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Original Research

Water Sustainability Assessment and Spatial and Temporal Variance Analysis - a Case Study of 12 Provincial Administrative Regions in Western China From 2012 to 2022

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Abstract

Western China is an inland region facing the problem of water scarcity due to its distance from the sea and mountainous topography. Studying the sustainability, spatial and temporal variation and drivers of water resources in western China is an important way to identify and solve water resources problems in the region. This study constructed a water resources sustainability evaluation index system, including four subsystems and 26 indicators, to examine the spatial, regional variation and temporal evolution of water resources sustainability in 12 provinces from 2012 to 2022. The results show that: (1) interannual trends show fluctuations and differences in resources, environment and socio-economics; (2) the scores of the water resources and socio-economic subsystems are relatively average, while the water environment subsystem shows significant differences and the water ecology subsystem scores lower; (3) the global spatial agglomeration effect shows a fluctuating and expanding trend, with a significant positive spatial autocorrelation, mainly attributed to density excesses, followed by inter- and intra-regional differences, leading to an uneven distribution of spatial development, concentrated in two types of spatial agglomerations. Conclusions: Studies have shown that the level of water sustainability in western China is gradually improving and that spatial and temporal differences in water indices are gradually decreasing.

Keywords: Western China, water sustainability, entropy method, cloud model, spatial autocorrelation

Introduction

Water resources (WR) are vital to the survival and advancement of human society. Their importance is highlighted by their inherent natural, environmental, ecological, and socio-economic characteristics [1]. Lately, the improvement of global socio-economic conditions and living standards has accentuated the widening gap between water supply and demand, necessitating sustainable water resource development [2]. As a nation facing considerable water scarcity, China faces a huge challenge [3]. Water resource

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sustainability is a critical element in determining the socio-economic, ecological, and environmental progress in western China. Consequently, performing an extensive evaluation of water resource sustainability and examining its spatiotemporal variations is of utmost importance. In particular, the refinement of water sustainability assessment between different provinces is important to ensure water security and promote quality development in western China [4].

Scholars have extensively analyzed water resource research, focusing on three primary aspects: innovating research methodologies, constructing evaluation index systems for the study subject, and elucidating the spatial and temporal distribution within the research scope. The research objects are broadly divided into WR carrying capacity evaluation [5], water security evaluation [6], and comprehensive evaluation of sustainable use integrated with multiple methods [7]. Among the many evaluation methods, in devising the index system methodology, it is primarily divided into the direct establishment according to the research needs and data availability and the establishment based on PSR model [8], based on DPSIR model [9, 10], based on system dynamics model [11] and so on. Regarding spatial and temporal distribution, research primarily focuses on three aspects: assessing differences in sustainable water resource utilization levels between various regions [12], evaluating sustainable water resource development levels in a specific study area over a time series [13], and conducting static evaluations of water resource sustainability levels within a certain region [14]. Regrettably, a review of the literature on WR in China reveals that the majority of existing research primarily targets the southern [15], northern [16], and eastern [17] regions of the country. Furthermore, the water resource data published in China are typically based on large geographic scales. In terms of time series, the research field has mostly been analyzed in a single dimension of time or space and lacks a systematic description of spatial and temporal differences in regional water sustainability (WRS) assessments.

In view of this, this study draws on previous studies on sustainability assessment, spatial distribution, and impact factors. Based on data from 12 provinces in western China from 2012 to 2022, 26 evaluation indicators were selected from four systems: water resources (W1), socio-economic (W2), water ecology (W3), and water environment (W4), and a dynamic evaluation model of WRS was developed using an improved EWM and cloud model. The model combines spatial autocorrelation and time lag techniques and considers the multiplicity of evaluation, thereby deepening the understanding of WRS in terms of spatial distribution. The aim of this study is to provide a scientific basis for the sustainable use and distribution of WR, which in turn supports the high-quality development of western China.

Materials and Methods

Study Areas

This study covers 12 provinces/autonomous regions/municipalities directly under the central government in western China from 2012 to 2022, as shown in Fig. 1. Being landlocked and far from the ocean, the region is characterized by high mountains and low precipitation. However, it covers a vast area and accounts for 50.1% of China's total annual average water volume. However, there are significant differences in the distribution of water resources in the southwest (Yunnan, Guizhou, Sichuan, Chongqing, and Guangxi) and the northwest (Inner Mongolia, Tibet, Shaanxi, Ningxia, Gansu, Xinjiang, and Qinghai), with the former being abundant, about 12 times the national average, and the latter being more limited, accounting for only 4.6% of the national total. In recent years, uneven spatial distribution and water quality shortages have affected the water resource systems of several cities in western

