Advance Journal of Food Science and Technology 10(1): 66-72, 2016
DOI: 10.19026/ajfst.10.1754
ISSN: 2042-4868; e-ISSN: 2042-4876

Submitted: April 28, 2015 Accepted: May 10, 2015 Published: January 05, 2016

Research Article

Assessing Soil Water Resources Carrying Capacity of Cultivated Land in Hebei Province Using a Variable Fuzzy Model

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Abstract: In this study, the concept of soil water resources carrying capacity of cultivated land is defined, the status of soil water resources in Hebei Province is analyzed. To evaluate the utilization of soil water resources of cultivated land and to use it rationally and scientifically, the assessment index system of soil water resources carrying capacity of cultivated land is established and the variable fuzzy model is used to assess the carrying capacity in this province in 2030. The assessment results show that the carrying capacity grade is the second grade, i.e., "Plan is average and can adapt to the local agricultural development" and indicate that soil water resources can basically meet the development of the local agricultural economy, while a rational development scale must be determined in Hebei Province.

Keywords: Assessment index system, Hebei province, soil water resources carrying capacity of cultivated land, variable fuzzy model

INTRODUCTION

The academic view that soil water is a kind of natural resources has been recognized in China and so many scholars have put forward the concepts of soil water resources from different aspects, such as agriculture, hydrological cycle, ecological environment and so on (Wang *et al*., 2006). Thus, the utilization scale of soil water resources will be necessary to be determined like other natural resources. Soil water resources is one of the necessary conditions for all of plants in land, though the study on soil water resources carrying capacity has great significance. According to the National Standards "Current Land Use Classification" in China (GB/T 21010-2007), the land is divided into 12 types, including cultivated land, garden land, forest land, grassland, etc and the cultivated land is divided into paddy, irrigated land and the dry land. This study will mainly study the soil water resources carrying capacity of cultivated land.

MATERIALS AND METHODS

Concept of soil water resources carrying capacuty of cultivated land: Soil water resources of cultivated land mainly refer to the soil water which can be absorbed by the crop and can affect the agro-ecological environment. Based on the extent of cultivated land, soil water resources is mainly used to maintain the crops' evapotranspiration and is closely to the agricultural production. At the same time, the ability that soil water can improve the agricultural ecological environment is much lower than the ability of supplying soil water to crops and it can increase the humidity through evaporation and other means only in the non-growing season in mountainous area and in the fallow period in the plains. Therefore, soil water resources carrying object is mainly planting in cultivated land in Hebei Province, where the cultivated land has been used to rotate the crops except in the northern mountainous area.

Firstly, the concept of soil water resources carrying capacity of cultivated land has been defined as following in this study, that is when soil water, fertilizer, gas and heat in soil maintain harmony, under the natural unified model condition, in which the source of soil water is natural precipitation, such as dry land and dry rice fields, or under the natural-manpower duality mode condition, in which the sources of soil water are natural precipitation and irrigation, such as irrigated land and paddy fields and under the condition of the economy development level and the technology development level in a certain social development stage, the ability of soil water can continuously support the development of agriculture. Secondly, the Variable Fuzzy Sets Assessment model (VFSA), which is an assessing model of nature resources carrying capacity will be introduced. Finally, soil water resources carrying capacity of cultivated land in Hebei province will be assessed based on VFSA.

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Model of Relative Membership Function (RMF): Supposed that $X_0 = [a, b]$ is attraction sets of Variable Fuzzy Set (VFS) $\underset{\sim}{V}$ on the real axis, i.e., $0 < D_{\underset{\sim}{A}}(u) \le 1$ and $X = [c, d]$ is a certain interval containing $X0$ ($X_0 \subset X$). According to definition of VFS, intervals $[c, a]$ and $[b, d]$ are repelling sets of VFS, i.e., $-1 \le D_{\underset{\sim}{A}}(u) < 0$. Suppose that M is the point of $D_{\underset{\sim}{A}}(u) = 1$ in attraction set $[a, b]$, according to actual problems M may not be the median value of interval $[a, b]$ (Chen, 2005, 2009).

