use in accordance with the level of c, we can obtain the relative affiliation of indicators for the standard identification matrix. For "increasing standard eigenvalues of indicators from level 1 to level c":

$$r_{ih} = \begin{cases} 0 & , \quad x_{ij} \le y_{ic} \\ \frac{x_{ij} - y_{ic}}{y_{i1} - y_{ic}} & , \quad y_{i1} > x_{ij} > y_{ic} \\ 1 & , \quad x_{ij} \ge y_{i1} \end{cases} \tag{7}$$

For the fuzzy concept of "sustainable use of water resources", there is a relative affiliation function of the standard characteristic value of h-level indicators to A, i.e.,

$$S_{ih} = \begin{cases} 0 & , \quad y_{ih} = y_{ic} \\ \frac{y_{ic} - y_{ih}}{y_{ic} - y_{i1}} & , \quad y_{i1} < y_{ih} < y_{ic} \\ 1 & , \quad y_{ih} = y_{i1} \end{cases} \tag{8}$$

where r_{ij}—sample j indicator i eigenvalue of A affiliation; y_{i1}, y_{ic}—level 1 indicator i, level c standard eigenvalue; s_{ih}—level h indicator i standard eigenvalue of A affiliation; and y_{ih}—level H indicator i standard eigenvalue. Similarly, we can obtain the relative affiliation function when "the standard eigenvalues of indicators from level 1 to level c decrease".

Step 2: Obtain the relative affiliation matrix of the sample set to each level. According to the fuzzy pattern recognition model, the formula for the relative affiliation of sustainable utilization system j to sustainable utilization level h is as follows:

$$u_{hi} = \begin{cases} 0 & , \quad h < a_j \text{ or } h > b_j \\ 1 / \sum\limits_{k=a_j}^{b_j} \left\{ \frac{\sum\limits_{i=1}^{m} \left[w_i (r_{ij} - s_{ih}) \right]^p}{\sum\limits_{i=1}^{m} \left[w_i (r_{ij} - s_{ik}) \right]^p} \right\} & , \quad a_j \le h \le b_j, d_{hj} \ne 0 \\ 1 & , \quad d_{hj} = 0 \end{cases} \tag{9}$$

where d_{hj}—generalized power distance between system j subsystem k and sustainable use level h. d_{hj} can be expressed as:

$$d_{hi} = \left\{ \sum_{i=1}^{m} \left[w_i \left(r_{ij} - s_{ih} \right) \right]^p \right\}^{\frac{1}{p}} \tag{10}$$

By substituting each known data point in the matrix into Equation (8), the relative affiliation vector of the sustainable use level h can be obtained, and then according to the level eigenvalue formula, we obtain:

$$H_j = (1 \quad , \quad 2 \quad , \quad \ldots \quad , \quad c) \cdot (u_{1j} \quad , \quad u_{2j} \quad , \quad \ldots \quad , \quad u_{cj})^T \tag{11}$$

where H_j, the sustainable utilization level characteristic value of subsystem k of the sustainable utilization system j, is used to evaluate and measure the degree of sustainable utilization of subsystem k, $k = 1, 2, \ldots, c$.

The application of H_j then enables the evaluation [30,31] of the degree of sustainable utilization of system j. When $H_j = 1$, system j is in advanced sustainable use. When $H_j = c$, system j is in unsustainable use. Usually, $1 < H_j < c$ and is in between "advanced sustainable use" and "unsustainable use". The following rules are used to classify the degree of sustainable use of the subsystems: $H_j \in [c - 0.5, c + 0.5]$. Then, subsystem k is classified as c, $c = 1, 2, 3, 4$.

2. Close value method

The main calculation steps of the close value method [32,33] are as follows:

Step 1: Create a matrix of metrics.

For m evaluation schemes and n evaluation indicators, let e_{ij} denote the value of the j evaluation indicator of the i evaluation scheme, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$. Then, the indicator matrix $E = (e_{i \times j})_{m \times n}$ can be established. Using Equation (12) to normalize the indicator matrix, the normalized indicator matrix $R = (r_{i \times j})_{m \times n}$ is obtained:

$$r_{ij} = \begin{cases} e_{ij} / \sqrt{\sum\limits_{i=1}^{m} e_{ij}^2} (\text{When A is a positive indicator}) \\ -e_{ij} / \sqrt{\sum\limits_{i=1}^{m} e_{ij}^2} (\text{When A is a negative indicator}) \end{cases} \tag{12}$$

Step 2: Identify virtual best and worst points.

