Ecological drought and its state assessment: a case study in the Yellow River estuary

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ABSTRACT

Water cycle has been intensified by global warming, leading to frequent extreme climate events. Drought is an extreme climate phenomenon. Runoff decrease and human water demand increase aggravate the water shortage of regional ecosystems, affecting regional water and land ecosystems and causing ecological drought, river cutoff and water pollution. Finally, the reverse succession and the imbalance of regional ecological structures take place. The clarification of the concept of ecological drought for effective evaluation of regional ecological drought degree has become an urgent important scientific issue to be resolved. Therefore, in this paper, the typical region of the Yellow River estuary was studied for the analysis of characteristics of regional ecological changes and the definition of the concept and connotation of ecological drought. Based on the representative monitoring and early warning indices to ecological drought, the evaluation method and the classification standard of regional ecological drought were proposed. The regional ecological drought includes four levels: I (Severe), II (General), III (Weak) and IV (None). The indicator thresholds of river runoff, biodiversity and vegetation coverage on different ecological drought levels were quantified. The research results can be technically beneficial for the improvement of global ecological drought emergent support capacity and reducing loss due to drought.

Key words: concept redefinition, ecological drought, leading indicators, state assessment, Yellow River estuary

HIGHLIGHTS

- The concept of ecological drought in areas with important ecological functions is discussed.
- A model with certain applicability for ecological drought assessment is proposed.
- The regional ecological drought can be divided into four levels.
- The thresholds of leading indicators to different ecological drought degrees are quantified.

1. INTRODUCTION

Ecological environment is the basic natural condition related to human survival and development (Wang et al. 2020). The maintenance of the benign cycle of ecosystems relies on the rational development and protection of water resources, and full considerations of ecological environment water demand and sustainable utilization of water resources (Kuemmerlen et al. 2019; Yu et al. 2019). Water is the most important condition for the benign cycle of ecological environment (Rinaldo et al. 2018). With the impact of climate change and human activities, regional drought may become more serious, and the drought will further aggravate the shortage of water for ecological environment systems (Ostad-Ali-Askari et al. 2019). Drought is divided into meteorological, agricultural, hydrological and socioeconomic drought in different research fields (Bachmair et al. 2016; Liang et al. 2019). The fifth assessment report from the Intergovernmental Panel on Climate Change (IPCC) states that the frequency, intensity and duration of global drought events have increased significantly in the last 50 years in the 21st century, and this trend will be further developed in the future (Porter et al. 2018). In China, drought is one of the natural disasters with high frequency, long duration and wide influence range and causes important loss to livings and production, especially agricultural production (Novoa et al. 2019; Yao et al. 2019). In addition, the once-in-a-thousand-year drought in Australia from 2002 to 2010 caused ecological loss of 800 million AUD in the Murray-Darling region (Millar & Stephenson 2015). The extreme drought event in the Amazon region in 2010 resulted in a net carbon loss of 2.2 Pg (1 Pg = 1,015 g), basically the annual carbon uptake of global forest ecosystem, in the regional tropical
rainforest ecosystem (Goulden & Bales 2019). The identification of drought and the measures to deal with and alleviate drought have become an urgent scientific problem to be solved (Jiang et al. 2019).

According to the conventional concepts of agricultural drought and drought resistance, some studies name wetland ecological issues as 'ecological drought', in which the object only refers to wetland, though this explains that drought will cause ecological loss of wetland. With the proposal of the concept of wetland ecological drought, the ecological drought evaluation function of annual average water level was proposed to analyze the early warning index and the level of Baiyangdian Wetland ecological drought in China (Zhang et al. 2010; Huang et al. 2019). Until 2016, the Science for Nature and People Partnership (SNAPP) of the United States proposed a concept of ecological drought, which is defined as a complex comprehensive process caused by the shortage of natural water supply (changes in hydrological processes caused by natural or artificial management), leading to changes in the growth state of surface vegetation and soil water conditions (Slette et al. 2019). It is a xerophytic ecological environment constructed by vegetation affected by the interaction between water stress and living environment. Ecological drought will negatively affect the ecosystem in many ways. This concept of ecological drought is developed to involve the impact of drought on terrestrial plants and soil water cycle. It is still understood as an impact, but whether it will be developed into a disaster and whether this disaster should be taken as ecological drought are still not clear.