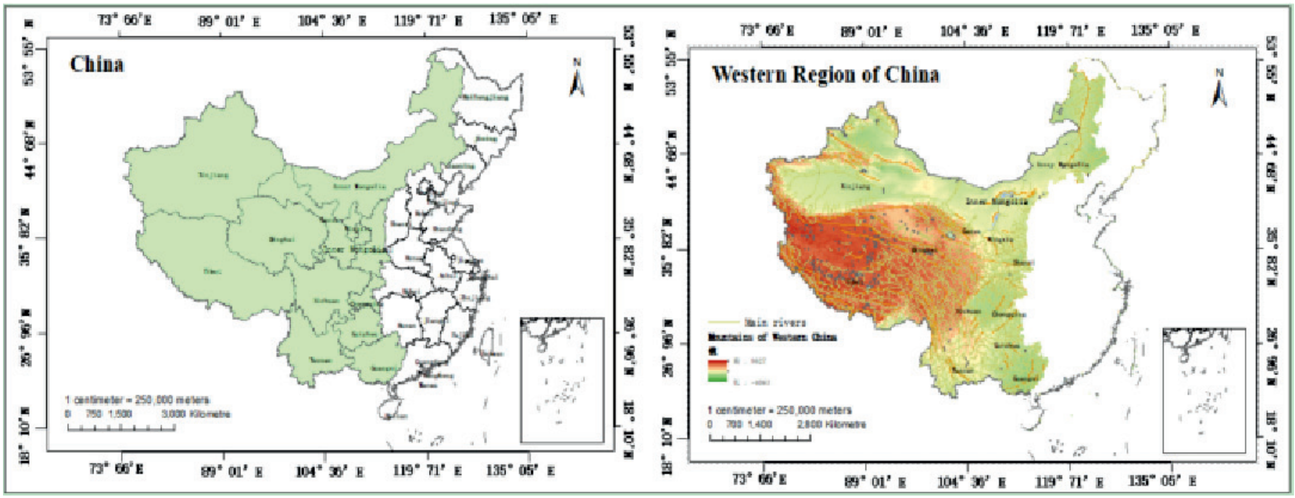

Fig. 1. Study area introduction.

China. This study aims to provide an in-depth analysis of the sustainable use and spatial distribution of water resources in this region, and to provide a scientific and rational basis for strategic decisions on regional water resources management and sustainable growth.

Research Method and Process

Research Process

This study presents a groundbreaking method for formulating a broad-based metric system aimed at assessing development standards, underpinned by a fresh perspective on development. The empirical study applies the EWM, TOPSIS method for prioritization and spatial autocorrelation analysis. To assess WRS in the 12 provinces of China's western region, data from the National Bureau of Statistics (NBS) of the People's Republic of China are utilized. The data undergo preprocessing to incorporate the dimensions of water resource sustainability evaluation into the indicator system. A comprehensive four-dimensional system is developed, comprising WR, environmental conditions, ecological aspects, and socio-economic factors. Weights for each indicator are derived through the EWM, while the TOPSIS technique is utilized to identify the most suitable solution for evaluating WRS. The composite evaluation score and analysis of each dimension are employed to evaluate and analyze the water resource sustainability development across the 12 provincial administrative regions in western China. Furthermore, Exploratory Spatial Data Analysis (ESDA) is conducted to detect spatial correlations among provinces, explore local space variations, and examine the evolution of spatial data.

Determination of Indicator Weights

In this study, we use SPSSAU software to process data and adopt EWM to quantify the importance of water resources sustainability evaluation indicators in western China.

In the first step, an eigenvalue matrix X is constructed from an initial dataset consisting of n evaluation indicators for the m programs under evaluation:

$$X = (x_{ij})_{n*m} \quad i = 1, 2, ..., m; j = 1, 2, ..., n \tag{1}$$

In the second stage, the indicators employed for assessing water resource sustainability in Western China are categorized into positive and negative indicators. Due to variations in scale and magnitude among the indicators, it is necessary to standardize the matrix. The calculation formula is:

$$Z_{ij} = (X_{ij} - X_j^{min})/(X_j^{max} - X_i^{min}) \tag{2}$$

$$Z_{ij} = (X_j^{max} - X_{ij})/(X_j^{max} - X_{ij}^{min}) \tag{3}$$

Equation (2) is associated with a positive indicator, while Equation (3) is indicative of a negative one. Normalisation matrix.

In the third step, R_{ij} signifies the standardised value obtained when assigning the jth determinant that influences prevention and control. Within the context of Equations (4) to (6), f_{ij} represents the weightage of the i-th item indicator under the umbrella of the j-th metrics. For an individual determinant j, the formula used to compute its information entropy H_j is as follows:

$$H_j = -1/\ln m \, \Sigma^m_{i=1} f_{ij} \cdot \ln f_{ij} \tag{4}$$

$$F_{ij} = Z_{ij} / \Sigma^m_{i=1} Z_{ij} \tag{5}$$

To eliminate the effect of $Z_{ij} = 0$ on the entropy calculation result, Z_{ij} is corrected for translation so that $Z_{ij} = Z_{ij} + 0.01$.

In the fourth step, in Equation (6), the weights of each factor W_j are calculated:

$$W_j = 1 – H_j / \Sigma^n_{i=1} (1-H_j) = 1 – H_j / n-\Sigma^n_{i=1} H_j \tag{6}$$

Cloud Model Building Based on EWM

Utilizing the cloud model, a sustainability assessment model for WR in western China was developed, encompassing the following steps:

In the first step, the standard cloud criteria are identified for every indicator.

$$E_x = (C^{max}_{jk}+C^{min}_{jk})/2; \quad E_n = (C^{max}_{jk}+C^{min}_{jk})/2.355; \quad H_e = u \tag{7}$$

In the second step, the membership degrees are calculated. The relative affiliation matrices $R_3 = (r_{jlk})_{s*p}$ and $R_4 = (y_{jlk})_{n*p}$ for the criterion and indicator layers were calculated using Equations (8) and (9), respectively.

