Regional comprehensive drought disaster risk dynamic evaluation based on projection pursuit clustering

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Abstract

We used system theory to analyze the structure of a regional drought disaster system and separated the drought disaster risk system into three subsystems. These were drought disaster-causing factors, disaster-inducing environments, and disaster-bearing bodies. Analysis of the main factors of these subsystems allowed the establishment of a regional comprehensive drought disaster risk evaluation index system. To simultaneously evaluate the distribution and development trends of the regional comprehensive drought disaster risk, we established a dynamic evaluation model. Based on the ideas of the projection pursuit clustering method and the dynamic comprehensive evaluation method, the model can make use of multi-dimensional space–time drought disaster information. The model was applied to evaluate comprehensive drought disaster risk in the Xuzhou region, China. The evaluation results show that the method was able to illustrate the development trend and distribution of the comprehensive drought disaster risk in the Xuzhou region. The clustering zoning results show that Pizhou City is the area with the highest risk in Xuzhou, while Fengxian has the lowest. The development trend of comprehensive drought disaster risk with time is not significant.

Keywords: Comprehensive drought disaster risk; Drought disaster zoning; Dynamics evaluation; Projection pursuit clustering; Time series analysis

Introduction

Drought is a random natural phenomenon. The effects of drought on human activity and the environment are typically negative, and extreme drought may produce disastrous consequences (Wilhite, 2003; Campos, 2008). Due to the complexity and uncertainty of drought, drought disaster management has

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been studied from the perspective of risk management (Mishra & Singh, 2011; 2015; Yoon et al., 2012; Hao et al., 2016). The quantitative assessment of drought disaster risk and predictability is key to scientific management (Knutson et al., 1998; Thompson & Powell, 1998; Wilhite & Hayes, 2000; Wilhite, 2003; Mishra & Singh, 2011, 2015; Yuan et al., 2013; Svoboda et al., 2015). Drought disaster risk assessment is accomplished using two major types of methods (Kim et al., 2013; Yuan et al., 2013; Rajsekhar et al., 2015; Chang et al., 2016; Yoo et al., 2016): (1) statistical methods based on probability theory; and (2) comprehensive assessment methods based on systems theory. The statistical methods use probability theory to simplify the complex drought disaster phenomenon. The comprehensive assessment method uses systems theory to comprehensively analyze the various influencing factors (Qu et al., 2014). Drought disaster risk problems have both natural and social aspects, involving complex mechanisms. Therefore, a risk analysis method based on systems theory has certain advantages. In this study, we used systems theory to define the drought disaster risk system structure, basic concepts, and mechanism analysis. We established a drought disaster risk assessment index system to describe the drought disaster risk and discuss the quantitative methods of the various indicators.

One important activity of drought disaster risk assessment is to assess the past, present, and future drought disaster system risk (time dimension) (Cardona et al., 2012; Şen, 2014; Mishra et al., 2015). The assessment method uses dynamic comprehensive assessment of the historical development status and future trends of the main factors of the drought disaster system. The assessment object in focus is a particular region. Another important activity of drought disaster risk assessment is to identify the regional drought disaster distribution status and zoning (space dimension) (Svoboda et al., 2015). This assessment method involves regional cluster zoning as the basis of the risk assessment or a combination of the risk assessment method and the cluster zoning method, which is completed synchronously. The assessment object includes many regions. There are many independent studies regarding these two kinds of assessment problems, but not much research has incorporated these two different objectives within an overall drought disaster risk assessment problem. That was done by comparing the drought disaster risk profile of one region for different years (time dimension) and comparing the drought disaster risk distributions of different regions in one year (space dimension), simultaneously. The results assess the overall drought disaster risk condition of different regions for different years. This approach involves a comprehensive assessment of the drought disaster risk on both a temporal and a spatial scale. The studies on this integrated assessment problem involving three-dimensional space–time data are limited.

In this study, a dynamic comprehensive evaluation method (Hwang & Yoon, 1981; Guo et al., 2007), applied to multiyear data, and a cluster evaluation method (projection pursuit clustering method) (Friendman & Turkey, 1974), commonly used in disaster regionalization, were combined. The combination established a comprehensive drought disaster risk dynamic assessment model based on projection pursuit dynamic clusters. This model was used to calculate an objective estimate of the index weight of the drought disaster risk assessment index system, dynamically assess the regional comprehensive drought disaster risk in recent years, and define cluster zones of multiple regional comprehensive drought disaster risk, simultaneously.

An application of the comprehensive drought disaster risk assessment in Xuzhou in East China is also presented in this study. The established model was applied to three cities and four counties in the Xuzhou area to assess the comprehensive drought disaster risk and to define multiple cluster zones of regional comprehensive drought disaster risk.
Regional comprehensive drought disaster risk assessment

Drought disaster is the result of natural events exerting their effects on human society and the environment (Knutson et al., 1998; Wu & Wilhite, 2004; Verdonk & Kiem, 2010; Lin et al., 2011; Cardona et al., 2012; Li et al., 2012). The factors that evoke drought disasters (or disaster-causing factors) must exist, and they determine the type of disaster. Drought factors mainly include temperature and a lack of precipitation. Disaster always acts within the context of natural and human environments. The comprehensive disaster-inducing environment determines the exposure level to disaster-causing factors and influences the intensity of the disaster-causing factors. Drought disaster-inducing environments are affected by natural environments such as water systems, topography, vegetation, soil, and water resources, as well as man-modified environments such as population distribution, industrial structure, level of economic development, and resource utilization. Disaster-bearing bodies include humans, all aspects of human production, and socio-cultural activities. With improved human awareness, drought disaster-bearing bodies also include ecological and environmental factors. Drought disaster loss is the interaction between disaster-causing factors, disaster-inducing environments, and disaster-bearing bodies. This interaction includes reduced crop production, limited drinking water, restrictions on socio-economic development, and environmental deterioration. From the viewpoint of systems theory, drought disaster can be viewed as a complex system composed of disaster-causing factors, a disaster-inducing environment, and a disaster-bearing body, namely, the drought disaster system (Blaikie et al., 1994; Shi, 1996).