It is assumed that x is a random point in interval X and if x locates at left side of M, the model of RMF is as follows:

$$D_{\underset{\sim}{A}}(u) = \begin{cases} \left(\dfrac{x-a}{M-a}\right)^{\beta} & x \in [a, M] \\ -\left(\dfrac{x-a}{c-a}\right)^{\beta} & x \in [c, a] \end{cases} \tag{1}$$

If x locates at right side of M, the model of RMF is as follows:

$$D_{\underset{\sim}{A}}(u) = \begin{cases} \left(\dfrac{x-b}{M-b}\right)^{\beta} & x \in [M, b] \\ -\left(\dfrac{x-b}{d-b}\right)^{\beta} & x \in [b, d] \end{cases} \tag{2}$$

If x locates out of interval X, the model of RMF is:

$$D_{\underset{\sim}{A}}(u) = 0 \qquad x \notin [c, d] \tag{3}$$

where, β is a nonnegative indicator and RMF will be a linear function if β = 1, which is subject to:

- If $x = a$ and $x = b$, $D_{\underset{\sim}{A}}(u) = 0$
- If $x = M$, $D_{\underset{\sim}{A}}(u) = 1$
- If $x = c$ and $x = d$, $D_{\underset{\sim}{A}}(u) = -1$

When $D_{\underset{\sim}{A}}(u)$ has been obtained by (1), (2) and Eq. (3), Relative Membership Degrees (RMD) $\mu_{\underset{\sim}{A}}(u)$ can be calculated as follows:

$$\mu_{\underset{\sim}{A}}(u) = \frac{1 + D_{\underset{\sim}{A}}(u)}{2} \tag{4}$$

And if $x \notin [c, d]$, $\mu_{\underset{\sim}{A}}(u) = 0$ (5)

Variable Fuzzy Sets Assessment model (VFSA): Supposed that assessment object is U and the number of assessment index is m according to actual problem, then the vector of index eigenvalue is as follows:

$$\vec{U} = (u_1, u_2, u_3 \ldots\ldots u_m) = u_i \tag{6}$$

where, i is the indices number and $i = 1, 2, \ldots\ldots m$.

The RMD vector $\vec{\mu}_{\underset{\sim}{A}}(u)$ can be obtained by calculating the RMD of U to each index and as follows:

$$\vec{\mu}_{\underset{\sim}{A}}(u) = (\mu_{\underset{\sim}{A}}(u)_1 \quad \mu_{\underset{\sim}{A}}(u)_2 \quad \ldots \quad \mu_{\underset{\sim}{A}}(u)_m) \tag{7}$$

According to the theory of opposite fuzzy sets, the matrices of relative membership degree and relative inferiority degree are as follows:

$$g = \begin{pmatrix} 1 & 1 & \ldots & 1 \\ 0 & 0 & \ldots & 0 \end{pmatrix}, \quad b = \begin{pmatrix} 0 & 0 & \ldots & 0 \\ 1 & 1 & \ldots & 1 \end{pmatrix} \tag{8}$$

Weight vector is:

$$\vec{w} = (w_1 \quad w_2 \quad \ldots \quad w_m) = w_i \tag{9}$$

And weight vector is subject to $\sum_{i=1}^{m} w_i = 1$. The generalized weighted distance of the RMD of the eigenvalue of u_i are as follows:

$$d_g = \left\{ \sum_{i=1}^{m} \left[w_i \left(1 - \mu_{\underset{\sim}{A}}(u)_i\right) \right]^p \right\}^{1/p} \tag{10}$$

$$d_b = \left\{ \sum_{i=1}^{m} \left[w_i \left(1 - \mu_{\underset{\sim}{A}^c}(u)_i\right) \right]^p \right\}^{1/p} = \left\{ \sum_{i=1}^{m} \left(w_i \mu_{\underset{\sim}{A}}(u)_i \right)^p \right\}^{1/p} \tag{11}$$

And the model VFSA is expressed as follows:

$$v_{\underset{\sim}{A}}(u) = 1 \Big/ \left[1 + \left(d_g / d_b\right)\right]^{\alpha} \tag{12}$$

where, α is the rule parameter and p is the distance parameter. Generally, $\alpha = 1, 2$ and $p = 1, 2$. $\alpha = 1$ is least single model and $\alpha = 2$ is least square model; $p = 1$ is hamming distance and $p = 2$ is Euclidean distance. Therefore, α and p can be arranged in 4 pairs, i.e., $p = 1, \alpha = 1$; $p = 1, \alpha = 2$; $p = 2, \alpha = 1$ and $p = 2, \alpha = 2$.