$$R_{jlk} = r_{jlk} / \Sigma^p_{k=1} r_{jlk}` \tag{8}$$

$$Y_{jlk} = y_{jlk} / \Sigma^p_{k=1} y_{jlk} \tag{9}$$

In the third step, Equations (10) and (11) are used to calculate the comprehensive affiliation vector D. Its formula is:

$$D = WR_4 = (d_k)_{1*p} \tag{10}$$

$$W = (W1, W2, ..., Ww) \tag{11}$$

The fourth step involves determining the final evaluation outcomes. Each level within the evaluation level set C is assigned a corresponding score $Z = \{z_1,z_2,... ,z_p\}$. The weighted average technique is utilized to ascertain the scores O_j for every indicator, the scores T_j for each standard level, and the cumulative score Q for the assessed entity.The formula is:

$$O_j = \Sigma^p_{k=1} z_k y_{jlk} \tag{12}$$

$$T_f = \Sigma^p_{k=1} z_k r_{fk} \tag{13}$$

$$Q = \Sigma^p_{k=1} z_k d_k \tag{14}$$

ESDA Method

In this study, the Global Moran (GM) index and local Moran (LM) index techniques are employed to assess the spatial clustering of water sustainability among the 12 provinces and municipalities in western China.

In the first step, the GM's I was employed as a global spatial autocorrelation (GSA) index to examine the spatial correlation features of WR in western China and to assess the level of resource sustainability. The index is calculated listed below:

$$\textit{Moran's } I = n\, \Sigma^n_{i=1} \Sigma^n_{j=1} W_{ij} (Xi\text{-}X)\ (Xj\text{-}X)\ /\ S^2\, \Sigma^n_{i=1} \Sigma^n_{i=1} W_{ij} \tag{15}$$

In the second step, the local autocorrelation of WRS in 12 provinces and municipalities in western China is analyzed using Moran scatter plots, LM's I statistics, and LISA clustering plots. The LM's I statistic formula is as follows:

$$\textit{Moran's } I_{local} = n\ (Xi\text{-}X)\ \Sigma^n_{j=1} W_{ij} (Xj\text{-}X)\ /\ \Sigma^n_{i=1} (Xj\text{-}X)^2 \tag{16}$$

Evaluation Indicator Construction and Data Calculation

Indicator System Construction

Drawing on the theories of WRS and sustainable development, an evaluation index system was developed in accordance with the principles of systematic, typical, comprehensive, scientific and comparable. This index system was developed based on the natural geographic environment and human characteristics of western China. To establish the system, frequency statistics, literature review and expert consultation were used. The indicator system includes four dimensions of water resources (W1), water environment (W2), water ecology (W3) and socio-economic development (W4), covering 9 primary indicators and 26 secondary indicators. The W1 subsystem mainly reflects the utilization of WR (W1-1) and WR conditions (W1-2); the W2 subsystem mainly describes the environmental pressure of WR (W2-1) and the management level of environmental pollution and prevention (W2-2); the W3 subsystem mainly reflects the water ecological safety W3-1 and biodiversity W3-2; the W4 subsystem mainly reflects the economic dynamics of WR W4-1, economic strength W4-2 and economic scale W4-3. This study draws on the studies of Guo Yanlong et al [18, 19] and De O. et al [20] on WRS, combined with the WR Evaluation Guide (SL/T238-1999), using data from 12 provincial administrative regions in western China for 2012-2022. By integrating relevant documentary standards and literature, this study combined entropy weight method and cloud model to construct a comprehensive evaluation model. Fuzzy transformation and maximum affiliation rules were also used to classify water resources sustainability into five levels, from very good to very poor, to achieve a comprehensive and detailed assessment of water resources sustainability in western China. As shown in Table 1.

Data Sources and Processing

The primary objective of this study is to delve into the WRS across the 12 provinces and urban zones of western China, with a distinct concentration on scrutinizing their temporal and spatial variations. These variables are utilized as explanatory factors in the analysis. We used statistical yearbooks for the western region of China up to 2023. The data sources utilized in this study include the China Statistical Yearbook database obtained from the NBS for the period spanning from 2012 to 2022.Additionally, statistical yearbooks, WR bulletins, social development statistical bulletins, and environmental quality status bulletins for each city were considered.Several indicators, not found in the annual statistical compendiums, were procured from the specific online platforms of the respective statistical bureaus. These yearbooks cover most of western China and have been systematically collected and collated to form the initial data set.

Results and Discussion

Water Sustainability Assessment Results

Analysis of the Relative Proximity of WRS in Western China

The relative proximity values for WRS in 12 provincial in western China were calculated using the TOPSIS EWM method and SPSSAU software. The outcomes derived from the computations can be found in Table 2, which displays the relative proximity rankings obtained using the EWM TOPSIS. The D+ and D- values signify the discrepancies between the assessment target and the meaningful solution, while the C values indicate the variations between the assessment object and the best predicted methods.The WRS indices for western China are ranked from highest to lowest as follows: 0.586 (Qinghai), 0.569 (Ningxia), 0.554 (Guangxi), 0.554 (Shaanxi), 0.553 (Chongqing), 0.538 (Gansu), 0.528 (Yunnan), 0.524 (Tibet), 0.518 (Guizhou), 0.503 (Inner Mongolia), 0.484 (Szechwan), 0.478 (Xinjiang).

Table 1. Water Sustainability Evaluation Indicator System.