With more and more attention paid to the impact of drought on ecosystems (Brown & Alastair 2017; Chadd et al. 2017), Crausbay et al. (2017) defined ecological drought as a 'sudden shortage of available water resources leading to the vulnerability of ecosystem exceeding its threshold and feedback in natural and human systems'. Munson et al. (2020) found that ecological drought should involve the sensitivity of ecosystems to the change in drought degree and the response of organisms at different levels. Therefore, ecological drought is defined as a 'shortage of available water leading to the performances of organisms or ecosystems deviating from the upper limits'.

Based on the understanding of this concept of ecological drought, MODIS was adopted to normalize vegetation index and land surface temperature data to establish the temperature vegetation dryness index for the quantitative study on the characteristics of ecological drought in different ecological functional areas and the analysis of the driving factors. In order to evaluate the ecological impact of drought, five watershed-scale drought plans in southwestern Montana were analyzed using the conceptual framework of ecological drought (McEvoy et al. 2018). The nonparametric density estimation and the super probability method were adopted to quantitatively assess the water quality risk caused by ecological drought (Kim et al. 2019). In certain papers, river ecological and minimum runoff values were taken as the indicators of ecological drought to establish an ecological drought monitoring framework (Park et al. 2020). Especially, the minor change in low runoff during drought will cause the violent response of regional aquatic ecosystems. The experimental results in the rivers of New Zealand showed that the impact on macroinvertebrates was relatively small when the runoff was reduced by 10% (James & Suren 2010). In contrast, the experimental results in the rivers of America showed that when the runoff was reduced to 96% of the annual average, the density and growth rate of salmon were reduced to 60–67% of the normal values (Mccargo & Peterson 2010). Therefore, ecological drought can be considered as a gradual disaster. The aquatic ecosystem is relatively fragile and has poor drought resistance. The longer the drought lasts, the more serious the loss will be, and even the aquatic ecosystem will be irreversibly affected.

Currently, the research mostly focuses on wetlands, and terrestrial ecology is also targeted later. And, the global research on regional ecological drought evaluation indices and the quantification of the indices is still undeveloped. In general, the concept and connotation of ecological drought are still not very clear, universal drought assessment indices are still absent and the specific division of ecological drought degree is rarely reported. These issues restrict and interfere with the development of drought resistance. In order to integrate eco-environmental impact into disaster prevention and mitigation planning, the planners should make two topics clear: a more comprehensive concept of ecological drought and how to categorize and evaluate the degree of ecological drought. Therefore, aiming at the dilemmas of ambiguous concepts of ecological drought and difficult effective evaluation, in this paper, the Yellow River estuary was taken as the research object to explore the regional climate, hydrology and ecological characteristics for the analysis of the interaction between regional drought and ecological factors, so a more accurate and clear concept of regional ecological drought would be proposed to resolve the problem of ambiguous cognition of regional ecological drought. An evaluation system was constructed to realize the assessment of ecological drought degree and to provide a scientific and technological scaffold for improving the ecological drought resisting emergency supportability in river basins and regions.
2. STUDY AREA AND MATERIALS

2.1. Study area
The Yellow River estuary refers to the entire region of Dongying city, with a land area of 7,923 km$^2$ (seen in Figure 1), located in the Yellow River Estuary Delta (Xiao et al. 2020). Diatom, dinoflagellate and green algae are distributed in the Yellow River estuary, with an average phytoplankton content of 0.475 mg/L. The regional zooplankton content, 0.295 mg/L, is much higher than those in the upper and middle reaches of the Yellow River. This region possesses low terrain, agreeable temperatures and good water quality with an average benthic biomass of 100 g/m$^2$. According to the survey, the Yellow River estuary is one of the spawning grounds of fish in the Yellow River Basin, and this region is rich in migratory fish and produces 10 native fish worth protecting: Silurus Lanzhouensis, Cyprinus Carpio, Silurus Huangzhouensis, Copperhead Norvegicus, Trout, Crucian Carp, Hemiculter Leucisclus, Loach, Wheatfish and Kaifeng catfish.

