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Assessment of Drought Evolution Characteristics and Drought Coping Ability of Water Conservancy Projects in Huang-Huai-Hai River Basin, China

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Abstract: Based on the national precipitation dataset in the Huang-Huai-Hai River Basin of China for the 1961–2011 period, the China-Z growing season index was calculated to analyze the characteristics of the evolution of meteorological droughts. Data from statistical droughts (the droughts which are defined and classified by the actual statistic data) were compared with those of meteorological droughts during the 2000–2011 period. Nine indexes were selected to evaluate the drought coping ability of water conservancy projects based on the fuzzy comprehensive assessment model. The results showed that the China-Z growing season index was a downward trend with a rate of −0.063 per decade from 1961 to 2011, which indicates an increasing trend in drought intensity. Droughts were more frequent than average during the 1961–1979 period and returned to normal frequency during the 1980–2011 period. Both the ratio of drought affected area (RDAA) and the ratio of drought suffering area (RDSA) of statistical droughts decreased more quickly than those of meteorological droughts (2000–2011). The indexes of water conservancy projects were lower than the average all-China indexes. Half of the 59 three-level water resources districts exhibited a relatively poor drought coping ability, which means that enhancing the drought coping ability of the water conservancy project was quite important.

Keywords: evolution characteristics of drought; water conservancy projects; drought coping ability; assessment; Huang-Huai-Hai River Basin

1. Introduction

Meteorological disasters caused by climate change have become more frequent and more widespread around the world [1,2]. The influence of meteorological disasters, such as drought and flood, involves social, economic and environmental fields [3–5]. Of all meteorological disasters, droughts account for 5%, but losses caused by droughts account for 30% of all disaster-related losses [6]. In China, droughts play a vital role because they make up 53% of natural disasters [6,7]. Statistical data show that, from 1950 to 2013, the average annual percentages of arable land considered statistical drought-affected area (the planting area with more than 10% reduction in yield caused by drought hazards, compared with the annual average yield) and drought-suffering area (the planting area with more than 30% reduction in yield caused by drought hazards, compared with the annual average yield) are 18.5% and 8.3%, respectively. Both ratios show simultaneous increasing trends.

The Huang-Huai-Hai River Basin of China is one of the regions that often experiences the most frequent and severe occurrences of drought. Drought events in Huang-Huai-Hai River Basin possess three characteristics: high intensity, wide range, and high frequency [8].

As an extreme event in the water cycle, the occurrence of drought can be affected by complex factors such as climate change, underlying surface conditions and the regulation of water conservancy projects [9]. Drought and flood events have a natural–artificial dualistic characteristic, which means that water conservancy projects such as reservoirs and ditches can influence the hydrological process to some extent, which then influences the characteristics of the drought and flood events [10–13]. From the hydrological process aspect, conservancy projects disturb the hydrologic regime downstream and directly affect variations in streamflow [14,15]. Zhao found that after the construction of Manwan Dam in Lancang River, China, the variability in maximum runoff occurrence in the post-dam period was less than that in the pre-dam period [16]. The ditches affect connectivity and flow stream of the rivers and the lakes. Thus influence the land surface processes in the hydrological process. For drought and flood events, water conservancy projects reduce or even eliminate high flows by storing water in reservoirs in the flood season and increase low flows by releasing the stored water for water supply during times of drought [17,18].

Due to the mechanism mentioned above, water conservancy projects, which mainly include projects to store, divert, lift and transfer water, are critical influencing factors of drought coping ability [19]. The layout, scale and connectivity of those projects determine the drought coping ability of the region. In recent years, scholars in other countries have mainly focused on the importance of water supply management in researching drought coping systems [20,21]. Scholars in China have made some progress in the study of drought coping ability of the water resources projects [22–24]. However, less research has been performed to understand the drought coping ability in multi-water sources and multi-project regions or basins.

Focusing on the issues mentioned above, in this paper we chose the China-Z index of growing season during 1961–2011 as the assessment index of drought categories in the Huang-Huai-Hai River Basin. The density and capability of several water conservancy projects were chosen to establish the assessment index system of the drought coping ability of water conservancy projects in the Huang-Huai-Hai River Basin. The fuzzy comprehensive assessment model was constructed on the basis of analytic hierarchy process (AHP) and fuzzing mathematics. The assessment result of the drought coping ability could provide evidence to assist in the regulation of the water conservancy projects.

2. Materials and Methods

2.1. Description of the Study Area

The Huang-Huai-Hai River Basin is located within the geographic coordinates of 95°–123° E and 30°–43° N, covering an area of 14.45×10^5 km^2. The basin ranges from south of the Inner Mongolia Plateau and Inland River Basin to north of Dabie Mountain, Jianghuai Hill district, Nantong-Yangzhou Navigation Canal and the Yangtze River and from east of the Tibetan Plateau and Northwest Catchment Area to west of the Bohai Sea and Huanghai Sea. The Huang-Huai-Hai River Basin contains 16 provinces and cities, namely, all of Beijing, Tianjin, and Shandong, most of Hebei and Henan and part of Jiangsu, Anhui, Hubei, Liaoning, Inner Mongolia, Ningxia, Qinghai, Gansu, Shanxi, Shaanxi and Sichuan.

The Huang-Huai-Hai River Basin consists of three important basins of China: the Yellow River Basin (eight of the two-level water resources districts and 19 of the three-level water resources districts), the Huai River Basin (five of the two-level water resources districts and 15 of the three-level water resources districts) and the Hai River Basin (four of the two-level water resources districts, 15 of the three-level water resources districts). The hierarchy of water resources districts is governed by the

Ministry of Water Resources of the People's Republic of China according to the watershed system and administrative division.

The climate of this region is quite complex and includes arid zones, semi-arid zones, semi-humid zones and humid zones. Annual average precipitation and evaporation are 555.6 mm and 1699.5 mm, respectively [25]. There are 106 large reservoirs (total storage $\geq$ 0.1 billion m^3) and 436 medium reservoirs (10 million m^3 $\leq$ total storage < 0.1 billion m^3) in the Huang-Huai-Hai River Basin. The geographical location of Huang-Huai-Hai River Basin and the distribution of reservoirs are depicted in Figure 1.