Through normalizing $v_{\underset{\sim}{A}}(u)$, RMD $v^{\circ}_{\underset{\sim}{A}}(u)$ can be obtained and then the Rank Feature Values (RFV) can be calculated by RFV equation:

Table 1: The rank standard of soil water resources carrying capacity of cultivated land

H	Grade	Description
H<1.5	I	Plan is good and is more adapted to the local agricultural development
1.5≤H<2.5	II	Plan is average and can adapt to the local agricultural development
H≥2.5	III	Plan is poor and cannot adapt to the local agricultural development

$$H = \begin{pmatrix}1 & 2 & \dots & c\end{pmatrix} \cdot \vec{v}^{\circ}_{\underset{\sim}{A}}(u)^T_h \tag{13}$$

And in VFSA model, the assessment results stability can be analyzed by model variability and model parameters variability.

In this study, H has been graded in order to judge the rationality of soil water carrying capacity of cultivated land. And H intervals grades Table 1.

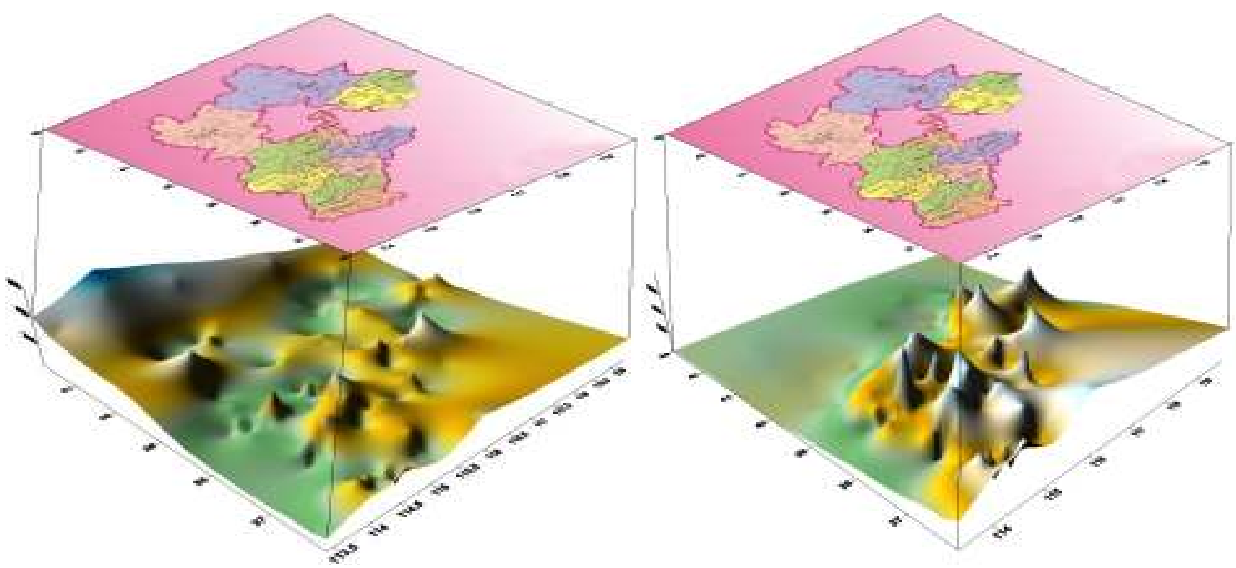
Introduction of Hebei province: Hebei Province is located in the central part of the North China Plain and is east of Taihang Mountains, west of Bohai Sea, south of Yanshan Mountain. There is mainly plain except mountainous area in the north. Total area of this province is 18,770,000 km^2, including 11 prefecture-level cities, 22 county-level cities and 114 counties.

