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China's regional vulnerability to drought and its mitigation strategies under climate change: data envelopment analysis and analytic hierarchy process integrated approach

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Abstract: Climate change makes extreme droughts more frequent with heavy economic losses in China, thus this study aims to evaluate China's regional vulnerability to drought and propose proper mitigation strategies for drought-vulnerable areas. In this paper, an integrated index containing exposure, sensitivity and adaptive capacity is developed to measure regional vulnerability to drought, and it is calculated by the integrated approach which combines slacks-based measure (SBM) model in data envelopment analysis (DEA) with genetic algorithm-based analytic hierarchy process (AHP). Accordingly, 65 cities in Anhui, Henan, Jiangsu and Shandong provinces of China are chosen as the study area. The results show that Anhui and Henan are more vulnerable to drought, and the proportions of cities with inefficient resilience to drought in the two provinces are 64.7% and 55.6% respectively. Compared with coastal areas, the inland regions have more drought-vulnerable cities. In addition, the cities in the south are less vulnerable to drought than those in the central and north regions. Meanwhile, we conclude that the integrated index can measure the efficiency of resilience to drought and reveal

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the causes of drought vulnerability. It also indicates that adequate investments in drought preparedness and promotion of water efficiency are the crucial ways for drought vulnerability reduction. Finally, this study proposes some policy recommendations to alleviate the impacts of drought under climate change.

Keywords: *drought vulnerability; mitigation strategy; data envelopment analysis; analytic hierarchy process; genetic algorithm*

1 Introduction

Climate change is the current hot topic concerned by policymakers and researchers, because of its impacts on human and natural systems which are expected to exist throughout the twenty-first century (Milly et al. 2005). The Intergovernmental Panel on Climate Change (IPCC) stated that the warmer climate would bring the variations of precipitation in spatial pattern, causing more extreme events. In particular, drought is one of the hazardous extremes appearing in many parts of the world every year (IPCC 2012).

China is a frequently drought-affected country in East Asia, and it is reported by the Ministry of Water Resources of China (MWRC) that severe and extreme droughts took place every two years on average from 1990 to 2007. During the past decade, drought hit China from south to north, resulting in serious consequences (Wang et al. 2012b). In 2010, five provinces in southwestern China suffered critical water scarcity, which rarely happened in the history. Then in 2011, severe drought occurred in the regions along the middle and lower reaches of the Yangtze River where there was usually abundant rainfall. In the period of 1990 to 2008, the average grain loss reached as much as 39.2 billion kilograms annually, and the average economic loss accounted for 1.47% of the average gross domestic product (MWRC 2011). Even worse, the frequency of drought is likely to escalate in China under future climatic scenarios, which would aggravate the harmful impacts on those drought-vulnerable areas (Hirabayashi et al. 2008; Dai 2013).

In 2011, a national anti-drought plan aiming to improve China's drought mitigation capabilities was approved by the State Council (MWRC 2011). To achieve the primary goal in the plan, we are required to deal with the basic problems of how to evaluate and reduce drought vulnerability. The attention should be paid to both of the two aspects, and they are also the fundamental components of drought risk management (Blaikie et al. 1994; Mechler et al. 2010; Yuan et al. 2013). Therefore, the approach combining drought vulnerability assessment with mitigation strategy generation is urgent for coping with climate change.

Presently, different indicators have been applied to evaluating drought vulnerability. Wu et al. (2011) investigated the drought vulnerability in China using the GIS-based assessment model which contained three main indicators of seasonal crop water deficiency, available soil water-holding capacity and irrigation. In the study carried out by Shahid and Behrawan (2008), a composite vulnerability index involving socio-economic and physical/structural indicators was proposed for drought risk assessment. Cao et al. (2011) selected the indicators from the aspects of sensitivity and resilience to assess the agricultural drought vulnerability in Dalian. According to the dimensions of vulnerability, Liu et al. (2013) evaluated the drought impacts in the middle Inner Mongolia of China from exposure, sensitivity and adaptive capacity respectively. In the meantime, a number of integrative approaches have also been employed for drought vulnerability. Alcamo et al. (2008) compared and analyzed the differences in estimating vulnerability to drought among various disciplines by an inference modeling approach. Based on the protection motivation theory, Krömker et al. (2008) developed the protection-capacity model to analyze the vulnerability to drought with respect to the protection capacity of agents.

However, to appropriately characterize and measure drought vulnerability is a tough task due to its wide inclusiveness. Though vulnerability has been conceptualized in many different ways, the scientific use of this concept has roots in natural hazards, and it reflects the interactions between human and environment (Polsky et al. 2007; Füssel 2007). Basically, regional vulnerability to drought is considered as the combination of exposure, sensitivity and adaptive capacity (IPCC 2007; Polsky et al. 2007; Pandey and Jha 2012; Liu et al. 2013), and it is the imbalance among the three dimensions that causes drought vulnerability. Therefore, the way to evaluate and reduce regional vulnerability to drought needs to focus on the three dimensions, which is a complex problem indeed.

Data envelopment analysis (Charnes et al. 1978), which combines multiple inputs and multiple outputs in examining relative efficiency and performance of decision making unit (DMU), has been widely used for the assessments in many domains (Seiford and Zhu 2002; Yang and Kuo 2003; Hsiao et al. 2011; Wang et al. 2012a; Soleimani-Damaneh et al. 2012). Also, the DEA method has been employed to study the vulnerability to natural hazards (Wei et al. 2004; Zou and Wei 2009; Saein and Saen 2012; Huang et al. 2012; Huang et al. 2013). Generally, the previous studies took disaster-related factors as inputs and losses as outputs to assess regional vulnerability. In a different way, this study interprets the cause of drought vulnerability as the excesses of exposure and sensitivity as well as the shortfalls of adaptive capacity, so that drought vulnerability can be measured by these excesses and shortfalls which are called slacks using the slacks-based measure model in DEA (Tone 2001). More importantly, the slacks are able to give information for making mitigation strategies.

To incorporate the importance of slacks, it is necessary to give them different weights which are commonly based on expert opinions (Seifert and Zhu 1997; Cooper et al. 2007; Tsutsui and Goto 2009; Hsiao et al. 2011; Kong and Fu 2012). Though analytic hierarchy process (Saaty 1980) is an available method to quantify opinions, there is still the difficulty in the consistency of judgment matrix (Xu

2000; Benítez et al. 2012). Jin et al. (2002) proposed the consistency index function optimized by accelerating genetic algorithm (Jin et al. 2002; Jin and Wei 2008) to obtain the accurate weights from judgment matrix. This approach named accelerating genetic algorithm-based analytic hierarchy process (AGA-AHP) is also used for the slacks' weights in this study.

The main purpose of this study is to develop an integrated index to evaluate China's regional vulnerability to drought and propose proper mitigation strategies under climate change. The integrated index containing exposure, sensitivity and adaptive capacity is calculated by the DEA-AHP integrated approach, which reveals the causes of drought vulnerability. Accordingly, we discuss the available mitigation strategies for different drought-vulnerable areas.

The rest of this paper is organized as follows. Section 2 introduces the integrated index of drought vulnerability, and gives the research framework for drought vulnerability evaluation and mitigation strategy generation. Then the study region and data are presented in Section 3. Section 4 provides the results and discussion. Finally, conclusions and recommendations are drawn in Section 5.