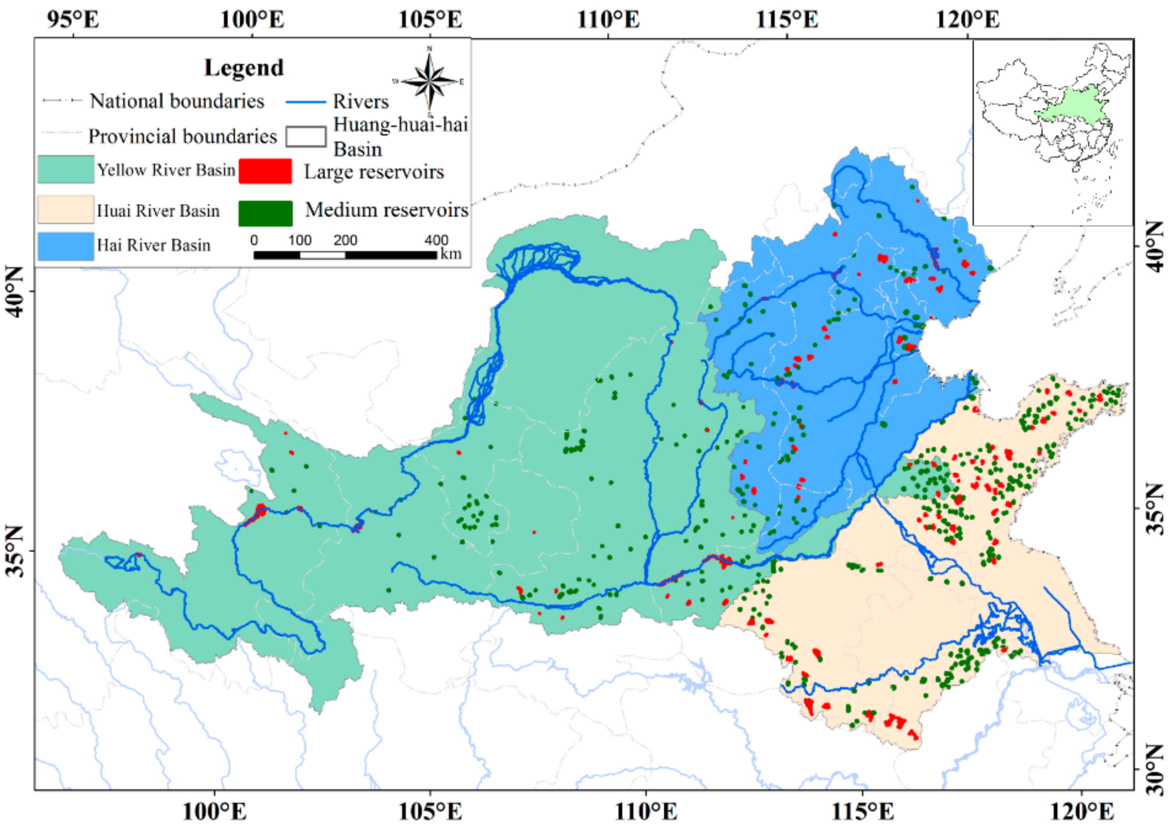
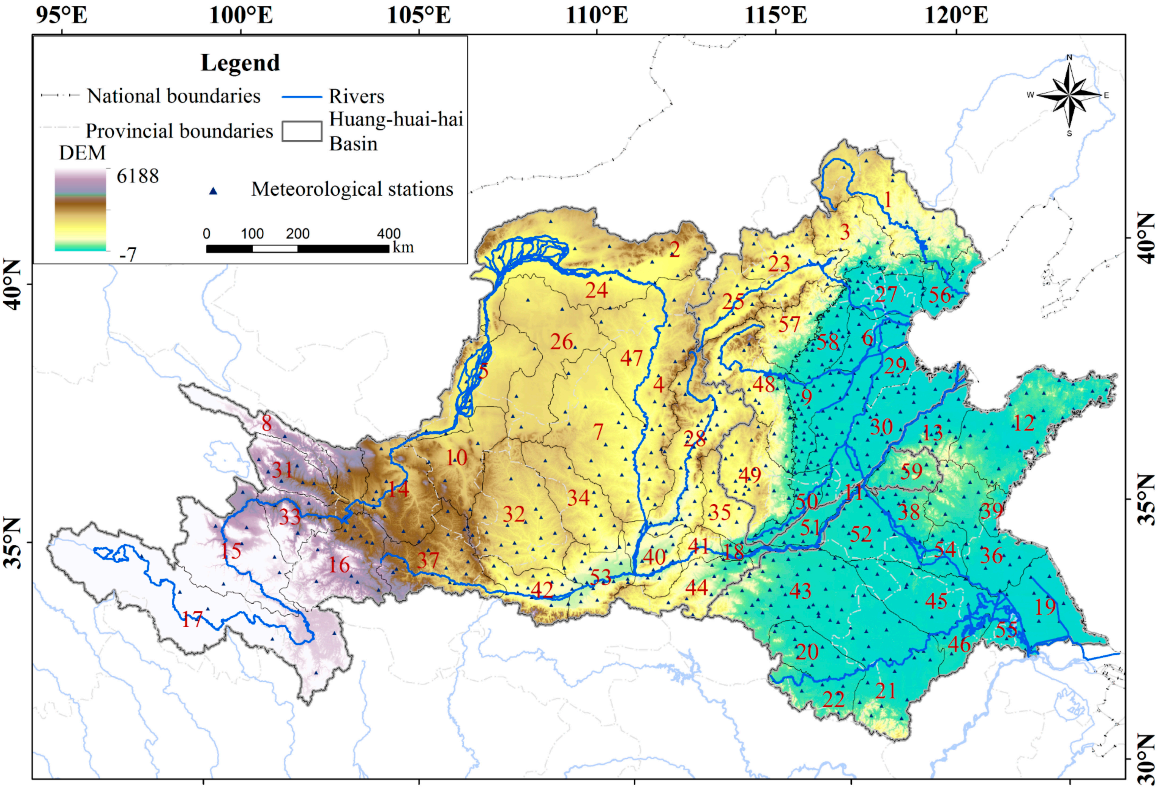


Figure 1. Distribution of large and medium reservoirs in Huang-Huai-Hai River Basin.

The Huang-Huai-Hai River basin is one of China's most important political, economic and cultural centers [26]. The basin has 34% of the Chinese population, and produces 38% of China's GDP but contains only 7% of national water resources. The basin also provides 23.6% of China's grain production and 34% of the whole nation's farmland [27].

2.2. Data Sources

This paper uses the precipitation data of growing seasons (from March to October) during the 1961–2011 period from 1109 meteorological stations located in the Huang-Huai-Hai River Basin (Figure 2), which was recorded by the National Meteorological Centre of China. The 1961–2011 data are more complete compared to those of other periods. Statistical droughts were observed by each region's administration, which used yield reduction and water shortage rate as criteria. The data of statistical droughts were taken from the statistical yearbook (2000–2011) of each province or city. However, data are scarce in some areas of Qinghai and Gansu Provinces.



Note:
1.Luan River Mountainous District
2.Shizuishan to the northern bank of Hekou Town
3.Northern Three Rivers' Mountainous District
4.Left Bank of Hekou Town to Longmen
5.Xiaheyan to Shizuishan
6.Eastern Plain of Daqing River
7.Right Bank of Wupu Downstream
8.Upstream of Xiangtang at Datong River
9.Ziya River Plain
10.Qingshui River and Kushui River
11.Main Stream of Huayuankou Dowmstream
12.Jiaodong's Rivers
13.Xiaoqing River Basin
14.Lanzhou to Xiaheyan
15.Maqu to Longyangxia
16.Daxia River and Yao River
17.Riverhead to Maqu
18.Main Stream of Xiaolangdi to Huayuankou
19.Lixia River District
20.Northern Bank of Wangjia Dam Upstream
21.Northern Bank of Wang-Beng
22.Southern Bank of Wangjia Dam Upstream
23.Cetian Reservoir at Yongding River to Sanjiadian
24.Shizuishan to the Sorthern Bank of Hekou Town
25.Upstream of Cetian Reservoir at Yongding River
26.Interior River Regions
27.Northern Four Rivers' Downstream plain
28.Fen River
29.Heilong Harbor and Yundong Plain
30.Tuhai Majia River
31.Huangshui District
32.Upstream of Zhangjia Mountain at Jing River
33.Main Stream of Longyangxia to Lanzhou
34.Upstream of Zhuangtou at Beiluo River
35.Qindan River
36.Yisu River District
37.Upstream of Baoji at Wei River
38.Eastern Lake District
39.Rigan District
40.Main Stream of Longmen to Sanmenxia
41.Sanmenxia to Xiaolangdi
42.Baojixia to Xianyang at Wei River
43.Northern Bank of Wangba District
44.Yiluo River District
45.Northern Bank of BahongDistrict
46.Southern Bank of BahongDistrict
47.Right Bank of Wupu upstream
48.Ziya River Mountainous District
49.Zhangwei River Mountainous District
50.Zhangwei River Plain District
51.Jindi River and Natural Wenyan Channel
52.Western Lake District
53.Xianyang to Tongguan at Wei River
54.Middle Part of Canal District
55.Gaotian District
56.Luan River Plain and Jidong CoastalRivers
57.Daqing River Mountainous District
58.Western Plain of Daqing River
59.Dawen River Basin

Figure 2. Meteorological stations and three-level water resources districts in the Huang-Huai-Hai River Basin.

2.3. *Assessment of Drought Category*

2.3.1. Ratio of Drought-Affected Area (RDAA) and Drought-Suffering Area (RDSA)

1. The ratios of meteorological drought affected area and the meteorological drought suffering area are determined based on the China-Z index (in Section 2.3.2).

$$\text{RDAA of meteorological drought } (\%) = \frac{\text{Meteorological drought affected area}}{\text{Area of the three}-\text{level water resources district}} \times 100 \quad (1)$$

$$\text{RDSA of meteorological drought } (\%) = \frac{\text{Meteorological drought suffering area}}{\text{Area of the three}-\text{level water resources district}} \times 100 \quad (2)$$

where meteorological drought affected area and drought suffering area are the area of moderate-severe droughts and the area of severe droughts.

