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Urbanization and the Emerging Water Crisis: Identifying Water Scarcity and Environmental Risk with Multiple Applications in Urban Agglomerations in Western China

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Abstract: Urbanization and climate change have combined to exacerbate water shortages in cities worldwide. While rapid urbanization is faced with the risk of water resource shortage, there are few studies on the impact of water resource shortage and the ecological environment in mega-regions. Taking the three major urban agglomerations in Western China as an example, the spatial–temporal agglomeration pattern and driving force for the risk of water shortage are analyzed. First, a new comprehensive index system for environmental risks of water resources has been established, which can be used to assess spatial changes in water resource shortage risks. Secondly, the relationship between water resource shortage and the urban agglomeration effect is discussed in regards to water resource vulnerability, exposure, and recoverability. The results showed: (1) From 2000 to 2018, the risk of total water shortage in 12 provinces (cities) in Western China decreased from 3.42 to 2.59; the risk of total water shortage in the Guanzhong Plain urban agglomeration dropped the fastest, with an average annual decline rate of 10.57%. (2) Water resource shortage in different cities of the three major urban agglomerations is out of sync in time and space; the risk level of water shortage is high in the north and low in the south. (3) Geological environmental change is an important influencing factor of water resource shortage; the negative impact of industrial water use on the risk of water shortage is the largest, with a contribution of 24.9%. In addition, this paper also puts forward policy suggestions to alleviate the risks of water shortage in the urbanization process in the western region. This research can provide a scientific basis for the sustainable development of urban water resources.

Keywords: environmental risk; water scarcity; water environmental sustainability; water pollution; urban agglomeration

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1. Introduction

With the high intensity and speed of economic development, the issue of water resource shortage and its risks have gradually become a hot topic, particularly in developing countries [1]. The 2020 World Economic Forum has identified water shortage as one of the most significant global threats in the coming ten years. China's urbanization process has experienced a low starting point and rapid development. China's permanent urban population rose from 170 million in 1978 to 830 million in 2018. The urbanization rate of permanent residents increased from 17.9% to 59.95%. China's urbanization will be in rapid development for quite a long time. Promoting urbanization is an effective strategy related to modernization construction [2]. The vast western area will become the main battlefield of urbanization construction. With many people and industries gathering in cities and many production and domestic sewage discharges, China's water resources face a dire situation. Problems, such as water shortage, severe water pollution, and deterioration of the ecological environment, are becoming increasingly prominent [3]. Water shortage has become a bottleneck restricting China's urbanization and economic development [4]. For Western China, the situation and risk of water shortage are also more serious.

On the one hand, the overall water situation in the western region is very complex. In 2018, the water resources of the 12 provinces and municipalities in the western region were 1615.28 billion m^3, accounting for 58.8% of China's total water resources [5]. However, the water resource endowment of each province and urban area in the region is quite different. Although the total amount of water resources in northwestern China is large, the amount of water resources per capita is small, and a large amount of ecological water is polluted [6,7]. Therefore, there is a severe water deficit in the local area. In addition, the southwest is relatively rich in water resources, but the development and utilization conditions are rather difficult because the spatiotemporal distribution does not match the demand [8,9]. Regional and seasonal water shortages are equally severe.

On the other hand, the western region has started to experience a rapid growth stage, with an urbanization rate of 30–70% [10]. The urbanization rate in most areas has maintained an average yearly growth rate of 1% or more. The problem of disharmony between urbanization construction and water resources carrying capacity is becoming more and more prominent [11]. Many cities and towns face water shortage problems regarding quantity, quality, resources, and engineering [12]. In this context, the risk of water shortage has attracted significant attention from all walks of life in Western China's urbanization process [13–15]. How can the water shortage risk be efficiently measured in Western China's urbanization process? What is the status of the water shortage risk in Western China's urbanization process? Does this water shortage risk have obvious regional heterogeneity in different regions? The answers to these questions will help to fully estimate and deal with the severe water shortage situation in Western China as soon as possible to remove the severe water constraints shortage, ensure the safety of water resources, and continuously achieve high-quality economic and social development.

There are many existing studies on the risk of water shortage. They mainly focus on selecting performance indexes and methods of water shortage risk assessment [16]. The current index system design methods of the water shortage risk assessment are primarily based on the fundamental framework of risk assessment, the causes of water shortage risk, and representative indicators concerning performance indicators of water shortage risk assessment. For example, in the design of indicators based on the primary risk assessment framework, researchers believe that the risk assessment indicators of natural disasters are Probability, Exposure, and Vulnerability [17]. Based on this research, some scholars began to choose relatively specific indicators to reflect these dimensions around the connotation of each dimension. Criterion layers, such as hazard [18], vulnerability [19], exposure [20], and recoverability [21], are relatively conventional selection criteria for assessment indicators of the water shortage risk. Water resource quantity, social demand, water resource reserve, water supply, and ecological environment are also the key factors affecting water resource risk assessment [22,23]. As the indicator system is gradually improved, some researchers have considered the water shortage rate as an alternative indicator of the water shortage risk [24]. At the same time, explanatory variables and risk factors, such as rainfall, a permanent population, tertiary industry, and other water consumption in daily life, were established [25]. The level of water shortage risk for future short-term years is predicted by calculating the historical year water shortage rate and classifying the level of water shortage risk [26].

There is a large amount of research on risk assessment methods for water resources, such as projection pursuit models or the combination of normal cloud assessment models [27]. Dempster/Shafer's evidence theory was used to construct the risk evaluation performance function [28], and others have evaluated and estimated the water shortage risk in different regions. Fuzzy comprehensive evaluation [29] is often used in risk assessment and management of water resources. This method is generally used to deal with uncertain problems that are difficult to quantify. Researchers often integrate fuzzy triangular theory (TFT) to build relevant models to ensure the authenticity of data [30] and use entropy as the weight of water resources risk assessment [31]. Due to the influence of social development and geographical location, the current research on the risk assessment of water resources in China is mostly concentrated in the regions with abundant and highly variable water resources, such as the Yangtze River Economic Belt and the Yellow River Basin in China. However, most are concentrated in the downstream regions, such as the Beijing–Tianjin–Hebei and the Yangtze River Delta [32,33].

Although some progress has been made in the study of water scarcity risk [34–36], some aspects still deserve further research. Firstly, previous studies have mainly focused on assessing water scarcity risk in single or multiple regions and their internal water scarcity risk [34–37], but they have focused less on assessing water scarcity risk in the western region, especially in the representative western urban agglomerations. Therefore, there is an urgent need to carry out a comprehensive analysis of water scarcity risk and its environment in the western region of China and to reveal the actual situation of domestic, industrial, and agricultural water use risk and its environmental management in the process of urbanization. Secondly, the obstacles to water scarcity risk in the western urban agglomerations should be further examined, and locally adapted policies and guidelines for sustainable water supply should be proposed. The Chengdu–Chongqing urban agglomeration, the Lanxi urban aggregation, and the Guanzhong urban agglomeration are the main typical areas in the west where urban water use is intensive, and they are essential ecological logistic barriers that provide various ecological services in China. In addition, although the total amount of water resources in the western region is large, the per capita water resources are small.

In recent years, with the accelerated urbanization and industrialization in the western region, the consumption of water resources has increased, and the water environment has suffered serious pollution [15]. Water resources are crucial to maintaining human life's health and socio-economic development [34]. Therefore, exploring the risk of water shortage and its environmental impacts in the western region is vital and urgent.

Therefore, this paper aims to analyze the water scarcity footprint and its environmental impacts in the western region and its three major urban agglomerations and to reveal the risk of water scarcity and its impediments in the western region. Based on these results, policy recommendations are made regarding the need for subregional management of water resources in western cities in accordance with the urbanization process and actual water consumption. This study can provide policy recommendations for western urban agglomerations to reduce environmental pollution of water resources and to promote regional ecological protection and the sustainable development of water resources (Figure 1).

