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Research Article

Study on Soil Water Resource Carrying Capacity Based on Multi-objective Model in Hebei

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Abstract: Based on analysis and summary of the present achievements concerned soil water resource, the conception and connotation of soil water resource were defined and its carrying capacity was given in this study. According to characteristics of soil water resource carrying capacity, the multi-objective model of soil water resource carrying capacity was established for Hebei province. In the model, objective functions consists of 4 parts, including agriculture output value, grain yield, proportion of agricultural water consumption and eco-environmental water consumption, each crop's planting area is defined as decision variable. After changing the multiple objectives into a single objective by fuzzy binary contrast method, this multi-objective model was solved by using the method of single objective programming. The results show that the agriculture output value and grain yield could be increased steadily and agricultural water consumption is decreased contrarily by the soil water resource optimum scheme in comparison with present situation. The consumptions of soil water resource are 6.80 and 7.62 billion m^3 respectively in 2020 and 2030 by developing agricultural technology of the water-saving irrigation, straw returning, film-covering planting and greenhouse cultivation. The amount of saving water for agriculture is 0.75 and 1.79 billion m^3 respectively in 2020 and 2030 year.

Keywords: Carrying capacity, fuzzy binary contrast method, multi-objective model, soil water resource

INTRODUCTION

Hebei is one of the most severe water shortage areas of China, Where the average annual water resources are 20.49 billion m^3, the water resources per capita are only 307 m^3 and water resources per hectare are 3165 m^3. The total water consumption is up to 19.37 billion m^3 in 2010. The water supply quantity of surface water is 3.61 billion m^3, its development and utilization rate is 94.6%; the exploitation of groundwater is 15.76 billion m^3, some of which the 5.44 billion m^3 is over-explored every year. At present, the gap between water supply and water demands is 5 to 6 billion m^3 in Hebei. The traditional water resources could not support the sustainable socio-economic development.

However, it is rich in soil water resource in Hebei. According to the evaluation of soil water resource, the average annual rainfall is 99.79 billion m^3; more than 70% transform directly into soil water. Therefore, the development and utilization of soil water resource is an effective measure for helping ease the shortage of water resources in Hebei.

MATERIALS AND METHODS

Soil water resource: The resource is defined as the general term of natural environment factors that can generate economic value and improve current and future human welfare in the certain period by United Nations Environment Programme (UNEP). Soil water exists ubiquitously in soil and it can be absorbed and utilized by crops and improve the agricultural environment. Soil water has characteristics of natural resources and is the most convenient fresh water to use in world. Therefore, soil water is a kind of resource. Nputotulu (1974) scholar first proposed the concept of soil water resource and then many scholars studied on soil water resource (Pariva *et al*., 2012; Liu *et al*., 2009; Xia and Li, 2001; Yu and Xiong, 2003; Yang *et al*., 2004; Wang *et al*., 2006; Shen, 2008; Li and Zheng, 2009; Bandyopadhyay and Mallick, 2003; Franz *et al*., 2012).

Based on analysis and summary of the present achievements concerned soil water resource, the conception and connotation of soil water resource were defined in the study. In General, soil water resource is the amount of water stored between the ground water table and the surface of the soil, which it can be recycled. In a narrow sense, soil water resource refers to the fresh water with update capabilities in a period of time, which it is recharged by precipitation and stored in soil evaluation layer, can be utilized for agricultural production and ecological environment under natural conditions.