2. In this paper, the ratios of statistical drought-affected area and statistical drought-suffering area are determined based on the statistical data from the 2000–2011 period. The ratio of each three-level water resources district is then calculated as follows:

$$\text{RDAA of statistical drought } (\%) = \frac{\text{Pracital drought affected area}}{\text{Planting area}} \times 100 \quad (3)$$

$$\text{RDSA of statistical drought } (\%) = \frac{\text{Pracital drought suffering area}}{\text{Planting area}} \times 100 \quad (4)$$

where statistical drought affected area and drought suffering area are the planting area with more than 10% and 30% reduction in yield caused by drought hazards, respectively, compared with the annual average yield.

2.3.2. China-Z Growing Season Index

The China-Z index (Z-index) was put forward by Ju et al. [28] and then was introduced to the National Meteorological Centre of China (NMCC) in the early 1990s. Fewer operation steps and a more objective presentation than the previous drought index have made it widely used in China [29]. As droughts' greatest impacts on agriculture are mainly during the growing season, this paper calculates the Z-index of the growing season.

The calculation of the Z-index was based on the assumption that the precipitation data obey the Pearson III distribution, is then normalized via the following normalization formula [30]:

$$Z_i = \frac{6}{C_s}\left(\frac{C_s}{2}\varphi_i + 1\right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6} \quad (5)$$

where i is the current growing season, C_s is the skewness coefficient, and φ_i is the standardized variate, C_s and φ_i can be both calculated from the precipitation data series of growing seasons as follows [28]:

$$C_s = \frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n\sigma^3} \quad (6)$$

$$\varphi_i = \frac{x_i - \overline{x}}{\sigma} \quad (7)$$

where x_i is the cumulative precipitation from March to October in ith growing season, one value per year, σ is the standard deviation, n is the length of the data series and $\overline{x}$ is the average precipitation of the growing season.

Then we divide the Z-index values of the normal precipitation distribution into seven levels to evaluate the categories of waterlog or drought [29] (Table 1).

Table 1. The drought and waterlog category of Z-index.

Level	CZI	Categories
1	$Z \geq 1.645$	Severe Waterlog
2	$1.037 \leq Z < 1.645$	Moderate Waterlog
3	$0.842 \leq Z < 1.037$	Slight Waterlog
4	$-0.842 < Z < 0.842$	Normal
5	$-1.037 < Z \leq -0.842$	Slight Drought
6	$-1.645 < Z \leq -1.037$	Moderate Drought
7	$Z < -1.645$	Severe Drought

The IDW (inversed distance weighted) interpolation method was applied to create continuous grid data for the Z-indexes in ArcGis. The Z-index in each three-level water resources district can then be calculated by the "Zonal" ArcGis tool. The ratios of drought affected area, drought suffering area and the drought area of different categories in each three-level water resources district can be calculated in the same way.

2.3.3. Nonparametric Test Method of Meteorological Drought

The nonparametric test of Mann–Kendall (MK) was adopted in this paper to evaluate the significance level of the trend.

The nonparametric test method of Mann–Kendall which was proposed by Mann and Kendall in 1945 [31], is widely used to test the trend of meteorological and hydrological data. The test statistic, Kendall's S, is calculated as follows:

$$S = \sum_{i=1}^{n-a} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \tag{8}$$

where x_i and x_j are the data values at times i and j, n is the length of the dataset and

$$sgn\left(x_j - x_i\right) = \begin{cases} 1,\ if(x_j - x_i > 0) \\ 0,\ if\ \left(x_j - x_i = 0\right) \\ -1,\ if(x_j - x_i < 0) \end{cases} \tag{9}$$

Under the null hypothesis that x_i is independent and randomly ordered, S is approximately normally distributed when $n > 8$, with zero mean and a variance of

$$\mathrm{Var}\ (\mathrm{S}) = \frac{n\,(n+1)\,(2n+5) - \sum_{i=1}^{m} t_i\,(t_i - 1)\,(2t_i + 5)}{18} \tag{10}$$

The standardized test statistic Z is computed by the following formula:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}},\ S > 0 \\ 0,\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}},\ S < 0 \end{cases} \tag{11}$$

The statistic Z follows the standard normal distribution with a mean of zero and a variance of one under the null hypothesis of no trend in the series. MK values of 1.65 and 1.96 represent the significance levels of 0.1 and 0.05, respectively.

The MK test provides another test statistic to evaluate the significance level of trend, which is calculated as follows:

$$S_k = \sum_{i=1}^{k} \sum_{j}^{i-1} \alpha_{ij} \tag{12}$$

in which $k = 2, 3, 4, \cdots, n$, $\alpha_{ij} = \begin{cases} 1,\ X_i > X_j \\ 0,\ X_i < X_j \end{cases},\quad 1 \leq j \leq i.$

$$UF_k = \frac{S_k - E\left(S_k\right)}{\sqrt{Var\left(S_k\right)}} \tag{13}$$

$|UF_k|$ is the standardized normal distribution, at a chosen level of significance a = 0.05. If $|UF_k| > \mathrm{U_a}$, the trend of the series is significant. When x is ranked in reverse order according to time, UB_k can be determined and used in the same way.

2.4. Assessment System of the Drought Coping Ability of Water Conservancy Projects

2.4.1. Selection of Assessment System

The assessment indexes of drought coping ability of water conservancy projects (DCAwcp) were selected based on principles that were independent, representative, measurable, comparable and operable [32], relating to current study results and the specific situation of the study area. The assessment system reflects the overall level of DCAwcp. The assessment system used in this paper mainly included three criterion layers: scale of projects, connectivity of projects and guarantee rate of projects [22,33] (Table 2).

Table 2. Drought coping ability of water conservancy projects (DCAwcp) assessment system.

Target Layer (A)	Criterion Layer (B)	Index Layer (C)		Calculation Method
Drought coping ability of water conservancy projects (DCAwcp)	Scale of projects (B1)	C1	Density of reservoir storage	Ratio of medium and small reservoirs' total storage to the area of arable-residential-industrial land in each three-level water resources district (+)
		C2	Capability of rural water-supply projects	Ratio of amount of water supplied daily by rural water-supply projects to the area of arable-residential-industrial in each three-level water resources district (+)
		C3	Density of electromechanical wells	Ratio of electromechanical well count to the area of arable-residential-industrial land in each three-level water resources district (+)
		C4	Design discharge of pumping stations of per unit area	Ratio of design discharge of all of the pumping stations to the area of arable-residential-industrial land in each three-level water resources district (+)
	Connectivity of projects (B2)	C5	Density of ditches	Ratio of ditch length to the area of arable-residential-industrial land in each three-level water resources district (+)
		C6	Capability of water lifting and water transfer projects	Ratio of daily capacity of water lifting and water transfer projects to the area of arable-residential-industrial land in each three-level water resources district (+)
	Guarantee rate of projects (B2)	C7	Density of irrigated arable land	Ratio of irrigated arable land area to the area of arable-residential-industrial land in each three-level district of water resources (+)
		C8	Efficiency of irrigation	Water efficiency of irrigation in each three-level water resources district (+)
		C9	Proportion of arable land which can ensure stable yield despite drought or flood area	Proportion of the area of arable land which can ensure stable yield despite drought or flood to the area of arable-residential-industrial land in each three-level water resources district (+)

Notes: "+" represents positive correlations between the assessment index and the drought coping ability of water conservancy projects; that is, the drought coping ability of water conservancy projects increases while the index increases. Density of the projects means "Dividing the amount (the storage, total length or total area) of a project by the area of arable-residential-industrial land in each three-level district of water resources".

Water conservancy project data presented in Table 2 were provided by the first National Census for Water in China in 2011 [34]. The reason why the reservoir storage excluded the large reservoirs is that the large reservoirs not only serviced the district (three-level water resources district) in which they are located, but also the surrounding districts. Furthermore, this paper used the arable–residential–industrial area instead of the area of the whole three-level district because drought mainly influences on these areas and it would thus be more precise in the assessment model.

2.4.2. Assessment Model

The fuzzy comprehensive assessment model was used to evaluate the drought coping ability. This model employs the analytic hierarchy process [35] (AHP) and fuzzing mathematics to evaluate the multi-index quantitatively with the fuzzy relation synthetic theory. It has been widely accepted in various assessments because of its systematic feature and intuitive results [36].

The main steps are described as follows (Figure 3):

(1) Build the factor set of the assessment objects: $U = \{u_1, u_2, u_3 \ldots u_n\}$, where u_i is the ith element of the assessment object. Because nine factors were chosen in this paper, the value of n is 9.