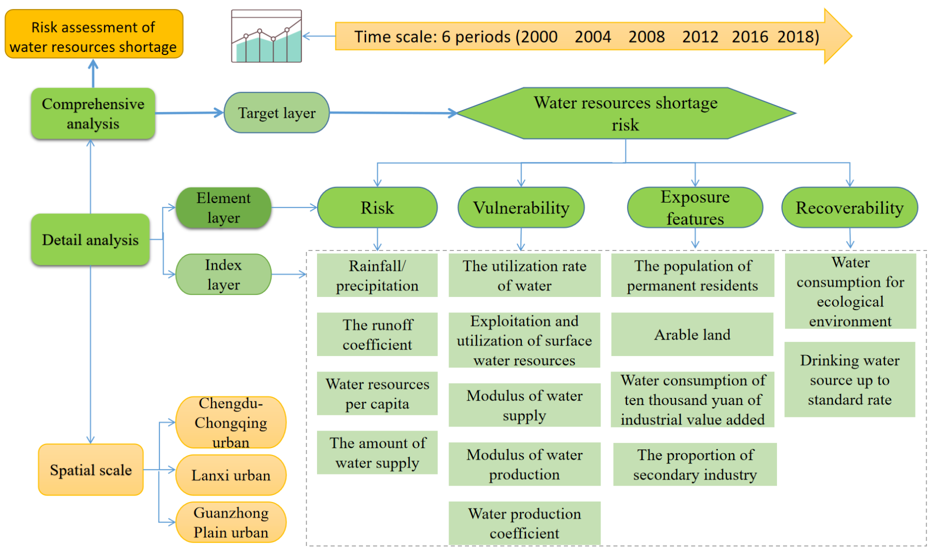


Figure 1. The overall framework of water scarcity and environmental risk assessment in Western China. (Source: The figure is drawn by the author).

2. Materials and Methods

2.1. Determination of the Index System and Data Sources

(1) Research time interval

The study area of this paper is the western region. The basic units are divided into two scales: provincial administrative units and prefectural administrative units. The provincial administrative units mainly include 12 provinces and urban areas: Sichuan, Shaanxi, Gansu, Qinghai, Yunnan, Guizhou, Chongqing, Guangxi, Inner Mongolia, Ningxia, Xinjiang, and Tibet. The prefecture-level administrative unit includes three typical urban agglomerations: Chengdu–Chongqing urban agglomerations, Guanzhong Plain urban agglomerations, and Lanxi urban agglomerations, as the research objects. Among them, the Chengdu–Chongqing urban agglomeration mainly includes 16 prefectural administrative units: Chongqing, Chengdu, Mianyang, Zigong, Luzhou, Deyang, Suining, Neijiang, Leshan, Ziyang, Yibin, Nanchong, Dazhou, Ya'an, Guang'an, and Meishan. The Guanzhong Plain urban agglomeration includes Xi'an, Baoji, Xianyang, Tongchuan, Weinan, Yangling, and Shangluo in Shaanxi, Yuncheng and Linfen in Shanxi, and Tianshui and Pingliang in Gansu, with a total of 11 prefectural-level administrative units. The Lanxi city group comprises nine prefecture-level administrative units: Lanzhou, Baiyin, Dingxi, and Linxia in Gansu Province, and Xining, Haidong, Haibei, Hainan, and Huangnan in Qinghai Province.

Considering that all provincial and prefecture-level administrative units in China formed the public release system of water resources bulletin around 2000, as well as the completeness and availability of the collected data, the time interval of this study is 2000–2018.

(2) Index selection

Referring to the current research results of current scholars and combining them with the basic features of water resources in Western China, this paper constructs a risk assessment index system for water resources shortage from four dimensions: risk, vulnerability, exposure, and recoverability. It is generally divided into fifteen third-level, one first-level, and four second-level indicators (Table 1).

In terms of risk, this paper uses rainfall/precipitation [35], runoff coefficient [16], per capita water resources [36], and total water supply [37] to measure risk. As the source of water resources, the change in rainfall directly affects the number of water resources. The runoff coefficient is the ratio of the runoff depth R to the depth of the precipitation P at any given period, representing whether the soil absorbs the rainfall more easily. Water resources per capita refer to the number of water resources per person per population in a region (watershed) in a certain period. The total water supply refers to the water needed for social and economic development during a specific time in a region (watershed). It primarily consists of groundwater and surface water. The characteristics of the indicators above show that the danger of water scarcity increases with decreasing value.

In terms of vulnerability, the utilization rate of water resources, the utilization rate of surface water resources [38], the water supply modulus [39], the water production modulus, and the water production coefficient were used to measure the vulnerability [40,41]. Among them, the utilization rate of water resource development refers to the water consumption ratio in a basin or region to the total water resources. It depicts the use and development of water resources. The utilization rate of surface water resource development refers to the ratio of surface water consumption in a basin or region to the total surface water resources. The water supply and yield ratios to the area are the modulus of water supply and the modulus of water yield. The water yield coefficient is the total water resources/annual rainfall to a certain extent. According to the properties of the indicators, there is a larger probability of water scarcity the lower their values are.

Table 1. Evaluation index system of water shortage risk level in the urbanization process in Western China.

Level 1 Indicator	Level 2 Indicator	Level 3 Indicator	Unit	Symbol
Water resources risk assessment index system	Risk	Rainfall/precipitation	Billion cubic meters	−
		The runoff coefficient	%	−
		Water resources per capita	Cubic meters per person	−
		The amount of water supply	Billion cubic meters	−
	Vulnerability	The utilization rate of water resources	%	−
		Exploitation and utilization of surface water resources	%	−
		Modulus of water supply	Ten thousand cubic meters per square kilometer	−
		Modulus of water production	Ten thousand cubic meters per square kilometer	−
		Water production coefficient	%	−
	Exposure features	The population of permanent residents	Ten thousand people	+
		Arable land	Thousands of hectares	+
		Water consumption of CNY 10,000 of industrial value added	Cubic meters	+
		The proportion of secondary industry	%	+
	Recoverability	Water consumption for ecological environment	Billion cubic meters	−
		Drinking water source up to standard rate	%	−

Note: "+" and "−" are used to indicate positive and negative indicators, respectively. The higher/smaller the index value, the higher the risk of water shortage.

Regarding exposure, we used indicators, such as resident population, cultivated land area, water consumption per CNY 10,000 of industrial added value, and proportion of secondary industry, to measure exposure [32]. Among them, the permanent resident population is the sum of the existing permanent resident population and the temporary migrant population. The size of the people will place enormous demands and pressures on water resources. Arable land can be used to grow crops and is regularly plowed. It is an indispensable condition of agricultural production activity. The larger the cultivated area is, the larger the irrigation water consumption is. The water consumption of CNY 10,000 of industrial added value is needed to produce CNY 10,000 of output value. It is an effective measure of industrial water consumption. The higher the water consumption while maintaining the output value, the greater the risk of water shortage. The proportion of secondary industry refers to the balance of mining, manufacturing, electricity, and construction in the national economy. These industries require more water and produce more pollution than other industries.

In terms of recoverability, this paper used ecological and environmental water consumption [32] and drinking water source compliance rate [42] to measure recoverability. Ecological and environmental water use refers to the minimum amount required to restore and construct the ecological environment or maintain the status quo so that the quality of the ecological environment does not decline. Nature depends on water and the survival and development of all animals, plants, and environmental water. Drinking water sources to standard rate refers to the rate of meeting drinking water sources standards within the city limits.

The data in this paper mainly come from the China Statistical Yearbook, China Regional Economic Statistical Yearbook, China Urban Statistical Yearbook, China Environmental Statistical Yearbook, China Water Resources Bulletin, and the statistical yearbooks and water resources bulletin of various provinces, cities, and prefectures from 2001 to 2019. Considering that some data are missing in the yearbook, we utilize the moving weighted average method to estimate the missing values of individual indicators in individual regions and years.

2.2. Evaluation Methods

(1) Information entropy weight (EMM) method

Entropy is derived from thermodynamics and can be used to measure system disorder [43]. The entropy weight method is an objective assignment method that determines weights according to the magnitude of indicator variability. Suppose the information entropy value of an indicator is smaller. In that case, it indicates that the greater the degree of variability of the indicator value, the more information is provided, and the greater the weight in the comprehensive evaluation; on the contrary, the greater the entropy value, the smaller the weight assigned to the indicator [44].

According to the annual evaluation indexes of relevant cities in provinces and typical urban groups in the western region, the entropy value is used to judge the uncertainty. The greater the uncertainty of the variable, the higher the degree of dispersion. The more information needed, the greater the entropy. The degree of dispersion is positively correlated with the weight.