2 Methodology

2.1 Components of drought vulnerability

Vulnerability is composed of exposure, sensitivity and adaptive capacity (IPCC 2007; Polsky et al. 2007), and essentially caused by the imbalance among the three dimensions. According to this interpretation, the composition of regional vulnerability to drought (Fig. 1) is set up based on the Vulnerability Scoping Diagram (Polsky et al. 2007). The small ring represents the dimensions of drought vulnerability, and each dimension contains abstract features exhibited in the big ring. Then, we select the obtainable indicators to characterize regional drought vulnerability.

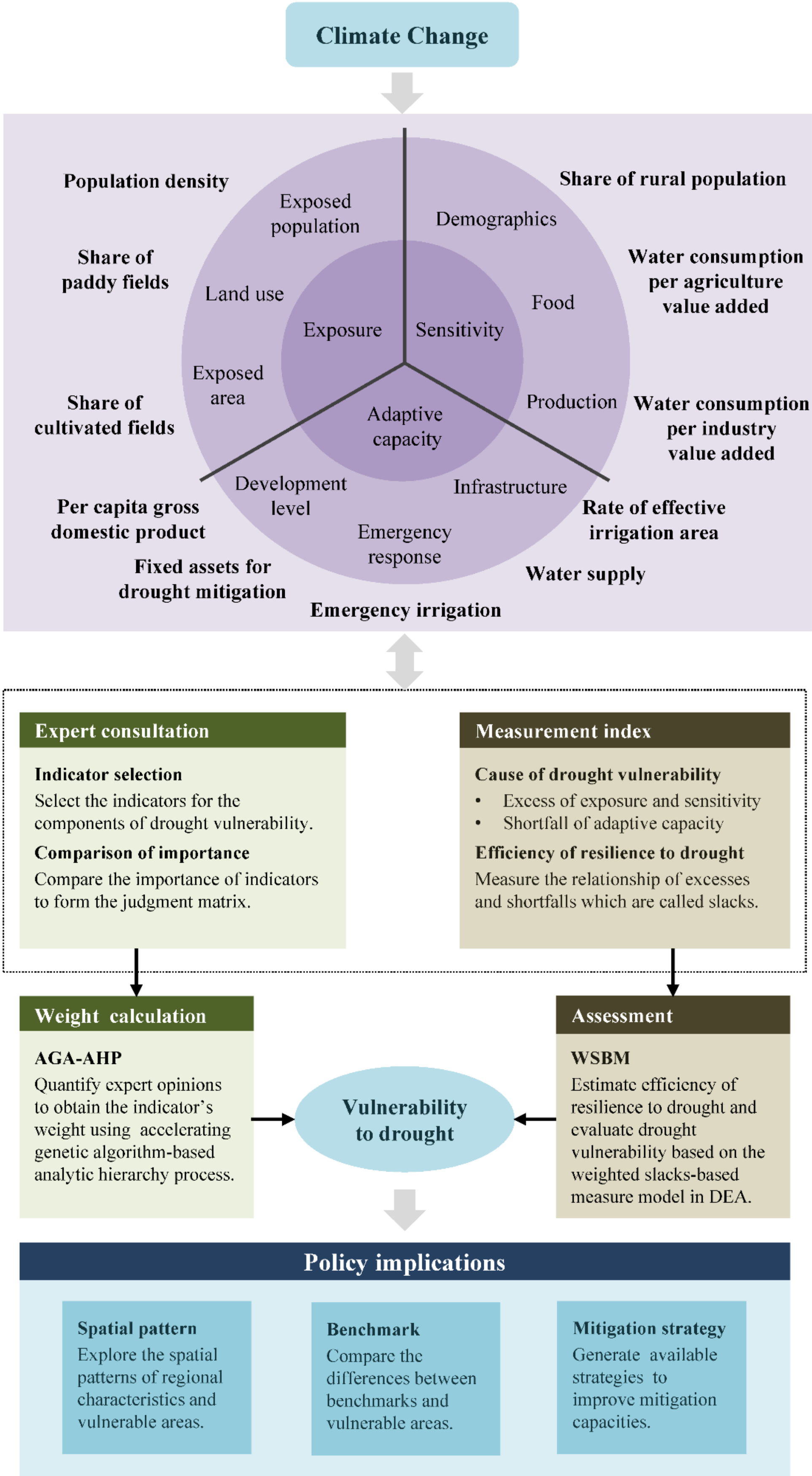
Climate Change
Population density
Exposed population
Demographics
Share of rural population
Share of paddy fields
Land use
Food
Water consumption per agriculture value added
Exposure
Sensitivity
Exposed area
Production
Share of cultivated fields
Adaptive capacity
Water consumption per industry value added
Development level
Infrastructure
Per capita gross domestic product
Rate of effective irrigation area
Emergency response
Fixed assets for drought mitigation
Water supply
Emergency irrigation
Expert consultation
Indicator selection
Select the indicators for the components of drought vulnerability.
Comparison of importance
Compare the importance of indicators to form the judgment matrix.
Measurement index
Cause of drought vulnerability
• Excess of exposure and sensitivity
• Shortfall of adaptive capacity
Efficiency of resilience to drought
Measure the relationship of excesses and shortfalls which are called slacks.
Weight calculation
AGA-AHP
Quantify expert opinions to obtain the indicator's weight using accelerating genetic algorithm-based analytic hierarchy process.
Vulnerability to drought
Assessment
WSBM
Estimate efficiency of resilience to drought and evaluate drought vulnerability based on the weighted slacks-based measure model in DEA.
Policy implications
Spatial pattern
Explore the spatial patterns of regional characteristics and vulnerable areas.
Benchmark
Compare the differences between benchmarks and vulnerable areas.
Mitigation strategy
Generate available strategies to improve mitigation capacities.

Fig. 1 Research framework for regional vulnerability to drought

2.1.1 Exposure indicators

Exposure refers to the status exposed to the external environment of a particular unit, which causes potential impacts of drought on the unit. Thus, the natural, geographic as well as socio-economic factors are appropriate for the characterization of this dimension. From the human and environment perspectives, this study employs exposed area, land use and exposed population to describe the exposure. Exposed area and population reflect the regions and population that could be affected by drought. In addition, the type of land use is an important characteristic related to the impacts of drought. However, these features are not easy to change dramatically during a short period, and they are measured by the indicators which are share of cultivated fields (ShareCF), share of paddy fields (SharePF) and population density (PopD).

2.1.2 Sensitivity indicators

Sensitivity means the degree to which a unit is affected by drought (IPCC 2007), and substantially, it connects drought with consequences. Therefore, we are required to pick out the most important objects affected by drought to feature this dimension. Here three aspects including demographics, food and production are taken into account. Different from exposure, the sensitivity is apt to change by the improvements, for example, an increase in water efficiency of agriculture will reduce the sensitivity. According to the three features, this study chooses the measurement indicators of share of rural population (ShareRP), water consumption per agriculture value added (WaterA) and water consumption per industry value added (WaterI).

2.1.3 Adaptive capacity indicators

Adaptive capacity refers to the responses to drought, which means to take measures to alleviate the impacts (Mechler et al. 2010; Anik and Khan 2012). Actually, we are required to improve adaptive capacity for drought vulnerability reduction, and it can start from three perspectives that are development level, emergency response and infrastructure. Correspondingly, the measurement indictors are per capita gross domestic product (PGDP), fixed assets for drought mitigation (FA), emergency irrigation (EI), water supply (WS) and rate of effective irrigation area (REI).