The maximum value $r_j^+ = \max\limits_{1 \le i \le m} \{r_{ij}\}$ and minimum value $r_j^- = \min\limits_{1 \le i \le m} \{r_{ij}\}$, of each evaluation index are calculated; then, the virtual best point $F^+ = (r_1^+, r_2^+, \ldots, r_n^+)$ is formed from all the maximum value indexes and the virtual worst point $F^- = (r_1^-, r_2^-, \ldots, r_n^-)$ is formed from all the minimum value indexes.

Step 3: Calculate the distance of each evaluation scheme from the virtual best to the worst point.

We calculate the Euclidean distances D and E of the ith evaluation solution A from the virtual optimal point B to the inferior point C, respectively, as follows:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(r_{ij} - r_j^+\right)^2 w_j^2} \tag{13}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(r_{ij} - r_j^-\right)^2 w_j^2} \tag{14}$$

where w_j is the weight of an evaluation index, calculated using the above combination weight.

Step 4: Calculate the close value of each indicator C_i.

Since the "best point" and "worst point" in the evaluation index are not in the same line in the Euclidean space, the closer the evaluation index i is to the "best point" (i.e., the smaller d_i^+ is), the larger its d_i^- must be from a geometric point of view; thus, it is necessary to introduce a close value C_i to reflect the degree of an index's closeness to the "best point" and distance from the "worst point", i.e.,

$$C_i = \frac{d_i^-}{d^+ + d_i^-} \tag{15}$$

where $d^+ = \min\limits_{1 \le i \le m} \{d_i^+\}, d^- = \max\limits_{1 \le i \le m} \{d_i^-\}$.

The value of C_i ranges from 0 to 1. In general, $d^+ \neq 0$ and $d^- \neq 0$. Therefore, the larger the value of A is, the closer it is to the "best point" and furthest it is from the "worst point", indicating that the degree of sustainable use of water resources is better.

Step 5: Rank and evaluate the evaluation programs based on the magnitude of the closeness value C_i.

3. Hierarchical analysis (AHP method)

The AHP method [34,35] calculates the degree of sustainable use index E, whose expression is:

$$E = \sum_{i=1}^{m} P_i E_i \tag{16}$$

$$E_i = \sum_{j=1}^{n} \lambda_{ij} M_{ij} \tag{17}$$

where m and n are the numbers of indirect and destination indicators, respectively; E_i and p_i are the evaluation value of indirect indicator i and its weight value, respectively; and M_{ij} and λ_{ij} are the evaluation value of destination indicator j for indirect indicator i and its weight value, respectively.

4. Spatial autocorrelation model

① Global spatial autocorrelation

Global spatial autocorrelation serves to judge the degree of aggregation of elements from a macroscopic perspective, and the calculation result is expressed using the global Moran's I index, whose value ranges from $[-1, 1]$. When the global Moran's $I < 0$, there is a negative correlation in space; when the global Moran's $I > 0$, there is a positive correlation in space; and when the global Moran's $I = 0$, there is no correlation at all. Using GeoDa V1.18.0.0 [36] software, the global Moran index for the sustainable use of water resources from 2014 to 2021 was constructed, and the calculation steps are as follows:

$$I_{GM} = \frac{\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} w_{ij}(z_i - \overline{z})(z_j - \overline{z})}{S^2 \sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} w_{ij}} \tag{18}$$

where I_{LM} indicates the global spatial Moran index. z_i indicates the degree of sustainable use of water resources in different districts (counties). $\overline{z}$ is the average value of sustainable use of water resources. n =13, and w_{ij} is the spatial weight matrix. S is the variance value.

② Local space autocorrelation

Local spatial autocorrelation is used to analyze the spatial correlation between neighboring units, indicating the spatial distribution characteristics between neighboring districts (counties). If the local Moran index is positive, the spatial distribution characteristics of H-H agglomeration or L-L agglomeration are between neighboring units. If the local Moran index is negative, the spatial characteristics of H-L or L-H agglomeration are between neighboring units. The calculation formula is as follows:

$$I_{LM} = \frac{n(z_i - \bar{z}) \sum_{j=1}^{m} w_{ij}(z_j - \bar{z})}{\sum_{i=1}^{n} (z_i - \bar{z})^2} \quad (19)$$

2.4. Data Processing

In this paper, data for the study area from 2014 to 2021 were selected, mainly from the Harbin City Water Resources Bulletin [37–44] and Harbin City Statistical Yearbook [45–52].