Construct the judgment matrix. To construct the judgment matrix of each annual evaluation index of relevant cities in western provinces and typical urban agglomerations, let each region be $A = (A_1, A_2, A_3, A_4, A_5 \ldots A_n)$. The 15 evaluation indexes are $B = (B_1, B_2, B_3, B_4, B_5 \ldots B_{15})$. X_{ij} indicates the value of the index B_j corresponding to region A_i.

$$X_{ij} = \begin{vmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mn} \end{vmatrix}_{m \times n} \quad (1)$$

Min–max normalized processing. Before calculating the characteristic proportion, the data are processed without dimensionalization. In this paper, the min–max normalization method is chosen. The judgment matrix is linearly transformed, and its deviation is normalized and mapped to between [0 and 1].

In this paper, the bigger, the better indicator is set as:

$$V_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \quad (2)$$

The smaller, the better indicator is set as:

$$V_{ij} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} \quad (3)$$

Determine entropy and upper weights. After dimensionless processing of the data, the characteristic ratio of the JTH evaluation index of the ith region is first calculated as follows:

$$P_{ij} = \frac{V_{ij}}{\sum_{i=1}^{m} V_{ij}} (0 \le P_{ij} \le 1) \quad (4)$$

Calculate the entropy value of the evaluation index:

$$e_j = -\frac{1}{\ln(m)\sum_{i=1}^{m} P_{ij} \cdot \ln P_{ij}} \tag{5}$$

Define the entropy weight of the evaluation index:

$$W_j = \frac{(1 - e_j)}{\sum_{i=1}^{n}(1 - e_j)} \tag{6}$$

(2) Fuzzy comprehensive evaluation method

The fuzzy comprehensive evaluation method is a method to make a comprehensive decision on a thing for a certain purpose in a fuzzy environment, considering the influence of multiple factors [45]. The method is characterized by clear and systematic results, and can better solve ambiguous and difficult problems [46]. Therefore, this method is often used to solve various non-deterministic problems.

In this paper, the fuzzy comprehensive evaluation method is used to evaluate each index of water shortage risk by comparing it with their standards. The evaluation results were described by the membership degrees of low risk, low risk, medium risk, high risk, and high risk belonging to the fuzzy level. The transformation from qualitative evaluation to quantitative evaluation is realized.

Construct the evaluation matrix. Based on the information entropy weight method above, the weights of the first-level evaluation indexes are calculated as $A = [a_1, a_2, a_3, a_4]$, while the weights of the second-level evaluation indexes are, respectively: $A_1 = [a_1, a_2, a_3, a_4]$, $A_2 = [a_1, a_2, a_3, a_4, a_5]$, $A_3 = [a_1, a_2, a_3, a_4]$, and $A_4 = [a_1, a_2]$. To judge the grade of the index value based on the grading standard and construct the judgment matrix:

$$R_{Risk} = (1_{ij})_{4\times 12} = \begin{vmatrix} r_{111} & r_{112} & \cdots & r_{1112} \\ r_{121} & r_{122} & \cdots & r_{1212} \\ r_{131} & r_{132} & \cdots & r_{1312} \\ r_{141} & r_{142} & \cdots & r_{1412} \end{vmatrix} \tag{7}$$

$$R_{Vulnerability} = (2_{ij})_{5\times 12} = \begin{vmatrix} r_{211} & r_{212} & \cdots & r_{2112} \\ r_{221} & r_{222} & \cdots & r_{2212} \\ r_{231} & r_{232} & \cdots & r_{2312} \\ r_{241} & r_{242} & \cdots & r_{2412} \\ r_{251} & r_{251} & \cdots & r_{2512} \end{vmatrix} \tag{8}$$

$$R_{Exposure\ features} = (3_{ij})_{4\times 12} = \begin{vmatrix} r_{311} & r_{312} & \cdots & r_{3112} \\ r_{321} & r_{322} & \cdots & r_{3212} \\ r_{331} & r_{332} & \cdots & r_{3312} \\ r_{341} & r_{342} & \cdots & r_{3412} \end{vmatrix} \tag{9}$$

$$R_{Recoverability} = (4_{ij})_{2\times 12} = \begin{vmatrix} r_{411} & r_{412} & \cdots & r_{4112} \\ r_{421} & r_{421} & \cdots & r_{4212} \end{vmatrix} \tag{10}$$

This is the weight synthesis and evaluation matrix. The synthesis operation results in:

$$B_i = A_i \times R_i = [b_{i1}, b_{i2}, b_{i3}, b_{i4} \cdots b_{i12}]\ (i = 1, 2, 3, 4) \tag{11}$$

The comprehensive evaluation decision matrix is:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{112} \\ b_{21} & b_{22} & \cdots & b_{212} \\ b_{31} & b_{32} & \cdots & b_{312} \\ b_{41} & b_{42} & \cdots & b_{412} \end{bmatrix} \tag{12}$$

Finally, the results of water shortage risk are calculated as follows:

$$B = A \times R = [a_1, a_2, a_3, a_4]\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = [b_1, b_2, b_3, b_4 \cdots b_{12}] \tag{13}$$

(3) Determination of evaluation criteria

The average method is adopted in this paper to grade each index and shortage risk result. After the sequence is arranged from smallest to largest, it is averaged into five parts. This is the standard and weight to establish the corresponding grade interval. Based on the evaluation index of the water shortage risk level, the classification standard and weight are determined, and the results are shown in Table 2 below.

Due to the availability and representativeness of the data, the tertiary indicators of the recoverability of the water shortage risk in the urban agglomerations of the western region replace the forest cover degree and the nature reserves area. The correlation between them is expressed as follows:

Protecting and increasing forest cover improves the sustainability and quality of ecosystem water use, as forests play an essential role in water quality protection and availability in the water cycle [47]. Higher forest cover implies, on the one hand, that the urban area is rich in water resources and that it can provide better water conditions for urban ecosystems [48]; on the other hand, higher forest cover indicates better water quality protection and ecosystem services, and more efficient and sustainable urban water recycling [49].

Nature reserves serve to protect water sources and guard against pollution. Nature reserves usually include natural environments with essential water source functions, such as mountain ranges, lakes, and rivers [50]. The establishment and management of these reserves help to maintain the pristine state of water sources and reduce the negative impacts of human activities on water resources, thus improving the water quality of drinking water sources. In addition, the ecosystems of nature reserves can filter and absorb pollutants from urbanization, reducing the risk of contamination of water bodies [51]. Therefore, a larger area of nature reserves may further contribute to a higher compliance rate of drinking water sources.

The risk values of water shortage in twelve provinces, urban districts, and three urban agglomerations in Western China from 2000 to 2018 were calculated with the evaluation index grading standard and fuzzy evaluation method. The value of risk is further divided into five levels. The corresponding grade standards and their risk characteristics are shown in Table 3.

Table 2. Classification standards of shortage risk indicators for water resources in Western China.