Target Level	Tier 1 Indicators	Secondary indicators	No.	Unit	Attributes	Grading Criteria for Evaluation Indicators					En	He	Weighting		
						I	II	III	IV	V					
W1	W1-1	Water resources per capita	W1-11	m^3/person	+	1957.7	2027.5	2097.3	2218.3	2339.4	267	0.00	0.2755	0.0455	0.0357
		Water Resources Development and utilization	W1-12	%	+	6500	6791	7082	7372.2	7662.3	410.0	5.39			0.0098
	W1-2	Precipitation	W1-21	mm	+	145.5	428.8	712.1	1140.7	1569.3	455.5	590.8		0.23	0.0313
		Surface water resources	W1-22	Billion m^3	+	2840	15252.1	27664.2	29469.1	31273.9	9716.8	1400.8			0.0162
		Groundwater resources	W1-23	Billion m^3	+	7745	7984.9	8224.9	8539.8	8854.8	1754.38	3475.1			0.1825
W2	W2-1	Water consumption in agriculture	W2-11	Billion m^3	-	3921.5	3840.7	3759.9	3680	3600	549.42	1798.07	0.0892	0.047	0.0142
		Industrial water consumption	W2-12	Billion m^3	-	1406.4	1325.5	1244.6	1137.5	1030.4	0.00	40.45			0.0121
		Domestic water consumption	W2-13	Billion m^3	-	57	37.2	17.4	9.2	1	11.45	8.07			0.0120
		Water consumption per capita	W2-14	m^3/person	-	2657.4	1662.2	667.1	443.1	219.2	153.49	1096.51			0.0087
	W2-2	COD concentration	W2-21	10 k tons	-	136	91.2	46.4	24.4	2.5	30.84	33.63		0.0422	0.0115
		Ammonia nitrogen concentration	W2-22	10 k tons	-	25.59	14.6	3.5	1.9	0.25	3.44	6.35			0.0093
		TN concentration	W2-23	10 k tons	-	37.38	22.4	7.3	3.9	0.42	0.00	1.74			0.0106
		TP concentration	W2-24	10 k tons	-	3.17	1.9	0.7	0.4	0.03	0.42	0.45			0.0108

Table 1. Continued.

W3	W3-1	Artificial ecosystem water replenishment	W3-11	Billion m^3	+	103.2	148.2	193.3	256.6	320	0.00	74.06		0.1949	0.1234
		Treatment of wastewater	W3-12	Billion RMB	-	1403448	1134231.6	865015.3	612507.6	360000	184362.67	8354.3	0.4479		0.01
		Water area and land for water facilities	W3-13	10,000 km^2	+	0.1	229.9	459.7	3195.0	5930.4	4090.6	143.5			0.0615
	W3-2	Fish integrity Index	W3-21	10 k tons	+	0	19.8	39.7	99.7	159.8	0.00	30.05		0.253	0.0569
		Shrimps and crabs	W3-22	10 k tons	+	0	0.3	0.5	3.3	6.1	0.00	0.00			0.0666
		Shellfish	W3-23	10 k tons	+	0	0.1	0.2	0.9	1.7	0.21	0.4			0.1295
W4	W4-1	Urbanisation rate	W4-11	%	+	22.87	37.4	52.0	61.3	70.5	0.00	6.54	0.2052	0.0483	0.0111
		Disposable income per capita Income	W4-12	RMB	+	5189	12123.3	19057.7	26583.0	34108.4	0.00	1051.89			0.0262
		Population density	W4-13	km^2	-	8373	5751.7	3130.4	1722.7	315	2582.27	3201.48			0.0110
	W4-2	Share of primary sector GDP	W4-21	%	-	9.1	8.5	7.9	7.5	7	1.98	3.44		0.0288	0.0110
		Share of gross domestic product in secondary and tertiary sectors	W4-22	%	+	90.9	91.5	92.1	92.5	93	0	0			0.0178
	W4-3	Water consumption per million Yuan GDP	W4-31	m^3	-	118	98.2	78.4	64.2	50	22	15		0.1281	0.1005
		Water consumption per 10,000 Yuan of industrial value added	W4-32	m^3	-	69	58.2	47.3	37.7	28	0	10			0.0098

Table 2. Relative Proximity of Western China Regions.

Item	Positive ideal solution distance D+	Negative ideal solution distance D-	Relative proximity C	Sorting results
Chongqing	2.869	3.555	0.553	5
Sichuan	3.483	3.261	0.484	11
Yunnan	2.921	3.263	0.528	7
Guizhou	3.1	3.334	0.518	9
Tibet	3.301	3.636	0.524	8
Shaanxi	2.854	3.542	0.554	4
Gansu	3.064	3.564	0.538	6
Qinghai	2.762	3.905	0.586	1
Xinjiang	3.375	3.09	0.478	12
Ningxia	2.882	3.809	0.569	2
Inner Mongolia	3.168	3.2	0.503	10
Guangxi	2.775	3.451	0.554	3

Over the period 2012-2022, Qinghai has the best performance in terms of water sustainability, followed closely by Ningxia. Both of these provinces have indices above 0.560, indicating that they have relatively good water sustainability. Furthermore, despite being situated in an arid zone, Ningxia has successfully implemented the Yellow River Water Conservancy Project, enabling efficient utilization of WR. The relative proximity values for the eight regions, including Yunnan, Guizhou, Gansu, Tibet, Shaanxi, Chongqing, Inner Mongolia, and Guangxi, are all above 0.500; however, their water sustainability indices remain relatively low. This indicates that although the water resource situation in these regions is moderate, there are still some pressures and challenges. Overall, the results indicate a degree of variation in water resource sustainability between the provinces in western China. These differences reveal the significance of WR management and the urgent need to take appropriate measures to improve areas with low sustainability indices.