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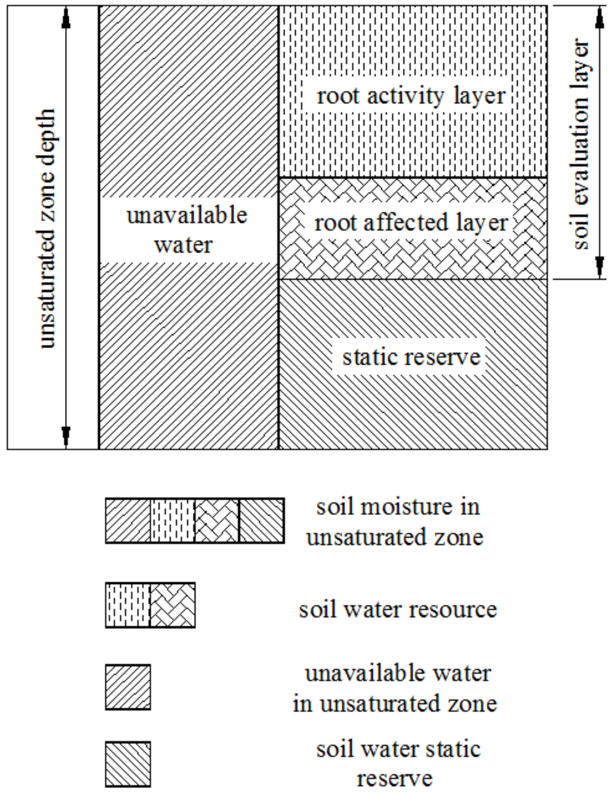

Fig. 1: The diagrammatic sketch of soil water resource evaluation layer

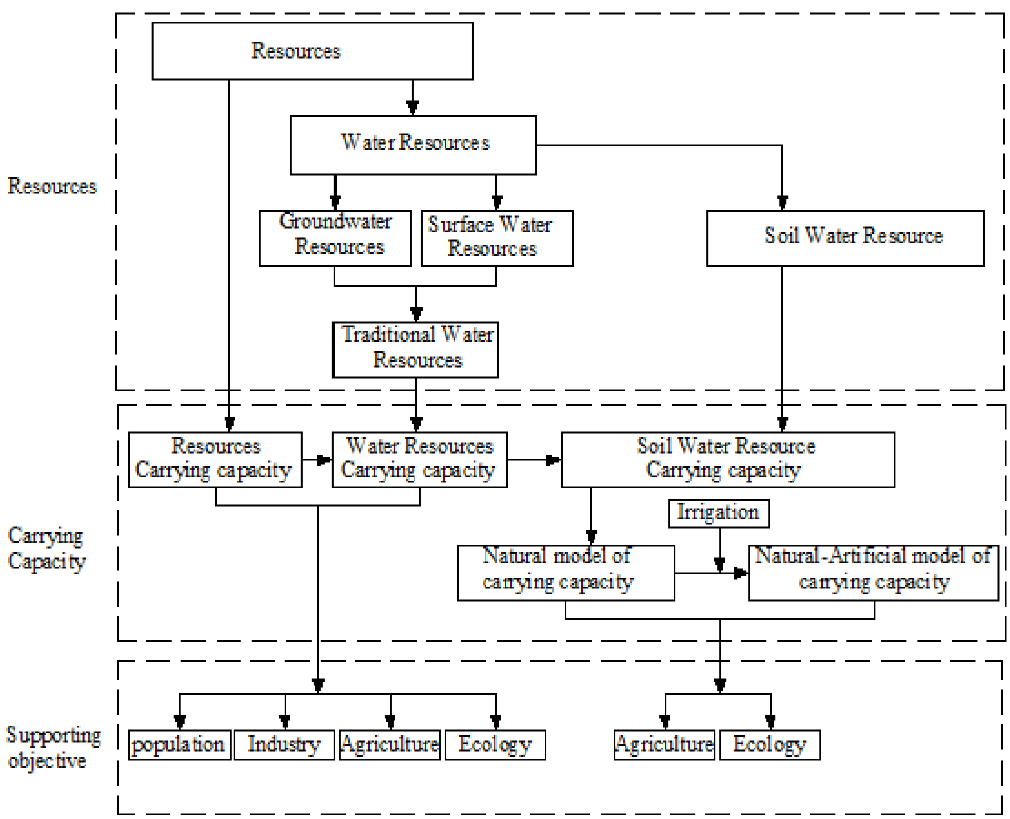

Fig. 2: The evolution process of soil water resource carrying capacity

In mountainous areas with shallow soil layer, soil water resource refers to effective rainfall stored in the entire soil layer. Plains where soil layer is thicker and groundwater is deep, soil water resource refers only to soil water bodies in the upper unsaturated soil which can be absorbed by vegetation root. Soil water that exists in the lower soil layer only exchanges with gravity water and cannot be absorbed and utilized by vegetation. This part of soil water can be regarded as static reserve. The soil evaluation layer is shown in Fig. 1.