(2) Confirm the remark set of the assessment objects: $V = \{v_1, v_2, v_3 \ldots v_m\}$, where v_j is the jth remark level of the assessment element. Because the drought coping ability of water conservancy projects is divided into five grades in this paper, weakest, poor, moderate, high, and extremely high, the value of m is 5.

(3) Determine the weight vector of the assessment elements: $A = \{a_1, a_2, a_3 \ldots a_n\}$, where a_i is the weight of the ith element, and meets the conditions: $\mathrm{a}_i > 0$ and $\sum_{i=0}^{n} \mathrm{a}_i = 1$. The analytic hierarchy process (AHP) is adopted to determine the weight of each element and is described as follows:First, the assessment system is divided into three layers: the target layer, the criteria layer and the index layer. Based on a pair-wise comparison, a 1–9 scaling method is adopted to determine which role each element plays in the index and a judgment matrix is obtained after assigning values to each element [37]. The following consistency ratio is used to test the consistency of the matrix.

$$\text{Consistency ratio CR} = \frac{CI}{RI} \tag{14}$$

where $CI = \frac{\lambda_{max} - n}{n-1}, RI = \frac{k-n}{n-1}$, CI is the deviation degree of consistency, RI is the stochastic degree of consistency, λ_{max} is the maximum eigenvalue of the judgment matrix, n is the order of the judgment matrix and k is the average value of the maximum eigenvalues of a stochastic positive reciprocal matrix A'.When $CR < 0.1$, it is generally considered that the inconsistent degree of matrix A is within the acceptable range and its eigenvector can be used as a weight vector.

(4) Build the fuzzy relation matrix R: following the above steps, a single factor u_i is evaluated between the element field U and the remark field V to obtain the fuzzy relationship matrix R.

$$\mathrm{R} = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} \tag{15}$$

where r_{ij} is the relative membership degree of the ith element in element field corresponding to the jth grades in remark field; $\sum r_{ij} = 1$. For an assessment system where there are five grades and all of the indicators are positive, the detailed method of membership degree function is expressed as:

$$r_{i1} = \begin{cases} 0.5\left(1 + \frac{c_1 - x_{ki}}{c_2 - x_{ki}}\right), x_{ki} \le c_1 \\ 0.5\left(1 - \frac{x_{ki} - c_1}{c_2 - c_1}\right), c_1 < x_{ki} \le c_2 \\ 0, x_{ki} > c_2 \end{cases} \tag{16}$$

$$r_{i2} = \begin{cases} 0.5\left(1 - \frac{c_1 - x_{ki}}{c_2 - x_{ki}}\right), x_{ki} \le c_1 \\ 0.5\left(1 + \frac{x_{ki} - c_1}{c_2 - c_1}\right), c_1 < x_{ki} \le c_2 \\ 0.5\left(1 + \frac{c_3 - x_{ki}}{c_3 - c_2}\right), c_2 < x_{ki} \le c_3 \\ 0.5\left(1 - \frac{x_{ki} - c_3}{c_4 - c_3}\right), c_3 < x_{ki} \le c_4 \\ 0, x_{ki} > c_4 \end{cases} \tag{17}$$

$$r_{i3} = \begin{cases} 0, x_{ki} \leq c_2 \\ 0.5\left(1 - \frac{c_3 - x_{ki}}{c_3 - c_2}\right), c_2 < x_{ki} \leq c_3 \\ 0.5\left(1 + \frac{x_{ki} - c_3}{c_4 - c_3}\right), c_3 < x_{ki} \leq c_4 \\ 0.5\left(1 + \frac{c_5 - x_{ki}}{c_5 - c_4}\right), c_4 < x_{ki} \leq c_5 \\ 0.5\left(1 - \frac{x_{ki} - c_5}{c_6 - c_5}\right), c_5 < x_{ki} \leq c_6 \\ 0, x_{ki} > c_6 \end{cases} \quad (18)$$

$$r_{i4} = \begin{cases} 0, x_{ki} \leq c_4 \\ 0.5\left(1 - \frac{c_5 - x_{ki}}{c_5 - c_4}\right), c_4 < x_{ki} \leq c_5 \\ 0.5\left(1 + \frac{x_{ki} - c_5}{c_6 - c_5}\right), c_5 < x_{ki} \leq c_6 \\ 0.5\left(1 + \frac{c_7 - x_{ki}}{c_7 - c_6}\right), c_6 < x_{ki} \leq c_7 \\ 0.5\left(1 - \frac{x_{ki} - c_7}{x_{ki} - c_6}\right), x_{ki} > c_7 \end{cases} \quad (19)$$

$$r_{i5} = \begin{cases} 0, x_{ki} \leq c_6 \\ 0.5\left(1 - \frac{c_7 - x_{ki}}{c_7 - c_6}\right), c_6 < x_{ki} \leq c_7 \\ 0.5\left(1 + \frac{x_{ki} - c_7}{c_7 - c_6}\right), x_{ki} > c_7 \end{cases} \quad (20)$$

where, $c_1,\ c_3,\ c_5,\ c_7$ are the dividing points of five grades, $c_2 = (c_1 + c_3)/2$, and so forth.

(5) Conduct a multi-index comprehensive assessment. Obtain the assessment result matrix B by synthetic fuzzy comprehensive operation.

$$\mathrm{B} = \mathrm{A}^{\circ}\mathrm{R} = (\mathrm{a}_1, \mathrm{a}_2, \mathrm{a}_3 \ldots \mathrm{a}_n) \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} = (\mathrm{b}_1, \mathrm{b}_2, \mathrm{b}_3 \ldots \mathrm{b}_n) \quad (21)$$

where "°" is the fuzzy synthetic operator, the weighted average operator $\mathrm{M} = (,\oplus)$ is used for synthesis in the paper, and $b_j = \sum_{i=1}^{n} a_i r_{ij}\ (j = 1, 2, \cdots m)$.

(6) Analyze the results. The remark grade corresponding to the maximum of each component in the assessment result matrix B is taken as the comprehensive assessment result according to the maximum membership degree principle.

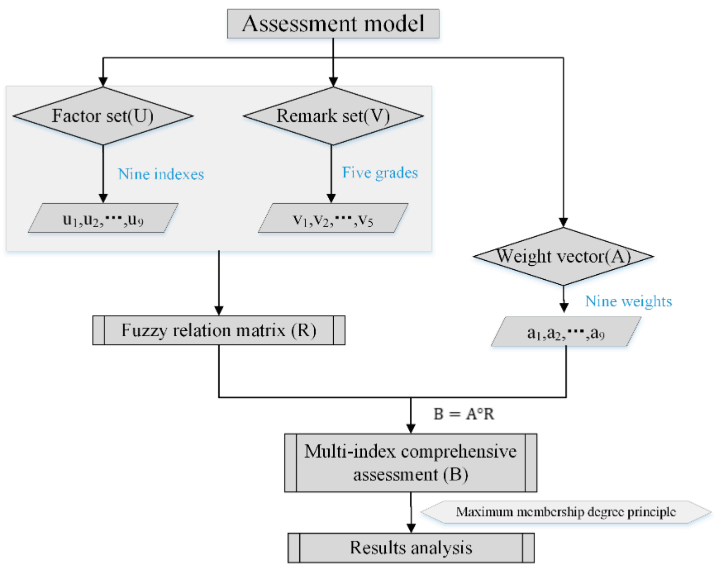


Figure 3. Framework diagram of the fuzzy comprehensive assessment model.

3. Results and Discussion

3.1. Spatial-Temporal Change Trends of Different Drought Category

The annual growing season Z-index in the Huang-Huai-Hai River Basin from 1961 to 2011 is presented in Figure 4. The average growing season Z-index for the study area is 0.0036. From the curve of the average value of five-years moving average, we can find that the average growing season Z-index decrease at a rate of −0.063 per decade for the 1961–2011 period, which indicates that drought intensity has an increasing trend. The Mann–Kendall test is used to test tendency and abrupt change. The value of the standardized test statistic Z is −1.345, and it can be seen from Figure 4b that $|UF_k|$ is below U_a, so the trend of growing season Z-index during the 1961–2011 period is not significant.