2.2. Data sources
Runoff data of Lijin station in 1956–2016 were obtained from the Yellow River Conservancy Commission. The Landsat TM images of the Yellow River estuary (version of 1986, 1996, 2006, 2015, 2016, 2017, 2018 and 2019, processed by ArcGIS and ENVI software) were collected from the Institute of Water Resources Protection in the Yellow River Conservancy Commission. Assessment index data from 2000 to 2016 were obtained from the Yellow River Shandong Bureau.
3. DEFINITION OF ECOLOGICAL DROUGHT CONCEPT

3.1. Runoff variation

Based on the measured runoff data of Lijin station from 1956 to 2016, the hydrological evolution characteristics of the estuary were analyzed. Figure 2 shows that the annual average runoff was 27.506 billion m$^3$, showing an obvious downward trend. In detail, the 1950s and 1960s were wet periods. From the 1970s to 1990s, affected by climate changes and human activities, the runoff decreased continuously. Since 2002, the runoff increased gradually. The annual runoff reduction rate of Lijin station is 19.46 m$^3$/s·a, with an M–K test value of −5.38, passing the 0.01 significance test, indicating that the runoff reduction trend of Lijin station is very significant. The turning point of runoff took place in 1985. The runoff of Lijin station was mainly concentrated between July and October, and this runoff accounted for 60.24% of the annual runoff. The largest runoff, accounting for 17.54% of the annual runoff, took place in August. The smallest runoff, accounting for only 2.99% of the annual runoff, took place in February. The proportion of average monthly runoff in the dry seasons increased and that in wet seasons decreased. Before 1985, in general, the average monthly runoff of Lijin station increased in winter (December–January of the next year) and summer (June–August), and decreased in spring (March–May) and autumn (September–November). After the turning point, the runoff in 12 months decreased, which was mainly affected by the operation and storage of Xiaolangdi Reservoir and downstream water intake. These results imply that the contradiction between supply and demand of water resources in the Yellow River estuary will be more serious due to the homogenized precipitation and reduced runoff.

3.2. Variation of wetland area

The wetland area data of the Yellow River estuary in 1986, 1996, 2006, 2015, 2016, 2017, 2018 and 2019 were analyzed. Figure 3 shows that the wetland area in the Yellow River estuary presents a volcanic trend: it increased slowly from 1986 to 1996, decreased rapidly after 1996 and was kept constant after 2015. The maximum wetland area is 1,674.84 km$^2$ in 1996, accounting for 65.2% of the total area of the estuary Delta; the minimum wetland area is 1,314.77 km$^2$ in 2019, accounting for 53.3% of the total area of the estuary delta. Figure 3 shows that before 2000, the natural wetland area in the Yellow River estuary was accounted for more than 90% of the total wetland area. During this period, the wetland in the Yellow River Delta was principally in a natural state, insignificantly affected by human development. The area of natural wetland decreased slowly and even increased to a small extent from 1992 to 1996. However, from 2015 to 2019, this region was greatly affected by human activities, and some wetlands were transformed into breeding land.

3.3. Ecological water demand analysis

The ecological water demand of the Yellow River estuary mainly includes the water demand of migratory fish in the estuary, offshore water demand (freshwater amount required to maintain the habitat protection of offshore fish near the estuary) and water demand of sediment transport (water amount required to prevent seawater intrusion). According to the report from the Yellow River Engineering Consulting Co., Ltd, the suitable discharge amount of the Yellow River from May to September was...
12 billion m³. 2.2 billion m³ was selected as the suitable discharge amount for crucial fish spawning from May to June and offshore water demand. The annual average sediment transport water demand of the downstream Yellow River should not be less than 20 billion m³, and the sediment transport water demand should not be less than 15 billion m³ in the flood seasons. Based on these assumptions, through the coupling of ecological water demand items, the total ecological water demand of the Yellow River estuary was evaluated (see Table 1).

Based on the measured runoff of Lijin section in non-flood seasons from 2012 to 2016, the ecological water demand and supply of the Yellow River estuary were analyzed. The runoff in 2012 and 2013 met the water demand indices, but the runoff did not meet the water demand indices from 2014 to 2016. The average runoff in these 5 years did not meet the water demand indices, and the degree of satisfaction was only 78.5%.

3.4. Proposed ecological drought concept
Drought, as the driving force, causes water deficit and changes the regional hydrological cycle conditions. For instance, the regional water volume, flow velocity, water surface area, river connectivity at different scales, biomass and species diversity are reduced or decreased (Raheem et al. 2019). When drought occurs, the material and energy in the food chain, area and depth of habitat, connections between habitats are reduced, competition between aquatic organisms for food is intensified, water environment is deteriorated and the spatial distribution characteristics of aquatic organisms are changed, leading to the decrease of diversity, reproductive capacity and population size of aquatic organisms (Kovach et al. 2019). Moreover, the runoff, flow velocity and sediment-carrying capacity of the flow are decreased or weakened, cutting off the exchange of material, energy and information flow in the horizontal and vertical directions of the river.