The Secondary Indicators	I	II	III	IV	V	The Upper and Lower Limit	Weight Value
Rainfall	[4455.586,7491.334]	[2999.74,4455.586)	[2053.34,2999.74)	[1220.516,2053.34)	[102.969,1220.516)	[102.969,7491.334]	0.050
The runoff coefficient	[0.545,1.885]	[0.467,0.545)	[0.295,0.467)	[0.183,0.295)	[0.043,0.183)	[0.143,1.885]	0.015
Water resources per capita	[5062.131,176190.370]	[3454.416,5062.131)	[2137.554,3454.416)	[1039.773,2137.554)	[126.227,1039.773)	[126.227,176190.370]	0.027
The amount of water supply	[232.220,590.14]	[146.804,232.220)	[88.976,146.804)	[66.700,88.976)	[24.590,66.700)	[24.590,590.14]	0.037
Utilization rate of water	[53.259,246.932]	[20.494,53.259)	[11.355,20.494)	[7.078,11.355)	[0.530,7.078)	[0.530,246.932]	0.017
Exploitation and utilization of surface water resources	[46.195,1375.051]	[17.106,46.195)	[10.300,17.106)	[6.591,10.300)	[0.502,6.591)	[0.502,1375.051]	0.018
Annual water supply modulus	[9.518,16.834]	[4.413,9.518)	[3.510,4.413)	[1.515,3.510)	[0.205,1.515)	[0.205,16.834]	0.038
Modulus of annual water output	[58.544,257.889]	[40.508,58.544)	[10.780,40.508)	[4.634,10.780)	[1.130,4.634)	[1.130,257.889]	0.014
Water production coefficient	[0.539,0.662]	[0.453,0.539)	[0.310,0.453)	[0.180,0.310)	[0.053,0.180)	[0.053,0.662]	0.089
The population of permanent residents	[258,613.076)	[613.076,2509.794)	[2509.794,3503.384)	[3503.384,4606.800)	[4606.800,8725]	[258,8725]	0.117
Arable land	[361.14,1268.800)	[1268.800,3995.096)	[3995.096,4927.740)	[4927.740,6231.900)	[6231.900,9286.93]	[361,9286.93]	0.105
Water consumption of CNY 10,000 of industrial value added	[83.547,247.209)	[247.209,473.035)	[473.035,915.181)	[915.181,1953.629)	[1953.629,10245.302]	[83.547,10245.302]	0.249
Proportion of secondary industry	[20.4,39.040)	[39.040,42.400)	[42.400,45.320)	[45.320,48.969)	[48.969,58.4]	[20.4,58.4]	0.018
Forest cover degree	[39.834,60.17]	[30.270,39.834)	[11.980,30.270)	[6.312,11.980)	[2.94,6.312)	[2.94,60.17]	0.154
Nature reserve area	[2060.818,4150.277]	[874.814,2060.818)	[147.908,874.814)	[89.114,147.908)	[20.484,89.114)	[20.484,4150.277]	0.051

Table 3. Risk grade classification.

Risk Level	Value at Risk	Meaning	Risk Characteristics
I	[0.000,1.000]	Low risk	Normal
II	[1.001,2.000]	Relatively low risk	Mild water shortage
III	[2.001,3.000]	Medium risk	Moderate water shortage
IV	[3.001,4.000]	Relatively high risk	An acute shortage of water
V	[4.001,5.000]	High risk	Excessive water shortage

3. Results and Discussion

According to the evaluation index grading criteria and the fuzzy evaluation method proposed above, we calculated the risk values of water shortage in 12 provinces (cities) in Western China from 2000 to 2018 at the provincial level and in the Chengdu–Chongqing, Lanxi, and Guanzhong urban agglomerations. According to the moving average method, the risk value of water shortage is divided into five levels and analyzed.

3.1. Analysis of the Risk of Water Shortage in 12 Provinces (Cities) in Western China

From 2000 to 2018, 12 provinces (cities) in Western China exhibited a steady decline in the risk of water shortage. The risk assessment value of the total water shortage in 12 provinces (cities) decreased significantly. The risk level of water shortage in most provinces (cities) decreased accordingly, as shown in Figure 2 below.

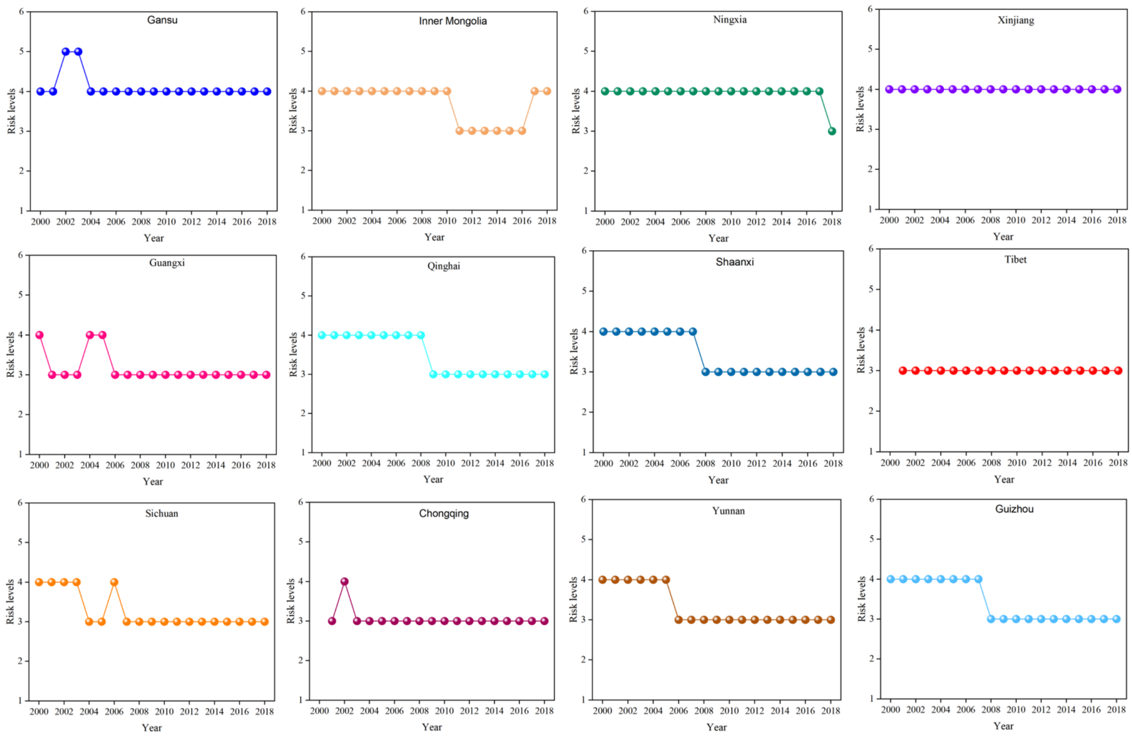


Figure 2. Risk levels of water shortage in 12 provinces (cities) in China West from 2000 to 2018 (I—1, II—2, III—3, IV—4, V—5, and VI—6).

Guizhou, Qinghai, and Shaanxi significantly declined in the total assessed value of water resources shortage risk. The total assessed value of water shortage risk decreased from 3.619, 3.665, and 3.648 in 2000 to 2.236, 2.412, and 2.397 in 2018, respectively. The decrease was 38.22%, 34.17%, and 34.28%, respectively. The comprehensive assessment value of water shortage risk in Xinjiang had the lowest decline. It fell from 3.413 in 2000 to 3.397 in 2018, a drop of just 0.44 percent.

Regarding the risk level of water resources shortage, except Xizang and Chongqing, which were at level III (moderate risk), the other ten provinces and municipalities were all at level IV (high risk) in 2000. In 2018, except for Gansu, Inner Mongolia, and Xinjiang, which were at level IV (high risk), the remaining areas were at level III (medium risk). From 2000 to 2018, eight provinces and municipalities, including Guangxi, Guizhou, Ningxia, Qinghai, Shaanxi, Sichuan, Yunnan, and Chongqing, dropped from level IV (high risk) to level III (moderate risk). Xinjiang and three other provinces and municipalities have maintained level IV (high risk). The risk of water shortage in Gansu and Inner Mongolia fluctuated somewhat, but it was generally at level IV (high risk). Tibet remained at level III (moderate risk). Both Gansu and Chongqing experienced the stage of risk level rising and quickly recovering in a short period. Shortly after a temporary drop in risk level, Inner Mongolia promptly returned to its previous state, which also demonstrates that the risk of water shortage facing the western regions of China has been alleviated somewhat with the acceleration of the urbanization process, especially after entering the quality-oriented new stage of urbanization. The risk of water shortage still has the possibility of rebounding at any time, which needs to be paid attention to.

In order to guarantee the sustainability of water resources and water environment pollution prevention in Northwest China, we need to strengthen the planning of ecological spatial patterns within Northwest China's urban agglomeration and create a Yellow River ecological corridor based on the skeleton of mountains, water, and green color [52]. In addition, the construction of ecological corridors improves downstream ecological conditions, realizes the filtering function of water pollutants, promotes soil and water conservation and pollution prevention in Northwest China, accelerates the construction of green cities with ecological livability and water resources recycling, and encourages public participation in water resources ecological and environmental protection [49,52].