Soil water resource carrying capacity: Carrying Capacity refers to that objects can withstand the maximum load without incurring any damage. The concept of carrying capacity was introduced to study the potential of resource utilization. Resource carrying capacity is defined by UNESCO as follows: A country or region's resource carrying capacity refers to the population of the country or region that can be continuing to provide in the foreseeable period by the use of local natural resources, energy, intelligence, technology and other conditions in keeping with its social and cultural living standard.

With the research on the resource carrying capacity increasingly, the water resource carrying capacity and water environment carrying capacity are hot field (Ashok, 2011; Al-Juaidi *et al*., 2014; Karasev and Suntsova, 2001). However, there is less work on soil water resource carrying capacity (Xu, 2001).

According to the characteristics of soil water resource, this study put forward the concept of soil water resource carrying capacity. Soil water resource carrying capacity refers to the ability that can be continuing to support the region's agricultural economic development and maintain a good ecological system under natural conditions (considering only precipitation, such as rain-fed agriculture and natural pasture) or natural-artificial binary mode (considering the natural rainfall and irrigation, such as artificial grassland, grain and cotton cultivation area) in a certain stage of development of social economy and science and technology condition. The evolution process of soil water resource carrying capacity is shown in Fig. 2.

Objective functions: According to the connotation of soil water resource capacity, the supporting objective is agriculture and ecology and its carrying ability represents the scale of the agriculture, forestry, animal husbandry and ecological environment. The target of development and utilization of soil water resource is the maximum comprehensive benefits, including economic, social and ecological benefits.

Economic benefits are the total output value of agriculture in region; the food security and the rational allocation of water resources need to be considered for social benefits. The conventional water resources for agricultural production can be replaced through development and utilization of soil water resource and this part of water can be used for life and industrial production. To a certain extent, this method can alleviate competitive water problems. The more conventional water replacement out, the ratio of agricultural water consumption is smaller. Therefore, social benefits are the total grain output and the ration of agricultural water consumption. Ecological benefits are agricultural ecological water consumption, that is, the leakage of agricultural irrigation water. Water leakage is inevitable in the process of agricultural irrigation. In irrigation works condition and the management level, irrigation area is greater, the more water leakage and it is advantageous to restore ecological environment and improve the situation of groundwater overdraft.

In the model, objective functions consists of 4 parts, including agriculture output value, grain yield, proportion of agricultural water consumption and eco-environmental water consumption, each crop's planting area is defined as decision variable.

Objective function 1: The maximum agriculture output value, which reflects economic benefits:

$$\max F_1 = \sum_{j=1}^{m} x_j y_j p_j + \sum_{j=1}^{m} x'_j y'_j p_j \tag{1}$$

where,

- x_j and x'_j = Crops irrigation area and the non-irrigation area respectively
- y_j and y'_j = Crop yield per unit area of irrigation and non-irrigation area
- p_j = Crop price $j = 1, 2, \ldots, m$
- m = The amount of crop species

Object function 2: The maximum grain yield, which reflects social benefits:

$$\max F_2 = \sum_{j=1}^{m} x_j y_j + \sum_{j=1}^{m} x'_j y'_j \tag{2}$$

Object function 3: The maximum agro-ecological environmental water consumption, which reflects ecological benefits:

$$\max F_3 = k \sum_{j=1}^{m} \left(x_j m_j \right) / \eta_j \tag{3}$$

where,

- m_j = Irrigation quota under soil water utilization
- η_j = Effective utilization coefficient of irrigation water
- k = Leakage recharge coefficient of the irrigation water

Object function 4: The minimum proportion of agricultural water consumption, which reflects social benefits:

$$\min F_4 = \frac{1}{W_t} \sum_{j=1}^{m} \left(x_j m_j \right) / \eta_j \quad (4)$$

where, W_t represents the total amount of water.