In drought disaster formation, disaster-causing factors have randomness and volatility, and the disaster-inducing environment and disaster-bearing body also exhibit randomness. Therefore, the formation, development, evolution, and consequences of drought disaster must include some uncertainty, and the loss of the drought disaster system will have uncertainty as well. Based on the structure of the drought disaster system (Blaikie et al., 1994; Shi, 1996), drought disaster risk can be defined as the probability of the formation of a drought disaster system, which involves the probability of disaster losses. This probability is affected by the risk of drought disaster-causing factors, instability of the disaster-inducing environment, and the vulnerability of the disaster-bearing body. Among these, the risk of drought disaster-causing factors is the possibility of the occurrence of drought disaster-causing factors with different intensities. The instability of the disaster-inducing environment indicates an ability to suppress the drought caused by the environmental factors in a certain region. Early researchers believed that the vulnerability of the disaster-bearing body reflects the sensitivity (or vulnerability) of the disaster-bearing body to withstand drought disaster loss or destruction. However, in recent years, the adaptability and resilience of the disaster-bearing body has been emphasized (UN/ISDR, 2002; Cardona et al., 2012). The vulnerability of the disaster-bearing body also includes adaptability and resilience to drought disaster. Therefore, in this study, the drought disaster uncertainty, in which only the sensitivity of the disaster-bearing body is considered, is defined as the drought disaster risk. Meanwhile, the drought disaster uncertainty, in which the sensitivity, adaptability, and resilience of the disaster-bearing body is comprehensively considered, is termed the comprehensive drought disaster risk. A comprehensive drought disaster risk forming process can be considered as a process of system dynamics. In the process, the system input is the risk of drought disaster-causing factors, the system transformation is the disaster-bearing body vulnerability, which is composed of the disaster-bearing body sensitivity and adaptability, the system limit or catalytic condition is the instability of the disaster-inducing environment.
environment, and the system output is the uncertainty of the drought disaster loss. The structure of the drought disaster system risk can be expressed with the following equation:

Regional comprehensive drought disaster risk \( (R) = f (\text{disaster-causing factors (} S_1), \text{disaster-inducing environment (} S_2), \text{disaster-bearing body (} S_3)) \).

Regional comprehensive drought disaster risk assessment is a process used to quantify the comprehensive drought disaster risk of one or more regions. Its purpose is to quantify drought disaster risk data, such as the causes, characteristics, probability, and consequences, to assess the severity, distribution, and future trends of comprehensive drought disaster risk within the current economic and social conditions, to classify the degree of drought disaster risk in the area, and, finally, to provide quantitative and relatively objective information to decision-makers for assessing issues and drought disaster mitigation decisions (Shi, 1996; Wilhite, 2003).

Regional comprehensive drought disaster risk mechanisms are complex. The historical drought disaster data statistics and the model simulation method cannot reflect the complexity and volatility of the drought disaster system in modern society, and it is difficult to achieve a comprehensive drought disaster risk evaluation. The risk assessment method based on both system theories considers drought disaster as an independent system in seeking the main factors of drought disaster risk. It is a quantified scientific method that can be used to study the complex problem of a drought disaster.

The following will be based on systems theory to establish a regional comprehensive drought disaster risk assessment index system and a dynamic evaluation method.

**Regional comprehensive drought disaster risk assessment index system**

Regional comprehensive drought disaster risk is determined by the risk of drought disaster-causing factors, the instability of the disaster-inducing environment, and the vulnerability of the disaster-bearing body. The vulnerability of the disaster-bearing body includes not only sensitivity but also adaptability. Therefore, this section analyzes the regional comprehensive drought disaster risk assessment indicators from the above four parts. Due to the complexity of drought disasters, the quantitative assessment of comprehensive drought disaster risk involves many factors, and the following principles were considered to produce a reasonable index system: (a) objectivity and accuracy; (b) representativeness and universality; (c) applicability and availability; (d) constitutive property; and (e) systematic quality synthesis and operability.

**Risk of drought disaster-causing factors**

A risk analysis of drought disaster-causing factors aims to obtain the characteristics of various types of drought in the region and analyze the frequency of the regional drought intensity, drought duration, and drought area characteristics, through the assessment of regional drought disaster-causing factors such as yearly precipitation, evaporation, soil moisture, and study of historic drought situation statistics.

Considering the regional characteristics of drought analysis, drought can be classified into point drought and regional drought (Santos, 1983). Point drought studies focus on the drought in a certain area from a spatial perspective; the analysis area is relatively small. The multi-point drought characteristics are synthesized, and the spatial heterogeneity of a larger regional area is considered. In this study, drought intensity and duration were selected as risk indexes of the point drought risk analysis, and the
regional drought intensity, drought duration, and drought area index were applied for regional drought risk analysis (Santos, 1983). The mathematical expectations of each index were used to describe the drought characteristics.

**Instability of the disaster-inducing environment**

The instability analysis of the disaster-inducing environment is the interaction evaluation between the drought disaster factor and the hazard environment. The disaster-inducing environment may play a role in amplifying and mitigating the drought disaster situation, and under different disaster-inducing environments, the same drought disaster-causing factors may lead to a different exposure quantity and a different disaster magnitude for the drought disaster-bearing body. The drought disaster situation may also be different. The drought natural disaster-inducing environment includes the drainage system, landform, vegetation, soil, and water resources of the drought-stricken area, and the drought human disaster-inducing environment includes population distribution, industrial structure, level of economic development, and resource utilization.

**Natural disaster-inducing environment**

1. **Topography.** The effects of topography on drought disaster formation occur in two main areas: altitude and topography (Shang, 2000; Gao et al., 2004). As the altitude increases, the water body proportion decreases, and the distance between the water source and the farmland increases. The convenience of irrigation is also influenced by topography. Consequently, with limited water supplies in a drought disaster, there is less water to irrigate crops.