Hebei Province has a temperate monsoon climate-warm temperate, semi-humid and semi-arid continental monsoon climate, the annual average temperature is between 39.2~55.4°F, annual frost-free period is 110 to 220 days and the average annual rainfall is between 400~800 mm which is unevenly distribution and annual variation.

According to "Rural Statistical Yearbook of Hebei Province", "Hebei Province Water Conservancy Statistical Yearbook," etc., in 2012 (Hebei Province Water Conservancy Statistical Yearbook, 2012; Rural Statistical Yearbook of Hebei Province, 2012), the cultivated land area of this province was about 5.9 million ha, the total planting area was about 8.8 million ha, irrigated area was about 4.6 million ha, saving water irrigated area was about 2.8 million ha, multiple cropping index was 1.49 and grain yield was about 31.7 million tons.

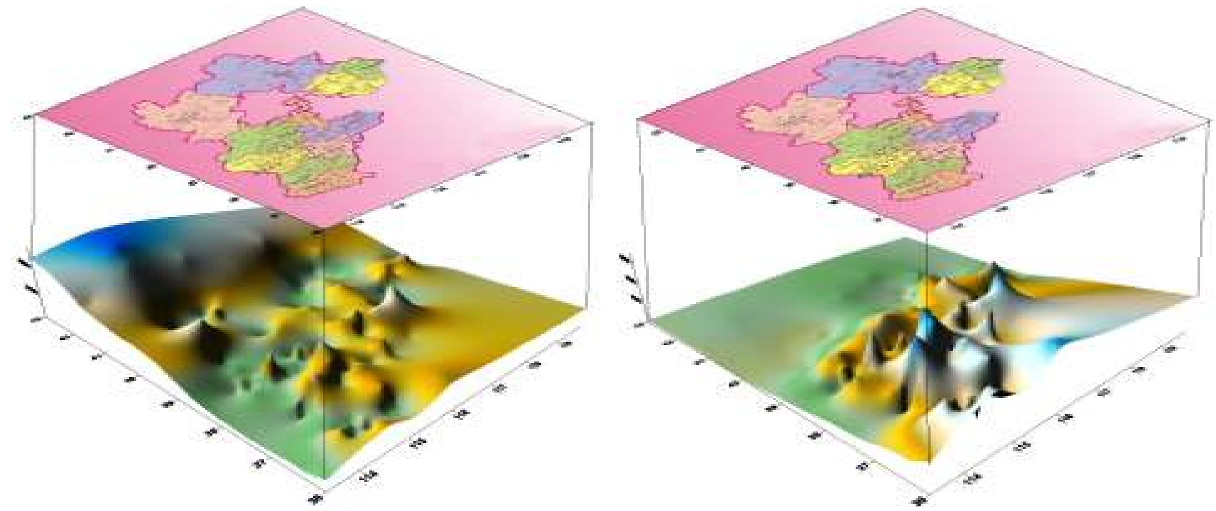
The utilization situation of soil water resources of cultivated land in Hebei province: According to the assessment results of soil water resources in Hebei Province, in years with 50% rainfall frequency (p = 50%), there are about 28.4 billion m^3 soil water resources and about 25.1 billion m^3 soil water resources in years with 75% rainfall frequency (p = 75%) (Zheng, 2009). According to the planting area and irrigated quotas of each kind of crop and other parameters, the utilization of soil water resources in Hebei Province can be calculated. The results shows: in years with 50% rainfall frequency the utilization of soil water resources is about 4.5 billion m^3 and in years with 75% rainfall frequency it is about 3.9 billion m^3.