The objective function 4 is taken minus sign to transform the maximum function as follows:

$$\max F_4 = -\left(\frac{1}{W_t} \sum_{j=1}^{m} \left(x_j m_j \right) / \eta_j \right) \quad (5)$$

Constraint conditions:

- Arable land constraints:

$$\sum_{j=1}^{m} x_j + \sum_{j=1}^{m} x'_j \le k_f A \quad (6)$$

where, A is arable land; k_f is multiple cropping index.

- **Planting structural constraints:**

$$x_{j\min} \le x_j \le x_{j\max}, x'_{j\min} \le x'_j \le x'_{j\max} \quad (7)$$

where, $x_{j\ \min}$ and $x_{j\ \max}$ are minimum and maximum suitable arable land in irrigation land; $x'_{j\ \min}$ and $x'_{j\ \max}$ are minimum and maximum suitable arable land in non- irrigation land.

- **Water resources constraints:** The present agricultural water use is the upper limit of agricultural water consumption:

$$0 \le W_{irr} \le W_{tagr} \quad (8)$$

where, W_{togr} is present agricultural water use.

- Agro-ecological environmental water constraints as follows:

$$W_{e\min} \le W_{env} \le W_{tagr} \quad (9)$$

where, $W_{e\min}$ is minimum agro-ecological environmental water.

- **Soil water resource constraints:**

$$W_{s\min} \le W_{soil} \le W_{tsoil} \quad (10)$$

where,

$W_{s\ \min}$ = Minimum utilization of soil water resource

W_{tsoial} = Total amount of soil water resource

W_{soial} = The utilization of soil water resources

- **Nonnegative constraints:**

$$x_j \ge 0 \quad x'_j \ge 0 \quad j = 1 \quad 2 \quad \cdots \quad m \quad (11)$$

Other constraints: Other constraints include the policy of agricultural development, the level of agricultural science and technology development, agricultural planning, water conservancy planning and planting habit in local.

SOLUTION OF THE MULTI-OBJECTIVE MODEL

Normalization of the multi-objective function: In order to eliminate the difference of each goal in quantity and dimension, it is necessary to normalize objectives. Firstly, in the constraint condition, the single objective optimization results were calculated and regarded as maximum potential value. F1max, F2max, F3max, F4max represent maximum potential value of four objectives respectively. Secondly, normalization value of objective is the ratio of actual value and maximum potential value. The calculation formula is as follows:

$$F_1^{'} = \frac{F_1}{F_{1\max}} \quad F_2^{'} = \frac{F_2}{F_{2\max}}$$
$$F_3^{'} = \frac{F_3}{F_{3\max}} \quad F_4^{'} = \frac{F_4}{F_{4\max}} \quad (12)$$

Synthesis of the multi-objective function: The multiple objectives were transferred into singular objective by weighted method. Singular objective is shown as follows:

$$\max F = \max\left(F_1 \quad F_2 \quad F_3 \quad F_4 \right) = \sum_{i=1}^{4} \alpha_i F_i^{'} = \sum_{i=1}^{4} \alpha_i \frac{F_i}{F_{i\max}} \quad (13)$$

Weightiness: Weightiness is determined by designing the questionnaire and with fuzzy binary contrast method (Wang *et al.*, 2003; Chen and Fu, 2005). For elements a_k and a_l in set $A = \{a_1\ a_2\ \ldots . a_n\}$ which is being compared, Pairwise comparisons on importance (excellence or other properties) are made by using three scales 0, 0.5 and 1 and the following rules:

If a_k is more important than a_l, then give a scale $e_{kl} = 1$, $e_{lk} = 0$

If a_k and a_l make no distinction, then give a scale $e_{kl} = 0.5$, $e_{lk} = 0.5$

If a_l is more important than a_k, then give a scale $e_{kl} = 0$, $e_{lk} = 1$

Table 1: The mood operator and quantitative scales of objective functions

Mood operator	Equal	Slight	Somewhat	Rather	Obvious	Remarkable
Quantitative scales	0.5	0.55	0.6	0.65	0.7	0.75
Mood operator	Very	Extra	Exceeding	Extreme	Incomparable	
Quantitative scales	0.8	0.85	0.9	0.95	1.0	