   Absolute elevation can be represented by a digital elevation model. The relative elevation is used to describe the slope. Presently, the principle of slope calculation for most geographic information system software is to consider the degree of elevation change of adjacent grids. In fact, the magnitude of the risk of drought disaster involves terrain changes of adjacent areas. Therefore, in the analysis of the terrain characteristics in the drought disaster risk analysis, it is necessary to consider replacing the usual slope with the relative standard deviation of an adjacent grid unit.

2. **Drainage system.** Drainage characteristics affect the regional water storage capacity as well as the agricultural irrigation and drought disaster relief capabilities during dry periods. Drainage system development is described by the water drainage density (Shang, 2000).

3. **Land resource structure.** The land resource structure type is the interaction product of natural elements, such as regional geomorphology, soil type, climate, vegetation, and hydrology. In different regions, land resource structure types are different, and the combination of agricultural land resources and environmental basis also differ, so the amount and quality of arable land is strictly limited. In different types and grades of cultivated land, the water holding and water retention performance differ, and can ease or exacerbate the impact of the drought disaster. In this study, the forest coverage rate is measured as the index of land resource structure (Shang, 2000; Tang, 2008).

4. **Water resources.** Water resources are sources of available water. These resources are limited by regional precipitation and hydrological conditions and are related to scientific technology and economic development. In this study, water resource development is represented by the utilization factor of water resources (Shang, 2000; Tang, 2008).
Human disaster-inducing environments.

(1) Population distribution. Demographic factors include disaster-inducing environments as well as a disaster-bearing body. Population increases reduce available resources per capita and increase water pollution. Increased water stress can decrease water safety, leading to inconvenience or more serious issues. Finally, as the dynamic production factor, human labor skills, and health levels could improve the management mode, this could, in turn, enhance drought disaster risk awareness and reduce the disaster response time, thus improving the ability to recover from drought disasters.

Demographic hazard characteristics include population density and regional daily water consumption per capita.

(2) Social and economic factors. Water resource availability limits the development of society and the economy. A poorly developed regional social and economic structure will aggravate the tension between the supply of water resources and demand. As a consequence, the risk of a regional drought disaster will increase. Considering the water consumption proportion resulting from social and economic activity, we express the social and economic water use as a proportion of the agricultural use.

The vulnerability of the disaster-bearing body

The vulnerability analysis of the disaster-bearing body includes the sensitivity analysis and the post-disaster adaptability analysis of the disaster-bearing body (Gao et al., 2004; Wang et al., 2005). The sensitivity of the bearing body refers to the impact extent of the drought disaster on the bearing body, while the adaptability of the disaster-bearing body reflects the disaster resistance and disaster relief capability of the bearing body.

Sensitivity analysis.

(1) Humans. The sensitivity of humans to drought disaster is expressed by the regional drought disaster tolerance or regional daily water consumption per capita. The regional population fitness index (P) calculation method is as follows (Ge et al., 2008):

\[ P = 1 - \frac{POP_{elder} + POP_{child}}{POP} \times 100\%, \]  \hspace{1cm} (1)

with POP referring to ‘Population’ in Equation (1) and where P is the regional population fitness index, \( POP_{elder} \) is the elderly population number in the region (>65 years), \( POP_{child} \) is the population number of children in the region (<14 years), and POP is the total population number in the region. These parameters are obtained from demographic data (Ge et al., 2008).

(2) Agriculture. The vulnerability of crops to agricultural drought disaster mainly depends on the crop planting structure, crop planting area, multiple cropping index, and the proportion of irrigated cropland to dry farmland.

The crop drought tolerance is usually expressed in the stage of the water sensitivity index. The index reflects the crop sensitivity to the water shortage and its impact on crop production. The index is
calculated as follows (Ge et al., 2008):

\[ C_d = \sum_{i=1}^{n} \lambda_{ij} \cdot \left( \frac{S_i}{S} \right), \]

where \( C_d \) is the crop drought tolerance index of the evaluation unit, \( S_i \) is the planting area of a specific crop \( i \) in the evaluation area, \( S \) is the total planting area for all crops in the evaluation area, and \( \lambda_{ij} \) is the water sensitivity coefficient of a specific crop \( i \) in growth stage \( j \). \( S_i \) and \( S \) are obtained from the agricultural statistical data, while the water sensitivity coefficient \( \lambda_{ij} \) is determined from field experiments (Ge et al., 2008).

(3) **Industry.** Industrial drought disaster vulnerability is related to the extent of industry dependence on water resources. It is described as the water demand per 10,000 CNY output value (Liu et al., 2005).

(4) **Livestock.** Livestock represents an important source of income. It is important to establish a drought disaster impact indicator for livestock water requirements, especially for pasturing area livestock. Therefore, the livestock drought sensitive index is used in this study (Liu et al., 2005).

(5) **Ecology and the environment.** The ecological and environmental impacts caused by drought disaster are qualitatively described in this study (Liu et al., 2005).

**Adaptability analysis.** The adaptability of the disaster-bearing body reflects the deliberate activity of society to counteract the drought disaster. This activity includes basic and special protective measures against the drought disaster (Ge et al., 2008).

(1) **Disaster prevention ability.** The drought disaster prevention ability includes all non-engineering measures taken before the drought disaster. These include drought-resistant engineering system construction, drought monitoring, drought forecasts, and drought warnings. The regional drought disaster prevention ability index is expressed by the effective irrigation rate, irrigation index, water retention area ration, irrigation capacity, amount of large water conservancy facilities, agricultural mechanization, use of water-saving irrigation technology, water conservancy facilities construction, and management level.

(2) **Drought disaster resistance ability.** The drought disaster resistance ability is the capability of drought disaster management. It also involves emergency protection and disaster victim placement. With the preparation of a drought disaster relief plan, the local drought disaster relief capacity has greatly improved. Drought disaster resistance index includes the number of wells per unit area of cultivated land and the total power of agricultural irrigation machinery.

(3) **Post-disaster restoration and reconstruction ability.** Restoration and reconstruction ability is the ability to rapidly recover to normal production and activity after a drought disaster. It is related to the disaster loss rate, the economic level, and the self-rescue capability of the disaster area. The restoration and reconstruction ability is influenced by the local gross domestic product (GDP) per capita. The local insurance rate is also considered in the social disaster security system in well-covered areas.

