Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28698

268 (2022) 264–272
August

Evaluation research on water resources carrying capacity based on improved matter-element extension model

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Received 14 April 2022; Accepted 12 July 2022

ABSTRACT

According to the current situation of water resources in cities in Henan Province, this paper establishes the index system based on the principle of "allocating the water resources reasonably for the development of agriculture, population, and industries". The water resources carrying capacity of cities in Henan Province from 2010 to 2020 was evaluated by the improved matter-element extension model along with improved entropy weight method and variation coefficient method, and suggestions were put forward for "constraining towns by water resources" from the perspective of spatial layout. According to the results: (1) the water resources carrying capacity of each city developed in a sound manner. 14 cities in Henan Provinces, including Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Anyang, Hebi, Xinxiang, Jiaozuo, Puyang, Xuchang, Sanmenxia, Nanyang, Xinyang and Jiyuan showed a positive trajectory during the study period, Luohe showed the best performance, Zhoukou, Zhumadian had the worst performance and Shangqiu had a complicated performance. (2) In terms of the time dimension, the overall performed of water resources carrying capacity showed an increasing trend year by year. The results of the study can provide theoretical support for the further sustainable development of water resources in cities of Henan Province.

Keywords: Water resources carrying capacity; Improved entropy method; Coefficient of variation method; Matter-element extension model; "Four fixed by water"

1. Introduction

With the expanding population and accelerated industrialization, many countries have shown a series of global water resources problems in production and life, such as the contradiction between water supply and demand, and water ecological imbalance. Water resources related problems have gradually become the main 'bottleneck' restricting regional agricultural and economic and social development [1–3]. On September 18, 2019, a symposium on ecological protection and high-quality development along the Yellow River Basin was held in Zhengzhou. It was emphasized that various methods should be adopted to promote the economical and intensive utilization of water resources based on the principle of "allocating the water resources reasonably for the development of agriculture, population, and industries", and take water resources as the largest rigid constraint [4]. Therefore, the research on water resources carrying capacity has far-reaching significance of optimizing the allocation of water resources and promoting sustainable economic development [5–7].

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2. Overview of the study area and data sources

2.1. Overview of the study area

Henan Province, abbreviated as "Yu", is located in northern China, with a provincial land area of about 167,000 km^2. By the end of 2020, the province has 17 prefecture-level cities and 1 county-level city. There are four major water systems – Yellow River, Huaihe River, Haihe River, Yangtze River. The per capita water resources in Henan Province is about 383 m^3, only 20% of the national per capita water resources. With the rapid economic development and population explosion, as well as the irrational development and utilization of water resources, the contradiction between water resources and economic, society and ecology is increasingly prominent throughout Henan Province [8].

2.2. Data sources

11 representative indicators were selected to evaluate the water resources carrying capacity of 18 cities from 2010 to 2020. The original data of the indicators used in this paper were obtained from the "Henan Provincial Water Resources Bulletin" "Henan Statistical Yearbook" and the city-level water resources bulletins, the official website of the Ministry of Water Resources and the statistical yearbook. Some of them were calculated by equations, such as water supply modulus = total water supply resources/total water supply area; the missing values in the directly collected data were filled by mean value method, so as to obtain the calculated data of each city in the evaluation years.

3. Research methods

3.1. Construction of index system

This paper selected indicators based on the principle of "allocating the water resources reasonably for the development of agriculture, population, and industries". By analyzing the current situation of water resources in each city of Henan Province and based on a large number of relevant studies [1,9–12], the relationship between "water-people-land-city-production" was determined, and 11 indicators were selected to build an evaluation system of water resources carrying capacity, including three layers of people, land and production. The evaluation results are expected to provide theoretical support for the spatial layout of "the urban development constrained by the water". The specific index system is shown in Table 1.

3.2. Weight determination

Considering the uncertainty characteristics of water resources system, such as randomness and fuzziness [13], this study selected the combination objective weight for determining the index weight value so as to avoid the influence of human factors.

Entropy weight method is an objective method to determine the weight value according to the amount of information provided by each index [14]. According to the degree of variation of indicators, the entropy weight of indicators is calculated using information entropy, and then the weights are corrected to make the evaluation results more objective and accurate. In this paper, the improved entropy weight method of Li and Zhou was adopted [15]. This method not only makes up for the shortcomings of the traditional entropy weight method, but also is endowed with the advantages of the index weight over widening the gap. Coefficient of variation is the ratio of standard deviation and average, and the weight is obtained by calculating the index information. It is an objective weighting method and can effectively reflect the gap between evaluation indexes. Therefore, the combination of the two results is more objective and accurate.