Table 2: The mood operator and quantitative scales of objective functions

Mood operator	Exceeding	Extra	Somewhat	Equal
Quantitative scales	0.9	0.85	0.6	0.5

where, k = 1 2 …n; l = 1 2 … n. After making comparisons between n elements, the qualitative sorting matrix is gained:

$$E = \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{pmatrix} = \left(e_{kl}\right)_{n\times n} \tag{14}$$

Matrix $E = (e_{kl})_{n\times n}$ is called the sorting scale matrix of the criteria set regarding importance, whose element e_{kl} satisfies:

$$\begin{cases} e_{kl} = \{0 \quad 0.5 \quad 1\} \\ e_{kl} + e_{lk} = 1 \\ e_{kk} = e_{ll} = 0.5 \end{cases} \tag{15}$$

The sorting scale $E = (e_{kl})_{n\times n}$ is consistent, if it is subject to:

$$\begin{cases} e_{kl} = 0 & if \quad e_{hk} > e_{hl} \\ e_{kl} = 1 & if \quad e_{hk} < e_{hl} \\ e_{lk} = e_{kl} = 0.5 & if \quad e_{hk} = e_{hl} = 0.5 \end{cases} \tag{16}$$

h = 1, 2, …, n. The above conditions are necessary and sufficient for E being the sorting consistency scale matrix.

Binary contrast matrix of four objective functions is shown as follows:

$$\begin{array}{ll} & \text{sum} \\ \mathbf{E}_F = \begin{bmatrix} 0.5 & 1 & 1 & 1 \\ 0 & 0.5 & 1 & 1 \\ 0 & 0 & 0.5 & 1 \\ 0 & 0 & 0 & 0.5 \end{bmatrix} & \begin{array}{l} 3.5 \\ 2.5 \\ 1.5 \\ 0.5 \end{array} \end{array} \tag{17}$$

The importance of objective functions are in sequence: the total output value of agriculture>the total grain yield>agro-ecological environmental water consumption>agricultural water consumption Table 1.

Based on the importance of objective functions in questionnaire and the relationship between mood operator and quantitative scales, quantitative scales of objective functions are shown in Table 2.

Solution method of single objective model: When the multi-objective model is merged into a single objective model, it is solved by using the method of single objective programming through MATLAB software. Linprog function is used to solve this single objective linear programming in optimization toolbox. Using method of Linprog function is as follows:

$$X = linprog\left(f \quad A \quad b \quad Aeq \quad beq \quad lb \quad ub\right) \tag{19}$$

where,

f = Linear objective function vector
A = Matrix for linear inequality constraints
b = Vector for linear inequality constraints
Aeq = Matrix for linear equality constraints
beq = Vector for linear equality constraints
set Aeq = [] and beq = [] if no equalities exist; lb and ub is vector of lower and upper bounds on decision variables respectively.

RESULTS AND DISCUSSION

Model parameters: Hebei is located in the Haihe River Basin and a semi-humid and semi-arid continental monsoon climate area, where cultivated area is 6.33 million hectare and effective irrigation area is 4.56 million hectare. The main planting crops consist of winter wheat, summer corn, cotton, vegetables and other crops. The cropping index is 137%.

Since irrigation agriculture is dominant in Hebei, natural-artificial binary model of soil water resource carrying capacity is built. Selected 2010 as the base year, based on investigation of crop planting area, yield, prices, etc., agricultural irrigation area, irrigation water utilization coefficient, the unit area crop yield were predicted with the trend methods in 2020 (short-term planning) and 2030 (long-term planning) respectively. According to analysis test data, it was obtained the amount of the improved utilization of soil water resource by the different agricultural saving-water technology. The parameters are shown in Table 3.

Result analysis: When the parameters of soil water resource carrying capacity model is determined, it is to solve by linprog function in optimization toolbox. The optimization results are shown in Table 4.