The sequential relationship analysis method and the coefficient of variation method were used to calculate the weight values of the 18 indicators, and the fuzzy identification model, the close value method, and the AHP method were used to calculate the degree of sustainable use of water resources in each district (county). Using ArcMap 10.2 software [53,54], the sustainable use of water resources in each district (county) of Harbin was mapped according to four levels of classification: high (level I), medium (level II), low (level III), and unsustainable (level IV). The global spatial autocorrelation and local spatial autocorrelation of each district (county) in Harbin City were examined and analyzed using the spatial analysis tool in GeoDa V1.18.0.0 software.

3. Results

3.1. Analysis of the Degree of Sustainable Use of Water Resources in Time Series

The results for the sustainable utilization of water resources in each district (county) in Harbin City from 2014 to 2021 and the ranking results of the previous years are shown in Table 2. The trend first rises and subsequently falls and then tends to stabilize for Bayan County, Acheng District, Yilan County, Shangzhi City, and Founder County; the trend is a cycle of repeated falling and rising for Shuangcheng District, Yanshou County, Wuchang City, Mulan County, Tonghe County, and the main city. The trend rises and then tends to stabilize for Hulan District, while there is a declining trend for Bin County.

Table 2. Evaluation results of the degree of sustainable use of water resources in each district (county) of Harbin City from 2014 to 2021.

District (County)		Zhu Cheng	Acheng	Hulan	Shuang Cheng	Wu Chang	Shang Zhi	Binxian	Yan Shou	Bayan	Mulan	Tonghe	Yilan
Level Eigenvalue	2014	2.315	1.503	1.880	1.469	2.103	2.057	1.388	2.094	1.476	2.106	2.206	1.859
	2015	1.770	1.275	1.455	1.651	1.757	1.603	1.202	1.778	1.348	1.869	1.867	1.457
	2016	2.380	1.701	1.640	1.604	2.360	2.114	1.579	2.299	1.634	2.313	2.520	2.004
	2017	1.843	1.305	1.234	1.243	1.744	1.554	1.211	1.772	1.244	1.789	1.882	1.496
	2018	2.440	1.726	1.605	1.627	2.279	2.119	1.615	2.200	1.470	2.159	2.311	1.843
	2019	2.517	1.735	1.558	1.564	2.333	2.131	1.648	2.220	1.555	2.244	2.432	1.913
	2020	2.259	1.584	1.439	1.442	2.272	1.972	1.470	2.114	1.439	2.104	2.274	1.758
	2021	2.547	1.751	1.616	1.518	2.312	1.982	1.820	2.214	1.533	2.373	2.338	1.851
Ranking	2014	13	4	6	2	9	7	1	8	3	10	12	5
	2015	9	2	4	7	8	6	1	10	3	13	12	5
	2016	12	5	4	2	11	7	1	8	3	9	13	6
	2017	12	5	2	3	8	7	1	9	4	10	13	6
	2018	13	5	2	4	11	7	3	10	1	9	12	6
	2019	13	5	2	3	11	7	4	9	1	10	12	6
	2020	11	5	1	3	12	7	4	10	2	9	13	6
	2021	13	4	3	1	10	7	5	8	2	12	11	6

3.2. Analysis of the Degree of Sustainable Use of Water Resources with Respect to the Spatial Distribution

In terms of the sustainable use level, it can be seen from Figure 2 that the spatial distribution pattern for the degree of sustainable use of water resources in Harbin City from 2014 to 2021 is relatively stable in the six districts (counties) of Tonghe County, Founder County, Mulan County, Yanshou County, Shangzhi City, and Wuchang City and shows changes in the seven districts (counties) of Bin County, Shuangcheng District, Bayan County, Acheng District, Yilan County, Hulan District, and the main city. The degree of sustainable use of water resources in all districts (counties) of Harbin City is mostly level II for the eight years studied.