The utilization situation of soil water resources of cultivated land of each city in Hebei province: The utilization situation of soil water resources of cultivated land are different because of the obvious differences in climate, planting structure, cultivated land area, soil texture, soil structure and other factors in each city in Hebei Province. According to the assessment results of soil water resources in Hebei Province, for example, in years with 50% rainfall frequency (p = 50%), the utilization ratio of the soil water resources can reach 27.24% in Baoding city, which is a plain city locating in the central of this province and the ratio can be above 20% in Tangshan city, Shijiazhuang city, Handan city and Xingtai city, while the ratio can be only 0.91% in Zhangjiakou city, which is a mountainous city locating



(a) (b)

Fig. 1: (a): The soil water resources; (b): The utilization of the soil water resources in Hebei province (p = 50%)



(a) (b)

Fig. 2: (a): The soil water resources; (b): The utilization of the soil water resources in Hebei province (p = 75%)

in the northern of this province. And in years with 75% rainfall frequency (p = 75%), the ratio can be above 20% in Shijiazhuang, Handan, Xingtai, Baoding and Hengshui cities (all of these cities are plain city), but the ratio is less than 10% in Zhangjiakou, Chengde and Qinghuangdao cities (all of these cities are mountainous city), respectively. Currently, soil water utilization ratio is relatively high in central and southern where is mainly planting area, while the low utilization ratio is in the northern mountainous and hilly areas, where most land is slope farmland.

The utilization situation of soil water resources of cultivated land of each county in Hebei province: Furthermore, the contrasts of the utilization situation of soil water resources of cultivated land are remarkable among these counties. In this study, climate, cultivated land area, soil texture, planting structure and etc., of each county in Hebei Province are selected to calculate the soil water resources in cultivated land and the utilization of soil water resources of cultivated land and the calculation result demonstrates the differences in these counties. According to the calculation result and the geographical coordinates of the counties (cities), Surfer software is used to simulate the situation of the soil water resources of cultivated land and the utilization of soil water resources of cultivated land in different rainfall frequency Fig. 1 and 2.

Figure 1 and 2, we can see that the soil water resources in the northern counties of Zhangjiakou and Chengde cities are much more than central and south, because the cultivated land area in northern counties are much greater than central and southern and washy area also includes part of Baoding, Shijiazhuang, Xingtai and Handan. On the other hand, the utilization of soil water resources in northern is much lower than other region. So there is much development potential of soil water resources of cultivated land in northern in Hebei Province.

RESULTS AND DISCUSSION

Establishment of assessment index system: In this study, according to the theory of sustainable development and making reference to the method of establishing water resources carrying capacity evaluation system, including indicator primary selection, index screening and index system optimization, the assessment index system of soil water resources carrying capacity of cultivated land in Hubei Province has been established (Cui *et al*., 2012; Wang *et al*., 2012). This assessment index system can reflect the actual situation about utilization of soil water resources of cultivated land, the development scale of agriculture, the management level and the benefit of planting. This index system includes 4 primary index and 17 secondary index. Primary index are water supply, water utilization, management and benefit. The primary index of water supply and water utilization reflect the development and utilization of soil water resources; management indicator reflects the development and utilization level of soil water resources; and benefit indicator reflects the efficiency of water production, grain yield and agricultural economic output and so on. Assessment index system is shown in Table 2.

Grade standard of index: In this study, the process of determining the indicator grade standard will be exemplified by the indicator "the ratio of irrigated area". Firstly, the data of irrigated area, cultivated land area in Hebei Province is collected by reviewing

Table 2: The index system of the soil water resources carrying capacity of cultivated land in Hebei province