2.2 Research framework

The framework of this study for drought vulnerability assessment and mitigation strategy generation under climate change is presented in Fig. 1. The indicators for measuring exposure, sensitivity and adaptive capacity as well as their importance are determined by consulting experts, and then we utilize the AGA-AHP approach to obtain the indicators' weights. In this study, the cause of vulnerability to drought is considered as the excesses of exposure and sensitivity and the shortfalls of adaptive capacity, so we use these excesses and shortfalls to estimate the efficiency of resilience to drought by the weighted SBM model. Accordingly, an integrated index of drought vulnerability is developed to analyze the characteristics of those drought-vulnerable areas that are defined as the units of inefficient resilience to drought. Finally, we discuss the available paths to reduce drought vulnerability for different kinds of areas, which is carried out in two ways. Benchmarking management means to compare the differences between benchmarks and drought-vulnerable areas, so that the disadvantages can be found out to be improved. On the other hand, the excesses and shortfalls from the integrated model also give information for mitigation strategy generation.

2.3 Integrated index of drought vulnerability

Exposure and sensitivity can be considered as the stresses which increase drought vulnerability, whereas adaptive capacity means the responses for vulnerability reduction. The imbalance between stresses and responses results in drought vulnerability eventually, and we use the score ρ to measure the efficiency of resilience to drought.

This study assumes that all the cities called DMUs are comparable, so they can be evaluated by the same criterions. DEA method utilizes all the selected indicators to find out those efficient DMUs, and then other DMUs are compared with them to obtain the potential improvements (Charnes et al. 1978). If there are n DMUs (i.e. n cities to be evaluated, $k = 1,\ldots,n$) with m stress indicators ($\boldsymbol{X} \in \mathbf{R}^{m\times n}$) and s response indicators ($\boldsymbol{Y} \in \mathbf{R}^{s\times n}$), the kth DMU's ρ is estimated by (Tone, 2001; Cooper et al. 2007; Tsutsui and Goto 2009)

$$
\begin{aligned}
\min \quad & \rho_k = \frac{\sum_{i=1}^{m} w_i \dfrac{x_{ik} - s_i^-}{x_{ik}}}{\sum_{r=1}^{s} h_r \dfrac{y_{rk} + s_r^+}{y_{rk}}} \\
\text{s.t.} \quad & x_{ik} = \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^-, \quad i = 1,\ldots,m, \\
& y_{rk} = \sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+, \quad r = 1,\ldots,s, \\
& \sum_{i=1}^{m} w_i = 1, \qquad\qquad (1) \\
& \sum_{r=1}^{s} h_r = 1, \\
& s_i^- \le s_i^{-B}, \; s_r^+ \le s_r^{+B}, \\
& s_i^-, s_r^+, \lambda_j \ge 0, \quad \text{for all } i, r, j.
\end{aligned}
$$

where $\boldsymbol{s}^- \in \mathbf{R}^m$ and $\boldsymbol{s}^+ \in \mathbf{R}^s$ are the stress excesses and response shortfalls, respectively, and they are all called slacks; $\boldsymbol{s}^{-B} \in \mathbf{R}^m$ and $\boldsymbol{s}^{+B} \in \mathbf{R}^s$ are the upper bounds imposed on the slacks, and they are assumed according to practical situation; $\boldsymbol{\lambda} \in \mathbf{R}^m$ is a non-negative vector; $\boldsymbol{w}$ and $\boldsymbol{h}$ are the weights given by experts. Eq. (1) optimizes the variables $\boldsymbol{s}^+$, $\boldsymbol{s}^-$ and $\boldsymbol{\lambda}$ to obtain the minimum score ρ which apparently belongs to (0, 1].

If the optimized ρ* is equal to 1, the DMU is defined to be efficient to cope with drought, and there is no drought vulnerability. If so, the slacks $\boldsymbol{s}^-$ and $\boldsymbol{s}^+$ all equal 0. In other words, the balance has been established without stress excesses and response shortfalls. Otherwise, there are the reductions $\boldsymbol{s}^-$ of stresses and improvements $\boldsymbol{s}^+$ of responses for the DMU to be efficient. The ratio $(x_{ik} - s_i^-) / x_{ik}$ evaluates the relative reduction rate of stress i, and the numerator in Eq. (1) means the weighted reduction rate of stresses. In contrast, the ratio $(y_{rk} + s_r^+) / y_{rk}$ evaluates the relative improvement rate of response r, and the denominator in Eq. (1) is the weighted improvement rate of responses.

Accordingly, this study defines drought vulnerability index (DVI) as 1− ρ*, which contains the exposure, sensitivity and adaptive capacity. Obviously, the smaller DVI indicates lower drought vulnerability.

2.4 Weights of the indicators for drought vulnerability

Analytic hierarchy process (Saaty 1980) is used to calculate the weights of stress and response indicators. The relative importance of indicator u compared with v is denoted by a_{uv} (u=1,…, t; v=1,…, t), so the judgment matrix is $\boldsymbol{A} = (a_{uv})_{t \times t}$. Suppose the weight of indicator u is W_u, then $\boldsymbol{A}$ is absolutely consistent as a_{uv} quantifies the ratio of W_u to W_v exactly. Therefore, we have (Jin et al. 2002)

$$\sum_{v=1}^{t} a_{uv} W_v = \sum_{v=1}^{t} (W_u / W_v) W_v = t W_u \qquad (2)$$

and

$$\sum_{u=1}^{t} \left| \sum_{v=1}^{t} a_{uv} W_v - t W_u \right| = 0 \qquad (3)$$

However, a_{uv} has the deviation in measuring the ratio of W_u to W_v due to the complex cognition in reality, and the smaller value of the left term in Eq. (3) indicates the greater consistency. Thereby, the consistency index function (CIF) is developed to check the consistency (Jin et al. 2002; Jin and Wei 2008), and the weights are calculated by

$$\begin{aligned} &\min \quad \mathrm{CIF}=\sum_{u=1}^{t}\left|\sum_{v=1}^{t} a_{uv}W_v - tW_u\right|/t \\ &\text{s.t.} \quad \sum_{u=1}^{t} W_u = 1 \end{aligned} \tag{4}$$

The variables $\boldsymbol{W}$ in Eq. (4) are optimized by accelerating genetic algorithm to obtain the minimum CIF (Jin et al. 2002; Jin and Wei 2008). If the value of CIF is less than 0.1, the judgment matrix is considered to be consistent and the weights are available.

The importance of indicators for drought vulnerability is given by experts, and the weights used in Eq. (1) are calculated by the AGA-AHP approach.

3 Study region and data

3.1 An overview of study region

Jiangsu and Shandong provinces lie on the east coast of China, and they are among the most developed areas of the country. However, the rapid developments make water demand increase sharply, and the water shortage resulting from drought has seriously affected these areas. Playing an important role of China’s agricultural bases, Anhui and Henan provinces have a huge dependency on precipitation. In recent decades, they were hit by drought frequently in the context of climate change. According to the national anti-drought plan of China, the four provinces of Anhui, Henan, Jiangsu and Shandong are all vulnerable to drought with heavy economic and agricultural losses (MWRC 2011).

Consequently, they are chosen as the study area (Fig. 2), and 65 cities in total (17 in Anhui, 18 in Henan, 13 in Jiangsu, and 17 in Shandong) are used to study the drought vulnerability.