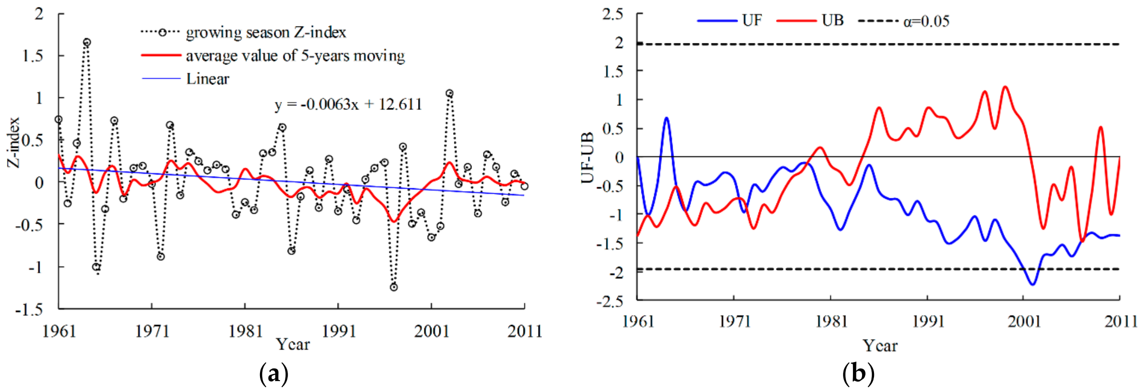


Figure 4. Trend of growing season Z-index in the Huang-Huai-Hai River Basin: (**a**) growing season Z-index; and (**b**) result of MK test.

The percentage of the years suffering drought divided into two periods, 1961–1979 and 1980–2011, is determined in order to analyze the frequency of different drought categories in the Huang-Huai-Hai River Basin. The yearly frequency of slight drought, moderate drought and severe drought is shown in Figures 5 and 6. It is clear that the yearly drought frequency of the Huang-Huai-Hai River Basin in different categories decreases in both periods. However, there is a higher yearly drought incidence frequency in the 1961–1979 period, followed by a stable period from 1980 to 2011. The findings also show that the yearly frequency of slight drought and moderate drought is substantially higher than that of severe drought and the yearly frequency of slight drought decreases considerably compared to the other droughts.

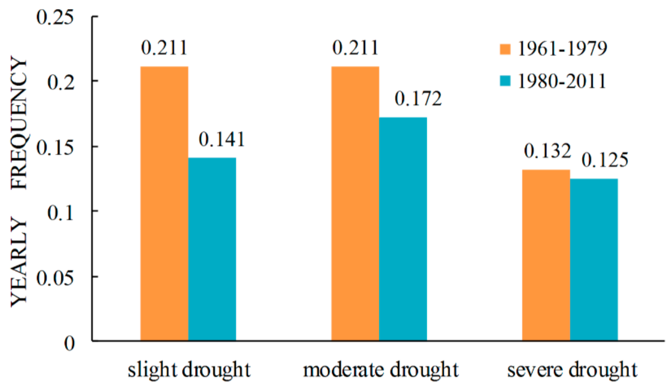


Figure 5. Yearly drought frequency of different categories in the Huang-Huai-Hai River Basin.

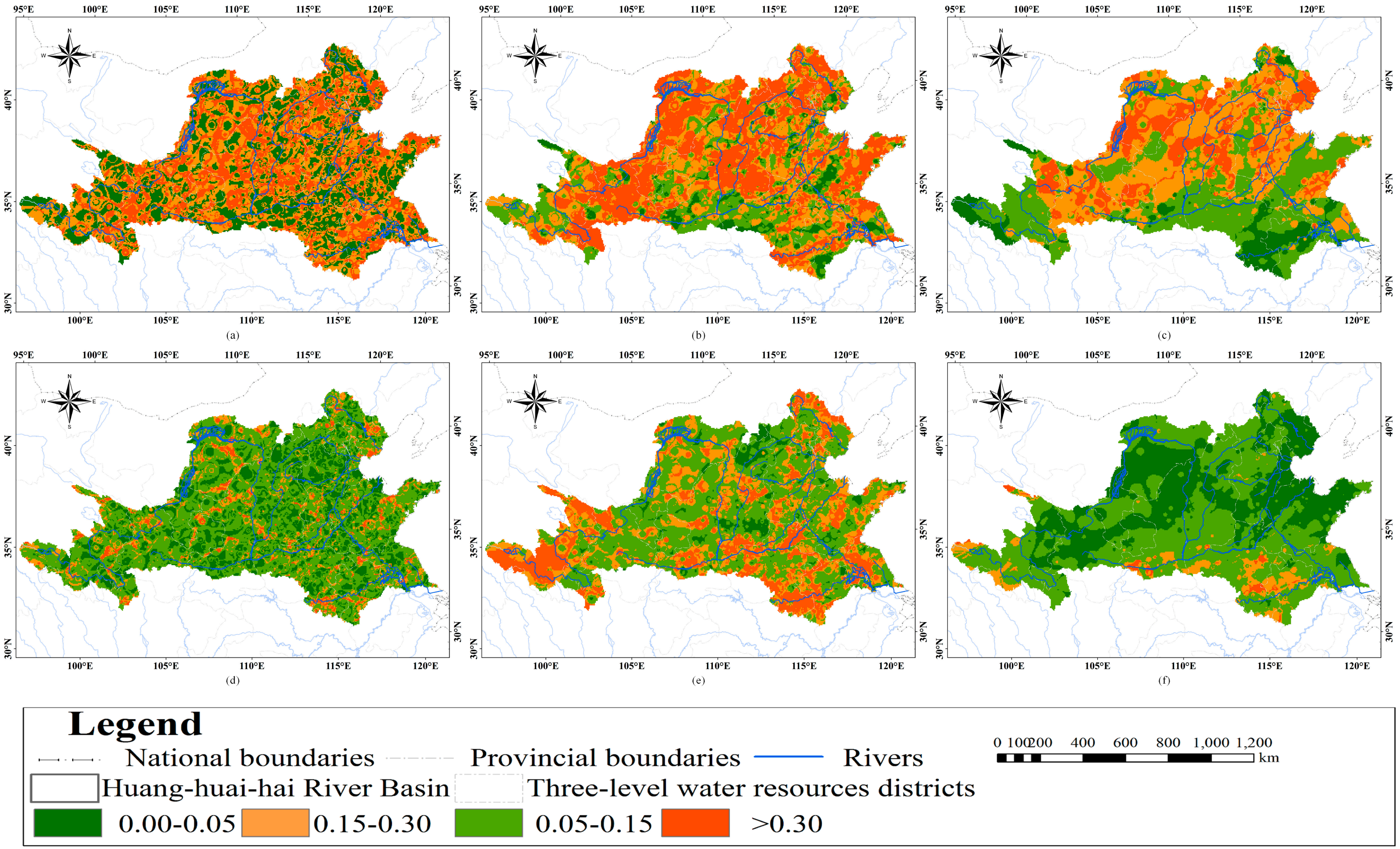


Figure 6. Yearly frequency of Drought in Different Categories: (**a**) yearly frequency of slight drought, 1961–1979; (**b**) yearly frequency of moderate drought, 1961–1979; (**c**) yearly frequency of severe drought, 1961–1979; (**d**) yearly frequency of slight drought, 1980–2011; (**e**) yearly frequency of moderate drought, 1980–2011; and (**f**) yearly frequency of severe drought, 1980–2011.

As shown in Figure 6, during the 1961–1979 period, the regions with high yearly frequencies of slight drought almost covers the whole Huang-Huai-Hai River Basin. Moderate and severe droughts mainly happen in the Yellow River and Hai River Basins. During the 1980–2011 period, the areas of high frequency of slight and severe drought reduces evidently, while the regions with high yearly frequency of moderate drought show no obvious changes.

Because statistical drought data exist only from 2000 to 2011, in order to contrast the variation of meteorological drought with those of statistical drought, the meteorological drought data during 2000–2011 period are chosen to calculate RDAA and RDSA (Figure 7a,b). The results show that, RDAA and RDSA of meteorological drought in the study area are −0.468 and −0.662, respectively. The two ratios indicate a downward trend, with RDAA decreasing more quickly than RDSA. Conversely, the variation trend differs in each three-level water resources district. The RDAA and RDSA of meteorological drought increases most quickly in the Riverhead-to-Maqu district, and decreases most rapidly in the Northern Bank of Wangjia Dam Upstream district.