As shown in Figure 3, the risk levels of water shortage in the 12 provinces (cities) in Western China's urbanization process in 2018 were mostly level III or above (medium and high risk). The risk level of Gansu, Inner Mongolia, and Xinjiang was level IV (higher risk level). The comprehensive assessment values of water shortage risk were 3.120, 3.054, and 3.397, respectively. Guangxi, Guizhou, Ningxia, Qinghai, Shaanxi, Sichuan, Tibet, Yunnan, and Chongqing are at level III (higher risk level). The comprehensive assessment values of water shortage risk are 2.333, 2.236, 2.932, 2.412, 2.397, 2.315, 2.313, 2.372, and 2.189, respectively. Xinjiang and Chongqing are the regions with the highest and lowest risks of water shortage among the 12 provinces and municipalities. In 2018, the risk levels of water shortage in the 12 provinces (cities) in Western China's urbanization process generally decreased from north to south. The reasons for the formation of this phenomenon are, on the one hand, the unique geographical conditions in Northwest China, as some areas have less precipitation and greater evaporation. Arid climate conditions determine the inborn shortage of water resources endowment. However, Northwest China's economic development and urbanization started late. It has reached the stage of fast urbanization, which puts a tremendous amount of strain on its water resources system from the people, industry, and society. Additionally, this somewhat increases the likelihood of water scarcity.

3.2. Analysis of the Chengdu–Chongqing Urban Agglomeration

The risk of water shortage in the Chengdu–Chongqing urban group showed a significant downward trend from 2000 to 2018. The comprehensive assessment value of water shortage risk in the remaining 18 cities declined to varying degrees. Accordingly, the risk level of water shortage in most cities decreased, as shown in Figure 4.

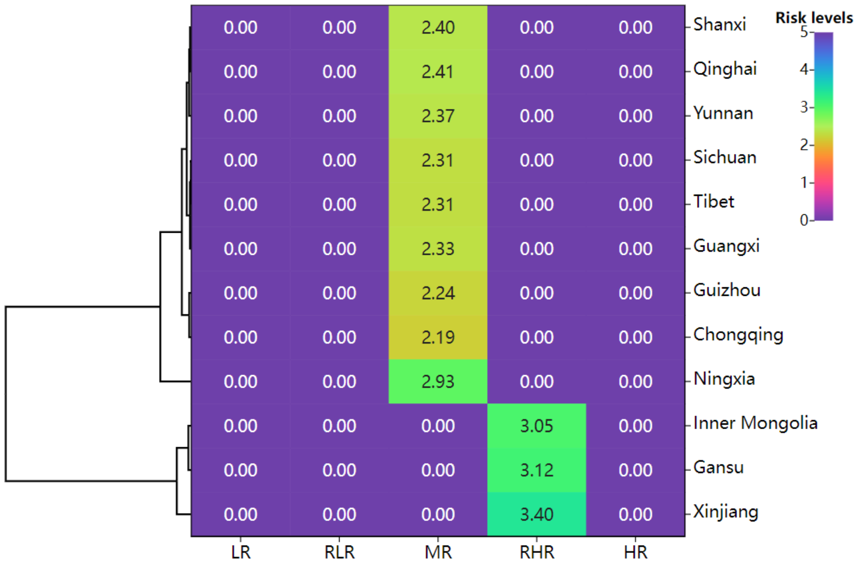


Figure 3. Cluster distribution of water shortage risk in Western China. (Low risk is abbreviated as LR. Relatively low risk is abbreviated as RLR. Medium risk is abbreviated as MR. Relatively high risk is abbreviated as RHR. High risk is abbreviated as HR).

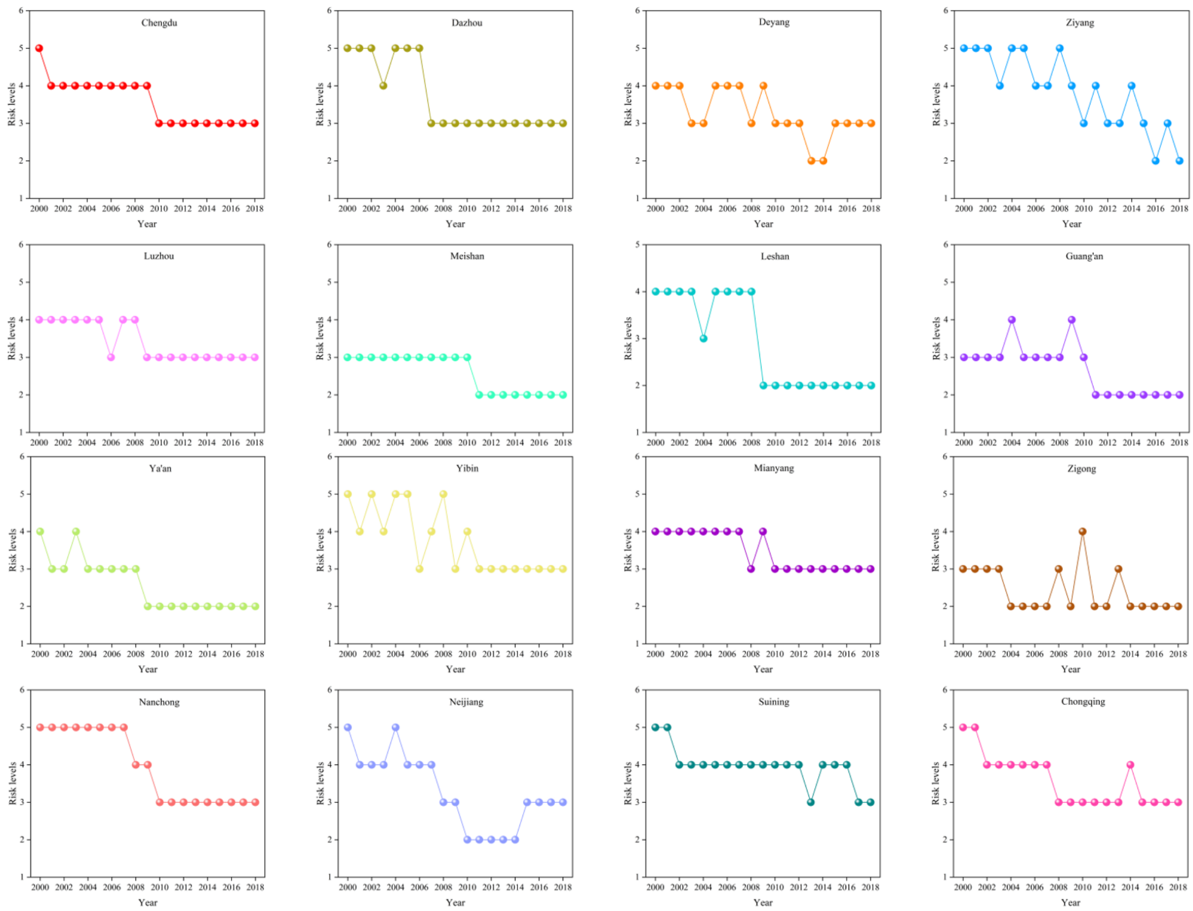


Figure 4. Risk levels of risky water resources shortage in the Chengdu–Chongqing urban agglomeration from 2000 to 2018.

From the comprehensive risk assessment value for water shortage, Leshan, Neijiang, Ya'an, and Ziyang had a significant decline, with a drop of more than 50%. The comprehensive assessment value of water shortage risk decreased from 3.965, 4.289, 3.412, and 4.240 in 2000 to 1.933, 2.123, 1.371, and 1.857 in 2018, respectively. The decrease was 51.25%, 50.50%, 59.81%, and 56.21%, respectively. The comprehensive assessment value of water resources shortage risk in Luzhou and Meishan decreased slightly. These two cities decreased from 3.431 and 2.592 in 2000 to 2.413 and 1.844 in 2018, respectively. The decrease was 29.68% and 28.88%, respectively. Each city experienced a fluctuating danger of water shortage from 2000 to 2018. The difference in the total assessed value of water scarcity risk among cities is also large.

In 2000, there was a potential for a water resources deficit. Guang'an, Meishan, and Zigong are level III (medium risk). The remaining 14 cities are all at level IV (higher risk) or above. Chengdu, Dazhou, Nanchong, Neijiang, Suining, Yibin, Chongqing, and Ziyang are at V-level (high risk). In 2018, the risk of water shortage in 16 cities was reduced to level III (moderate risk) or below. Seven cities (Guang'an, Leshan, Meishan, Ya'an, Ziyang, and Zigong) were downgraded to Grade II (lower risk).