**Regional comprehensive drought disaster risk assessment index system**

Based on the above analysis, the regional comprehensive drought disaster risk assessment index system is established according to the actual situation of the study area. The system is illustrated in Figure 1.
Regional comprehensive drought disaster risk dynamic evaluation based on projection pursuit clustering

The purposes of comprehensive drought disaster risk assessment are to study the relationship between the regional comprehensive drought disaster risk and the main influencing factors, to analyze the development process and future trend of the regional comprehensive drought disaster system, and to delineate...
the drought disaster risk divisions of the study area. Thus, the comprehensive drought disaster risk assessment model is constructed to assess the influences of time and spatial dimension data on the drought disaster risk.

To meet the above requirements, a regional comprehensive drought disaster risk dynamic evaluation model was established using the dynamic comprehensive and clustering evaluation method. This model includes index weight selection and the dynamic assessment of comprehensive drought disaster risk. It retains the clustering division of comprehensive drought disaster risk for the study area. Its basic principles are as follows.

**Projection pursuit dynamic cluster evaluation method**

Projection pursuit is a statistical method for dealing with complex multifactorial problems (Friendman & Turkey, 1974; Ni & Cui, 2007). It is based on space projection transformation theory by analyzing the projection properties of low-dimensional space to study the characteristics of high-dimensional data. The projection pursuit clustering model is a clustering analysis model based on the projection pursuit method. It has been widely used in water quality evaluation, environmental monitoring, disaster assessment, water resources evaluation, and many areas of climatic regionalization. However, in this model, the density window parameters are questionable and the operation results still need re-analysis. In view of the above problems, Ni & Cui (2007) introduced a dynamic clustering method to build the projection index, and the projection pursuit dynamic cluster (PPDC) model was established. The PPDC model combined the projection pursuit principle and the dynamic clustering method. It could be applied to the drought disaster risk regionalization and used to reanalyze the operation results. The model principles are introduced in the following section.

**Comprehensive risk dynamic evaluation model based on projection pursuit clustering**

The regional disaster comprehensive risk assessment is the basis of regional disaster risk regionalization. It is the evaluation of the regional disaster risk based on the state value or the average drought disaster risk factor during the study period. However, with economic development and intensified human activity, a comprehensive assessment is needed to evaluate the dynamic changes of the drought disaster risk state in the study area. Based on the foregoing consideration, a comprehensive drought disaster risk dynamic evaluation was established based on the dynamic comprehensive evaluation method and projection pursuit dynamic clustering. The model building steps were as follows.

**Step 1: Normalization of the evaluation index value.** The normalization of the evaluation index value is important for both static and dynamic evaluation. Three kinds of processing methods are employed to deal with non-dimensional temporal spatial data – the standard sequence method, complete sequence method, and incremental sequence method (Yi et al., 2009). The complete sequence normalized treatment method is applied to keep the full characteristics of the index values and to analyze the drought disaster risk trends for each time period.

During a p year study period, the research area vector \( S \) includes \( m \) evaluation areas \( S = \{s_1, s_2, \ldots, s_m, (m \geq 2)\} \), and the comprehensive drought disaster risk assessment index vector \( R \) is composed of \( n \) evaluation indexes \( R = \{R_1, R_2, \ldots, R_n\} \), where \( m, n, p \) are positive integers. The stereo sequence data of regional comprehensive drought disaster risk assessment index is expressed with a three-dimensional index matrix \( X = (x_{ij})_{m \times n \times p} \), where \( x_{ijk} \) is the \( j \)th evaluation index value of the \( k \)th year in area \( i \). Then,
the complete sequence normalized treatment method is applied to eliminate the dimension and value range of each index. The processing method is as follows:

For the larger values: \( y_{ijk} = \frac{[x_{ijk} - \min_{i,k} (x_{ijk})]}{[\max_{i,k} (x_{ijk}) - \min_{i,k} (x_{ijk})]} \). (3)

For the smaller values: \( y_{ijk} = \frac{[\max_{i,k} (x_{ijk}) - x_{ijk}]}{[\max_{i,k} (x_{ijk}) - \min_{i,k} (x_{ijk})]} \). (4)

where \( \min_{i,k} (x_{ijk}) \), \( \max_{i,k} (x_{ijk}) \) are the minimum and maximum values of the \( j \)th evaluation index in \( m \) areas over the \( p \) year study. Parameter \( i \) is the \( ith \) evaluation area, \( i = (1, \ldots , m) \). Parameter \( j \) is the \( j \) evaluation index, \( j = (1, \ldots , n) \), while \( k \) is the \( k \) evaluation year, \( k = (1, \ldots , p) \).

**Step 2: Linear coupling spatial dimension data.** Dynamic comprehensive evaluation often uses the ‘twice-weighted method’ to weight the comprehensive evaluation index values. To prevent using a weighted method that is first weighted by time dimension and then by spatial dimension, which may pollute evaluation index values, and because of the need to analyze the calendar year trend of the comprehensive evaluation results after a dynamic comprehensive evaluation, we recommend a weighted method that is weighted first by spatial dimension and then by time dimension to evaluate a comprehensive evaluation object. The projection pursuit method was used for the spatial dimension weighted synthesis, \( n \)-dimension data \( \{y_{ijk} | j = 1,2, \ldots ,n\} \) are integrated into vector \( a = (a_1,a_2, \ldots ,a_n) \) representing the projection direction, and the two-dimensional projection value \( z_{ik} \) is evaluated:

\[
  z_{ik} = \sum_{j=1}^{n} a_j y_{ijk} (i = 1, 2, \ldots , m, k = 1, 2, \ldots , p),
\]

where \( a \) is the unit length vector, \( m \) is the evaluation area number, and \( z_{ik} \) is the comprehensive drought disaster risk assessment result for \( p \) years.