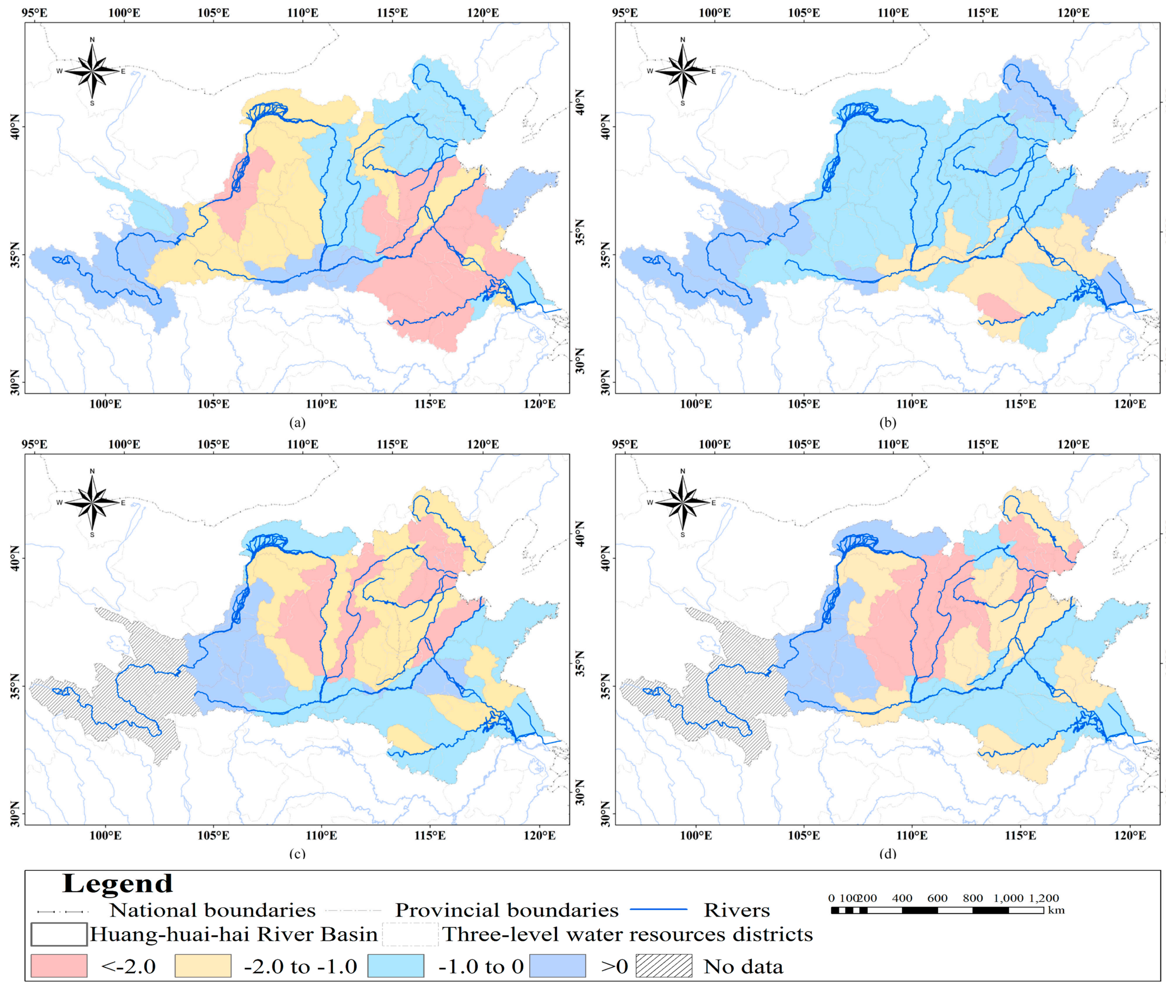


Figure 7. The ratio of drought affected area (RDAA) and the ratio of drought suffering area (RDSA) of meteorological droughts and statistical droughts: (**a**) RDAA of meteorological droughts; (**b**) RDSA of meteorological droughts; (**c**) RDAA of statistical droughts; and (**d**) RDSA of statistical droughts.

The variation of RDAA and RDSA of statistical droughts is much more complex, although it also shows a decreasing trend during 2000 to 2011 (Figure 7c,d). RDAA and RDSA are −0.903 and −1.390, respectively. The increase of statistical drought RDAA is the greatest in the Lanzhou-to -Xiaheyan district, while the decrease is largest in the Northern Four Rivers Downstream Plain district.

Meanwhile, the increase of statistical drought RDSA in the Qingshui River and Kushui River district, while the decrease is largest in the Upstream of Cetian Reservoir at Yongding River district.

The reason why the two ratios of statistical droughts decrease faster than those of meteorological droughts is that the construction of water conservation projects relieve the drought to a certain degree. The difference between the RDAA and RDSA of meteorological droughts and those of statistical droughts can reflect the drought coping ability in this region. If the difference is positive, the projects play a positive part in enhancing the drought coping ability; otherwise, they do not. As shown in Figure 8, excluding the districts where real data are absent, the water conservation projects in the Hai River Basin and eastern Yellow River Basin play a significant role in promoting the drought coping ability. The projects in the Huai River Basin play a relatively weak role.

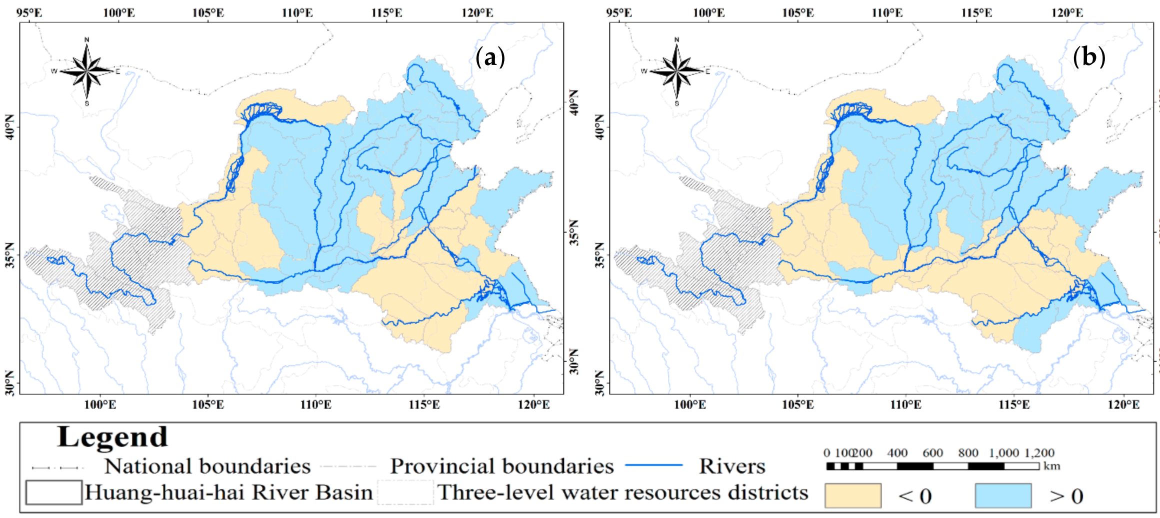


Figure 8. The difference between meteorological droughts and statistical droughts in: RDAA (**a**); and RDSA (**b**).

3.2. Density or Capability of Water Conservancy Projects

According to the above calculation methods, in Table 3 and Figure 9a–i, we can obtain the density or ability of water conservancy projects in each district. The mean value of each density or capability in the Huang-Huai-Hai River Basin is shown in Table 3, as well as the maximum and minimum values.

Table 3. Density or capability of water conservancy projects in the Huang-Huai-Hai River Basin.