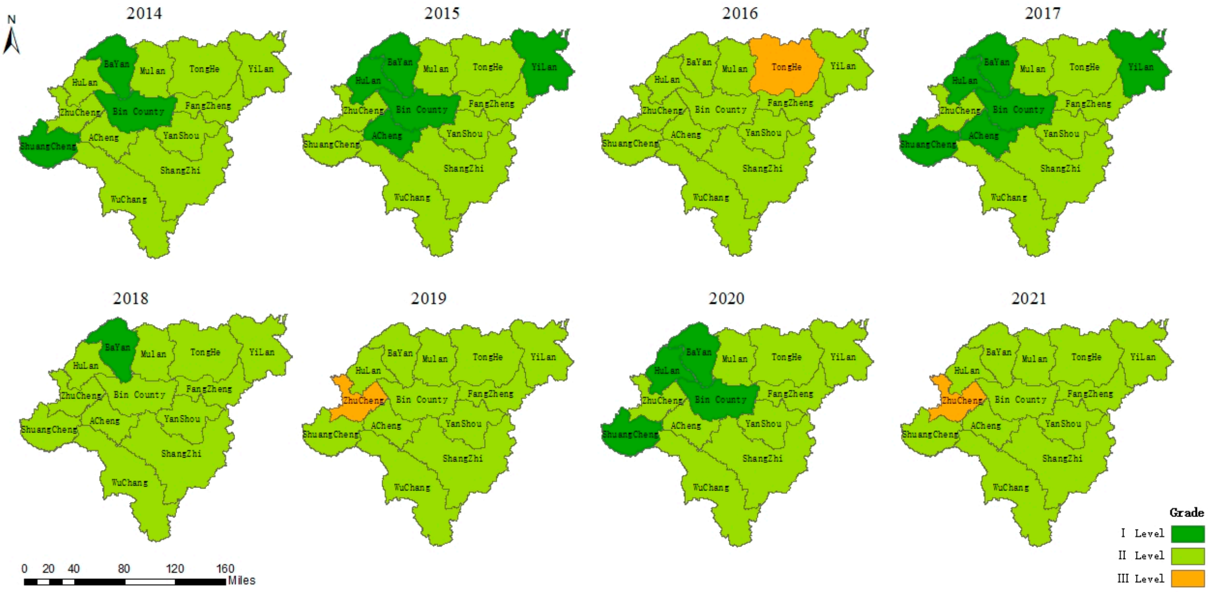


Figure 2. Spatial distribution of the degree of sustainable use of water resources in Harbin from 2014 to 2021.

3.3. Analysis of the Spatial Correlation Pattern for the Degree of Sustainable Use of Water Resources

Based on the global correlation test, the results in Figure 3 show that the Moran indexes of the degree of sustainable water resource utilization in Harbin City for 2014–2021 are −0.211, −0.159, −0.104, −0.128, −0.175, −0.200, −0.188, and −0.248, respectively. This study indicates that the spatial distribution for the degree of sustainable water resource utilization in the 13 districts (counties) of Harbin City showed a negative correlation for 2014–2021.The blue circle in the figure refers to the 13 districts (counties) of Harbin City.