**Step 3: Time dimension synthesis.** When the time series of the evaluation index value is weighted for time dimension synthesis, the appropriate weighted synthesis method should be chosen according to the purpose of the evaluation. In this study, we recommend a method where time intervals closer to the study time have a higher index weight. This is named the ‘stressing the present, conversant with the past’ method and is given by the following:

\[
  u_i = \sum_{k=1}^{p} [\exp (\lambda \cdot k) \cdot \sum_{j=1}^{n} a_j y_{ijk}] (i = 1, 2, \ldots , m),
\]

where \( u_i \) is the comprehensive evaluation value of area \( i \) and \( \lambda \) is the weighting factor = \((2p)^{-1}\) in the study. Therefore, the comprehensive evaluation value for each area is represented as \( U = (u_1,u_2, \ldots ,u_m) \).

**Step 4: Structure projection index function.** Dynamic clustering is applied to construct the projection index (Friendman & Turkey, 1974; Ni & Cui, 2007). To begin, \( l(u_i,u_j) (i,j = 1,2, \ldots ,m) \) is the absolute
distance of each set of two comprehensive evaluation values, that is \( l(u_i, u_j) = |u_i - u_j| \). The clustering region is divided into \( M \) classes of drought disaster risk area, where \( 2 \leq M < m \), and \( \Theta_h (h = 1, 2, \ldots, M) \) represents the drought disaster risk dataset for class \( h \). The equation is:

\[
\Theta_h = \{ u_i | d(A_h - u_i) \leq d(A_t - u_i), t = 1, 2, \ldots, M, t \neq h \},
\]

where \( d(A_h - u_i) = |u_i - A_h| \), \( d(A_t - u_i) = |u_i - A_t| \), and \( A_h \) and \( A_t \) are the cluster centers for class \( h \) and class \( t \), respectively. Their initial values are randomly generated. In this study, the random formula is based on the following equation: \( A_j^0 = j \times [\max(u_i) - \min(u_i)]/(M + 1) + \min(u_i) \). Then, the cluster centers are iteratively determined by the mean value of each class evaluation value. The steps above are repeated until \( \sum_{j=1}^{M} (A_j^j - A_j^{j-1})/A_j^j \leq \varepsilon \), where \( \varepsilon \) is the allowable error.

Second, the adjacent degree within a class sample is represented by the concentration class \( d_d(a) \):

\[
d_d(a) = \sum_{h=1}^{M} d_h, \text{ where } \quad d_h = \sum_{u_i, u_j \in \Theta_h} l(u_i - u_j).
\]

The smaller the value \( d_d(a) \) is, the higher the concentration degree.

The sample dispersion degree is expressed as the dispersion degree within the class:

\[
l_t = \sum_{u_i, u_j \in U} l(u_i - u_j).
\]

The larger the \( l_t(a) \) value is, the higher the dispersion degree.

The projection index is represented as \( Q_Q(a) = l_t(a) - d_d(a) \). Clearly, when \( Q_Q(a) \) reaches the maximum value, we achieve our objective to disperse the clustering between class samples and to concentrate the clustering within a class.

**Step 5: Projection index function optimization.** When the index value of the sample is given, the projection index function \( Q_Q(a) \) changes only with the projection direction, reflecting the different characteristics of the data structure. The projection direction with the most likely exposed high-dimensional data structure indicates the optimal projection direction, which can be estimated by maximizing the projection index function, using the following equation:

\[
\max Q_Q(a) = l_t(a) - d_d(a), \quad \text{s.t.} \quad \sum_{j=1}^{p} a^2(j) = 1.
\]

This is a complex nonlinear optimization problem and the optimization variable is \( \{ a_j | j = 1, 2, \ldots, n \} \). The biological survival rules and the genetic algorithm (Holland, 1992) are used to solve the above problems.

Using the above step, the regional comprehensive drought disaster risk dynamic evaluation model is established. The trend analysis and the clustering division of the regional comprehensive drought disaster risk can be estimated.
Comprehensive drought disaster risk evaluation of the Xuzhou area

Establishment of a comprehensive drought disaster risk assessment system in the Xuzhou area

Xuzhou is located in the climate transition zone between the northern subtropical zone and the southern tropical zone of China. It consists of three cities (Xuzhou urban, Xinyi, and Pizhou) and four counties (Fengxian, Peixian, Tongshan, and Suining), covering an area of about 11,258 km². The precipitation is influenced by the East Asian monsoon, where water resources are unevenly distributed and flood and drought disasters occur frequently. Water shortage is the main factor that restricts the development of local agricultural production. The gradually increasing gap between water supply and water demand is a bottleneck affecting the social and economic development of Xuzhou. It is important to strengthen local drought disaster risk measures to improve drought disaster resistance capability.

In an earlier section, we analyzed the theory and method of constructing a comprehensive drought disaster risk assessment index system. In this section, because the assessment area is small, we neglect topographic features. According to the characteristics of drought disaster in the Xuzhou area, combined with the available data, we chose the main evaluation indexes, established a regional comprehensive drought disaster risk index system in Xuzhou, as shown in Table 1, and used the index system to verify the feasibility of the dynamic clustering evaluation method proposed in this study.

In Table 1, $C_1$ and $C_2$ are drought disaster-causing factors, which were obtained through regional historical precipitation data, and the SPI (Standardized Precipitation Index) (McKee et al., 1993) was used to analyze the drought intensity and duration of every historical drought, revealing the mathematical expectation of these drought characteristics. Because the analysis of drought disaster risk was obtained through the mathematical expectation of drought characteristics, the data should be the same throughout the year.

$C_3$, $C_4$, $C_5$, $C_8$, and $C_{10}$ are data from the statistical yearbook of JiangSu province; $C_7$ are data from the water resources bulletin; and $C_9$ are data from the rural statistical yearbook of JiangSu province. $C_6$ is the crop drought tolerance index, which is expressed as the stage water sensitivity index and is calculated from the statistical yearbook and agricultural sector data in formula (2).

Considering the actual situation in the Xuzhou area during 2004 to 2007, the comprehensive drought disaster risk dynamic evaluation system was determined (Table 1).