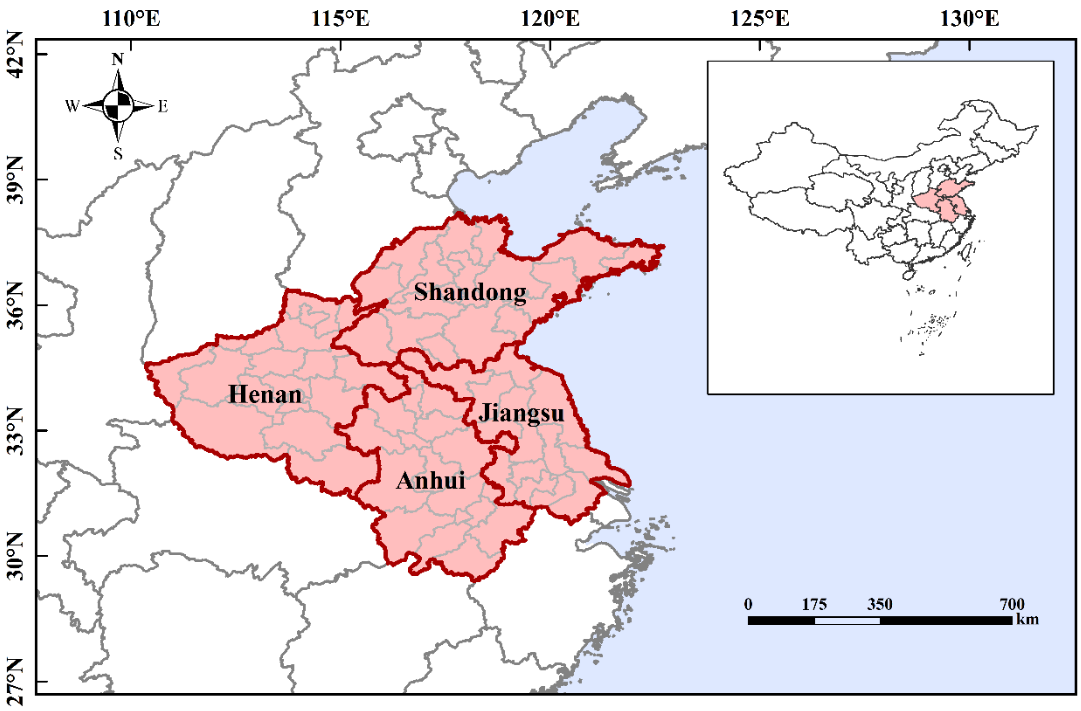

Fig. 2 Study area including Anhui, Henan, Jiangsu and Shandong provinces in China

3.2 Data source and assumptions

The data are collected from the statistical yearbooks of Anhui, Henan, Jiangsu and Shandong Province of China (Statistics Bureau of Anhui, Henan, Jiangsu and Shandong Province 2008), as well as the anti-drought plans of the four provinces. This study investigates the drought vulnerability of 65 cities in the base year of 2007.

There are also some assumptions on the upper bounds of the slacks of indicators (Table 1). In a short period, the indicators of exposure and sensitivity seem to only reduce in the small ranges. The maximum reduction in ShareCF of all the cities in 2008 is less than 5%, so the upper bound of this indicator is fixed as 5%. Similarly, the decreases in SharePF and ShareRP are supposed to be less than

5% and 10% respectively, according to practical situations. Though the majority keeps population growth, there are still a few depopulated cities, and the average reduction rate is not beyond 0.5% which is taken as the upper bound of PopD. It was proposed in the Eleventh/Twelfth Five Year Plan of China that the water consumption for industry aimed to reduce by 30% during the periods, so we assume the percentage decrease of WaterI and WaterA is within 10%. In contrast, the improvements in adaptive capacity can increase sharply. This study assumes that the increments in EI, FA, and WS can reach the average levels of all the cities in the base year. Definitely, the REI should be less than 100%, and the growth of PGDP is less than 20% in accordance with the cities' increasing trends.

Table 1 Assumed upper bounds of the slacks of indicators

Indicator	Upper bound	Indicator	Upper bound
ShareCF	5%	PGDP	20% of current level
SharePF	5%	FA	Average current level
PopD	0.5% of current level	EI	Average current level
ShareRP	10%	REI	100%−current level
WaterA	10% of current level	WS	Average current level
WaterI	10% of current level		

*Current level is the value of indicator in the base year, while average current level is the average one of 65 cities in the base year.

4 Results and discussion

4.1 Regional characteristics

Exposure and sensitivity, which both increase drought vulnerability, have regional differences in the study area, and Fig. 3 exhibits their spatial patterns. Obviously, the cities differ remarkably in the indicators of exposure and sensitivity due to the geographic and socio-economic factors. We classify these indicators into three groups to analyze the regional characteristics of study area.