Interannual Changes in the WRS in Western China

Considering the long-period nature of WR, we selected 2012, 2017 and 2022 as representative years at 5-year intervals to capture the trend of WRS in western China. By analyzing the interannual distribution changes of the four dimensions, we were able to clearly identify the WRS performance of each region. Regions with higher score indices indicate better performance in WRS. This approach can help us to accurately capture and understand the changes and influencing factors of WRS, providing an important basis for WR management and policy decisions, as shown in Fig. 2.

Interannual distribution of W1: During 2012-2022, significant changes are shown in the shift of the Tier 1 score from Tibet and Gansu to Yunnan and Guizhou, and the Tier 4 score tends to the arid and semi-arid regions of the northwest. This reflects the development of surface water resources partially alleviating the water scarcity in the northwest. Overall, the interannual distribution of W1 in western China changed during this period, especially the trend of water shortage in southwest China intensified. Interannual distribution of W2: The overall score distribution shows a gradual increase from northwest to southwest during 2012-2022. This indicates that the W2 conditions are better in the southwest and worse in the northwest. In general, the total hardness of river water in most areas is low and meets various water needs. Interannual distribution of W3: Between 2012 and 2022, water sustainability improves in Qinghai, Ningxia and Tibet, while Gansu and Sichuan have poorer water sustainability. The study focus in 2022 is broadly distributed across western China, reflecting the change in focus and geographic distribution of resources over the decade.Interannual distribution of W4: The interannual distribution of W4 in western China shows changes during the period 2012-2022. The primary distribution area expands from Tibet to Qinghai and Gansu, the secondary and tertiary distribution areas contract, and the quaternary and quintuple distribution areas are relatively stable. It indicates that there are adjustments in the distribution areas at all levels during this decade, reflecting the socioeconomic progress and providing reference for the formulation of corresponding policies.

Evaluation of the Subsystems

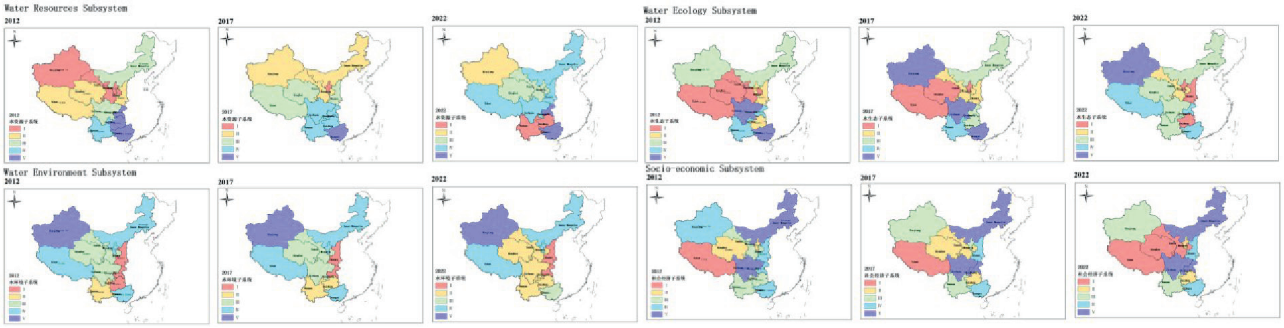

Fig. 2. Interannual regional variations in water sustainability.

The WRS scores for each indicator including the subsystem scores of W1, W2, W3, and W4, as well as the total WRS scores for western China, were calculated from the overall evaluation level scores. These scores are presented in Table 3.

In the WR condition (W1) subsystem, provinces score 77-83. Guangxi scored the highest, reflecting its better water resources conditions, while the five northwestern provinces and Inner Mongolia were relatively low, highlighting the obvious gap between the provinces in terms of water supply and demand.Water environment (W2) subsystem, each province scored 73-90, with good water environment management in the northwest and poor water environment condition in some southwestern provinces (e.g. Sichuan), which need to strengthen water environment protection and management.Water ecology (W3) subsystem, the provinces scored 57-73 points, the overall score is low. Southwest China performs well in protecting and restoring water ecosystems, while some provinces in northwest China need to further improve their water ecology status. In the socio-economic subsystem (W4), the scores do not vary much, and there is no obvious spatial distribution trend. Among them, Chongqing performs well in managing and efficiently using water resources, while some provinces in the northwest, such as Gansu, need to improve their agricultural water use efficiency. In the overall WRS score of 12 provinces in western China, the scores range from 72-76, with relatively balanced overall development, but generally weak. The spatial distribution is roughly: Guangxi > five southwestern provinces > five northwestern provinces > Inner Mongolia. This indicates that although the overall development is balanced, there are still differences among provinces in the WR system.

Spatial Autocorrelation Analysis

Water Sustainability GSA Analysis

ArcGIS 10.8 was used to measure the GM'sI index for WRS in western China for the period 2012-2022, as listed in Table 4. During the study period, the GM’s I indices for 2012-2022 all passed the 1% significance test, with z-values exceeding the critical value of 1.96. This indicates a significant positive spatial autocorrelation of the water indices in the 12 provinces of western China. The spatial pattern demonstrates some clustering characteristics, suggesting that there is a convergence in the spatial distribution of high and low values of the water index. From 2012 to 2022, the GM’s I index remains above 0.3000, displaying a wave-like development trend characterized by periods of increase, decrease, increase, and decrease again. This trend indicates that the WRS in spatial agglomerations in western China is gradually improving, while spatial differences are diminishing. In addition, the GSA aggregation effect also shows some volatility over the sample period. In comparison, GM’s I values show some degree of fluctuation from year to year, suggesting that the degree of spatial aggregation of the water index has changed over time. The GM’s I index reached its highest value in 2014, with an index of 0.6347, indicating the strongest spatial agglomeration during that year.2013 saw the smallest GM’s I index with an index of 0.3244, a relatively weak spatial agglomeration effect.