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<th>Subsystem</th>
<th>Index</th>
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<td></td>
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<td>Crop drought tolerance $C_6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water demand per 10,000 CNY GDP $C_7$</td>
</tr>
<tr>
<td></td>
<td>Resilience of disaster bearing body $B_4$</td>
<td>Effective irrigation rate $C_8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of wells per unit area of cultivated land $C_9$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GDP per capita $C_{10}$</td>
</tr>
</tbody>
</table>
Comprehensive drought disaster risk dynamic evaluation model in Xuzhou

According to the dynamic evaluation model based on projection pursuit clustering, all indexes were normalized through formula (3), and the normalized data of Xuzhou’s comprehensive drought disaster risk evaluation index system is shown in Table 2.

Table 2. Normalized data of Xuzhou’s comprehensive drought disaster risk evaluation index system.

<table>
<thead>
<tr>
<th>Index</th>
<th>Year</th>
<th>Xuzhou urban</th>
<th>Fengxian</th>
<th>Peixian</th>
<th>Tongshan</th>
<th>Sunning</th>
<th>Xinyi</th>
<th>Pizhou</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>2004</td>
<td>0.761</td>
<td>1.000</td>
<td>0.804</td>
<td>0.543</td>
<td>0.783</td>
<td>0.457</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>0.761</td>
<td>1.000</td>
<td>0.804</td>
<td>0.543</td>
<td>0.783</td>
<td>0.457</td>
<td>0.000</td>
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<td>2006</td>
<td>0.761</td>
<td>1.000</td>
<td>0.804</td>
<td>0.543</td>
<td>0.783</td>
<td>0.457</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>0.761</td>
<td>1.000</td>
<td>0.804</td>
<td>0.543</td>
<td>0.783</td>
<td>0.457</td>
<td>0.000</td>
</tr>
<tr>
<td>C₂</td>
<td>2004</td>
<td>0.535</td>
<td>1.000</td>
<td>0.403</td>
<td>0.408</td>
<td>0.175</td>
<td>0.849</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>0.535</td>
<td>1.000</td>
<td>0.403</td>
<td>0.408</td>
<td>0.175</td>
<td>0.849</td>
<td>0.000</td>
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<td></td>
<td>2006</td>
<td>0.535</td>
<td>1.000</td>
<td>0.403</td>
<td>0.408</td>
<td>0.175</td>
<td>0.849</td>
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</tr>
<tr>
<td></td>
<td>2007</td>
<td>0.535</td>
<td>1.000</td>
<td>0.403</td>
<td>0.408</td>
<td>0.175</td>
<td>0.849</td>
<td>0.000</td>
</tr>
<tr>
<td>C₃</td>
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<td>0.852</td>
<td>0.722</td>
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<td>0.868</td>
<td>1.000</td>
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<td>2005</td>
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<td>0.846</td>
<td>0.721</td>
<td>0.977</td>
<td>0.862</td>
<td>0.993</td>
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<td></td>
<td>2006</td>
<td>0.047</td>
<td>0.839</td>
<td>0.712</td>
<td>0.971</td>
<td>0.855</td>
<td>0.983</td>
<td>0.822</td>
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<td></td>
<td>2007</td>
<td>0.036</td>
<td>0.830</td>
<td>0.698</td>
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<td>C₄</td>
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<td>0.074</td>
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<td>0.243</td>
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<td>2006</td>
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<td>0.424</td>
<td>0.596</td>
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<td>0.312</td>
<td>0.254</td>
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<td>0.210</td>
<td>0.466</td>
<td>0.658</td>
<td>0.246</td>
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<tr>
<td>C₅</td>
<td>2004</td>
<td>0.354</td>
<td>0.821</td>
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<td>0.939</td>
<td>0.777</td>
<td>0.850</td>
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<td>0.781</td>
<td>0.885</td>
<td>0.773</td>
<td>0.999</td>
<td>1.000</td>
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<tr>
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<td>2006</td>
<td>0.091</td>
<td>0.773</td>
<td>0.764</td>
<td>0.889</td>
<td>0.802</td>
<td>0.855</td>
<td>0.962</td>
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<tr>
<td></td>
<td>2007</td>
<td>0.000</td>
<td>0.798</td>
<td>0.752</td>
<td>0.710</td>
<td>0.778</td>
<td>0.790</td>
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<tr>
<td>C₆</td>
<td>2004</td>
<td>0.398</td>
<td>0.382</td>
<td>0.209</td>
<td>0.357</td>
<td>1.000</td>
<td>0.000</td>
<td>0.280</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>0.320</td>
<td>0.349</td>
<td>0.202</td>
<td>0.243</td>
<td>0.877</td>
<td>0.148</td>
<td>0.266</td>
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<td>2006</td>
<td>0.235</td>
<td>0.438</td>
<td>0.184</td>
<td>0.192</td>
<td>0.890</td>
<td>0.173</td>
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<tr>
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<td>2007</td>
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<td>0.404</td>
<td>0.148</td>
<td>0.251</td>
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<td>0.427</td>
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<td>C₇</td>
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<td>0.498</td>
<td>0.859</td>
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<td></td>
<td>2007</td>
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<td>0.977</td>
<td>0.871</td>
<td>0.840</td>
<td>0.927</td>
<td>0.898</td>
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<td>C₈</td>
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<td>0.948</td>
<td>0.809</td>
<td>0.779</td>
<td>0.338</td>
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<td>0.943</td>
<td>0.809</td>
<td>0.854</td>
<td>0.384</td>
<td>0.773</td>
<td>0.191</td>
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<td></td>
<td>2006</td>
<td>0.000</td>
<td>1.000</td>
<td>0.847</td>
<td>0.810</td>
<td>0.401</td>
<td>0.781</td>
<td>0.195</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>0.438</td>
<td>0.791</td>
<td>0.829</td>
<td>0.790</td>
<td>0.477</td>
<td>0.782</td>
<td>0.191</td>
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<tr>
<td>C₉</td>
<td>2004</td>
<td>0.000</td>
<td>0.985</td>
<td>0.956</td>
<td>0.060</td>
<td>0.132</td>
<td>0.026</td>
<td>0.143</td>
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<tr>
<td></td>
<td>2005</td>
<td>0.027</td>
<td>0.986</td>
<td>0.957</td>
<td>0.059</td>
<td>0.132</td>
<td>0.027</td>
<td>0.146</td>
</tr>
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<td></td>
<td>2006</td>
<td>0.044</td>
<td>1.000</td>
<td>0.562</td>
<td>0.054</td>
<td>0.218</td>
<td>0.028</td>
<td>0.151</td>
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<td>2007</td>
<td>0.043</td>
<td>0.997</td>
<td>0.990</td>
<td>0.055</td>
<td>0.220</td>
<td>0.029</td>
<td>0.153</td>
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<tr>
<td>C₁₀</td>
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<td>0.016</td>
<td>0.114</td>
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<td>0.000</td>
<td>0.061</td>
<td>0.065</td>
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<tr>
<td></td>
<td>2005</td>
<td>0.224</td>
<td>0.038</td>
<td>0.156</td>
<td>0.192</td>
<td>0.013</td>
<td>0.101</td>
<td>0.100</td>
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<tr>
<td></td>
<td>2006</td>
<td>0.283</td>
<td>0.058</td>
<td>0.202</td>
<td>0.255</td>
<td>0.046</td>
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<tr>
<td></td>
<td>2007</td>
<td>0.353</td>
<td>0.087</td>
<td>0.259</td>
<td>0.340</td>
<td>0.073</td>
<td>0.171</td>
<td>0.184</td>
</tr>
</tbody>
</table>
The normalized data were used into steps 2 and 3 of the dynamic evaluation model. The zoning drought disaster risk of the Xuzhou area was divided into three classes: most dangerous, more dangerous, and not dangerous, exhibited by $M = 3$ in step 4. Structuring the projection index function and solving the complex nonlinear optimization problem, we obtained the final optimal projection direction vector as:

$$
\mathbf{a} = \{0.453, 0.316, 0.198, 0.036, 0.209, 0.117, 0.019, 0.446, 0.617, 0.130\}.
$$

The projection direction vector takes into account the different weights of calendar data in the time dimension and also takes into account the pulling distance between the clusters. By projecting the projection direction vector into formula (5), a comprehensive drought disaster risk assessment for various regions can be carried out over the years. The comprehensive evaluation results are considered in formula (6), and the comprehensive drought disaster risk in different regions can be evaluated. The comprehensive drought disaster risk assessment results in each region are considered in the cluster model of (7), and the regions can be clustered and divided. This method achieves these three purposes simultaneously, which is the biggest difference compared to other evaluation methods.

**Comprehensive drought disaster risk dynamic evaluation in Xuzhou**

(1) *Trend analysis of evaluation objects.* Applying the optimal projection direction vector $\mathbf{a}$ into step 2, formula (5) of the dynamic evaluation model, yearly drought disaster risk assessment values were calculated (Table 3). The evaluation value in Table 3 shows that the drought disaster risk change trend, in recent years, is not significant in the cities and counties of Xuzhou. Only the Suining County comprehensive evaluation values show a significantly increasing trend, suggesting that the Suining County drought disaster risk has decreased. Through analysis of each index value we see that the Suining index values of proportion for primary industry, extent of drought-tolerant crops, effective irrigation rate, number of electromechanical wells, and local GDP per capita move in a favorable direction, while changes in the other index values are not significant.

(2) *Comprehensive evaluation of the evaluation object.* Following step 3, formula (6), the integrated spatial dimension data were synthesized by the time dimension. The comprehensive drought disaster risk evaluation values in seven cities and counties within the Xuzhou area were obtained (Table 3, line 6). The assessment values show that Pizhou has the most severe comprehensive drought disaster

<table>
<thead>
<tr>
<th>Year</th>
<th>Xuzhou urban</th>
<th>Fengxian</th>
<th>Peixian</th>
<th>Tongshan</th>
<th>Sunning</th>
<th>Xinyi</th>
<th>Pizhou</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>0.803</td>
<td>2.207</td>
<td>1.821</td>
<td>1.244</td>
<td>1.105</td>
<td>1.241</td>
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<td>2.186</td>
<td>1.817</td>
<td>1.243</td>
<td>1.116</td>
<td>1.295</td>
<td>0.614</td>
</tr>
<tr>
<td>2006</td>
<td>0.687</td>
<td>2.239</td>
<td>1.595</td>
<td>1.230</td>
<td>1.185</td>
<td>1.279</td>
<td>0.613</td>
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<tr>
<td>2007</td>
<td>0.870</td>
<td>2.153</td>
<td>1.854</td>
<td>1.216</td>
<td>1.234</td>
<td>1.305</td>
<td>0.554</td>
</tr>
<tr>
<td>Dynamic comprehensive clustering analysis</td>
<td>Most dangerous</td>
<td>Not dangerous</td>
<td>Not dangerous</td>
<td>More dangerous</td>
<td>More dangerous</td>
<td>More dangerous</td>
<td>Most dangerous</td>
</tr>
</tbody>
</table>
risk, followed by the Xuzhou urban areas. The comprehensive drought disaster risk in Fengxian County is relatively small.

(3) Clustering analysis of the evaluation objects. The regional comprehensive drought disaster risk dynamic evaluation model based on Projection Pursuit Clustering facilitated a trend analysis and comprehensive evaluation of the drought disaster risk status for the calendar year and also estimated the dynamic clustering division of the regional drought disaster risk.

According to the above, the drought disaster risk is zoned into three types of risk: most dangerous, more dangerous, not dangerous. This is represented by $M = 3$ in step 4. Using the optimal projection vector in the model, according to step 4, the initial clustering center points can be generated: $(7.512, 10.577, 13.641)$. According to the idea of dynamic clustering in step 4, after three iterations, we obtained the clustering center points for drought disaster risk: $(5.775, 9.396, 15.070)$, corresponding to the regional cluster center. The three classes are: most dangerous (urban Pizhou City), more dangerous (Tongshan County, Suining County, and Xinyi City), and not dangerous (Fengxian and Peixian). The distribution of drought disaster risk in the Xuzhou area is shown in Figure 2. In the figure, the dark grey region represents the most dangerous region of drought disaster risk, while the white region means the lowest dangerous region of drought disaster risk in the Xuzhou area.