Table 1 | Ecological water demand in the Yellow River estuary (Lijin station)

| Month          | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Minimal value (m³/s) | 75  | 75  | 75  | 75  | 150 | 150 | 75  | 75  | 75  | 75  | 75  | 75  |
| Suitable value (m³/s)  | 120 | 120 | 120 | 120 | 250 | 250 | 120 | 120 | 120 | 120 | 120 | 120 |
The continuous reduction of runoff indicates that the Yellow River estuary is threatened by hydrological and socioeconomic drought. The Yellow River estuary possesses the largest delta wetland in the basin, and this wetland accounts for one-third of the Yellow River wetland area, showing that the Yellow River estuary possesses multiple ecological service functions, such as runoff regulation, flood control, water resources operation and storage, groundwater recharge, water quality purification (water pollution uptake), climate regulation and cultural services (such as tourism, entertainment, scientific research and education). Therefore, the estuary is important from an ecological point of view. However, the existing water amount cannot meet the ecological water requirement, which will inevitably have a certain impact on the regional ecological environment. Considering that water is the fundamental reason for the formation of the Yellow River estuary wetland and the main control factor of wetland ecological evolution, the vulnerability and variability of the wetland ecosystem depend on water. Therefore, regional ecological drought refers to a phenomenon of water shortage caused by the imbalance of water acquisition and loss, or water supply and demand, and is a major form threatening regional ecological safety.

To sum up, in this paper, ecological drought in the regions with important ecological functions is defined as follows: when a regional water shortage/pollution accident occurs and the regional water resources cannot meet the water requirement of ecological environment, adverse influence and even a disaster effect are subjected to the regional ecological environment. This situation is called ‘ecological drought’.

4. ECOLOGICAL DROUGHT ASSESSMENT MODELING

The assessment of ecological drought is a complex systematic problem containing multiple indices. Human beings and nature are the driving factors of ecosystem changes, and the impact of ecological drought will be transferred to human society through ecosystem services (Xu et al. 2017). Considering that ecological drought is affected by natural driving force, ecological structure, ecological service functions and socioeconomic pressure, the Drive-Pressure-State-Impact-Response model (DPSIR) was adopted to build the index system of ecological drought assessment (Kagalou et al. 2012). The DPSIR model is an evaluation model constructed by the European Environment Agency by combing the merits of PSR and DSR models. The shuffled frog leaping algorithm and the projection pursuit method are integrated into the DPSIR model. In detail, the projection index functions were optimized with the shuffled frog leaping algorithm, and the projection values of the ecological drought complex system were determined to evaluate the regional ecological drought. The ecological drought evaluation model was established as follows:

1. Normalization of the indices: Because the assessment of ecological drought is complex and involves multiple indices, in order to eliminate the influence of dimensions of indices, those indices positively correlated to ecological drought degree were normalized as follows:

$$x_{ij} = \frac{(x_{ij}^* - x_{\text{min}j})}{(x_{\text{max}j} - x_{\text{min}j})}$$  \hspace{1cm} (1)

Those indices negatively correlated to ecological drought degree were normalized as follows:

$$x_{ij} = \frac{(x_{\text{min}j} - x_{ij}^*)}{(x_{\text{max}j} - x_{\text{min}j})}$$  \hspace{1cm} (2)

where $x_{\text{max}j}$ and $x_{\text{min}j}$ stand for the maximum and minimum values of index $j$ in the index system, respectively. The $x_{ij}$ values calculated by Equations (1) and (2) are normalized to be an evaluation index positively correlated to ecological drought degree, and the index is in the range of [0,1].