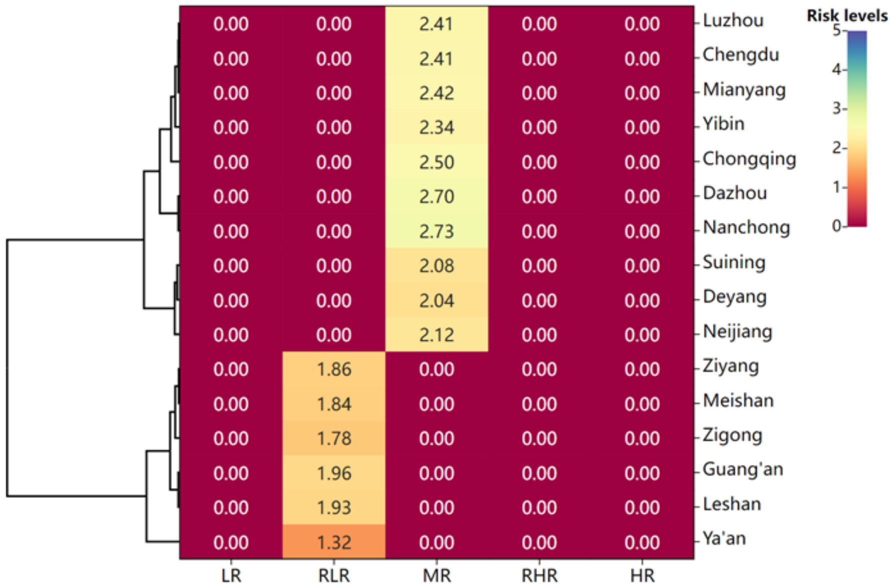
The Chengdu–Chongqing region is an essential strategic region in China to accelerate the development of the western region, enhance the level of inland openness, and strengthen the country's comprehensive strength [53]. In 2022, the GDP of the Chengdu–Chongqing region accounted for 7.3% of the national GDP [54]. The rapid development of the economy has brought great pressure on the supply of water resources. In particular, the accelerated urbanization has led to a continuous increase in domestic water consumption. The primary source of water supply in Chengdu is the Minjiang River, which is a single source of water supply [55].

In recent years, the massive exploitation of water resources in the upper reaches of the Minjiang River has led to the drying up of some of the river's tributaries, resulting in a tight water supply for the city of Chengdu. Chongqing Municipality also faces the same problem, with water scarcity putting tremendous pressure on the city's sustainable development and hindering socio-economic development [55]. However, the Chengdu–Chongqing regional government has adopted new quality-oriented urban water planning and management, alleviating the water shortage risk in Chengdu–Chongqing cities [56]. The bearing status has also been effectively improved. However, seasonal, regional, engineering, and water shortage problems remain prominent, making the situation grim.

As shown in Figure 5, the water shortage risk of the Chengdu–Chongqing urban agglomeration in 2018 is concentrated in grade II (low risk) and grade III (medium risk) ranges. The risk level of Guang'an, Leshan, Meishan, Ya'an, Ziyang, and Zigong is level II (low risk). The comprehensive assessment values of water shortage risk are 1.958, 1.933, 1.844, 1.371, 1.857, and 1.776, respectively. Nanchong had the highest risk of water shortage (2.727). Ya'an had the lowest risk of water shortage. The cluster distribution of water shortage risk in the Chengdu–Chongqing urban group is irregular. The overall pattern is low in the west and high in the east. Nanchong, Dazhou, and Chongqing have the highest risk of water shortage. This phenomenon is because hills and mountains dominate the eastern part of Sichuan. The sloping land has a large area. Although rainfall is relatively abundant, special geographical and geological conditions cause difficulties in water storage. Additionally, the demand for water resources in areas with concentrated populations and high social and economic development levels increases rapidly. The risk of water shortages is correspondingly higher.

3.3. Analysis of the Lanxi Urban Agglomeration

The water shortage risk of nine cities in the Lanxi urban clusters decreased gradually from 2000 to 2018. The comprehensive assessment value of water shortage risk in nine cities decreased significantly. Accordingly, the risk level of water shortage in most cities decreased, as is demonstrated in Figure 6.



	LR	RLR	MR	RHR	HR
Luzhou	0.00	0.00	2.41	0.00	0.00
Chengdu	0.00	0.00	2.41	0.00	0.00
Mianyang	0.00	0.00	2.42	0.00	0.00
Yibin	0.00	0.00	2.34	0.00	0.00
Chongqing	0.00	0.00	2.50	0.00	0.00
Dazhou	0.00	0.00	2.70	0.00	0.00
Nanchong	0.00	0.00	2.73	0.00	0.00
Suining	0.00	0.00	2.08	0.00	0.00
Deyang	0.00	0.00	2.04	0.00	0.00
Neijiang	0.00	0.00	2.12	0.00	0.00
Ziyang	0.00	1.86	0.00	0.00	0.00
Meishan	0.00	1.84	0.00	0.00	0.00
Zigong	0.00	1.78	0.00	0.00	0.00
Guang'an	0.00	1.96	0.00	0.00	0.00
Leshan	0.00	1.93	0.00	0.00	0.00
Ya'an	0.00	1.32	0.00	0.00	0.00

Figure 5. Cluster distribution of water shortage risk in the Chengdu–Chongqing urban agglomeration in 2018. (Low risk is abbreviated as LR. Relatively low risk is abbreviated as RLR. Medium risk is abbreviated as MR. Relatively high risk is abbreviated as RHR. High risk is abbreviated as HR).