Table 5 shows that agriculture output value is 262.17 and 181.08 billion Yuan respectively for normal year (P = 50%) and slight dry year (P = 75%) in 2020; Grain yield is 48.14 and 39.74 million t; Agricultural water consumption is 13.04 and 12.52 billion m^3 and its ratio is 59% and 61.6%; The soil water resource

Table 3: The amount of the improved utilization of soil water resource by different agricultural technology

The type of crops	Water saving irrigation (m^3/hm^2)	Straw returning (m^3/hm^2)	Film-covering planting (m^3/hm^2)	Greenhouse cultivation (m^3/hm^2)
Rice	1200	150		
Wheat	750	525		
Maize	450	300	225	
Beans	150			
Root crops	225		150	150
Cotton	450		300	
Oil plants	225		75	
Vegetable	450		225	
Greenhouse vegetable				300
Other plants	300		150	105

Table 4: The optimization results of soil water resource carrying capacity model

		Normal year (P = 50%)		Slight dry year (P = 75%)	
Planning year	Crop species	Irrigation area ($\times10^3$ ha)	Non-Irrigation area ($\times10^3$ ha)	Irrigation area ($\times10^3$ ha)	Non-irrigation area ($\times10^3$ ha)
2020	Rice	42.67		32.73	
	Winter wheat	2987.47		2089.98	897.5
	Corn	1119.75	1867.72	1076.9	2210.6
	Bean	161.07	77.67	100	262.67
	Potato	155.79	80.6	79.92	250.27
	Cotton	447.93	150	283.2	473.73
	Oil crop	423.87		301.13	
	Vegetable	761.8		324.67	
	Greenhouse vegetable	351.73		212.73	
	Others	50.43		82.47	
2030	Rice	45.47		33.27	
	Winter wheat	3067.62		2172.6	737.2
	Corn	1706	1247.4	1332.87	1746
	Bean	169.53	30.47	101.73	270.67
	Potato	216.27	31.6	105.53	277.13
	Cotton	471.93	56.27	322.33	483.25
	Oil crop	440.87		304.53	
	Vegetable	733.2		328.53	
	Greenhouse vegetable	404.8		316.33	
	Others	57.07		146.53	

Table 5: The effect of soil water resource utilization in 2020 and 2030

Planning year	Guarantee rate	Utilization of soil water resource (billion m^3)	Agricultural output value (billion yuan)	Grain yield (million t)	Agricultural water consumption (billion m^3)	Ratio of the agricultural water consumption (%)	Ecological water consumption (billion m^3)
2020	P = 50%	6.80	262.17	48.14	13.04	59	1.19
	P = 75%	7.67	181.08	39.74	12.52	61.6	1.09
2030	P = 50%	7.62	319.00	52.20	12.00	48.8	1.85
	P = 75%	8.17	222.36	50.01	11.53	50.9	1.70

Table 6: The scheme of soil water resource utilization in 2020 and 2030 million hectare

Planning year	Water-saving irrigation area	Straw returning area	Film-covering planting area	Greenhouse cultivation area
2020	3.76	3.94	0.96	0.46
2030	4.94	4.67	1.24	0.50

utilization is 6.80 and 7.67 billion m^3. Agriculture output value is 319.0 and 222.36 billion Yuan respectively for normal year (P = 50%) and slight dry year (P = 75%) in 2030; Grain yield is 52.20 and 50.01 million t; Agricultural water consumption is 12.00 and 11.53 billion m^3 and its ratio is 48.8 and 50.9%; The soil water resource utilization is 7.62 and 8.17 billion m^3. The agriculture output value and grain yield could be increased steadily and Agricultural water consumption is decreased contrarily by the soil water resource optimum scheme in comparison with present situation, as shown in Fig. 3 and 4 The agriculture saving water is 0.75 and 1.79 billion m^3 for normal year (P = 50%) in 2020 and 2030; it is 1.27 and 2.26 billion m^3 for slight dry year (P = 75%).