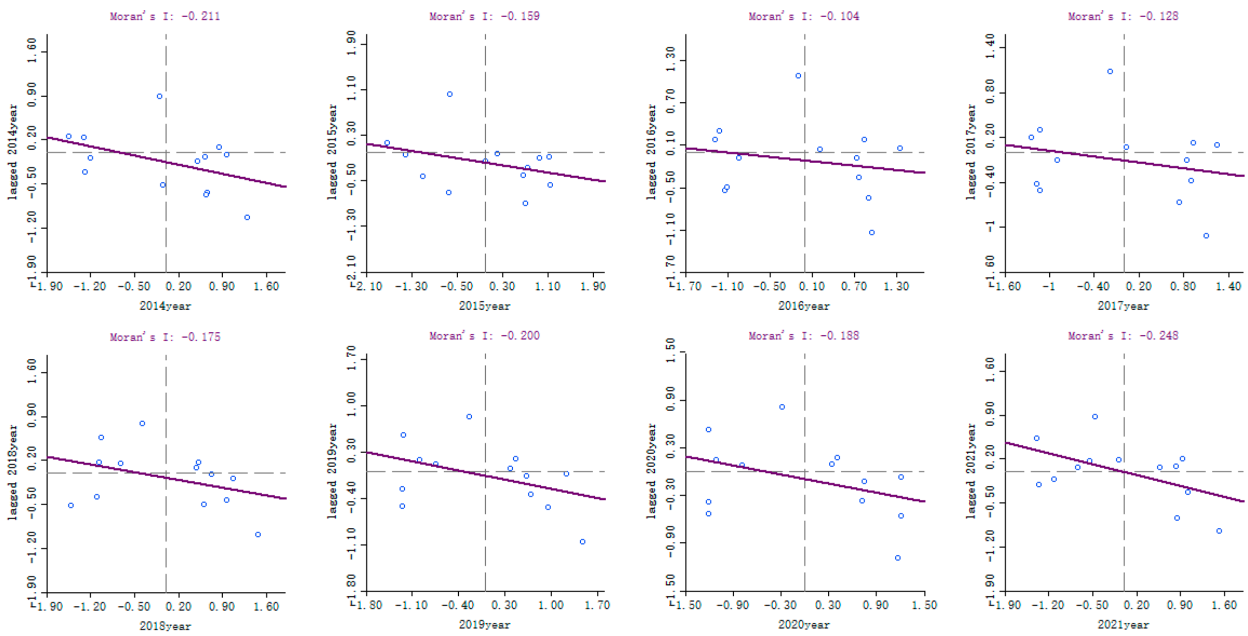


Figure 3. Scatterplot of global Moran indexes of sustainable water use in Harbin City, 2014–2021.

In the local correlation test, all of the results from 2014 to 2021 passed the significance test at the 95% confidence level, indicating that the degree of sustainable water resource use showed the aggregation of phase differences in some districts (counties). The results of their local spatial autocorrelation are shown in Figure 4. From the local spatial autocorrelation analysis, we can see that the "L-H" agglomeration of sustainable water resources utilization in Harbin City from 2014 to 2021 is mainly distributed in the main urban area and Wuchang City; the "H-H" agglomeration is mainly distributed in Hulan District and Bayan County; the "H-L" agglomeration is mainly distributed in Shuangcheng District and Yilan County; and there is no "L-L" agglomeration type.

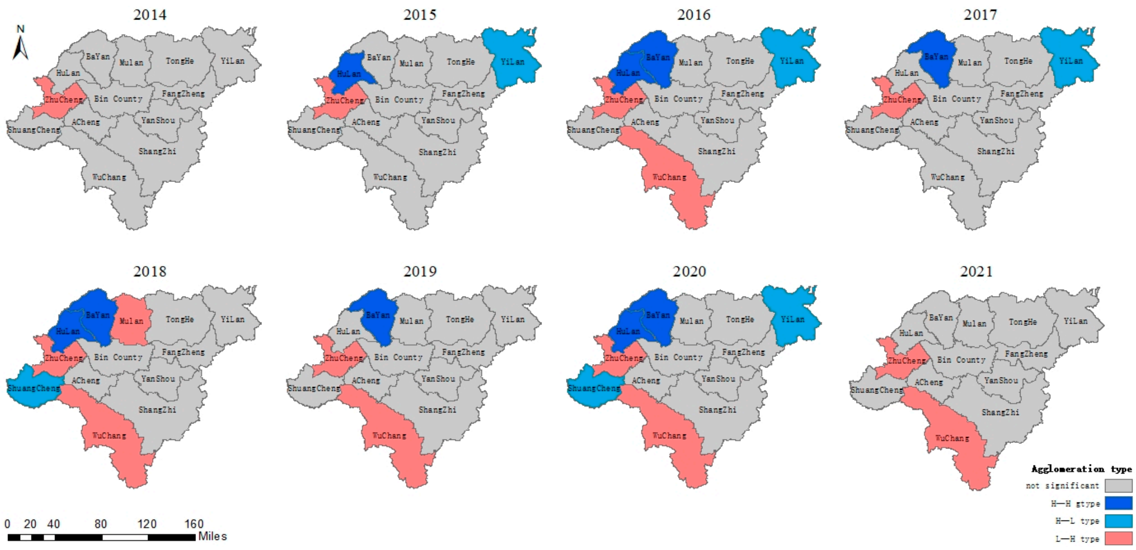


Figure 4. Local spatial autocorrelation results of the degree of sustainable water resources use in Harbin City, 2014–2021.

3.4. Method Feasibility Test Results

In terms of weight determination, it can be seen from Figure 5 that the overall trend of the weights obtained using a single method and subjective–objective integrated assignment is consistent, but overall, the weights of the same indicator obtained using subjective–objective integrated determination are more consistent over the years, indicating that subjective–objective integrated determination can not only retain the advantages of decision makers' judgment based on experience but also avoid the disadvantages of excessive intervention with respect to decision makers' subjective thinking, making this method more valuable for the determination of indicator weights.