The main calculation process is as follows:

(a) A group of data with m samples and n indexes are standardized and normalized, according to the equation as follows:

$$x'_{ij} = \max\left\{x_{1j}, x_{2j}, \ldots, x_{mj}\right\} - x_{ij} \quad (1)$$

Table 1
Comprehensive evaluation index system of water resources carrying capacity

Target layer	Criterion layer	Index layer	Criterion attribute
Water resources carrying capacity	Population constrained by water resources	Per capita water resources A_1 (m^3)	Positive
		Water use per capita living A_2 (d/L)	Negative
		Population density A_3 (person km^{-2})	Negative
	Agriculture constrained by water resources	Water supply modulus A_4 (10,000m^3 km^{-2})	Positive
		Irrigated area A_5 (10,000 hm^{-2})	Negative
		Irrigation water per unit area A_6 (m^3 hm^{-2})	Negative
		Effective water duty A_7 (%)	Positive
	Industries constrained by water resources	Per capita GDP A_8 (Yuan)	Positive
		10,000 yuan GDP agricultural water consumption A_9 (m^3)	Negative
		Industrial water consumption per 10,000 yuan GDP A_{10} (m^3)	Negative
		10,000 yuan GDP tertiary industry water consumption A_{11} (m^3)	Negative

Notes: "Positive" indicates that the greater the index value, the greater the water resources carrying capacity; "Negative" indicates that the larger the index value is, the more unfavorable it is to improve the water resources carrying capacity.

$$r_{ij} = \frac{x'_{ij} - x'_{j\min}}{x'_{j\max} - x'_{j\min}} \quad (2)$$

where $i = 1, 2, ..., m$; j is the item that needs to be normalized; x_{ij}' is the positive index value.

(b) The entropy of evaluation index j is determined:

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} \left(p_{ij} \ln p_{ij} \right) \quad (3)$$

among which, $P_{ij} = r_{ij} / \sum_{i=1}^{m} r_{ij} \left(0 \le p_{ij} \le 1 \right)$.

(c) The entropy weight (weight) of each evaluation index is determined:

$$w_{1j} = \begin{cases} (1-\bar{e})w_j^1 + \bar{e}w_j^2, e_j < 1 \\ 0, e_j = 1 \end{cases} \quad (4)$$

among them, $\bar{e}$ is the average value of all entropy values not equal to 1, w_j^1 and w_j^2 are as follows:

$$\begin{cases} w_j^1 = \dfrac{1-e_j}{\sum_{j=1}^{n} \left(1-e_j\right)} \\ w_j^2 = \dfrac{1+\bar{e}-e_j}{\sum_{k=1, e_k \ne 1}^{n} \left(1+\bar{e}-e_k\right)} \end{cases} \quad (5)$$

(d) Coefficient of variation of indicators:

$$c_j = \frac{\sigma_j}{\bar{x}_j} \left(j = 1, \cdots, n \right) \quad (6)$$

among them, σ_j is the standard deviation of item j; $\bar{x}_j$ is the average of item j.

(e) The weight of each evaluation index coefficient of variation method is shown as follows:

$$w_{2j} = \frac{c_j}{\sum_{j=1}^{n} c_j} \quad (7)$$

The weights obtained by entropy weight method and coefficient of variation method are combined to obtain more objective results [14]:

$$w_j = \frac{\sqrt{w_{1j} \cdot w_{2j}}}{\sum_{j=1}^{n} \sqrt{w_{1j} \cdot w_{2j}}} \quad (8)$$

3.3. Improved matter element extension evaluation model

Extenics is a discipline founded by Chinese Scholar Cai and Yang [16]. This model can effectively solve the incompatibility. The matter-element extension model can transform the multiple indexes in the evaluation system into a single index, and quantify the evaluation results [17]. In order to avoid the situation that the actual value of the evaluation index exceeds the nodal interval and to ensure that the constructed correlation function meets the calculation requirements, this paper adopts the improved method of Meng et al. [18] as follows:

(a) The classical domain is determined:

Assuming that the number of evaluation matter-element is s, the range of evaluation matter-element eigenvalue is $[a_{jl}, b_{jl}]$ ($j = 1, 2, ..., n$; $l = 1, 2, ..., s$), and then the improved element R_0' with the same characteristics are shown as follows:

$$R_0' = \begin{bmatrix} N & N_1 & N_2 & \cdots & N_s \\ A_1 & \left[\dfrac{a_{11}}{b_{1p}}, \dfrac{b_{11}}{b_{1p}}\right] & \left[\dfrac{a_{12}}{b_{1p}}, \dfrac{b_{12}}{b_{1p}}\right] & \cdots & \left[\dfrac{a_{1s}}{b_{1p}}, \dfrac{b_{1s}}{b_{1p}}\right] \\ A_2 & \left[\dfrac{a_{21}}{b_{2p}}, \dfrac{b_{21}}{b_{2p}}\right] & \left[\dfrac{a_{22}}{b_{2p}}, \dfrac{b_{22}}{b_{2p}}\right] & \cdots & \left[\dfrac{a_{2s}}{b_{2p}}, \dfrac{b_{2s}}{b_{2p}}\right] \\ & \vdots & \vdots & \vdots & \vdots \\ A_n & \left[\dfrac{a_{n1}}{b_{np}}, \dfrac{b_{n1}}{b_{np}}\right] & \left[\dfrac{a_{n2}}{b_{np}}, \dfrac{b_{n2}}{b_{np}}\right] & \cdots & \left[\dfrac{a_{ns}}{b_{np}}, \dfrac{b_{ns}}{b_{np}}\right] \end{bmatrix} \quad (9)$$

where N_l is the lth matter element to be evaluated; A_j means the jth index to be evaluated; $v'_{ij} = \left[\dfrac{a_{jl}}{b_{jp}}, \dfrac{b_{jl}}{b_{jp}}\right] = \left[a'_{jl}, b'_{jl}\right]$ is the numerical range of the improved jth index about the evaluation grade l, and b_{jp} is the maximum value of each index in the section area. The section area R_p is as follows:

$$R_p = \begin{bmatrix} P & A_1 & \left[a_{1p}, b_{1p}\right] \\ & A_2 & \left[a_{2p}, b_{2p}\right] \\ & \vdots & \vdots \\ & A_n & \left[a_{np}, b_{np}\right] \end{bmatrix} \quad (10)$$

where P refers to the total evaluation type; $[a_{jl}, b_{jl}]$ is the range taken by P with respect to A_j, that is, the domain.

(b) The matter element to be evaluated is identified and the method used in (a) is improved:

$$R_d = \begin{bmatrix} P & A_1 & \dfrac{v_1}{b_{1p}} \\ & A_2 & \dfrac{v_2}{b_{2p}} \\ & \vdots & \vdots \\ & A_n & \dfrac{v_n}{b_{np}} \end{bmatrix} \quad (11)$$

where R_d is the matter element to be evaluated; v_j is the value of the sample to be evaluated corresponding to A_j, b_{jp} means the same.

(c) The paste progress is calculated.

The correlation degree in the classical matter element extension model is replaced by the closeness degree to avoid the impact on the accuracy of the evaluation results caused by using approximation processing when calculating the correlation degree [19].

The distance between the matter element to be evaluated and the classical domains is as follows:

$$\rho\left(v'_j, v'_{jl}\right) = \left| v'_j - \frac{a'_{jl} + b'_{jl}}{2} \right| - \frac{b'_{jl} - a'_{jl}}{2} \tag{12}$$

where v_j' is the meaning of v_j/b_{jp}, a_{jl}' and b_{jl}' in Eq. (11) have the same meaning as Eq. (12).

The closeness of matter element to be evaluated with respect to level l can be expressed as:

$$K_l\left(p\right) = \sum_{j=1}^{n} \omega_j \rho\left(v'_j, v'_{jl}\right) \tag{13}$$

where ω_j is the weight obtained by Eq. (8).