2. Construction of the projection pursuit index function: The essence of projection pursuit is to find the optimal projection direction (OPD) which can reflect the data characteristics and extract data information to the maximum extent.

$$z_i = \sum_{j=1}^{p} a_j x_{ij}$$  \hspace{1cm} (3)

where $a_j$ represents the unit vector. $a_i \in [-1, 1]$ and $\sum_{j=1}^{p} a_j^2 = 1$. 
If \( a = (a_1, a_2, \ldots, a_p) \) is the OPD, the projection value of ecological drought degree can be calculated by using the above equation, and then the ecological drought degree can be quantitatively analyzed. During the combination of projection values, it is expected to extract variation information as much as possible, so a projection index function \( Q(a) \) was constructed as the basis for the determination of the OPD. \( Q(a) \) can be calculated by the following equation:

\[
Q(a) = S_zD_z
\]  
\[
S_z = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (z_i - \bar{z})^2}
\]  
\[
D_z = \sum_{i=1}^{n} \sum_{k=1}^{n} (R - r_{ik})f(R - r_{ik})
\]  

where \( S_z \) denotes the standard deviation of the projection value \( z_i \), \( D_z \) stands for the local density of the projection value \( z_i \), and \( \bar{z} \) represents the average value of projection values \( z_1, z_2 \) and \( z_n \). \( R \) represents the window radius of local density and can be determined by experiments. Generally, \( R \) is set to be 0.1. \( f(R - r_{ik}) \) represents the unit step function. Under the condition of \( R > r_{ik} \), \( f(R - r_{ik}) = 1 \). If not, \( f(R - r_{ik}) = 0 \). The larger the intraclass density \( D_z \) is, the more significant the classification is. When the index function \( Q(a) \) reaches the limit, the OPD is found.

(3) Optimization of the projection index function by the shuffled frog leaping algorithm: When the sampling scheme set is fixed, the index function \( Q(a) \) only changes along with the projection direction \( a \). When \( Q(a) \) reaches the maximum, the corresponding direction \( a \) is the OPD vector. Therefore, the optimization objective function is expressed as follows:

\[
\begin{align*}
\text{max} & \ Q(a) \\
\|a\| & = 1
\end{align*}
\]  

The objective function is a complex nonlinear optimization problem with \( a = (1, 2, \ldots, p) \) as the optimization variables and can be optimized and solved with the shuffled frog leaping algorithm.

(4) Determination of ecological drought classification standard and evaluation of the adaptability of ecological drought on the basis of the calculated projection values of samples in the study area and projection values of the standard: First, according to the index values corresponding to the evaluation levels and OPD \( a^* \) calculated on the basis of the normalized values, the ranges of projection values corresponding to each level will be obtained by using the equations above. In this way, the ecological drought degree evaluation and classification standard \( \{x_{ij} | i = 1, 2, \ldots, n; j = 1, 2, \ldots, p \} \) will be determined. After calculating following the equations above, the ecological drought degree projection value \( y \) of the estuary will be obtained. According to the ranges of projection values corresponding to each level, the range to which ecological drought belongs will be determined.

A large number of indexes for evaluation can thoroughly reflect the ‘driving force’, ‘pressure’, ‘state’, ‘impact’ and ‘response’ characteristics of ecological drought. However, too many indexes will cause the lack of representativeness and independence of the evaluation model and even deviations of the calculation results. Thereby, the rough set method was adopted to thoroughly screen the set of indexes to improve the representativeness and independence of the evaluation indexes and to ensure the diversity of the evaluation indexes (Vafaeyan & Thibault 2009).

5. RESULTS AND DISCUSSION

5.1. Results

After the thorough screening with the rough set method, the optimized assessment indexes were obtained and are listed in Table 2.

The data of indices of the Yellow River estuary from 2014 to 2016 were taken as the input for modeling and calculations. The regional ecological drought was divided into four levels: I (Severe), II (General), III (Weak) and IV (None). The OPD of each index was obtained (see Table 3).

Accordingly, the evaluation levels of ecological drought in the Yellow River estuary are shown in Table 4.
The data of indices of the Yellow River estuary from 2000 to 2016 were taken as the input for the evaluation system model, and the results are shown in Table 5. From 2000 to 2002, the degree of ecological drought in the Yellow River estuary was serious, and the ecological environment situation was urgent. In the years of 2008, 2009, 2014 and 2015, the degree of ecological drought was weak. In 2016, the degree of ecological drought reached the level of General. The reason is that with the social and economic development of the Yellow River estuary, the supportability of water intake, water use and water resources allocation was increased. Even if the river runoff decreased, the regional ecological drought resisting capacity could deal with the drought. Nevertheless, the problem of water resources supply and demand in the Yellow River estuary is still prominent and has had a certain impact on the regional ecological environment. The main reasons for the regional ecological drought are the increase of water resources demand and the decrease of wetland area caused by the rapid economic and social development and continuous increase of population. It is urgent to alleviate the ecological drought in the Yellow River estuary by optimizing the allocation of water resources, transferring water from other basins, saving and intensively using water resources, aquatic ecological environment remediation and other measures.