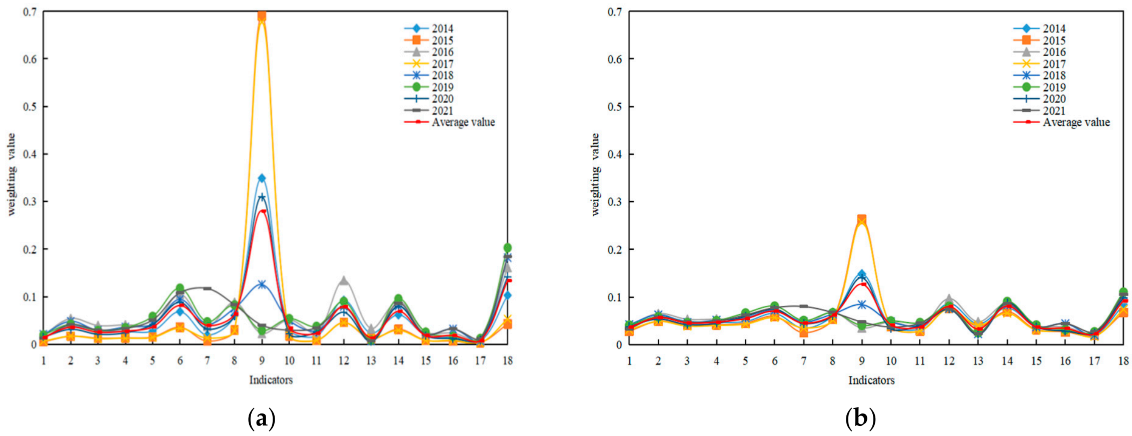
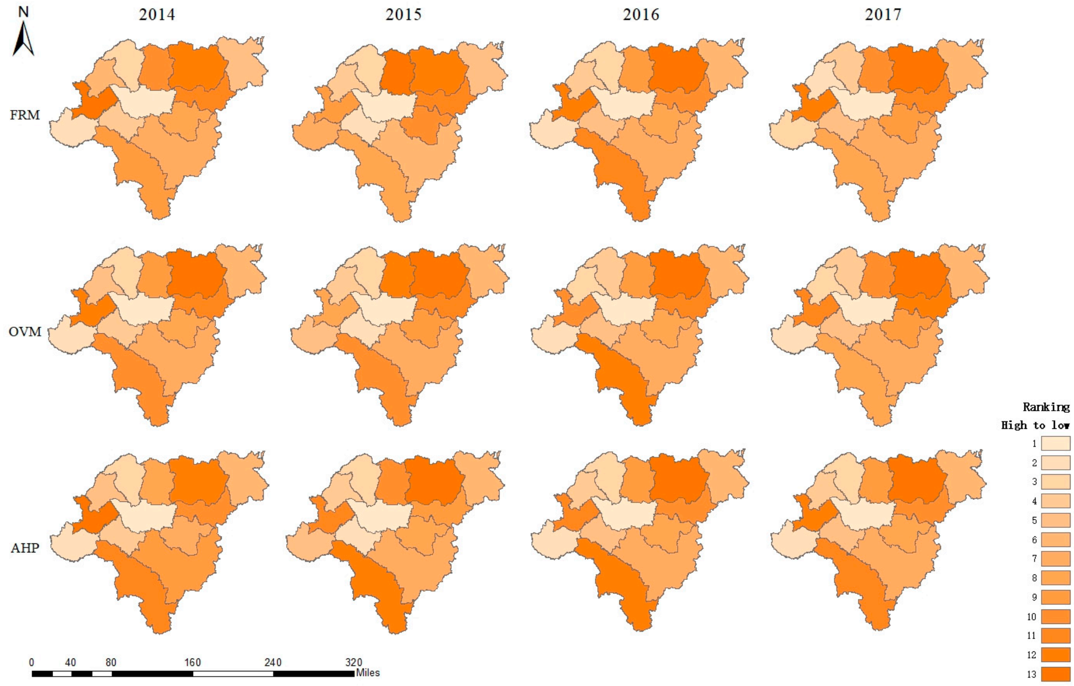
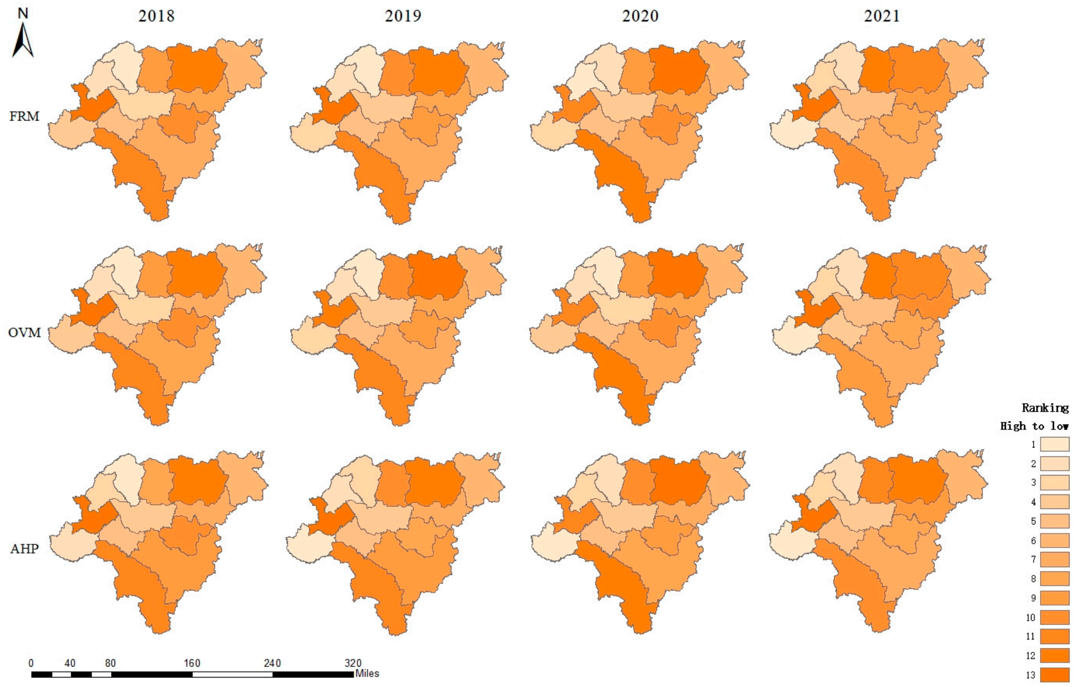