(d) The evaluation level of the sample to be evaluated is determined:

$$K_{l0}\left(p\right) = \max\left\{K_l\left(p\right)\right\} \quad \left(l = 1, 2, \cdots, s\right) \tag{14}$$

If the maximum paste progress of each grade is $K_{l0}(p)$, it is determined that p belongs to category $l0$. The calculation method is as follows:

$$\bar{K}_l\left(p\right) = \frac{K_l\left(p\right) - \min\limits_{1 \le l \le s} K_l\left(p\right)}{\max\limits_{1 \le l \le s} K_l\left(p\right) - \min\limits_{1 \le l \le s} K_l\left(p\right)} \tag{15}$$

Then the rank variable eigenvalue l^* of p is calculated as follows:

$$l^* = \frac{\sum_{l=1}^{s} l \cdot \bar{K}_l\left(p\right)}{\sum_{l=1}^{s} \bar{K}_l\left(p\right)} \tag{16}$$

Correlation degree indicates the degree to which the evaluation object conforms to the standard. When $K_l(p) \geq 1$, the evaluation object exceeds the standard range. When $0 \leq K_l(p) \leq 1$, the evaluation index meets the requirements, the greater the value is, the closer is to the standard range; when $-1 \leq K_l(p) \leq 0$, the evaluation object does not meet the standard requirements, but there are corresponding transformation conditions; when $K_l(p) \leq -1$, the evaluation object completely fails to meet the standard, not to mention any transformation conditions [20].

3.4. Obstacle factor analysis

Obstacle factor analysis is a diagnostic method to further identify the main influencing factors based on the constructed index system, which is widely used in many fields. Based on the comprehensive evaluation of water resources carrying capacity of cities in Henan Province, this paper uses obstacle degree model to further analyze obstacle factors to better determine the main influencing factors of water resources carrying capacity in different regions, which is conducive to improving water resources management and water resources carrying capacity. The specific process is as follows:

(a) The factor contribution F_j of the jth evaluation index is calculated:

$$F_j = w_j w_j^* \tag{17}$$

where w_j is the weight of index j, that is, the combination weight obtained by Eq. (8), and w_j^* is the weight of the criterion layer where index j is located.

(b) Calculation of deviation Q_j:

$$Q_j = 1 - x'_{ij} \tag{18}$$

(c) Calculation of barriers to evaluation indicators:

$$H_j = \frac{F_j P_j}{\sum_{j=1}^{n} F_j P_j} \tag{19}$$

4. Evaluation process and result analysis

4.1. Evaluation process

The combination weights of indicators for each evaluation year were obtained using the improved entropy weight method and variation coefficient method described above, as shown in Table 2. In this paper, based on the current situation of water resources in Henan Province, the Agricultural and Rural Domestic Water Quotas, Industrial and Urban Domestic Water Quotas and the generally accepted grading standards for water resources carrying capacity evaluation indexes issued by the Henan Provincial Administration of Market Supervision on September 2, 2020 [14,21–23], the evaluation index is divided into five grades I–V, representing carriable, weak carriable, crisis, overload, and strong overload. Please check Table 3 for details, and Table 4 for the evaluation results of each year in each region.

Select 2020 as an example to list the detailed evaluation process:

(1) R_0' be obtained by improving the classical domain (Table 3) according to Eq. (9):

$$R'_0 = \begin{bmatrix} N & N_1 & N_2 & \cdots & N_5 \\ A_1 & \left(0.9565, 1\right) & \left(0.7391, 0.9565\right) & \cdots & \left(0, 0.2174\right) \\ A_2 & \left(0.03810\right) & \left(0.3810, 0.5714\right) & \cdots & \left(0.8095, 1\right) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_{11} & \left(0, 0.0870\right) & \left(0.0870, 0.2609\right) & \cdots & \left(0.9565, 1\right) \end{bmatrix}$$

(2) According to Eq. (11), the matter-element R_d to be evaluated is obtained:

Due to length of this paper, only the matter-element to be evaluated in Zhengzhou in 2020 is listed below (similarly available in other regions), which is recorded as R_{d_1}:

$$R_{d_1} = \begin{bmatrix} P & A_1 & 0.0472 \\ & A_2 & 0.7043 \\ & A_3 & 0.9578 \\ & A_4 & 0.6135 \\ & A_5 & 0.2951 \\ & A_6 & 0.2366 \\ & A_7 & 0.9399 \\ & A_8 & 0.8011 \\ & A_9 & 0.1388 \\ & A_{10} & 0.0694 \\ & A_{11} & 0.0743 \end{bmatrix}$$

The matter-element to be evaluated and the closeness of each grade are calculated according to Eqs. (12)–(16) (Table 5).