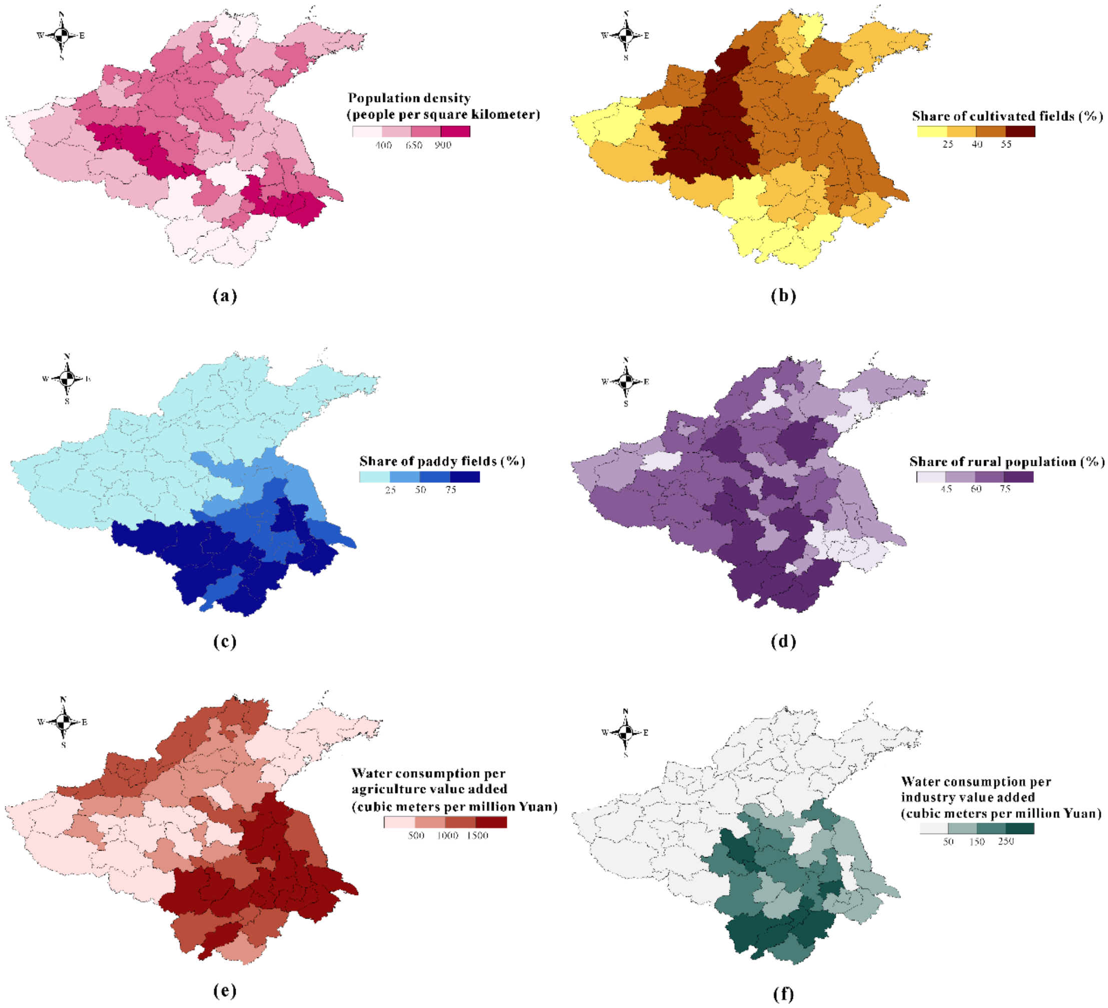

Fig. 3 Exposure and sensitivity indicators of the cities in study area

4.1.1 Population density and rural population

Population density and share of rural population describe the human perspective in regional vulnerability to drought. As is known, Henan and Shandong are the provinces of large population in China, so most of the areas within them, especially east-central Henan and west-central Shandong, have higher population densities. Also, north Anhui bordering on the two provinces is in a similar situation. In addition, due to the high economic development, the cities along the Yangtze River in both Jiangsu and Anhui are highly populated. As far as demographics are concerned, the major agricultural provinces Anhui and Henan have higher shares of rural population than Jiangsu and Shandong, and particularly, slow development leads to the lowest urbanization level in Anhui. Compared with inland areas, the coastal regions are more developed and their shares of rural population are much lower.

4.1.2 Cultivated land and paddy fields

Cultivated land and paddy fields are closely related to the geographic factors which play important role in regional vulnerability to drought. Henan, Jiangsu, Shandong and north Anhui have high shares of cultivated fields, and especially there is more than half the land under cultivation in east-central Henan, west Shandong and north Anhui. In contrast, the cultivated fields of mountainous areas including south Anhui and west Henan are much fewer, and the percentages in total land are mostly below 25%. In the meantime, climatic conditions have crucial effects on the cultivation modes. The southern parts of study area have more paddy fields because of the abundant rainfall, and in Anhui and Jiangsu the shares of paddy fields in total cultivated land are beyond 50%. By comparison, dry land is more suitable for the north and it is also the dominant type of land use in Henan and Shandong.

4.1.3 Water consumption for agriculture and industry

Water consumption for agriculture and industry reflects the socio-economic aspects of regional vulnerability to drought, and is determined by the types of agriculture and industry. Because the predominant cultivation mode in Anhui and Jiangsu is paddy land, the water consumption per agriculture value added in most areas of the two provinces is larger. Besides, the northern parts of Henan and Shandong consume more water for agriculture than others. Similarly, the industry type and development level make more water consumed by industry in Anhui and Jiangsu. In particular, the industry value added in south Anhui consumes a great deal of water.

4.2 Spatial pattern of drought-vulnerable areas

The weights of selected indicators are shown in Fig. 4. The ShareCF and SharePF measuring exposed area and type of land use are all closely related to drought impacts, and they are considered to be more important in drought vulnerability evaluation. On the other hand, due to the crucial role water plays during drought period, the indictors of WS, REI and EI which reflect adaptive capacity more directly have greater importance. Especially, water supply is the major factor for drought mitigation. These weights are used in Eq. (1) to evaluate drought vulnerability.

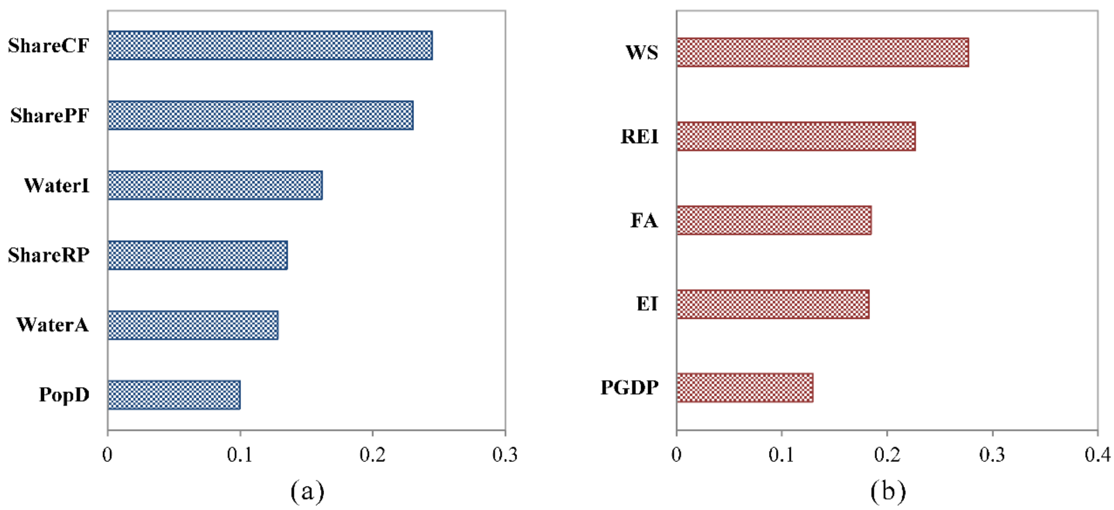

Fig. 4 Weights of indicators for (a) exposure, sensitivity and (b) adaptive capacity

The evaluation results show that 33 cities of four provinces have inefficient resilience to drought (Table 2). Comparatively, Anhui and Henan have more drought-vulnerable cities which account for 64.7% and 55.6% of the units in the two provinces respectively, while the proportions in Jiangsu and Shandong are 38.5% and 41.2% respectively.

The statistical characteristics of drought vulnerability index in four provinces are quite different (Table 2). The mean DVI of drought-vulnerable cities in Anhui is larger than those of others, and it accurately indicates that this region is more vulnerable to drought as a whole. However, the cities in Henan vary greatly in the drought vulnerability reflected by the coefficient of variation of DVI. By comparison, Jiangsu is least vulnerable to drought with the minimum mean DVI, and the DVIs of drought-vulnerable cities in this region are also relatively close. In addition, though Shandong has less drought-vulnerable cities than Anhui, their averages and coefficients of variation of DVI are similar.

Table 2 Drought-vulnerable cities and their statistical characteristics of drought vulnerability index in four provinces

Province	City	Drought vulnerability index	
		Mean	Coefficient of variation
Anhui	Anqing, Bengbu, Bozhou, Chaohu, Chuzhou, Fuyang, Hefei, Huaibei, Huainan, Lu'an, Maanshan	0.472	0.532
Henan	Jiyuan, Jiaozuo, Luohe, Nanyang, Pingdingshan, Puyang, Xinxiang, Zhengzhou, Zhoukou, Zhumadian	0.326	0.726
Jiangsu	Changzhou, Suqian, Xuzhou, Yancheng, Yangzhou	0.219	0.504
Shandong	Binzhou, Heze, Liaocheng, Linyi, Rizhao, Tai'an, Zaozhuang	0.424	0.595

The spatial pattern of drought-vulnerable cities is illustrated in Fig. 5. By comparison with coastal areas, the inland regions have more drought-vulnerable cities owing to the geographic and socio-economic factors, and these cities have worse performances in the efficiency of resilience to drought. We also can see that the cities in the south study area are less vulnerable to drought than those in the central and north regions comparatively.