Local Spatial Autocorrelation Analysis of WRS

In order to visually describe the changes in the spatial distribution of water indices in different regions of western China, local spatial autocorrelation indices were used to describe the changes in the spatial distribution of water indices in different regions of western China, revealing the local spatial characteristics of water indices in each province. during 2012-2022, the spatial clustering of water indices was mainly reflected in the high-high (H-H) and low-low (L-L) categories, without significant low-high (L -H) or high-low (H-L) clustering. The provinces with high-high clustering are mainly in the southwest and the areas with low-low clustering are mainly in the northwest. Although the water index in the northwest tends to develop in the desirable direction, there is still a gap with the southwest. In addition, the spatial clustering type of water index in each region shows dynamic changes over time. As shown in Fig. 3.

Discussion

Table 3. Regional composite scores and subsystem scores.

Region	Regional composite score		W1		W2		W3		W4	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Chongqing	75.07	4	82.09	1	84.12	5	60.54	5	73.51	2
Sichuan	73.97	7	81.38	4	73.37	12	69.90	2	71.23	11
Yunnan	74.06	6	81.05	5	79.55	9	64.29	3	71.36	10
Guizhou	73.46	8	81.40	3	81.01	7	60.44	8	71.00	12
Tibet	75.13	3	79.46	9	88.80	2	60.47	6	71.79	7
Shaanxi	73.39	10	79.99	6	82.85	6	58.36	10	72.35	6
Gansu	73.32	11	78.85	11	85.14	4	57.72	12	71.57	9
Qinghai	75.52	2	79.42	10	89.15	1	60.47	7	73.03	5
Xinjiang	72.75	12	77.96	12	77.50	10	62.33	4	73.22	4
Ningxia	74.84	5	79.64	7	87.95	3	58.36	11	73.42	3
Inner Mongolia	73.40	9	79.60	8	80.27	8	59.32	9	74.39	1
Guangxi	75.59	1	81.84	2	76.72	11	72.14	1	71.67	8

Table 4. 2012-2022 GM'I Index for WRS in Western China.

Year	2012	2013	2014	2015	2016	2017
Moran’s I	0.5728	0.3244	0.6347	0.6283	0.5327	0.6273
Z statistic	3.8220	2.4657	4.1500	4.0574	3.5827	4.0940
P	0.000	0.000	0.000	0.000	0.000	0.000
Year	2018	2019	2020	2021	2022	
Moran’s I	0.5794	0.5614	0.6265	0.5417	0.5538	
Z statistic	3.7293	3.700	4.0193	3.5818	3.6471	
P	0.000	0.000	0.000	0.000	0.000	

Based on the study’s findings regarding the inter-annual distribution variation, composite scores and sub-system scores, as well as spatial correlation analysis of WRS in western China, the following recommendations are proposed:

1) In terms of inter-annual distributional changes in WRS, the findings show that water scarcity becomes more prominent in southwest China during the period 2012-2022, while a trend towards alleviating water scarcity gradually emerges in northwest China, which is consistent with Li et al. findings. Moreover, the W2 exhibits a progressive enhancement from the northwest to the southwest, indicating that water environmental protection efforts in the southwest have yielded positive results over the past decade. This observation aligns with the research findings of Wang et al. Regarding the W3 subsystem, improvements have been observed in most regions, suggesting an overall enhancement of the water ecology.However, some areas still face challenges in terms of the slow recovery of water ecosystems, which aligns with the conclusions drawn by Chen et al. Concerning the W4 subsystem, the region's WRS development exhibits variations and inconsistencies. These observations are consistent with the research outcomes presented by Guo et al. and Zhang et al.

2) The overall assessment of water resource sustainability indicates that the WRS in western China is relatively low. The spatial distribution of the overall scores reveals that Guangxi province has the highest level of water resource sustainability, followed by the five southwestern provinces, the five northwestern provinces, and Inner Mongolia. These findings align with the results reported in the research conducted by Qiang L et al. and Li Jy et al. The main factors contributing to this variability include locational characteristics, resource advantages and industrial structure. Consequently, customized policies and measures are essential to accommodate the unique