The development and utilization of soil water resource by water-saving irrigation, straw returning, film-covering and greenhouse cultivation is an effective

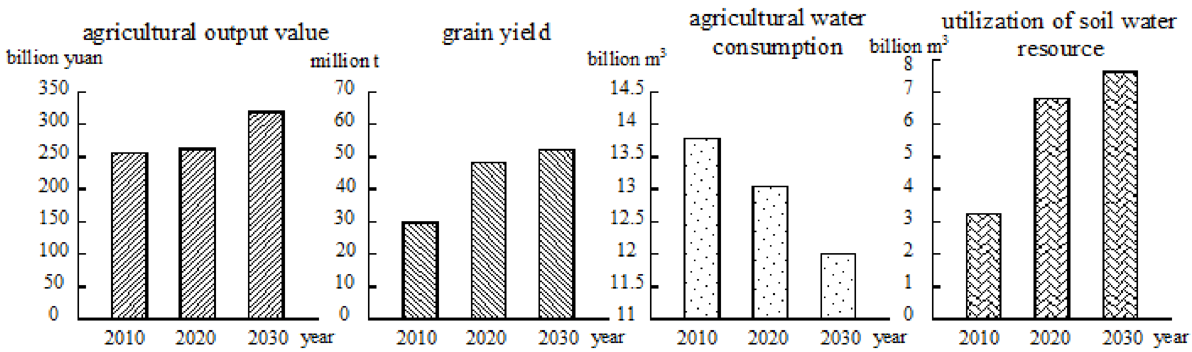

Fig. 3: The comparative map of benefits (P = 50%) in Hebei

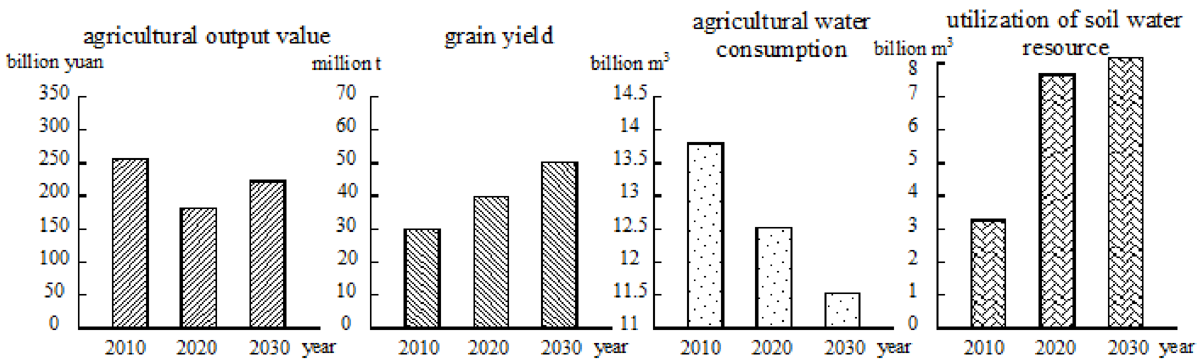

Fig. 4: The comparative map of benefits (P = 75%) in Hebei

measure for water saving and increasing grain yield. The area of water-saving irrigation, straw returning, film-covering planting and greenhouse cultivation is shown in Table 6 in 2020 and 2030.

CONCLUSION

Based on analysis and summary of the present achievements concerned soil water resource, the conception of soil water resource carrying capacity was defined in the study. Soil water resource carrying capacity refers to the ability that can be continuing to support the region's agricultural economic development and maintain a good ecological system under natural conditions (considering only precipitation, such as rain-fed agriculture and natural pasture) or natural-artificial binary mode (considering the natural rainfall and irrigation, such as artificial grassland, grain and cotton cultivation area) in a certain stage of development of social economy and science and technology condition.

The multi-objective model of soil water resource carrying capacity was established in Hebei. In the model, objective functions consists of 4 parts, including agriculture output value, grain yield, proportion of agricultural water consumption and eco-environmental water consumption, each crop's planting area is defined as decision variable. After changing the multiple objectives into a single objective by fuzzy binary contrast method, this multi-objective model was solved by using the method of single objective programming.

The results show that the agriculture output value and grain yield could be increased steadily and agricultural water consumption is decreased contrarily by the soil water resource optimum scheme in comparison with present situation. The consumptions of soil water resource are 6.80 and 7.62 billion m^3 respectively for normal year (P = 50%) in 2020 and 2030 by developing agricultural technology of the water-saving irrigation, straw returning, film-covering planting and greenhouse cultivation. The agriculture saving water is 0.75 and 1.79 billion m^3 respectively for normal year (P = 50%) in 2020 and 2030.

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