If the DVI over 0.5 belongs to high drought vulnerability level, the share of cities with high vulnerability in all drought-vulnerable units is 33.3%, including 4 cities in Anhui (Bengbu, Bozhou, Hefei and Maanshan), 4 cities in Henan (Nanyang, Pingdingshan, Xinxiang and Zhumadian) and 3 cities in Shandong (Heze, Linyi and Rizhao). Most of the high vulnerable cities are in the central and north study area, but few in the south.

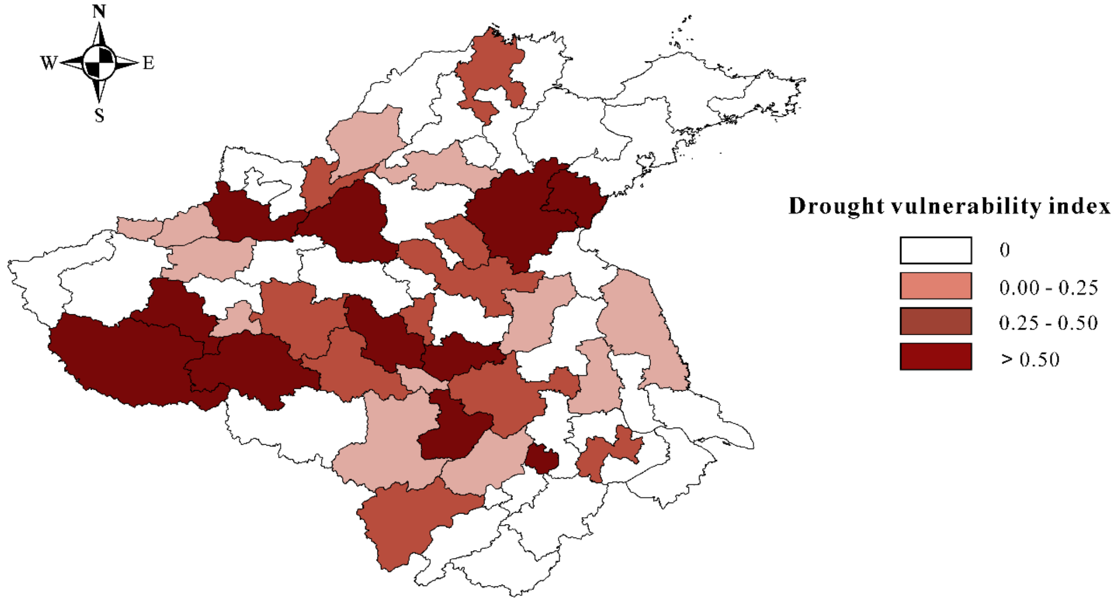

Fig. 5 Spatial pattern of drought-vulnerable cities

4.3 Grouping of drought-vulnerable cities

In order to analyze the characteristics of drought-vulnerable cities, 6 groups are formed based on their indicators which are also compared with those of all the cities in the study area (Table 3). The comparison coefficient is the ratio of the mean level of drought-vulnerable group to that of all the 65 cities. The larger coefficient of exposure and sensitivity indicates more potential to raise drought vulnerability, and the smaller one of adaptive capacity has the same effect. Thereby, the conclusions are as follows. (1) The insufficient emergency irrigation in the group G1 makes the resilience to drought inefficient, and the main cause of drought vulnerability in the groups G2 and G6 is the low adaptive capacity whose indicators are all below the average level. (2) Though Group G3, G4, and G5 have not such a shortage of adaptive capacity, their exposure and sensitivity are large enough to bring out drought vulnerability. The comparison coefficients of SharePF and WaterI in G3, G4 and G5 are both much higher, increasing drought vulnerability.

Consequently, the imbalance among exposure, sensitivity and adaptive capacity results in vulnerability to drought, and the way for mitigation is required to follow the three dimensions.

Table 3 Comparison coefficients between drought-vulnerable groups and all the 65 cities

Indicator		Group*					
		G1	G2	G3	G4	G5	G6
Exposure	PopD	1.00	1.05	0.91	1.37	1.10	0.97
	ShareCF	0.92	1.22	1.11	0.87	1.17	1.14
	SharePF	0.67	0.09	1.76	2.61	1.34	0.90
Sensitivity	ShareRP	0.96	1.09	1.05	0.74	0.98	1.27
	WaterA	0.43	0.27	0.82	1.63	2.45	1.40
	WaterI	0.97	0.65	1.35	2.11	1.42	0.87
Adaptive capacity	PGDP	1.10	0.66	0.59	1.89	0.53	0.36
	EI	0.26	0.38	1.99	0.29	0.86	0.26
	FA	1.15	0.52	0.94	0.53	1.25	0.31
	REI	0.96	0.95	1.03	1.18	1.04	0.96
	WS	0.68	0.48	1.01	1.95	1.58	0.60

* G1: Binzhou, Hefei, Jiyuan, Jiaozuo, Rizhao, Tai'an, Yangzhou, Zaozhuang, Zhengzhou.

G2: Liaocheng, Linyi, Luohe, Nanyang, Pingdingshan, Puyang.

G3: Chaohu, Xuzhou, Yancheng.

G4: Changzhou, Maanshan.

G5: Huainan, Suqian, Xinxiang.

G6: Anqing, Bengbu, Bozhou, Chuzhou, Fuyang, Heze, Huaibei, Lu'an, Zhoukou, Zhumadian.

4.4 Drought vulnerability reductions

The drought vulnerability reductions can be carried out by two stages: firstly, the benchmarks of resilience to drought need to be found out according to the characteristics of evaluation units, and then we investigate the appropriate ways to reduce drought vulnerability.

4.4.1 Benchmarking management

Normally, the drought-vulnerable cities will choose benchmarks from those with similar conditions of exposure and sensitivity at the provincial scale. Accordingly, this study divides the cities of the same province into classes based on the exposure and sensitivity indicators. In each class, benchmark is defined as the city whose DVI is equal to 0. As shown in Fig. 6, there are 15 classes in total and we analyze the differences in the exposure, sensitivity and adaptive capacity indicators between benchmarks and drought-vulnerable cities to improve the efficiency of resilience to drought. The comparison results in all city classes are as follows.