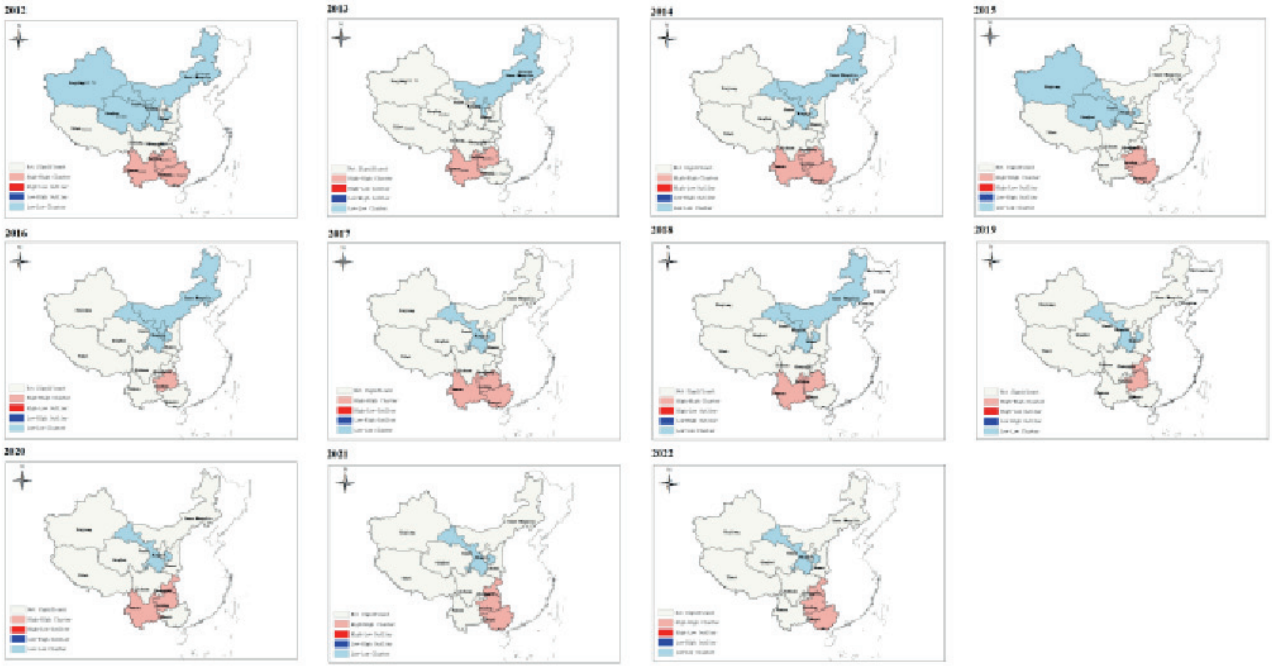

Fig. 3. Spatial clustering of WRS indices for different provinces in western China based on local spatial autocorrelation analysis.

circumstances of each subsystem and foster WRS.

(3) In the assessment of the WRS subsystem in western China, the findings show that the southwest region has serious water shortage problems and environmental pollution challenges, which is consistent with the study by Chaochao Zeng, Lixia Dong, Guangchun Yao, and Jie Chen. In addition, the northwest region faces a higher risk of water and environmental pollution due to the influence of industry and agriculture, but there are differences with the study of Xingxing Xu, Fanchao Meng, and Jianxin Zou. This may be due to the different research methods and sample selection. In the W4 subsystem, the level of socio-economic development in western China shows significant volatility and variability, which is consistent with the findings of Deng Bo, Zhang Li, and Xiao Xin. However, there are significant spatial differences and subsystem inconsistencies in WRS in western China. Therefore, future research can delve into the determinants, assessment methods, and governance approaches that influence the sustainable use and conservation of WR in the region.

(4) This study used GIS and spatial correlation analysis to reveal the spatial differences and clustering characteristics of WRS in western China. This is consistent with the studies of Liu's team, Yue's team, and Xu's team. In particular, WRS in southwest China is relatively better, mainly in H-H clusters, while in northwest China is relatively worse, mainly in L-L clusters, a result consistent with the findings of Liu's team and Zhang's team. Moreover, the spatial clustering types of WRS show dynamic changes between 2012 and 2022, such as Yunnan Province no longer shows HH clustering after 2019, which is consistent with the study of Guo et al. Therefore, the cooperation and coordination of WRS assurance across provinces and regions should be strengthened in the future to achieve a more balanced and coordinated WR utilization and conservation.

(5) Owing to the nonexistence of stringent guidelines for categorizing indicators, the classification of these markers in this analysis for western China relies on the average of the collected data for these indicators from 2012 to 2022. The results of this study are only applicable to the western region of China, and subsequent studies can supplement the indicator classification based on national standards to make the evaluation results comparable with other regions in China.

Conclusions

This paper presents a WRS assessment indicator framework for western China, utilizing the DPSIR model and incorporating EWMs, TOPSIS, cloud models, spatial autocorrelation, and other multivariate statistical methods. The study conducts an assessment of WRS and analyzes the spatial and temporal evolution characteristics of each province in western China from 2012 to 2022. From the analysis, the ensuing deductions have been made:

(1) Regarding the interannual distribution of WRS, the analysis of the WRS subsystems in western China from 2012 to 2022 reveals fluctuating trends and differentiation in resource availability, environmental conditions, and socio-economic aspects. Over the past decade, the W1, W2, W3, and W4 subsystems have all experienced improvement in the western region, with W2 exhibiting the most rapid progress and the

W3 subsystem developing at a slower pace. In order to advance the WRS and foster regional development, it is imperative to take into account the unique features of each subsystem and devise tailored policy measures.

(2) The 12 provinces in western China have an overall balanced WRS score between 72 and 76, but there is a presence among the specific indicators. Guangxi has the highest overall score, followed by the five southwestern provinces, then the five northwestern provinces, and Inner Mongolia has the lowest score. This requires us to be alert to the vulnerability of WR in each region and to adjust the water management strategies and inputs in each region accordingly, especially in ecological protection, agricultural water use and water environmental protection.