Figure 5. Changes in weight values of different indicators from 2014 to 2021: (**a**) Coefficient of variation method weight value, (**b**) Subject–objective combination weight value.

To verify the rationality and validity of using the "G1-CVM" combination for the evaluation of the sustainable use of water resources, the close value method and the AHP method were compared based on the same evaluation index system, and the results of the analysis are shown in Figure 6. From the figure, we can see that the results of the three methods are the same, which shows that the reliability of the "G1-CVM", combined with the fuzzy identification model, is quite high.



(**a**)



(**b**)

Figure 6. (**a**) Comparison of three approaches to determining the degree of sustainable water use in Harbin City, 2014–2017. (**b**) Comparison of three approaches to determining the degree of sustainable water use in Harbin City, 2018–2021.

4. Discussion

Analysis of the spatial distribution pattern of regional water resources' sustainable use is an effective way to understand the spatial geographical differences and spatial distribution characteristics of regional water resources. From the evaluation results and spatial distribution, we can see that the counties with more sustainable use of water resources are located in the northwest of Harbin City, mainly in the three districts (counties) of Hulan District, Bayan County, and Bin County, which have a sustainable use status of level II or above. The sustainable use of water resources in the main city and Tonghe County ranked low among the 13 counties, still with a level III sustainable use status in some years, At the low level of sustainable use of water resources, where the utilization rate of water resources is low, the economy type needs to be changed from water-consuming to water-saving, and the integrated management of water resources needs to be strengthened in order to use water resources rationally. From the values of the indicators measured over the years, we can see that the per capita comprehensive water consumption, residential water consumption, the proportion of the tertiary industry, and the ecological environment water consumption rate in the main urban area and the two counties of Tonghe County are larger than the values for other years, i.e., the demand for water resources is relatively high, while there is a lack of water supply, which leads to a relatively low level of sustainable utilization of water resources.

The sustainable use of water resources was analyzed in the studies of Nadira A S [55], S N R [56], and Bathla S [57] et al., but the spatial correlation pattern was not. From the spatial correlation pattern, we can see that the clustering type appears in several counties in western Harbin: the main urban area and Wuchang City continue to show the "L-H" clustering pattern, indicating that the sustainable use of water resources in these two counties is low; hence, these two counties must learn from the surrounding counties, accelerate the construction of a conservation-oriented society, promote green development, and prevent water resources from becoming a factor limiting economic development. Shuangcheng District and Yilan County show "H-L" clustering in some years, while the sustainable use of water resources in the surrounding counties is low, and their water use patterns can be studied based on the surrounding counties. Hulan District and Bayan County show "H-H" clustering in some years, and the high sustainable use of water resources in these two counties will radiate to the surrounding areas, having positive effects on the surrounding areas to improve the sustainable use of water resources.