4.2. Water resources carrying capacity results

As can be seen from Table 4, the water resources carrying capacity of the cities in Henan Province showed a stable and positive trend as a whole from 2010 to 2020. In the past many years, the water resources carrying capacity of Zhumadian, Luohe and Sanmenxia shown a sound trajectory and has moved toward grade I (carriable); Zhumadian and Zhoukou's has changed to grade IV (overload) and grade V (strong overload) for many years, with the poor performance. Combined with Table 4, the proportion of grades is calculated and the results are shown in Fig. 1. It can be seen from Fig. 1 that the transformation to grade I (carriable) and grade II (weak carriable) accounts for a large proportion and the proportion of transformation to grade I has increased significantly. It can be seen that in recent years, with the support and implementation of many national policies, 18 cities in Henan Province, the corresponding indicators of water

Table 2
Combination weight of evaluation indexes in Henan Province

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
A_1	0.1325	0.1279	0.1103	0.1033	0.1171	0.1253	0.1326	0.1315	0.1135	0.1108	0.1495
A_2	0.1041	0.1061	0.1006	0.1137	0.1076	0.1004	0.0877	0.0868	0.1051	0.0952	0.0889
A_3	0.1143	0.1202	0.1291	0.1269	0.1175	0.1187	0.1240	0.1197	0.1212	0.1259	0.1231
A_4	0.0945	0.0920	0.0965	0.0971	0.0901	0.0904	0.0930	0.0917	0.0895	0.0933	0.0898
A_5	0.1002	0.0973	0.1049	0.1040	0.0961	0.1000	0.1045	0.0996	0.1016	0.1052	0.1026
A_6	0.0736	0.0866	0.0769	0.0784	0.0980	0.0813	0.0864	0.0931	0.0901	0.0969	0.0916
A_7	0.0412	0.0412	0.0412	0.0395	0.0370	0.0415	0.0461	0.0461	0.0492	0.0221	0.0217
A_8	0.0883	0.0841	0.0900	0.0895	0.0821	0.0803	0.0826	0.0798	0.0822	0.0850	0.0853
A_9	0.0971	0.0788	0.0983	0.0953	0.1024	0.0980	0.0940	0.0932	0.1001	0.0975	0.0843
A_{10}	0.0847	0.0980	0.0783	0.0744	0.0710	0.0664	0.0711	0.0682	0.0708	0.0830	0.0853
A_{11}	0.0695	0.0678	0.0739	0.0779	0.0811	0.0977	0.0780	0.0903	0.0767	0.0851	0.0779

Table 3
Nodal domain and classical domain of matter-element extension model

Index	N_1 (carriable)	N_2 (weak carriable)	N_3 (crisis)	N_4 (overload)	N_5 (strong overload)
A_1	(2200, 2300)	(1700, 2200)	(1000, 1700)	(500, 1000)	(0, 500)
A_2	(0, 80)	(80, 120)	(120, 150)	(150, 170)	(170, 210)
A_3	(0, 200)	(200, 400)	(400, 500)	(500, 700)	(700, 1100)
A_4	(20, 40)	(15, 20)	(10, 15)	(5, 10)	(0, 5)
A_5	(0, 15)	(15, 30)	(30, 45)	(45, 60)	(60, 70)
A_6	(0, 1900)	(1900, 3000)	(300, 4000)	(4000, 6000)	(6000, 8000)
A_7	(80, 100)	(60, 80)	(50, 60)	(40, 50)	(0, 40)
A_8	(50000, 120000)	(40000, 50000)	(20000, 40000)	(14000, 20000)	(0, 14000)
A_9	(0, 370)	(370, 900)	(900, 1300)	(1300, 1900)	(1900, 2000)
A_{10}	(0, 24)	(24, 50)	(50, 100)	(100, 150)	(150, 160)
A_{11}	(0, 20)	(20, 60)	(60, 140)	(140, 220)	(220, 230)