Density or Capability	Mean Value	Maximum Value	Minimum Value
Reservoir storage (10^4 m^3/km^2)	5.55	19.96 (Northern Bank of Wangjia Dam upstream)	0 (Jindi River, Natural Wenyan Ditch)
Capability of rural water-supply projects (10^4 $m^3/(day\ km^2)$)	29.319	127.74 (Gaotian District)	1.91 (Luan River Mountainous District)
Density of electromechanical wells (set/km^2)	4.816	10.39 (Main Stream of Xiaolangdi to Huayuankou)	0.16 (Huangshui)
Design discharge of pumping stations per unit area ($m^3/(s\ km^2)$)	0.204	0.204 (Canal District)	0 (Riverhead to Maqu)
Density of ditches (km/km^2)	0.179	0.472 (Shizuishan to the Northern Bank of Hekou Town)	0 (Riverhead to Maqu)
Capability of water lifting and water transfer projects (10^4 $m^3/(day\ km^2)$)	7.097	111.38 (Northern Four Rivers' Downstream plain)	0 (Qingshui River and Kushui River, and 14 other three-level districts)
Density of irrigated arable land (km^2/km^2)	0.162	0.447 (Tuhai Majia River Basin)	0 (Riverhead to Maqu)
Water efficiency of irrigation (%)	55.9	45.2 (Qingshui River and Kushui River)	67.2 (Northern Three Rivers' Mountainous District)
Proportion of arable land which can ensure stable yield despite drought or flood area (%)	2.3	1.1 (Fen River)	3.6 (Lixia River Basin)

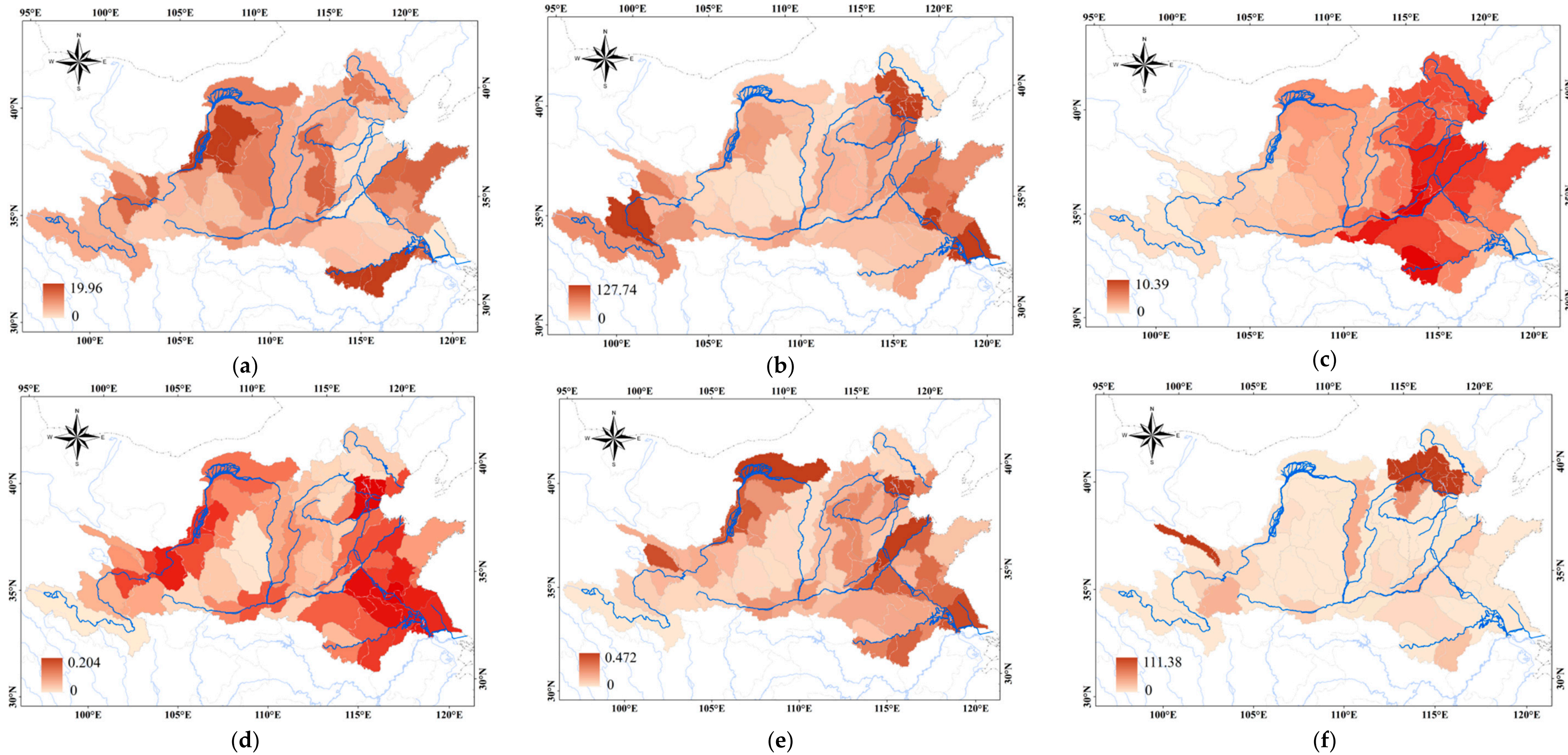


Figure 9. *Cont.*

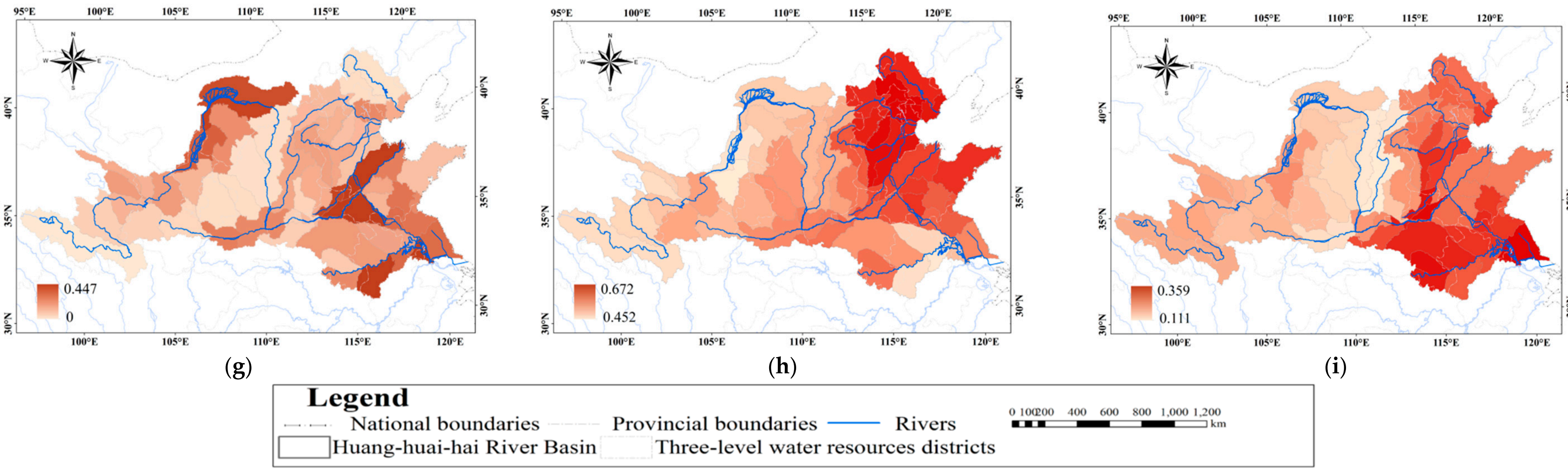


Figure 9. Density or capability of water conservancy projects in the Huang-Huai-Hai River Basin: (**a**) reservoir storage; (**b**) capability of rural water-supply projects; (**c**) density of electromechanical wells; (**d**) design discharge of pumping stations of per unit area; (**e**) density of ditches; (**f**) capability of water lifting and water transfer projects; (**g**) density of irrigated arable land; (**h**) water efficiency of irrigation; and (**i**) proportion of arable land which can ensure stable yield despite drought or flood area.

In first-level districts, several density or capability indexes, namely, density of irrigated arable land, density of ditches, capability of rural water-supply projects, design discharge of pumping stations per unit area and proportion of arable land which can ensure stable yield despite drought or flood area are highest in the Huai River Basin. The capability of water lifting and water transfer projects, the density of electromechanical wells and the water efficiency of irrigation are highest in Hai River Basin. Reservoir storage is relatively high in the Yellow River Basin.

As the main grain producing area in China, the Huang-Huai-Hai River basin is sensitive to drought. However, the above result reveals that the density or ability of water conservancy projects in the study area is much lower than the average national level. Thus, enhancing the assessment and regulation of drought coping ability of the water conservancy projects in the Huang-Huai-Hai River Basin is particularly urgent.