The methods of determining weights can be divided into two categories: the subjective weighting method and objective weighting method. The subjective weighting method mainly includes the Delphi method, sequential relationship analysis (G1), and the hierarchical analysis method (AHP), which determine the weights of each index based on experts' experience in scoring and ranking and are more subjective. The objective weighting method mainly includes the entropy weighting method (EVM) and coefficient of variation method (CVM), which determine the weights of indexes based on objective data and indexes and are more objective. Since sustainable water resource utilization is a complex system influenced by several factors, the G1 method was used in combination with the coefficient of variation method in this study to improve the scientific accuracy of the results. Compared with the commonly used subjective ascertainment method of hierarchical analysis (AHP), the G1 method has a clear process and simple operation and solves the shortcomings of the AHP method, which requires consistency testing, having better practicality. As can be seen from the comparison, the weights of the same indicator obtained by using the "G1-CVM" combination of weights have been more consistent over the years, indicating that the improved method is reasonable for determining the weights of the indicators. Since G1 determination has previously been applied in water security evaluation and has not been used for water resources, the close value method and the AHP method were used for comparison in order to verify its applicability. Because different evaluation models are not necessarily comparable in terms of values, while the evaluation models themselves are comparable, the values reflecting water resources' sustainable use level were ranked from the highest to the lowest row. The results of the comparison of the three methods for the same year show that the consistency of the three methods, in terms of ranking order, is very high. Due to the different theories of these methods, some districts (counties) have deviations, but basically, they all differ by one ranking, and the relative variability is very low, which indicates that the methods are feasible.

This paper constructs a sustainable use of water resources evaluation model based on the improved combination of weights, which can not only effectively avoid the inconsistency between the objective weighting and the subjective cognition, but also reduce the arbitrariness of the subjective weighting method, and better synthesize the results of the subjective judgment of the experts and the characteristics of the data, which can provide reliable data for the further analysis and evaluation of the relevant issues, and provide a new way of determining the weights, Ideas. In addition, the method has the advantages of improving the objectivity, accuracy and scientificity of indicator weights, convenient calculation, easy to understand, and not limited by the number of indicators in the indicator system. Compared with other methods, this method can avoid the shortcomings of difficult to obtain data and complicated operation and has better applicability for the analysis of sustainable utilization of water resources in this region as well as other regions. However, there are still shortcomings in this study: the study only analyzes the sustainable use of water resources in the study area on the basis of existing data, and there is still a lack of prediction of the sustainable use of water resources in the region in the future.

5. Conclusions

The objectives of this study were, on the one hand, to analyze the degree of sustainable use of water resources in Harbin city in terms of time, space, and autocorrelation, and on the other hand, we applied "G1-CVM" combination weighting to the determination of the fuzzy identification model and analyzed the feasibility of its application in the evaluation of sustainable water resource use. The following conclusions were drawn:

1. In terms of temporal and spatial distribution, over the past 8 years, the overall utilization of sustainable water resources in Harbin City showed a cyclical trend of increasing and then decreasing, and the spatial distribution pattern of sustainable water resources utilization in each district (county) was relatively stable, with the three regions of Binxian, Bayan, and Shuangcheng having better sustainable water resource utilization, and the three regions of Tonghe, the main city, and Wuchang having worse sustainable water resources utilization. In terms of the spatial correlation pattern, the overall spatial distribution of water resources sustainable utilization in the 13 counties of Harbin City showed a negative correlation from 2014 to 2021, and in the local spatial autocorrelation analysis, the main urban area, Wuchang City, Hulan District, Bayan County, Shuangcheng District, and Yilan County showed the clustering type. In the local spatial autocorrelation analysis, the main urban area, Wuchang City, Hulan District, Bayan County, Shuangcheng District, and Yilan County were the main counties that showed the clustering type.
2. In the determination of the index weights, the combination of "G1-CVM" was used to render the weights of the same index more consistent over the years. Comparing the selected close value method and the AHP method, the calculation results are consistent with the fuzzy identification model, indicating that the combination of "G1-CVM" is practical and feasible.

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