Table 4
Evaluation results of water resources carrying capacity in cities

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Zhengzhou	II conversion	II conversion	I conversion	II conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion
Kaifeng	III conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion
Luoyang	III conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	I conversion	I conversion
Pingdingshan	III conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion
Anyang	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	I conversion	II conversion	II conversion	I conversion
Hebi	III conversion	III conversion	II conversion	II conversion	I conversion	I conversion	II conversion	I conversion	I conversion	I conversion	I conversion
Xinxiang	III conversion	III conversion	III conversion	III conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	I conversion
Jiaozuo	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	I conversion	I conversion	I conversion
Puyang	V conversion	V conversion	III conversion	III conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion
Xuchang	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	I conversion	I conversion	I conversion
Luohe	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion
Sanmenxia	II conversion	II conversion	II conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion	I conversion
Nanyang	III conversion	III conversion	III conversion	III conversion	III conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion
Shangqiu	V conversion	V conversion	V conversion	II conversion	I conversion	II conversion	II conversion	II conversion	II conversion	I conversion	V conversion
Xinyang	III conversion	III conversion	III conversion	III conversion	III conversion	III conversion	III conversion	III conversion	III conversion	III conversion	II conversion
Zhoukou	V conversion	V conversion	V conversion	V conversion	V conversion	V conversion	V conversion	V conversion	V conversion	V conversion	V conversion
Zhumadian	IV conversion	IV conversion	IV conversion	IV conversion	IV conversion	IV conversion	IV conversion	IV conversion	IV conversion	I conversion	IV conversion
Jiyuan	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	II conversion	I conversion	I conversion	I conversion

resources carrying capacity of 18 cities in Henan Province under the index system have improved significantly.

From the perspective of each criterion layer, it can be seen from Table 2 and Fig. 2 that the weight of each indicator in the criterion layer of "population growth constrained by water" accounts for a large proportion, among which the per capita water resources, per capita domestic water consumption and population density have a greater impact on the whole evaluation and the rapid population growth has led to the increase in water demand, which to a certain extent makes the water resources carrying capacity fluctuate. From 2010 to 2020, the per capita water resources and the overall per capita domestic water consumption is on the decline; In the second place, the weights of each indicator under the criterion layer strike the balance, and the original data show that each indicator has continued to improve during the evaluation years. The improvement of each index under the layer provides effective support for the carrying capacity of water resources; the overall weight of the "land expansion constrained by water" criterion layer is the smallest. Among them, the weight value of irrigated area is the largest. Based on the positioning of Henan Province as an "agricultural province" and the characteristics of agriculture itself, t the indicators under this criterion layer are scattered and difficult to control, and the improvement efficiency is low compared with other criterion layers.

From the regional evaluation results, it can be seen from Tables 4 and 5 that the water resources carrying capacity of many places in Henan Province shows a stable or significant improvement trend, such as Zhengzhou, Luoyang and Hebi but Zhoukou, Zhumadian and Shangqiu perform poorly, and are in the state of overload or strong overload for many years. The overall performance in 2010 was the worst, with the percentage of transformation to loadable only 5.6%, and the cumulative percentage of transformation to critical and below 61.1%. In 2010, the overall performance was the worst.

4.3. Obstacle factor of water resources carrying capacity

The obstacle factor model is used to diagnose the obstacle factors of water resources carrying capacity, and the obstacle degree of the index layer of water resources carrying capacity is obtained. The obstacle degree of each city in each year is ranked, and the top three obstacle factors of each city are analyzed. As this paper can only list part of the results, only those in the past three years from 2018 to 2020 are listed, as shown in Table 6.

As shown in Table 6, from the time dimension, per capita GDP (A_8) is the most important obstacle factor in 18 cities, followed by unit area irrigation water (A_6) and population density (A_3), and finally agricultural water consumption per 10,000 yuan of GDP (A_9) and per capita water resources (A_1). In terms of the spatial dimension, except for Hebi, Xinxiang, Jiaozuo, Shangqiu and Jiyuan, the main obstacle factors of the other 13 cities are per capita GDP (A_8) and unit area irrigation water (A_6), followed by agricultural water consumption per 10,000 yuan of GDP (A_9), population density (A_3) and per capita water resources (A_1).

On the whole, the water resources carrying capacity of cities in Henan Province is generally limited by GDP, and Henan, as a province with a large agricultural and population, is generally limited by GDP. The farmland irrigation water, population density and per capita water resources have significant effects on the water resources carrying capacity of each city.

5. Conclusions and suggestions

Based on the data of cities in Henan Province from 2010 to 2020, a comprehensive study of water resources carrying capacity was conducted, and the following main conclusions were drawn:

The 18 cities in Henan Province showed an overall stable and positive trend in terms of water resources carrying capacity in time and space. The 14 cities of Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Anyang, Hebi, Xinxiang, Jiaozuo, Puyang, Xuchang, Sanmenxia, Nanyang, Xinyang and Jiyuan all showed a positive trend during the study period; Luohe performed the best, Zhoukou and Zhumadian showed the worst performance and Shangqiu showed a complicated performance.