(3) In the spatial correlation analysis, WRS in western China exhibited fluctuating growth and interannual fluctuation characteristics. There is an overall global positive spatial autocorrelation, and despite significant spatial differences among provinces, there is an overall aggregation trend. In particular, the spatial aggregation is most prominent in 2014. The degree of spatial aggregation shows fluctuations over time. Local autocorrelation analysis reveals that the number of cities with H-H and L-L aggregation decreases from 9 in 2012 to 4 in 2022, indicating that the aggregation of spatial distribution is gradually weakening. Meanwhile, the center of gravity of WRS in western China is shifting to northwest China, implying that WRS in northwest China is improving and growing faster than that in southwest China, leading to a narrowing regional gap.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. YAN X., CAO H., YIN P., LIU J., ZHU Z. Concentration Field Estimation on Effluent Mixing and Transport with a Parameter-based Field Reconstruction Convolutional Neural Network and Random Forests. Water Resour. Res, **59** (5), **2023**.
2. SEIJGER C. How Shifts in Societal Priorities Link to Reform in Agricultural Water Management: Analytical Framework and Evidence from Germany, India and Tanzania. Sci. Total Environ, 163945, **2023**.
3. ROMAGNNOLI M., SCARPARO A., CATANI M., GIANNI B., PAST L., CAVAZZINI A.A. Development and Validation of a GC GC-ToFMS Method for the Quantification of Pesticides in Environmental Waters. Anal. Bioanal. Chem. **2023**.
4. LI B., LIU K., WANG M., WANG Y., HE Q., ZHUANG L., ZHU, W. High-Spatiotemporal-Resolution Dynamic Water Monitoring Using LightGBM Model and Sentinel-2 MSI Data. Int. J. Appl. Earth Obs. Geoinf, **118** (103278), 103278, **2023**.
5. SEDIGHKIA M., ABDOLI A. A Hydro-Environmental Optimization for Assessing Sustainable Carrying Capacity. Sustain. Water Resour. Manag, **9** (1), **2023**.
6. ZI YI. Spatial and temporal analysis of water resources ecological footprint and ecological carrying capacity in xi'an city. J. Water Resour. Res, **11** (01), 30, **2022**.
7. FORTUNA A.-M., STARKS P.J. Use of Archived Data to Derive Soil Health and Water Quality Indicators for Monitoring Shifts in Natural Resources. J. Environ. Qual, **52** (3), 523, **2023**.
8. KARAMOUZ M., ZARE M., EBRAHIMI E. System Dynamics-Based Carbon Footprint Assessment of Industrial Water and Energy Use. Water Resour. Manage, **37** (5), 2039, **2023**.
9. GUSEV E.M., NASONOVA O.N., KOVALEV E.E., SHURKHNO E.A. Scenario Projections of Changes in Snow Water Equivalent Due to Possible Climate Changes in Different Regions of the Earth. Water Resour, **48** (1), 133, **2021**.
10. NI Y., WU T., WEI J., SHOU T. Identifying priority protected areas based on land-water coupling ecosystem services assessment: A case study in the shanghai metropolitan area, China. Pol. J. Environ. Stud, **31** (6), 5175, **2022**.
11. YU Y., PI Y., YU X., TA Z., SUN L., DISSE M., ZENG F., LI Y., CHEN X., YU R. Climate Change, Water Resources and Sustainable Development in the Arid and Semi-Arid Lands of Central Asia in the Past 30 Years. J. Arid Land, **11** (1), 1, **2019**.
12. XU W. The Effect Evaluation of Weather Modification in the Range of 2009-2010 Years in Xinjiang. J. Water Resour. Res, **04** (05), 450, **2015**.
13. LI J. Evaluation Methods for Water Resource Suitability in Territorial Spatial Planning: A Case Study of Baiyin City in a Semi-Arid Region. Int. J. Environ. Res. Public Health, **19**, 12973, **2022**.
14. KATTEL G.R., SHANG W., WANG Z., LANGFORD J. China's South-to-North Water Diversion Project Empowers Sustainable Water Resources System in the North. Sustainability , **11** (13), 3735, **2019**.
15. LIU N., JIANG W., HUANG L., LI Y., ZHANG C., XIAO X., HUANG Y. Evolution of Sustainable Water Resource Utilization in Hunan Province, China. Water (Basel), **14** (16), 2477, **2022**.
16. KUANG W., HU Y., DAI X., SONG X. Investigation of Changes in Water Resources and Grain Production in China: Changing Patterns and Uncertainties. Theor. Appl. Climatol, **122** (3–4), 557, **2015**.
17. GU X., BAI W., LI J., KONG D., LIU J., WANG Y. Spatio-Temporal Changes and Their Relationship in Water Resources and Agricultural Disasters across China. Hydrol. Sci. J, **64** (4), 490, **2019**.
18. GUO Y., JIANG X., ZHANG L., ZHANG H., JIANG Z. Effects of Sound Source Landscape in Urban Forest Park on Alleviating Mental Stress of Visitors: Evidence from Huolu Mountain Forest Park, Guangzhou. Sustainability, **14**, 15125, **2022**.
19. GUO Y., MA YELIN ZHU X., ZHANG D.C.H. Research

on Driving Factors of Forest Ecological Security: Evidence from 12 Provincial Administrative Regions in Western China. Sustainability , 15.**2023.**

20. DE O. VIERIA, E., SANDOVAL-SOLIS S. Water Resources Sustainability Index for a Water-Stressed Basin in Brazil. J. Hydrol. Reg. Stud, **19**, 97, **2018**.