Primary index	Secondary index	Calculation formula of the index	Grading standard (I)	Grading standard (II)	Grading standard (III)
Water supply (A_1)	Fulfilling rate of the water supply ability of the water conservancy project A_{11} (%)	Water supply of the water conservancy project /the ability of the water supply of the water conservancy project ×100%	≥66.36	61.62~66.36	≤61.62
	The ratio of the agricultural water supply A_{12} (%)	Water supply of irrigation/ water supply of the water conservancy project ×100%	≤66.38	66.38~70.53	≥70.53
	The utilization ratio of the soil water resources A_{13} (%)	The utilization of soil water resources/the quantity of the soil water resources ×100%	≥37.33	34.67~37.33	≤34.67
Water utilization (A_2)	The ratio of the irrigated area A_{21} (%)	Effective irrigation area/cultivated land area ×100%	≥77.09	71.59~77.09	≤71.59
	The ratio of the water saving irrigated area A_{22} (%)	The area of saving water irrigated land/effective irrigation area ×100%	≥71.45	66.34~71.45	≤66.34
	The ratio of the area of irrigated land to the area of paddy A_{23}	The area of irrigated land/the area of paddy	≥46.56	43.24~46.56	≤43.24
	Multiple cropping index A_{24}	Planting area/cultivated land area	≥1.56	1.45~1.56	≤1.45
	The ratio of the grain crops planting area to the economic crops A_{25}	The grain crops planting area/the economic crops planting area	≥2.04	1.90~2.04	≤1.90
Management (A_3)	The ratio of the agro-technician A_{31} (%)	The number of agro-technician/the number of planting ×100%	≥3.17	2.95~3.17	≤2.95
	The ratio of the area of the straw returning A_{32} (%)	The area of the straw returning/the planting area ×100%	≥68.40	63.52~68.40	≤63.52
	The ratio of the area of film covering A_{33} (%)	The area of film covering/the planting area ×100%	≥24.18	22.46~24.18	≤22.46
	The ratio of the area of facility agriculture A_{34} (%)	The area of facility agriculture/the planting area ×100%	≥12.49	11.59~12.49	≤11.59
	The ratio of the area of intensive management A_{35} (%)	The area of cultivated land in irrigation district/the area of cultivated land ×100%	≥20.88	19.39~20.88	≤19.39
Benefit (A_4)	Water use efficiency A_{41} (kg/m³)	Total output of crops/the utilization of the agricultural irrigation	≥2.79	2.59~2.79	≤2.59
	Utilization coefficient of irrigation water A_{42}	Crops water utilization/water diversion	≥0.67	0.62~0.67	≤0.62
	Grain yield per hectare A_{43} (t/hm^2)	Total output of crops/the planting area	≥13.23	12.29~13.23	≤12.29
	Per capita income of the planting A_{44} (Yuan/capita)	Planting output/the number of planting	≥7300	6800~7300	≤6800

"China Agricultural Statistics Yearbook", "Rural Statistical Yearbook of Hebei Province", "60 Years of New China Agricultural Statistics" and so on from 1990 to 2008 (China Agricultural Yearbook Editing Committee, 2000-2012; New China Agricultural 60 Years Statistical Data, 2000-2012). Secondly, the indicator of "the ratio of irrigated area" can be calculated according the formula in Table 2. Then the calculation result will be analyzed and regressed by SPSS software and the indicator which is predicted in 2030 by the regression result is 82.6%. So the interval of this indicator is (66.10 and 82.60%). At last, the interval is divided into 3 grades and each grade standard can be obtained. Using the same method to calculate the grade standard of other index, the calculation results are shown in Table 2.

Assessment procedure: In this study, the assessment object is soil water resources carrying capacity of cultivated land in Hebei Province and the planning year is selected 2030. The assessment procedures are as follows:

Step 1: Calculating the index eigenvalue. The parameters of irrigated area, the non-irrigated area of all kinds of crops and the amount of irrigation water in Hebei Province in 2030 can be calculated by multi-objective linear programming and the multi-objective model include 3 sub-objective function, they are maximum grain yield, maximum economic benefit and minimum ratio of water for agriculture. And the eigenvalue of each indicator can be calculated by using the formula in Table 2. The results are shown in Table 3.

Step 2: Calculating the index weight. The index weight can be determined by the method introduced in reference literature (Chen, 2002).