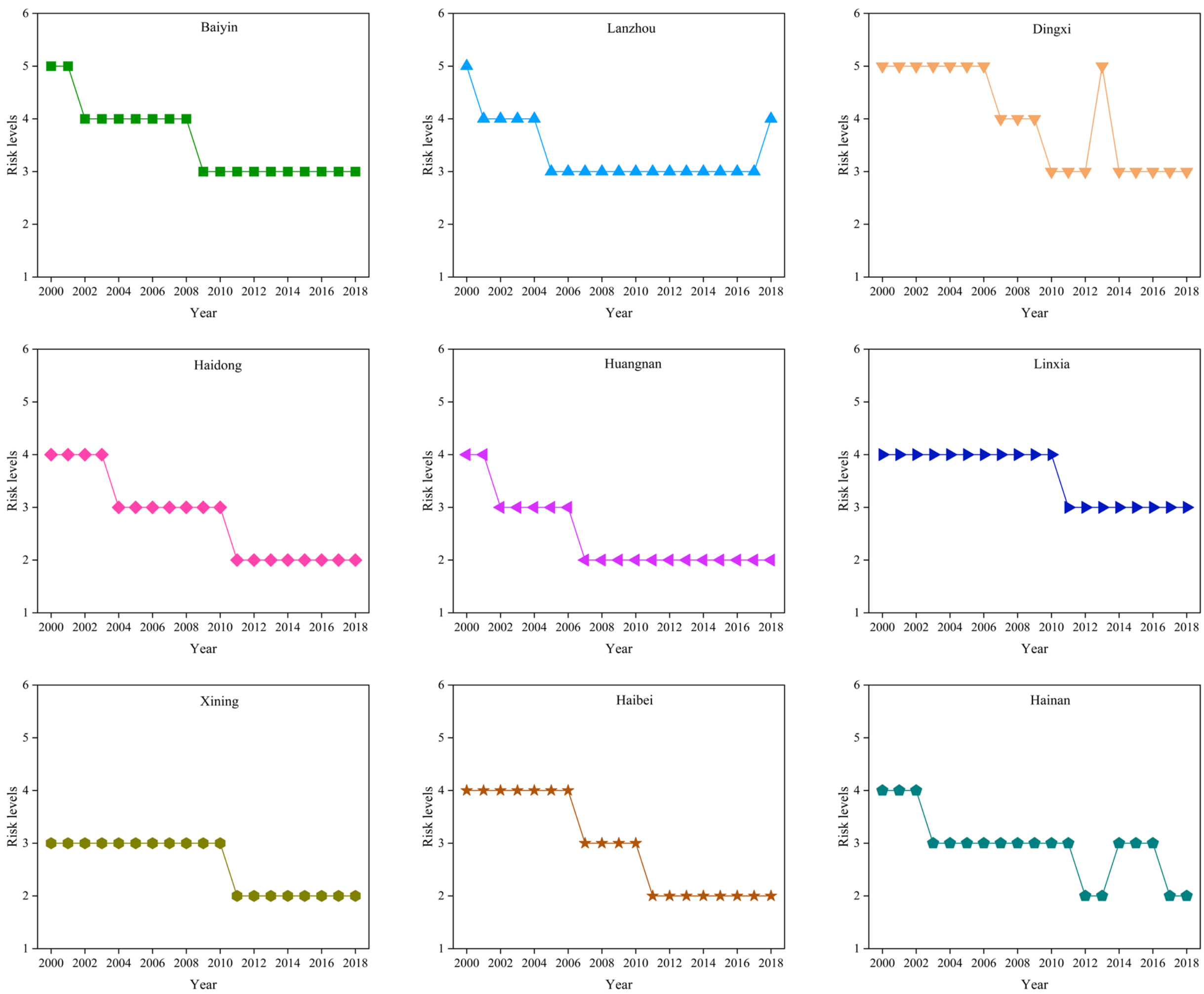


Figure 6. Risk levels of water resources shortage in the Lanxi urban agglomeration from 2000 to 2018.

According to the comprehensive assessment value of water shortage risk, the most significant decline was observed in southern Huanghe, Haidong, and northern Huanghe. The risk value of water shortage risk decreased from 3.110, 3.598, and 3.398 in 2000 to 1.248, 1.717, and 1.695 in 2018, respectively. The decrease was 59.87%, 52.28%, and 50.12%. Lanzhou had the lowest decline in the comprehensive risk assessment value for water shortage. From 4.324 in 2000 to 3.807 in 2018, there was a decrease of 11.96%.

Regarding the risk level of water shortage, Xining was at level III (medium risk) in 2000. Five of the remaining eight cities were rated IV (high risk), and three were rated V (high risk). In 2018, except Lanzhou, which was at grade IV (high risk), all other regions were at grade III (medium risk) or grade II (low risk). From 2000 to 2018, four cities in Haibei, Haidong, Hainan, and Huangnan dropped from grade IV (high risk) to grade II (low risk). It is worth noting that Lanzhou experienced a long-term decline in risk level and then suddenly rose in its stage. Hainan, Dingxi experienced a long-term decline in risk level after a sudden rebound and quickly recovered before the rebound stage.

As shown in Figure 7, most of the risk levels for water shortage in the urbanization process of nine cities in the Lanxi urban agglomeration in 2018 are grade II or above. Lanzhou's risk level is level IV (higher risk level), with the maximum risk level for water shortage (3.810). Baiyin, Dingxi, and Linxia are level III (high risk), with the risk assessment values of water shortage being 2.560, 2.836, and 2.676, respectively. Haibei, Haidong, Hainan, Huangnan, and Xining are level II (low risk), with the risk assessment values of water shortage being 1.695, 1.717, 1.957, 1.248, and 1.831, respectively. Lanzhou and Haibei are the regions with the highest and lowest water shortage risks among the nine cities in the Lanxi urban agglomeration. In 2018, the risk of water shortage in the urbanization process of nine cities in the Lanxi urban agglomeration was generally at a moderate risk level, implying a low risk in the west and a high risk in the east (see Figure 7).

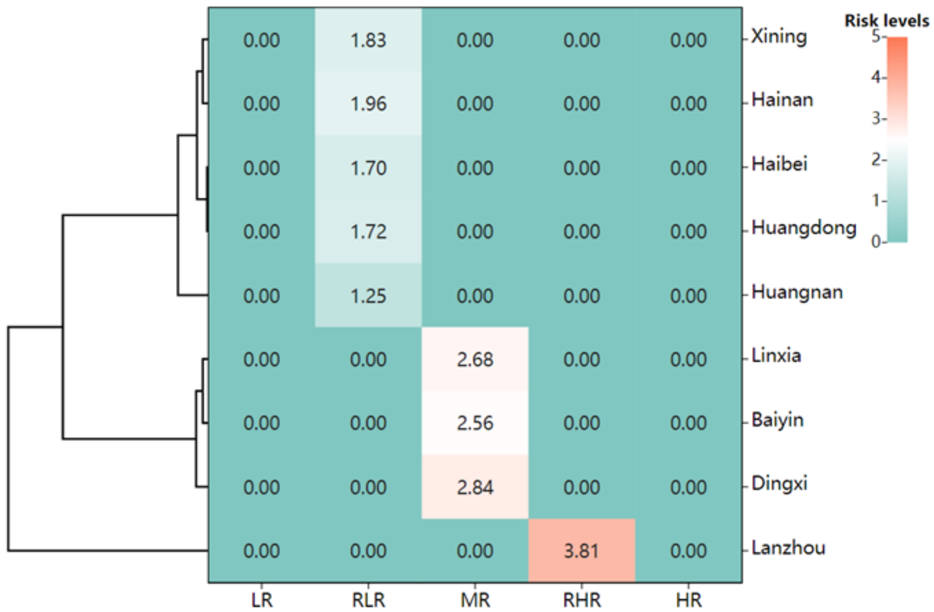


Figure 7. Cluster distribution of risk levels for water resources shortage in the Lanxi urban agglomeration in 2018. (Low risk is abbreviated as LR. Relatively low risk is abbreviated as RLR. Medium risk is abbreviated as MR. Relatively high risk is abbreviated as RHR. High risk is abbreviated as HR).

The following factors cause this phenomenon: First, the economic development and urbanization degree of the nine cities in the Lanxi urban agglomeration are relatively low [57]. Second, compared with the western region of the urban agglomeration, the eastern region of the urban agglomeration is mainly located in the Loess Plateau region of Gansu Province [58]. The terrain in the area is winding and undulating, the soil is loose, and soil erosion is severe. And, mainly for the continental climate, there is less rainfall, and water reserves are relatively insufficient. Thirdly, the economic development and urbanization level in the eastern part of the urban agglomeration are higher than in the western part, resulting in greater population, industry, and social pressure on its water resources system [59].

3.4. Analysis of the Urban Agglomeration in Guanzhong Plain

From 2000 to 2018, the water shortage risk of 11 cities in the Guanzhong Plain urban agglomeration showed a slow downward trend. The comprehensive assessment value of water shortage risk in 11 cities decreased significantly. Accordingly, the risk level of water shortage in most cities decreased, as shown in Figure 8.

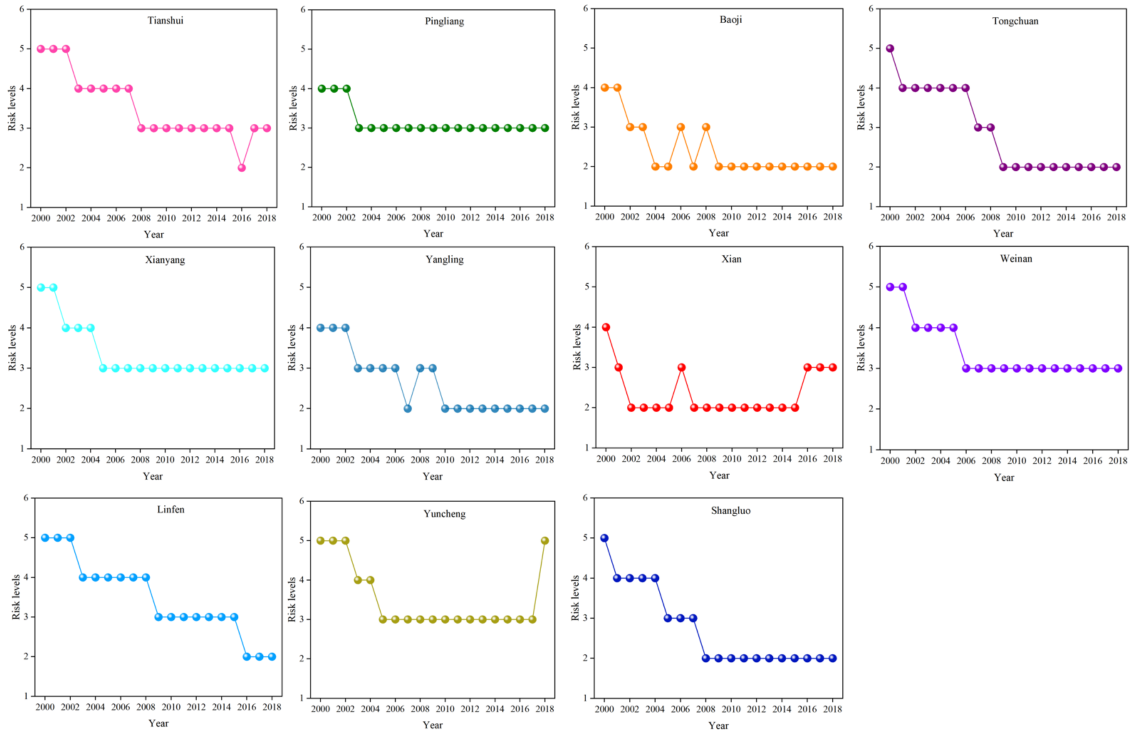


Figure 8. Risk levels of water resources shortage in urban agglomerations in Guanzhong Plain from 2000 to 2018.