3.3. Assessment of Drought Coping Ability of Water Conservancy Projects (DCAwcp)

3.3.1. Nodes of Assessment Indexes

Classification methods of index nodes directly influence the assessment result. For the indexes which have been given a classification method in some references [22], we adopted the provided method. For the other indexes, we assumed that they had five grade ranges and that the occurrence probabilities of the five grade ranges are 15%, 20%, 30%, 20% and 15%. We could then determine the five grade ranges which were separated by four nodes ($\overline{X} \pm 1.04S$, $\overline{X} \pm 0.39S$, $\overline{X}$ is China's average value of some index, S is the standard deviation). After the above steps, we consulted specialists about the results of the division and amended the nodes according to their reviews. The final classification system is shown in Table 4.

Table 4. Nodes of Assessment indexes.

Nodes	a	b	c	d
Density of reservoir storage ($\times10^4$ m^3/km^2)	0.523	6.037	12.653	18.166
Capability of rural water-supply projects ($\times10^4$ m^3/(day km^2))	19.172	29.987	68.331	79.146
Density of electromechanical wells (set/km^2)	0.52	0.591	2.074	3.309
Design discharge of pumping stations of per unit area (m^3/(s·km^2))	0.022	0.034	0.077	0.089
Density of ditches (km/km^2)	0.02	0.143	0.291	0.415
Capability of water lifting and water transfer projects ($\times10^4$ m^3/(day·km^2))	4.941	7.729	17.611	20.399
Density of irrigated arable land (km^2/km^2)	0.042	0.109	0.19	0.258
Water efficiency of irrigation (%)	50	55	60	65
Proportion of arable land which can ensure stable yield despite drought or flood area (%)	0.012	0.018	0.026	0.032

3.3.2. Selection of Weight Matrix

Selection of a weight matrix has a significant impact on the assessment result. The weight and consistency ratio of each index can be determined by the analytic hierarchy process method introduced previously. We take the target layer (A) and the criteria layer (B) as an example, whose judgment matrix, λ_{max} and CR are shown in Table 5. The construction of the judgment matrix between criteria layer and index layer uses the same method. The result shows CR values are all below 0.1; thus, the consistency is reasonable. The weights of the indexes are presented in Table 6.

Table 5. Judgment Matrix of Target Layer.

Criteria Layer	Scale Degree of Projects	Connectivity Degree of Projects	Guarantee Rate of Projects	Weight
Scale degree of projects	1	2	3	0.545455
Connectivity degree of projects	1/2	1	3/2	0.272727
Guarantee rate of projects	1/3	2/3	1	0.181818
λmax = 3, CI = 0, RI = 0.58, CR = 0 < 0.1				

Table 6. Weight of each assessment index.

Assessment Index	Weight
Density of reservoir storage	0.2618
Capability of rural water-supply projects	0.0873
Density of electromechanical wells	0.1309
Design discharge of pumping stations of per unit area	0.0655
Density of ditches	0.1818
Capability of water lifting and water transfer projects	0.0909
Density of irrigated arable land	0.0992
Water efficiency of irrigation	0.0331
Proportion of arable land which can ensure stable yield despite drought or flood area	0.0496

3.3.3. Assessment of Drought Coping Ability of Water Conservancy Projects in the Huang-Huai-Hai River Basin

Drought coping ability of water conservancy projects (DCAwcp) in fifty-nine three-level districts of water resources in Huang-Huai-Hai River Basin is evaluated by a fuzzy comprehensive assessment model based on the Fortran programing language. It is classified into five assessment grades according to the maximum membership degree principle. The DCAwcp is delimited according to the following sequence (I to V): weakest, poor, moderate, high, and extremely high (Figure 10).

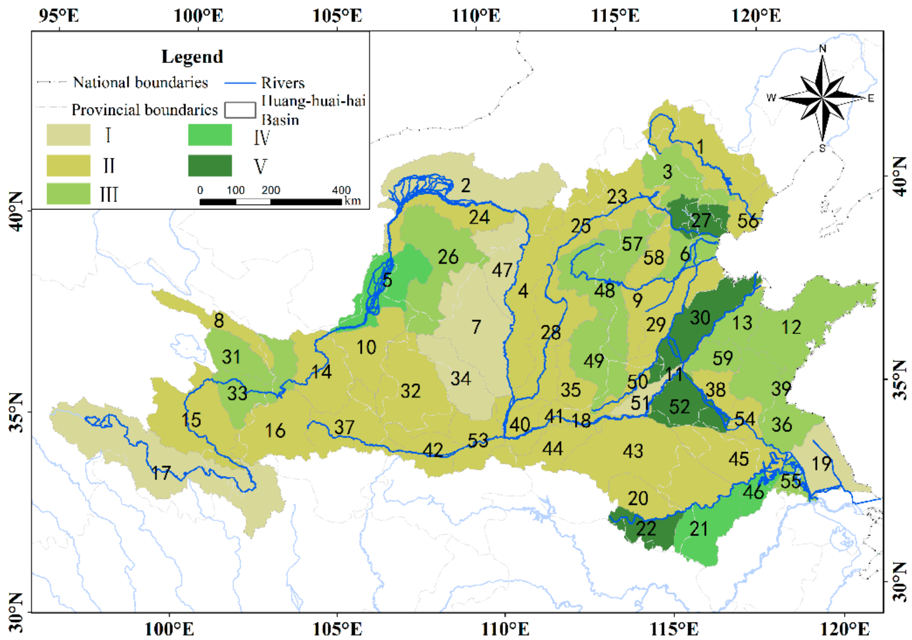


Figure 10. Drought coping ability of water conservancy projects in Huang-Huai-Hai River Basin.

It can be seen from Figure 10 that DCAwcp is poor (II) in thirty-one three-level districts (49.31% area of the Huang-Huai-Hai River Basin), including Luan River Mountainous District and the left bank of Hekou Town to Longmen. Seven districts (18.68% area of the Huang-Huai-Hai River Basin) including Shizuishan to the northern bank of Hekou Town, Riverhead to Maqu and the Lixia River District have the weakest level (I) of DCAwcp. Xiaheyan to Shizuishan and six other districts (10.26% area of the Huang-Huai-Hai River Basin) have high (IV) or extremely high (V) DCAwcp. Through the analysis of three-level districts of water resources in which the coping ability is extremely high, we observe that the Southern Bank of Wangjia Dam Upstream has a high density of reservoir storage and electromechanical wells; the Northern Four Rivers Downstream Plain has high capabilities of rural water-supply projects, water lifting, water transfer projects and a high irrigation efficiency; the Tuhai

Majia River Basin has a high density of ditches and irrigated land; and the Western Lake District has a high density of electromechanical wells and a high design discharge of pumping stations of per unit area. These all confirm that the indexes with higher weight have more significant impact on DCAwcp.

4. Conclusions

This paper used the Huang-Huai-Hai River Basin as the study area to analyze the evolution characteristics of drought and evaluate the drought coping ability of regional water conservancy projects. The main conclusions are as follows:

1. The growing season Z-index of shows a downward trend of −0.063 per decade from 1961 to 2011, which means that the drought intensity has an increasing trend over time. The frequency of droughts in 1961–1979 is higher than that in 1980–2011, indicating that 1961–1979 is a period with high drought frequency, whereas 1980–2011 is a stable period.
2. The ratio of drought-affected area and the ratio of drought-suffering area of meteorological and statistical drought decrease during the 2000–2011 period, and the ratio of drought-suffering area decreases more quickly than the ratio of drought-affected area. Water conservation projects in the Hai River Basin and the eastern Yellow River Basin play a significant role in promoting drought-coping ability. Projects in the Huai River Basin play a relatively weak role.
3. The density or ability of water conservancy projects in the Huang-Huai-Hai River Basin is much lower than the average national level. The result of the fuzzy comprehensive assessment model shows that thirty-one of the three-level districts of water resources (49.31% area of the basin) including the Luan River Mountainous District and the left bank of Hekou Town to Longmen have poor drought coping ability (DCAwcp). Seven districts (18.68% area of the basin), including Shizuishan to the northern bank of Hekou Town and the Lixia River District have the weakest level of DCAwcp. Only Xiaheyan to Shizuishan and six other districts (10.26% area of the basin) have high or extremely high DCAwcp.

The present results indicate that enhancing the construction of water conservancy projects in the districts with poor or the weakest DCAwcp is very critical. This paper only analyze the drought coping ability of water conservancy projects, but the drought coping ability is also closely related to several factors such as water management plans and national policy. Thus, further research should take the factors mentioned above into account.

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