5.2. Discussion

The entropy method was adopted to calculate the weight of evaluation index (Yazdi 2018). Based on the theory and method of information entropy, the entropy method determines the weight of each index according to the different degree of index values data. In general, the greater the different degree of the index values of an index is, the better the order is, the smaller the entropy value is and the greater the final weight is. The original index data of the Yellow River estuary are expressed as $S = \{X_{ij}\}_{17 \times 28}$, in which $X_{ij}$ represents the original data of the $j$th index in the $i$th year. The value $i$ is in the range of 17 years from 2000 to 2016. The value $j$ is in the range of 28 different types of indices in the ecological drought evaluation model. The calculation steps are presented as follows:

### Table 2: Assessment indexes of ecological drought

| Framework | Index | ID | Index direction |
|-----------|-------|----|-----------------|
| Drive     | SPI index | D$_1$ | – |
|           | Natural growth rate of population | D$_2$ | – |
|           | Proportion of primary industry | D$_3$ | – |
|           | River runoff | D$_4$ | + |
|           | Urbanization rate | D$_5$ | – |
| Pressure  | Water resources per capita | P$_1$ | + |
|           | Average water resources per mu | P$_2$ | + |
|           | Arable land area per capita | P$_3$ | – |
|           | Green space area per capita in cities and towns | P$_4$ | + |
|           | Water consumption per capita | P$_5$ | + |
|           | Domestic water consumption of urban residents | P$_6$ | + |
| State     | Industrial added value water consumption | S$_1$ | – |
|           | Groundwater development and utilization rate | S$_2$ | – |
|           | Proportion of agricultural water | S$_3$ | – |
|           | Leakage rate of pipe network | S$_4$ | – |
|           | Average irrigation water consumption per mu | S$_5$ | – |
|           | Water consumption per unit GDP | S$_6$ | – |
| Impact    | Vegetation coverage | I$_1$ | + |
|           | Quality compliance rate of drinking water source | I$_2$ | + |
|           | Urban green space area per capita | I$_3$ | + |
|           | Proportion of eco-environmental water consumption | I$_4$ | + |
|           | Biodiversity | I$_5$ | + |
| Response  | Reuse rate of reclaimed water | R$_1$ | + |
|           | Ratio of water-saving irrigation area | R$_2$ | + |
|           | Popularization rate of urban water-saving appliances | R$_3$ | + |
|           | Popularization rate of urban tap water | R$_4$ | + |
|           | Utilization coefficient of irrigation water | R$_5$ | + |
|           | Reuse rate of industrial water | R$_6$ | + |
Table 3 | Assessed rating for selected indexes

| ID | Dimension | Assessed rating and its value range | OPD |
|----|-----------|-----------------------------------|-----|
| D1 | /         | ≤ – 2.0 (-2.0, – 1.5]             |     |
| D2 | %         | > 20 15-20 2-15                   |     |
| D3 | %         | > 30 15-30 3-15                   |     |
| D4 | m³        | < 50 50-100 100-150               |     |
| D5 | %         | < 20 20-50 50-80                 |     |
| P1 | m³        | < 500 500-1,000 1,000-1,700   | 0.210 |
| P2 | m³/hm²    | < 400 400-700 700-1,500       | 0.161 |
| P3 | hm²       | < 0.1 0.1-0.6 0.6-1           |     |
| P4 | m²        | < 20 20-100 100-180            | 0.171 |
| P5 | m³/a      | > 1,000 800-1,000 500-800  < 500 | 0.196 |
| P6 | L/d       | > 200 150-200 100-150      | 0.248 |
| S1 | m³/10⁴ currency | > 90 60-90 30-60 | 0.160 |
| S2 | %         | > 100 60-100 30-60             |     |
| S3 | %         | > 75 55-75 40-55              |     |
| S4 | %         | > 50 15-30 5-15               |     |
| S5 | m³/hm²    | > 400 300-400 200-300       | 0.193 |
| S6 | m³/10⁴ currency | >100 80-100 50-80  < 500 | 0.185 |
| I1 | %         | < 20 20-40 40-60               | 0.205 |
| I2 | %         | < 90 90-98 98-100             | 0.166 |
| I3 | m²        | < 7 7-8 8-10                   | 0.198 |
| I4 | %         | < 2 2-5 5-10                   | 0.185 |
| I5 | Category  | < 10 10-50 50-100             | 0.167 |
| R1 | %         | < 10 10-20 20-30               |     |
| R2 | %         | < 30 30-50 50-75              | 0.151 |
| R3 | %         | < 50 50-70 70-90              | 0.195 |
| R4 | %         | < 70 70-80 80-90             | 0.206 |
| R5 | /         | < 0.45 0.45-0.5 0.5-0.6     | 0.171 |
| R6 | %         | < 40 40-60 60-80            | 0.181 |