As can be seen from the yearly comprehensive drought disaster risk evaluation values and regional comprehensive drought disaster risk evaluation values, from 2004 to 2007, the drought disaster risk ranking of each city (or county) did not change significantly. Because the drought disaster-causing factors values are relatively smaller while other factors do not change much, the comprehensive drought disaster risk values of Fengxian and Peixian have been small each year, and the Pizhou and Xuzhou urban drought disaster-causing factors values are relatively greater, suggesting that the comprehensive drought disaster risk is greater. In the more dangerous class, representing such areas as Tongshan County, Suining County, and Xinyi City, the significant increasing trend in the comprehensive drought disaster risk factors ($C_4$, $C_8$, $C_9$, and $C_{10}$) suggests a slight change in the sorting of the comprehensive drought disaster risk for this class.

Fig. 2. Distribution of comprehensive drought disaster risk in the Xuzhou area.
From the above analysis process and results, it can be seen that this method can accurately reflect the development process and distribution of regional comprehensive drought disaster risk simultaneously and can provide decision-makers with a large amount of evaluation data. This is the greatest advantage of this method.

It should be noted that the evaluation values of this method are relative values and are not suitable for direct comparison with evaluation results of other methods. However, from the distribution map of the evaluation results (Figure 2), the evaluation results of this study are consistent with the distribution of historical drought disaster losses and previous research results (Sun et al., 2011).

Comparison of comprehensive risk assessment and drought disaster causing factors risk assessment

In drought disaster risk assessment, often only the drought disaster-causing factors are considered. For further comparison of drought disaster-causing factors and other factors (environment instability and body vulnerability) affecting the drought disaster risk assessment system, the projection pursuit dynamic clustering method is used for comprehensive evaluation. The evaluation weight is still proportional to the optimal projection direction. The evaluation results are shown in Table 4.

The correlation coefficient between drought disaster-causing factors risk values and comprehensive risk values is 0.82 and the coefficient between the risk values of other factors and comprehensive risk values is 0.95. As a result, other drought disaster factors (environment instability and body vulnerability) have a greater impact on the comprehensive drought disaster risk than drought disaster-causing factors. This fully reflects that the drought disaster risk is the result of the combination of natural factors and social factors. With the intensification of human activity, the impact of social factors on drought disaster risk will become more significant.

Conclusions

Systems theory was successfully used to study the basic concepts and evaluation methods for comprehensive drought disaster risk assessment. The comprehensive drought disaster risk system was divided into three subsystems: drought disaster-causing factors, disaster-inducing environments, and disaster-bearing bodies. The representative indexes of each subsystem that may be considered in the

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Xuzhou urban</th>
<th>Fengxian</th>
<th>Peixian</th>
<th>Tongshan</th>
<th>Sunning</th>
<th>Xinyi</th>
<th>Pizhou</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drought disaster causing factors</td>
<td>7.085</td>
<td>10.604</td>
<td>6.781</td>
<td>5.171</td>
<td>5.654</td>
<td>6.551</td>
<td>0.000</td>
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<td>Not</td>
<td>More</td>
<td>More</td>
<td>More</td>
<td>More</td>
<td>Most</td>
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<tr>
<td>Other factors</td>
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<td>13.014</td>
<td>11.623</td>
<td>7.848</td>
<td>7.037</td>
<td>7.418</td>
<td>5.335</td>
</tr>
<tr>
<td>Clustering analysis</td>
<td>Most dangerous</td>
<td>Not</td>
<td>Not</td>
<td>More</td>
<td>More</td>
<td>More</td>
<td>Most</td>
</tr>
<tr>
<td>Clustering analysis</td>
<td>Most dangerous</td>
<td>Not</td>
<td>Not</td>
<td>More</td>
<td>More</td>
<td>More</td>
<td>Most</td>
</tr>
</tbody>
</table>

Table 4. Assessment results comparison of comprehensive risk and disaster-causing factors risk.
comprehensive drought disaster risk assessment process were discussed and enumerated. The Xuzhou area was used as an example, and a regional comprehensive drought disaster risk evaluation index system was established to describe the comprehensive drought disaster risk system based on Xuzhou area characteristics.

The goals of comprehensive drought disaster risk assessment are to analyze drought disaster development trends and drought disaster risk zoning, as well as to establish a dynamic evaluation model. Based on the ideas of the projection pursuit clustering method and the dynamic comprehensive evaluation method, a comprehensive risk assessment model was effectively established that accounts for the multi-dimensional spatio-temporal drought disaster risk, which could realize the three goals of comprehensive drought disaster risk assessment, simultaneously, and was the biggest difference compared to other evaluation methods. The method represented a complex nonlinear optimization problem, and the genetic algorithm was therefore recommended to provide a good solution.

The theoretical model was applied to the comprehensive risk assessment of drought disaster in the Xuzhou area. Results demonstrate that this model incorporated the multi-dimensional spatio-temporal drought disaster risk data for dynamic evaluation and accurately reflected the regional drought disaster development trend and the distribution of drought disaster risk, simultaneously.

The assessment result shows that Pizhou City was the region with the highest risk in Xuzhou area, while Fengxian had the lowest. The change trend of comprehensive drought disaster risk in Xuzhou area was not significant from 2004 to 2007. A comparison of comprehensive risk assessment and drought disaster-causing factors risk assessment shows that other drought disaster factors (environment instability and body vulnerability) have a greater impact on comprehensive drought disaster risk assessment, and need to attract more attention.

A regional comprehensive drought disaster risk dynamic evaluation method based on projection pursuit clustering provides an instrument for drought disaster risk management, from the aspects of time and space, to assess regional drought disaster risk. A macro perspective is achieved allowing an overall understanding of the distribution and development trends of regional drought disaster. This information provides a basis for regional drought disaster zoning and planning and also allows for the evaluation and implementation of drought disaster control and drought disaster resistance policy. However, it needs to be pointed out that the assessment results exhibit relative risk, which can reflect the different risks within the evaluation area, but the drought disaster risk value cannot be compared with other methods or other areas directly.

Acknowledgements

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References


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