According to the analysis results of the obstacle factor in the index layer (Table 6), during the study period, per capita GDP (A_8) was the most important obstacle factor in 18 cities, followed by irrigation water per unit area (A_6) and population density (A_3), and finally Agricultural water consumption per 10,000 yuan of GDP (A_9) and per capita water resources (A_1).

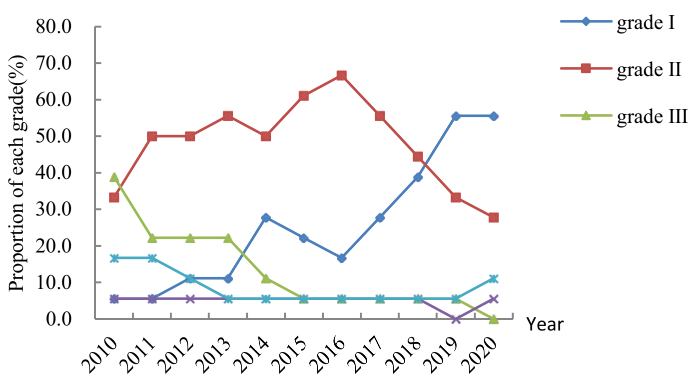

Fig. 1. The proportion of each grade in the evaluation year.

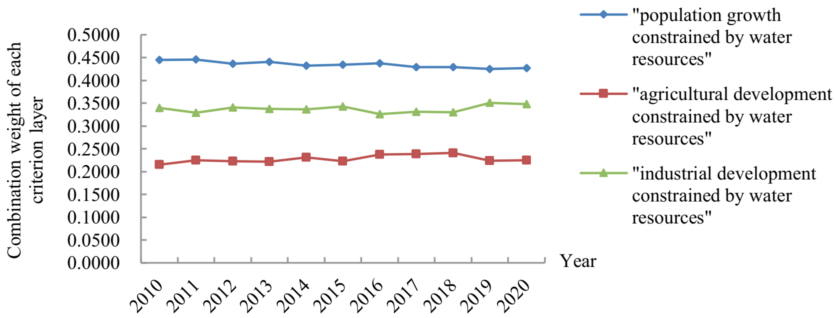

Fig. 2. Combination weights of each criterion layer in each evaluation year.

Table 5
Closeness of the matter-element to be evaluated to the classical domain (2020)

Paste progress	$K_1(p)$	$K_2(p)$	$K_3(p)$	$K_4(p)$	$K_5(p)$	Grade	l^*
Zhengzhou	–0.2192	–0.4343	–0.6172	–0.6849	–0.4794	I conversion	2.2210
Kaifeng	–0.3017	–0.2286	–0.3370	–0.4608	–0.3336	II conversion	2.5390
Luoyang	–0.2087	–0.2539	–0.3035	–0.4534	–0.4439	I conversion	1.8901
Pingdingshan	–0.2783	–0.2018	–0.3974	–0.5207	–0.3466	II conversion	2.4695
Anyang	–0.3230	–0.3911	–0.5765	–0.6813	–0.3785	I conversion	2.6201
Hebi	–0.1456	–0.2550	–0.5083	–0.5620	–0.4576	I conversion	1.9438
Xinxiang	–0.2538	–0.3433	–0.4866	–0.5262	–0.3624	I conversion	2.3927
Jiaozuo	–0.2538	–0.3433	–0.4866	–0.5262	–0.3624	I conversion	2.3927
Puyang	–0.4029	–0.2585	–0.4573	–0.5792	–0.3098	II conversion	2.8486
Xuchang	–0.1834	–0.3510	–0.5304	–0.6384	–0.4241	I conversion	2.2780
Luohe	–0.1974	–0.3668	–0.5520	–0.6428	–0.4279	I conversion	2.2826
Sanmenxia	–0.1321	–0.3071	–0.5422	–0.5487	–0.5068	I conversion	1.5973
Nanyang	–0.3081	–0.2158	–0.2293	–0.2879	–0.4672	II conversion	2.5284
Shangqiu	–0.2902	–0.3545	–0.4791	–0.5075	–0.2764	V conversion	2.8006
Xinyang	–0.2279	–0.1456	–0.1497	–0.3485	–0.5522	II conversion	2.3632
Zhoukou	–0.4040	–0.3602	–0.4676	–0.4223	–0.2800	V conversion	3.4601
Zhumadian	–0.3127	–0.5077	–0.5103	–0.2918	–0.3666	IV conversion	3.1921
Jiyuan	–0.2311	–0.2879	–0.4002	–0.4395	–0.4759	I conversion	1.8233