Table 3: The calculating result of the soil water resources carrying capacity of cultivated land in Hebei province in 2030

Primary index	Weight of primary index	Secondary index	Eigen value	Difference degree $D_A(u)$ h = 1	h = 2	h = 3	Weight of secondary index	Relative membership degree $\mu_A(u)$ h = 1	h = 2	h = 3
A_1	0.20	A_{11}	64.70	-0.35	0.70	-0.65	0.319	0.32	0.85	0.18
		A_{12}	56.18	1.00	-1.00	-1.00	0.319	1.00	0.00	0.00
		A_{13}	38.83	1.00	-1.00	-1.00	0.362	1.00	0.00	0.00
A_2	0.28	A_{21}	75.17	0.22	-0.22	-1.00	0.213	0.61	0.39	0.00
		A_{22}	69.66	0.22	-0.22	-1.00	0.225	0.61	0.39	0.00
		A_{23}	45.40	0.22	-0.22	-1.00	0.188	0.61	0.39	0.00
		A_{24}	1.52	0.24	-0.24	-1.00	0.200	0.62	0.38	0.00
		A_{25}	2.30	0.27	-0.27	-1.00	0.175	0.64	0.36	0.00
A_3	0.27	A_{31}	3.09	0.23	-0.23	-1.00	0.182	0.61	0.39	0.00
		A_{32}	66.69	0.22	-0.22	-1.00	0.234	0.61	0.39	0.00
		A_{33}	23.58	0.22	-0.22	-1.00	0.234	0.61	0.39	0.00
		A_{34}	12.16	0.22	-0.22	-1.00	0.195	0.61	0.39	0.00
		A_{35}	20.35	0.21	-0.21	-1.00	0.156	0.61	0.39	0.00
A_4	0.25	A_{41}	2.72	-0.33	0.66	-0.67	0.286	0.33	0.83	0.17
		A_{42}	0.66	-0.30	0.59	-0.70	0.179	0.35	0.80	0.15
		A_{43}	12.90	-0.35	0.70	-0.65	0.304	0.32	0.85	0.18
		A_{44}	0.71	-0.40	0.81	-0.60	0.232	0.30	0.90	0.20

Table 4: The assessment result of the soil water resources carrying capacity of cultivated land in Hebei province in 2030

	H					
Parameter combination	p = 1, α = 1	p = 1, α = 2	p = 2, α = 1	p = 2, α = 2	Stability region	Grade
Calculation result	1.56	1.50	1.70	1.61	1.50~1.70	II

Step 3: Calculating the index Difference Degree $D_A(u)$ by using Eq. (1) to (3). The results are shown in Table 3.

Step 4: Calculating the index RMD $\mu_A(u)$ by using Eq. (4). The results are shown in Table 3.

Step 5: Calculating the index $v_A(u)$ by using Eq. (12). The results are shown in Table 4.

Analysis of assessment results: In the assessment process of soil water resources carrying capacity of cultivated land, four groups assessment results has been obtained by changing the combination of parameters *p* and *α*. The assessment results stabilize in a small range, the stability region is 1.5~1.7, which shows the credibility of assessment results is high. In 2030, the assessment result is II, i.e., "Plan is average and can adapt to the local agricultural development", that is to say, there is a considerable scale of the development and utilization of soil water resources in Hebei Province, soil water of cultivated land can basically meet the requirements of sustainable development of agriculture, while it is necessary to pay attention to the rational development and utilization scale of soil water resources of cultivated land.

CONCLUSION

Soil water resources is a main influencing factor to agricultural production, assessment of it's carrying capacity is necessary. In this study, a variable fuzzy model is used to assess soil water resources carrying capacity of cultivated land in Hebei Province in order to use it rationally and scientifically. The assessment results indicate that soil water resources of cultivated land in Hebei Province can basically meet the development of the local agricultural economy, while a rational development scale must be determined. Therefore, the agriculture structure need to be optimized furthermore in the future, the agricultural water consumption need to be decreased according to the State Council of China and the level of cropping management need to be improved to ensure the agricultural economy can be developed sustainably.

ACKNOWLEDGMENT

This study is supported by the project of Provincial Natural Science Foundation of Hebei (E2015204205), the research project of Hebei Provincial Department of science and technology (15963608D), the scientific research project of Water Resources Department of Hebei Province (2010-117) and Youth Fund of Agriculture University of Heibei (QN201324).

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