Table 4 | Ecological drought assessment

| Z-value range | Rating | Ecological drought degree | Statement |
|---------------|--------|---------------------------|-----------|
| Z < 1.312     | I      | Severe                    | The functions of ecosystem are devastated by frequent aquatic ecological crises and disaster events. |
| 1.312 < Z < 2.267 | II     | General                   | The functions of ecosystem are partially destroyed by increased aquatic ecological crises and disaster events. |
| 2.267 < Z < 3.126 | III    | Weak                      | The functions of ecosystem are almost normal with fewer aquatic ecological crises and disaster events. |
| Z ≥ 3.126    | IV     | None                      | The functions of ecosystem are good with rare aquatic ecological crises and disaster events. |
(1) Nondimensionalization:

\[
\begin{align*}
A_{ij}^{(+)} &= \frac{X_{ij} - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}} \\
A_{ij}^{(-)} &= \frac{X_{\text{max}} - X_{ij}}{X_{\text{max}} - X_{\text{min}}}
\end{align*}
\]  

(8)

where \(A_{ij}^{(+)}\) represents dimensionless equations of positive indices; \(A_{ij}^{(-)}\) represents dimensionless equations of negative indices. In the case of the occurrence of \(\ln 0\) during the calculation of information entropy, the value of 0 was replaced with 0.000001.

(2) Calculate the proportion \(P_{ij}\) of the \(j\)th index value in the sum of the \(j\)th index values of all the objects evaluated.

\[
P_{ij} = \frac{A_{ij}^{(+/-)}}{\sum_{i=1}^{17} A_{ij}^{(+/-)}}
\]  

(9)

(3) Calculate the information entropy \(e_j\) of the \(j\)th index.

\[
e_j = -\frac{1}{\ln 17} \sum_{i=1}^{17} P_{ij} \times \ln P_{ij}
\]  

(10)

(4) Calculate the redundancy \(g_j\) and weight \(w_j\) of the \(j\)th index. The larger the entropy value is, the smaller the redundancy and the smaller the weight.

\[
\begin{align*}
g_j &= 1 - e_j \\
w_j &= \frac{g_j}{\sum_{j=1}^{28} g_j}
\end{align*}
\]  

(11)

According to the analysis results, among the 28 evaluation indexes (weight characteristics shown in Figure 4), the three indexes with the largest weight values are river runoff (0.1273), biodiversity (0.1231) and vegetation coverage (0.1031),
indicating that these three evaluation indexes have great influence on regional ecological drought. Namely, sufficient river runoff, abundant biodiversity and high vegetation coverage are important factors to improve the ecological drought resisting capacity in the Yellow River estuary. In other words, the ecological drought can be estimated preliminarily based on the threshold changes of river runoff, regional biodiversity and vegetation coverage.

River runoff (R), biodiversity (B) and vegetation coverage (VC) are selected as the leading indicators to express the different ecological drought degree, and thus, the dynamic thresholds of leading indicators under different ecological drought degrees can be seen in Table 6. It is implied that natural factors have potential influence on the evolution of ecological drought, and most of the natural environmental factors are stable and even contribute to the ecological self-regulation mechanism. Human activity factors have great potential to damage the ecological environment, and unscientific production and living styles can accumulate a large number of damage factors in a short time, to directly or indirectly damage the natural environment and to interfere with the regulation ability of ecosystems. As a consequence, the degree of ecological drought is worsened. Therefore, it is difficult for a single remedial measure to effectively alleviate the regional ecological drought. We should focus on integrated, comprehensive, practical and macroscopic strategies such as water source protection, ecological restoration, ecological water supply and improvement of water resources allocation capacity.