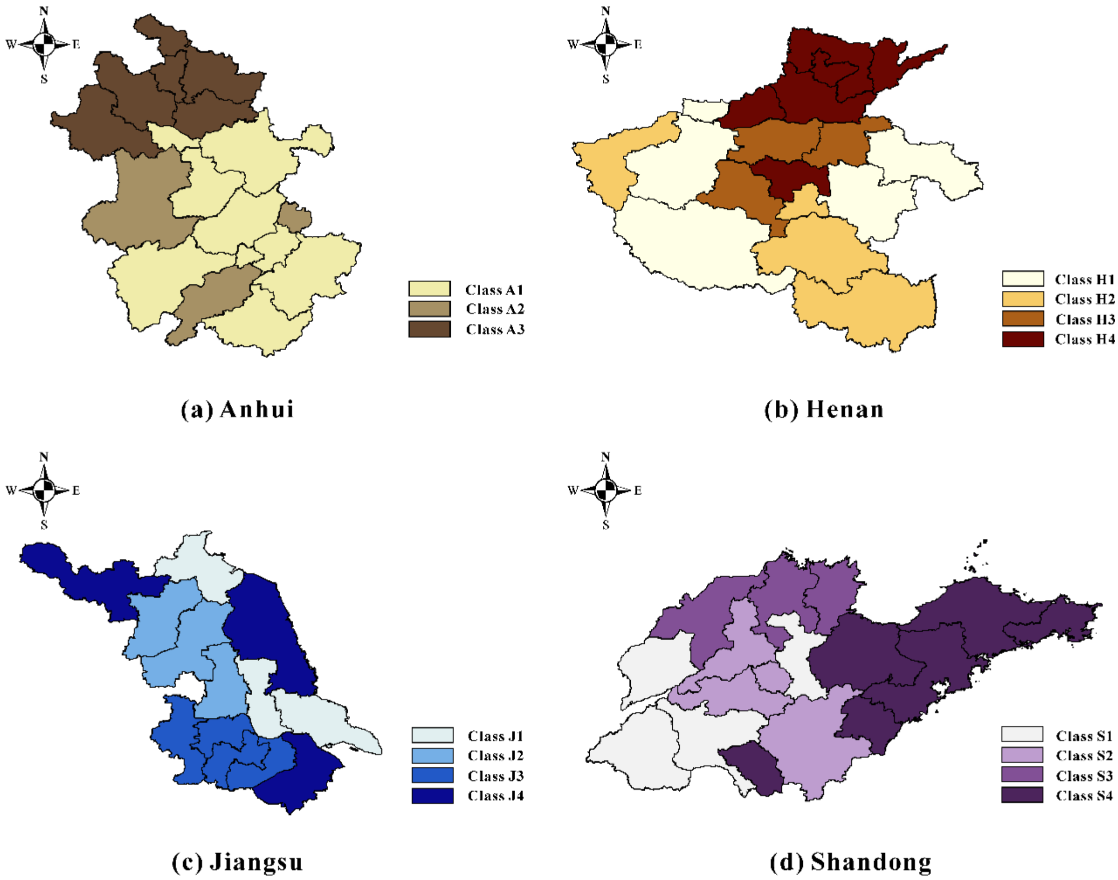

Fig. 6 Classes of cities in (a) Anhui, (b) Henan, (c) Jiangsu and (d) Shandong

(1) In Anhui province, there are 3 classes named A1, A2 and A3. In Class A1, the average exposure and sensitivity of drought-vulnerable cities are higher than those of benchmarks, but the PGDP and REI are lower. Similarly, the reductions in the exposure and sensitivity are needed in Class A2. The cities of Class A3 located in the north Anhui are the important agricultural areas, among which Suzhou with efficiency score of 1 has higher FA and EI than the drought-vulnerable cities.

(2) There are 12 benchmarks in the 4 classes of Henan province. The inefficient cities in Class H1 have greater exposure and sensitivity, whereas those in Class H3 are short of adaptive capacity. Besides, the EI, REI and WS result in the differences between the efficient and inefficient cities in Class H2, but in Class H4 the high exposure seems to be the main cause of drought vulnerability.

(3) 4 classes are formed in Jiangsu province, and the cities of Class J1 all have efficient resilience to

drought. However, the drought-vulnerable cities in the classes of J2, J3, and J4 should improve adaptive capacity, especially the economic level and water supply, compared with the benchmarks.

(4) Shandong province is also divided into 4 classes. In Class S1 and S4, the high exposure and sensitivity as well as the low adaptive capacity brings out drought-vulnerable cities. Meanwhile, it seems that the reductions in exposure of Class S2 and the improvements in adaptive capacity of Class S3 will make the cities efficient to resist drought.

Furthermore, the 15 classes of cities form 4 homogeneous regions in the study area (Fig. 7) based on their exposure and sensitivity. In each homogeneous region, the comparisons between drought-vulnerable cities and benchmarks are also made. (1) Region R1 is composed of the classes A3, H3, H4, S2 and S4, where there are 10 benchmarks for 14 drought-vulnerable cities. On average, the main gaps of adaptive capacity between benchmarks and drought-vulnerable cities are in PGDP, EI and FA. (2) In the region R2 including Class S1, S3, H1and H2, 56.3% of the cities are vulnerable to drought, and their adaptive capacity is much lower than that of benchmarks. (3) Class A1 and J4 form the region R3, and the proportion of benchmarks in R3 is 41.7% whose indicators of PGDP, REI and WS are higher than those of the drought-vulnerable cities in this region. (4) Region R4 covers most of Jiangsu and three cities in Anhui. By comparison with benchmarks, the cities with inefficient resilience to drought are much required to improve the PGDP, EI, FA and WS.

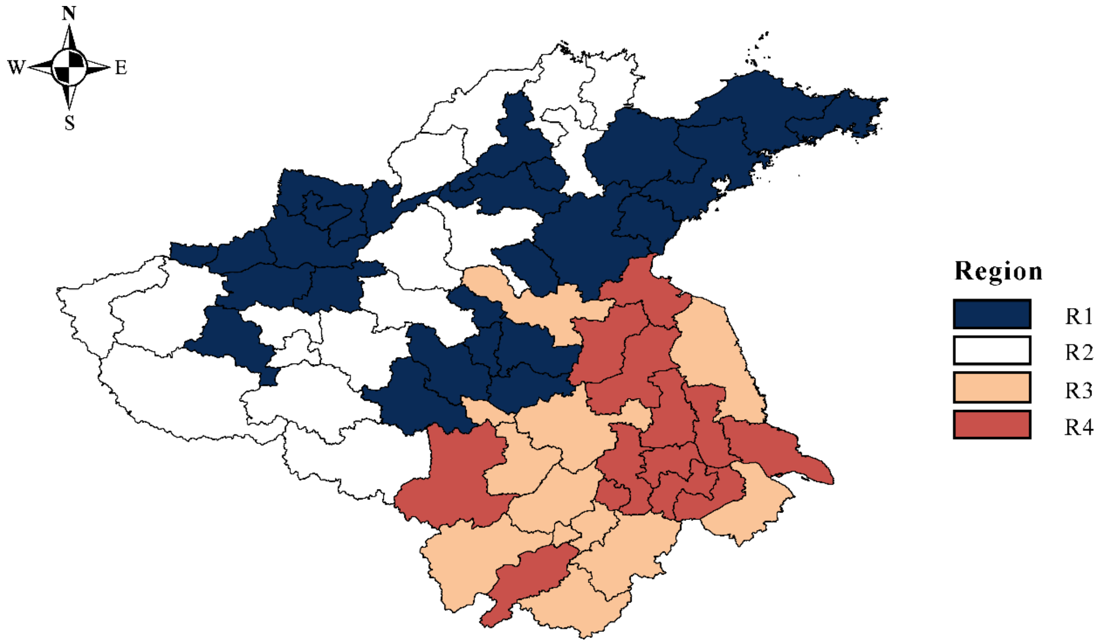

Fig. 7 Homogenous regions of study area

4.4.2 Improvements in resilience to drought

The slacks, indicating the excesses of exposure and sensitivity and the shortfalls of adaptive capacity, provide the directions for drought vulnerability reduction. However, their changes cannot exceed the upper bounds, that is, we reduce the exposure and sensitivity and improve the adaptive capacity within the given ranges. If the calculated slack reaches the bound, it exactly means that the desire for reduction/improvement has not yet been satisfied indeed. Thus, the ratios of slacks to bounds are used to determine the drought mitigation strategies (Table 4). This study considers that it is hard to reduce the exposure, so the mitigation strategy is made only according to the sensitivity and adaptive capacity. The higher ratio implies the greater need for change in the indicator to which more attention should be paid in decision making process.