Linfen, Shangluo, and Tongchuan significantly declined in the risk assessment value for water shortage, which decreased from 4.518, 4.120, and 4.186 in 2000 to 1.979, 1.533, and 1.515 in 2018, respectively. The decrease was 56.19%, 62.78%, and 63.81%. Yuncheng has the lowest reduction in the risk assessment value for water shortage. From 4.396 in 2000 to 4.023 in 2018, there was a decrease of only 8.48 percent.

From the risk level of water shortage perspective, in 2000, 11 cities were all in grades IV (high risk) and V (high risk). In 2018, except Yuncheng, which was classified as grade V (high risk), all other regions were classified as grade II (low risk) and grade III (medium risk). From 2000 to 2018, 10 cities, such as Baoji, Linfen, Pingliang, Shangluo, Tianshui, Tongchuan, Weinan, Xi'an, Xianyang, and Yangling, all dropped from grade IV (high risk) and grade V (high risk) to grade II (low risk) and grade III (medium risk). Yuncheng has been rated V (high risk). Yuncheng has seen a steady decline in risk levels and a rapid rebound. Tianshui, Xi'an, and Yangling experienced a short period of risk level decline and were quickly restored to the original situation.

The main water resources of the Guanzhong Plain urban agglomeration are distributed in the Qinling Mountains, and the distribution pattern of water resources shows a trend of high in the south and low in the north, decreasing from south to north [60]. Rainfall in the Guanzhong Plain urban agglomeration is mainly concentrated in the east, with relative water shortages in the country's northwestern part and the Longdong region of Gansu Province [60]. In addition, the urbanization process of population and industrial aggregation is accompanied by severe ecological and environmental problems [59]. In particular, the Guanzhong Plain's major urban reliance on coal-based energy consumption has led to serious water pollution problems, making the contradiction between socio-economic development and ecological protection in the Guanzhong Plain urban agglomeration prominent [61]. Therefore, to reduce the risk of water shortage in the Guanzhong Plain urban agglomeration in the future, it is necessary to promote the recycling of urban water resources on the one hand, and, on the other hand, it is necessary to encourage change in the energy consumption structure of the cities in the Guanzhong Plain, to reduce the pollution of the water environment, and to promote the sustainable development of water resources.

Plain urban agglomeration in 2018 is demonstrated in Figure 9. In the urbanization process of 11 cities in the Guanzhong urban agglomeration in 2018, more than half of the water shortage risk levels were level III or above (medium and high risk). The risk level of Yuncheng is V (high risk level), with the risk assessment value for water shortage being 4.023. Pingliang, Tianshui, Weinan, Xi'an, and Xianyang are level III (medium risk), with the risk assessment value for water shortage being 2.201, 2.106, 2.141, 2.003, and 2.010, respectively. Yuncheng and Tongchuan were the areas with the highest and lowest water shortage risks, respectively, among the 11 cities. In 2018, the risk of water shortage in the urbanization process of 11 cities in the Guanzhong urban agglomeration showed a decreasing pattern from north to south. This phenomenon is because, compared with the southwest region, the Guanzhong region has unique geographical conditions, with less precipitation and greater evaporation in some areas.

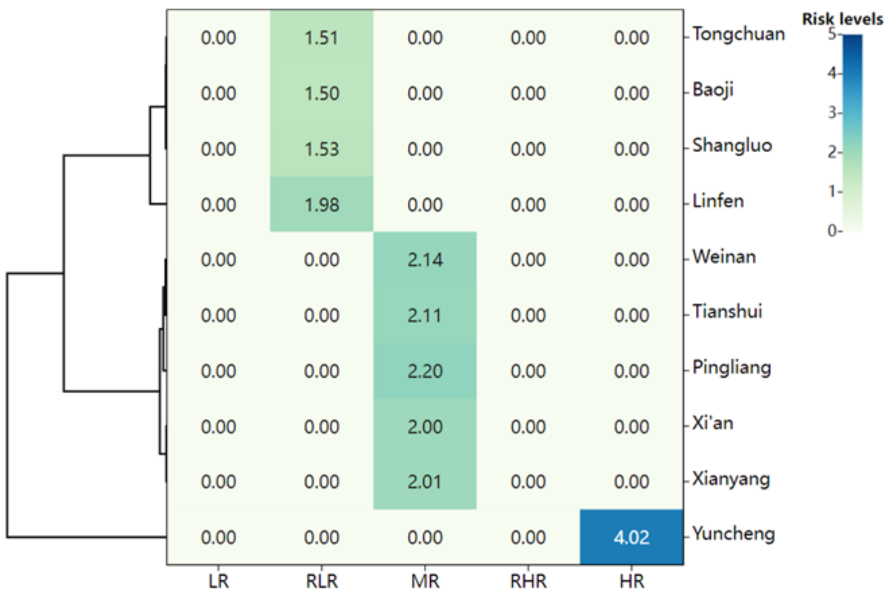


Figure 9. Cluster distribution of water resources shortage risk in the Guanzhong Plain urban agglomeration. (Low risk is abbreviated as LR. Relatively low risk is abbreviated as RLR. Medium risk is abbreviated as MR. Relatively high risk is abbreviated as RHR. High risk is abbreviated as HR).

4. Conclusions

This study analyzes the influencing factors of water resources shortage risk in three major urban agglomerations in Western China from 2000 to 2018 and establishes a new comprehensive evaluation index system of water resources environmental risk from the aspects of water resources vulnerability, exposure, and recoverability. Secondly, the entropy and fuzzy comprehensive evaluation methods are utilized to measure the risk value of water resources shortage in the twelve western provinces (municipalities) as well as the three major urban agglomerations and to classify them into grades. Finally, on this basis, the temporal and spatial aggregation characteristics and environmental impact factors of water shortage risk in the western provinces (cities) and the three major urban agglomerations are investigated. The results show that from 2000 to 2018, the risk of water shortage in twelve provinces (cities) in Western China has been mitigated to a certain extent, with the overall risk value decreasing from 3.42 to 2.59; among the three major urban agglomerations, the Guanzhong Plain urban agglomeration has the fastest decrease in the total water shortage risk, with an average annual decrease rate of 10.57%, followed by the Chengdu–Chongqing urban agglomeration, with an average yearly decline rate of 8.03%. In terms of risk level, the overall water shortage risk of the western urban agglomeration is still at the medium or below level in the country, and water shortage is still very serious along with the process of urbanization and industrialization in the western part of the country. Secondly, the water shortage of different cities in the three major urban agglomerations is not synchronized in time and space, and the risk level of water shortage shows a situation of "high in the north and low in the south." Finally, due to the special geographic environment and the complexity of water shortage risk in the west, geological and environmental changes are an important influencing factor in water shortage; industrial water use has the biggest negative impact on water shortage risk, with a contribution of 24.9%. Therefore, in order to systematically mitigate the risk of water shortage in the urbanization process in the west in the future, in addition to focusing on the overall management of the western region, it is also necessary to take targeted measures around the level of each urban agglomeration and to carry out differentiated management. In addition, environmental changes in water resources are also a key concern for the sustainable development of urban water resources in the future.

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