Nowadays, Henan is supported by a number of national strategies, and it is the first year of the "14th Five-Year Plan". It is necessary to follow the national strategic guidance and accelerate the construction of a sustainable development system. All localities should seek development paths suitable for local areas and allocate water resources reasonably, striking the relationship between power and "people-land-property". The development of a city is inseparable from water, and "the city constrained by water" is the ideological precursor for the development of various places. Recommendations are as follows:

In terms of "population growth constrained by water", it is necessary to strengthen the public awareness of water conservation. In particular, Anyang, Xinxiang, Zhumadian, Puyang, Zhoukou, and Kaifeng have relatively large domestic water consumption per capita. Large-scale densely populated areas, such as municipal governments and colleges and universities, can set an exemplary model. Based on the survey on water shortage areas, relevant lectures, and public welfare video clips, etc., the national awareness of water conservation can be aroused. In terms of land constrained by water", the efficient water-saving irrigation facilities can be improved. The government and the society jointly invest to build and effectively promote advanced water-saving facilities, such as sprinkler irrigation, seepage irrigation and drip irrigation according to local conditions, so as to minimize the losses in the water distribution and irrigation. Jiyuan, Sanmenxia and Jiaozuo, where the effective irrigation rate of farmland is low, should pay special attention to the water conservation facilities and accelerate the promotion of these facilities. In terms of "production constrained by water", the industrial structure and the water use structure should be optimized. The government has issued relevant policies to limit the number of high-water-consuming industries, supervise enterprises to transform and innovate production equipment, and increase the reuse rate of water; the government can

Table 6
Obstacle factors of main indicators in Henan Province from 2018 to 2020

Year	2018			2019			2020		
	1	2	3	1	2	3	1	2	3
Zhengzhou	A_8	A_6	A_9	A_8	A_6	A_9	A_8	A_6	A_1
Kaifeng	A_8	A_6	A_3	A_8	A_6	A_3	A_8	A_6	A_3
Luoyang	A_8	A_6	A_3	A_8	A_6	A_3	A_8	A_6	A_3
Pingdingshan	A_8	A_6	A_9	A_8	A_6	A_9	A_8	A_6	A_9
Anyang	A_8	A_6	A_1	A_8	A_6	A_9	A_8	A_6	A_9
Hebi	A_8	A_6	A_3	A_8	A_6	A_3	A_8	A_3	A_3
Xinxiang	A_8	A_6	A_3	A_8	A_6	A_3	A_8	A_1	A_6
Jiaozuo	A_8	A_1	A_3	A_8	A_6	A_3	A_8	A_6	A_3
Puyang	A_8	A_6	A_1	A_8	A_6	A_3	A_8	A_6	A_9
Xuchang	A_8	A_6	A_9	A_8	A_6	A_9	A_8	A_6	A_9
Luohe	A_8	A_6	A_9	A_8	A_6	A_9	A_8	A_6	A_9
Sanmenxia	A_8	A_6	A_3	A_8	A_6	A_3	A_8	A_6	A_3
Nanyang	A_8	A_6	A_3	A_8	A_6	A_3	A_8	A_6	A_3
Shangqiu	A_8	A_6	A_9	A_8	A_3	A_9	A_8	A_6	A_9
Xinyang	A_8	A_6	A_1	A_8	A_6	A_3	A_8	A_6	A_1
Zhoukou	A_8	A_6	A_9	A_8	A_6	A_9	A_8	A_6	A_1
Zhumadian	A_8	A_6	A_1	A_8	A_6	A_3	A_8	A_6	A_1
Jiyuan	A_8	A_3	A_1	A_8	A_3	A_1	A_8	A_3	A_1

introduce preferential policies to encourage the development of low-water-consuming and high-return industries, especially in Puyang, Nanyang and Pingdingshan, because these places have larger industrial water consumption per 10,000 yuan of GDP than other cities. It is necessary to take action to improve related aspects as soon as possible.

Fund

National Water Pollution Control and Governance of Science and Technology Major Special (No. 2018ZX07111003-005); Chinese Academy of Environmental Planning, MEP, Research Project of Water Ecological Environment Management (No. 2019A060).

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