As shown in Table 4, 75.6% of the drought-vulnerable cities need to further develop economy so that there would be more funds to cope with drought. Those developed cities, however, seem to be less eager to reduce drought vulnerability by increasing economy than other means. In addition, 33.3% of the cities much desire more investments in drought mitigation, and the proportion of those expecting the improvements in emergency irrigation is 24.2%. By comparison, most of the drought-vulnerable cities only want small changes in water supply and rate of effective irrigation area.

On the other hand, 30.3% of the drought-vulnerable cities are required to promote the water efficiency of agriculture as soon as possible, and about one fifth of those cities are expected to have higher water efficiency of industry. However, reducing the share of rural population is not the main manner adopted by the cities of inefficient resilience to drought.

Table 4 Ratios of the computed slacks to their upper bounds for drought-vulnerable cities (Unit: %)

Class	City	Sensitivity			Adaptive capacity				
		ShareRP	WaterI	WaterA	PGDP	EI	FA	REI	WS
A1	Anqing	0	53	23	100	14	49	0	0
	Chaohu	18	0	100	100	2	74	0	7
	Chuzhou	3	0	0	100	100	53	0	0
	Hefei	0	100	100	100	100	100	0	100
	Huainan	0	83	0	100	27	33	0	0
A2	Lu'an	2	0	34	100	25	18	0	0
	Maanshan	0	42	100	39	100	35	0	23
A3	Bengbu	71	100	100	100	100	100	7	80
	Bozhou	21	100	0	100	14	45	4	0
	Fuyang	1	18	1	100	10	41	2	1
	Huaibei	0	100	26	100	10	64	0	0
H1	Nanyang	1	85	21	100	11	100	0	1
	Zhumadian	14	43	0	100	6	81	0	0
H2	Luohe	0	10	0	20	0	5	0	0
	Zhoukou	0	20	10	100	9	59	3	0
H3	Pingdingshan	17	100	47	100	95	100	13	0
	Zhengzhou	0	6	6	3	2	11	0	0
H4	Jiyuan	0	9	16	0	3	5	0	0
	Jiaozuo	0	0	4	12	8	8	4	0
	Puyang	0	30	100	100	9	100	3	0
	Xinxiang	4	99	100	100	100	100	0	0
J2	Suqian	2	0	60	100	17	55	0	0
	Yangzhou	0	0	56	57	29	1	0	0

J3	Changzhou	0	0	100	91	100	93	13	0
J4	Xuzhou	0	100	100	100	100	100	0	20
	Yancheng	0	0	25	100	0	68	0	0
S1	Heze	15	100	100	100	35	0	0	0
	Liaocheng	0	0	39	100	2	3	15	2
S2	Linyi	26	0	6	100	100	100	48	0
	Tai'an	5	0	47	100	32	100	6	1
S3	Binzhou	6	0	100	49	6	17	0	0
S4	Rizhao	16	0	0	100	48	100	0	0
	Zaozhuang	3	0	0	100	32	100	15	0

5 Conclusions and policy implications

5.1 Conclusions

Climate change raises the regional vulnerability to drought in China, thus mitigation strategies are extremely needed. This study develops an integrated index containing exposure, sensitivity and adaptive capacity to measure drought vulnerability. Then, the DEA-AHP integrated approach is employed to calculate the drought vulnerability index and generate mitigation strategies. The study area covers 65 cities in Anhui, Henan, Jiangsu and Shandong provinces of China, and the main conclusions obtained are as follows.

(1) The integrated index can reveal the causes of drought vulnerability, and it indicates that 33 cities in four provinces have inefficient resilience to drought. Comparatively, Anhui and Henan have more drought-vulnerable cities which account for over 50% of the units in the two provinces.

(2) Compared with coastal areas, the inland regions have more drought-vulnerable cities with

worse performances in the efficiency of resilience to drought. In addition, most of the high vulnerable cities locate in the central and north study area.

(3) The causes of drought vulnerability are the excesses of exposure and sensitivity and the shortfalls of adaptive capacity. In the drought-vulnerable groups G1, G2 and G6, the low adaptive capacity makes the resilience to drought inefficient. However, as for the groups G3, G4, and G5, their exposure and sensitivity are large enough to bring out vulnerability to drought.

(4) Developing economy is the primary way for 75.6% of the drought-vulnerable cities to reduce vulnerability. Additionally, 33.3% of the cities much desire more investments in drought mitigation, and the proportion of those expecting the improvements in emergency irrigation is 24.2%. On the other hand, 30.3% of those cities are required to promote the water efficiency of agriculture, and about one fifth of the cities are expected to have higher water efficiency of industry.

The framework for regional drought vulnerability evaluation and mitigation strategy generation in this paper contributes to making effective drought plans and preparedness for vulnerable areas, and it also could be applied to the vulnerability assessment of drought management for other regions of the world. This study suggests that emergency water projects and water efficiency promotion are essential to cope with drought under global change.

5.2 Policy implications

(1) Enhance the responses to climate change. In the past decade, China was hit by severe droughts

with heavy losses in the context of climate change. However, a lack of responses to drought made the situations worse. Though measures have been taken to improve the mitigation capacities in China, it is necessary to further enhance the responses to drought, and make emergency plans to alleviate the impacts of drought. Particularly, the cities in north-central Anhui, south and northeast Henan as well as south and west Shandong are more vulnerable to drought and need the enhancements in response to climate change.

(2) Advance the economic developments and increase the investments in drought preparedness. The results show that most of the drought-vulnerable cities need to develop economy, and nearly 33.3% of the ones are short of facilities and techniques to reduce drought vulnerability. Therefore, economic growth is extremely needed so that there can be more funds for coping with drought. Additionally, the increments of investment in drought preparedness are required due to the mismatches between drought effects and financial expenditure on the infrastructure for mitigation. Comparatively, Anhui and Henan are less developed than Jiangsu and Shandong, however, more vulnerable to drought. Therefore, to quicken economic growth and increase investments in drought mitigation in Anhui and Henan are the effective ways for drought vulnerability reduction.

(3) Promote the water efficiency of industry and agriculture. The developments of industry and agriculture completely rely on water, but most of the cities in China are short of this resource. Particularly, water scarcity will be more severe with global warming. Thus, the available path to balance limited water resources and developments is to promote the water efficiency. It seems that there will be high risk of loss caused by drought in Anhui and Jiangsu due to the low efficiency of agriculture and industry. As a result, the promotions of water efficiency in both the two provinces are expected.

(4) Ensure the need for drinking water of rural areas. During drought periods, drinking water is the central issue to be concerned. Nevertheless, the rural areas are seriously threatened because of inadequate infrastructures. According to the national anti-drought plan of China, more projects are required to ensure the drinking water of rural areas. Especially, for Anhui, Henan and Shandong which have high shares of rural population, more projects for drinking water are desired. Meanwhile, the locations of them should be arranged reasonably according to the geographic and socio-economic factors.

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