For the areas with ecological drought similar to the Yellow River estuary, it is suggested to formulate a systematic and comprehensive macro strategy, especially paying attention to the work of multi-water source joint commissioning and supply and biodiversity habitat protection. From the systematic point of view, for the regions with important ecological functions, ecological drought shows a strong feedback effect under the dual influence of human beings and nature. Reasonable construction of regional evaluation index models and scientific selection of indices are the effective guarantee for ecological drought evaluation. On the basis of existing studies, the ecological drought evaluation model constructed in this paper, through case study, systematizes and simplifies ecological drought, which is abstract and difficult to define. Moreover, the qualitative ecological drought evaluation indexes are quantified and digitized, and individual problems are integrated. These characteristics play a great role in disaster prevention and mitigation. The effectiveness of the evaluation model and its practicability and operability in the actual regional ecological drought evaluation process were also verified by real cases. Thereby, this model can serve as an effective evaluation tool for the policymakers.

**Table 6 | Thresholds of leading indicators to different ecological drought degrees**

| Ecological drought degree | Thresholds of leading indicators |
|---------------------------|----------------------------------|
| I (Severe)                | R < −10.2%; B < −10%; VC < −9%  |
| II (General)              | R ∈ [−10.2%, −7.6%]; B ∈ [−10%, −7%]; VC ∈ [−9%, −6%] |
| III (Weak)                | R ∈ [−7.6%, −3.4%]; B ∈ [−7%, −5%]; VC ∈ [−6%, −3%] |
| IV (None)                 | R ∈ [−3.4%, 3.4%]; B ∈ [−5%, 5%]; VC ∈ [−3%, 3%] |
Nonetheless, because the data used in this paper were on a time scale, the degree of ecological drought on the scale of spatial distribution in the Yellow River estuary cannot be reflected. Meanwhile, the regional ecosystem constantly changes under the effect of natural environment and human disturbance. The evaluation of ecological drought can only represent the basic state at a specific moment, and the evolution mechanism of ecological drought is not explained. Therefore, the dynamic assessment of ecological drought on the regional grid scale should be highlighted in the future. It is believed that with the deep study on ecological drought, the evaluation indices will be clearer, and the model constructed in this paper will be more meaningful.

6. CONCLUSIONS

Based on the current concept of ecological drought, the potential characteristics of ecological drought were analyzed in this paper, and the concept of ecological drought in areas with important ecological functions was discussed. Based on the clarified concept of ecological drought, an evaluation model of regional ecological drought degree was constructed. Taking the Yellow River estuary of China as the case study, the usability of the model was verified. This paper draws the following conclusions:

1. The concept of ecological drought in the region with important ecological functions was defined.
2. The regional ecological drought was divided into four levels: I (Severe), II (General), III (Weak) and IV (None). From 2000 to 2016, three severe ecological droughts happened due to water shortage; thus, water resources is one of the key elements for the mitigation of ecological drought.
3. The indicator thresholds of river runoff, biodiversity and vegetation coverage on different ecological drought levels were quantified to predict an ecological drought in potential. The threshold values of representative indexes can play a role of quick judgment for ecological drought.
4. To a certain extent, the research results eliminate the blind area and disunity for the concept of ecological drought and realize the evaluation of ecological drought by modeling. This work can provide theoretical scaffolds and technical strategies for planners to formulate disaster prevention and mitigation policies.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Bachmair, S., Svensson, C., Hannaford, J., Barker, L. J. & Stahl, K. 2016 A quantitative analysis to objectively appraise drought indicators and model drought impacts. Hydrology and Earth System Sciences 20 (7), 2589–2609.

Brown, A. 2017 Ecological resilience: drought sensitivity. Nature Climate Change 7 (2), 96–96.

Chadd, R. P., England, J. A., Constable, D., Dunbar, M. J., Extence, C. A., Leeming, D. J., Murray-Bligh, J. A. & Wood, P. J. 2017 An index to track the ecological effects of drought development and recovery on riverine invertebrate communities. Ecological Indicators 82, 344–356.

Crausbay, S. D., Ramirez, A. R., Carter, S. L., Cross, M. S. & Sanford, T. 2017 Defining ecological drought for the twenty-first century. Bulletin of the American Meteorological Society 98 (12), 2543–2550.
