An Optimal Water Allocation Model Based on Water Resources Sustainable Assessment in Shanshan Region, Northern China

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Abstract. With the socioe-conomic development of Shanshan region, water demand is rapidly growing. To make adjustments to the water resources carrying capacity, socioe-conomic and ecological environment, this study performed an index system for the water sustainability of Shanshan region. Based on the method of membership degree of fuzzy set theory, sustainable degree and the ability of sustainable development of Shanshan are measured. Take the simulation results of optimal water allocation as actual index value. According to a multi-level fuzzy comprehensive evaluation, the result shows that the sustainable degree of Shanshan region is increased gradually with the increase of planning level years (2015, 2020, 2030). In 2030 the sustainable degree reached 0.74, which is in the higher level of sustainable development. The plan suggests that the policy of rapid socio-economic development and better environmental protection may achieve the most sustainable development of Shanshan region in the future.

Introduction

Water is the most essential resource for the sustainable development of human society and for basic support of all human and natural systems [1]. However, the problem of coordinating the relationship among socio-economic, ecological environment and water resources is the most serious issue for sustainable development. Water Resources Optimal Allocation (WROA) (which includes the connotation of sustainable development, and sustainable degree evaluation as well as optimized allocation of water resources) may provide a solution to the above problems to achieve the goal of sustainable development in a region. Furthermore, the information of WROA is likely to be a helpful tool for policy makers at all levels (locally, regionally, and nationally).

In general, the connotation of sustainable development has its origins in United Nations human environment conference. IUPN (1980) proposed that we must study the natural, social, ecological and economic basic relationship, in order to ensure the sustainable development of the world. Lester R. Brown (1981) put forward to control the population growth, protect the resource and develop renewable energy to achieve the sustainable development. WCED (world commission on environment and development) in 1987 came up with the definition of sustainable development that is not only to meet the needs of contemporary people, but also not against the ability of the development for future generations to meet their own needs. Subsequently, China firstly brings into sustainable development strategy in the long-term planning of China's economy and society. The current study is commonly believed that sustainable development mainly includes the sustainable social development, sustainable ecological development, and sustainable economic development. This paper considering the regional water resources carrying capacity and the diversity of its influence factors sets up a regional index system of sustainable development, which coordinates the development of resources, socio-economic and ecological environment. [2]

The research of Water Resources Optimal Allocation (WROA) originated in the 1950s.With the development of mathematical programming and computer simulation technology, the research method and application system of Water Resources Optimal Allocation has made great progress. Wang et al. (2003) presented a Water resources optimal allocation theory and method for the sustainable development of socio-economic and water resources [3]. Zhao et al. (2011) developed the multi-objective model for optimal allocation of water resources based on sustainable development, which comprehensively considered the social，economic and environmental benefits and applied the genetic algorithm [4]. The development of water exploitation and utilization is increasing sophistication, the way of using water changed from consuming to saving and ecological environment development. Current research in water resource allocation is not comprehensive combined with the connotation of sustainable development and the simulation results of optimal water allocation do not performed sustainable evaluation.

Study Area

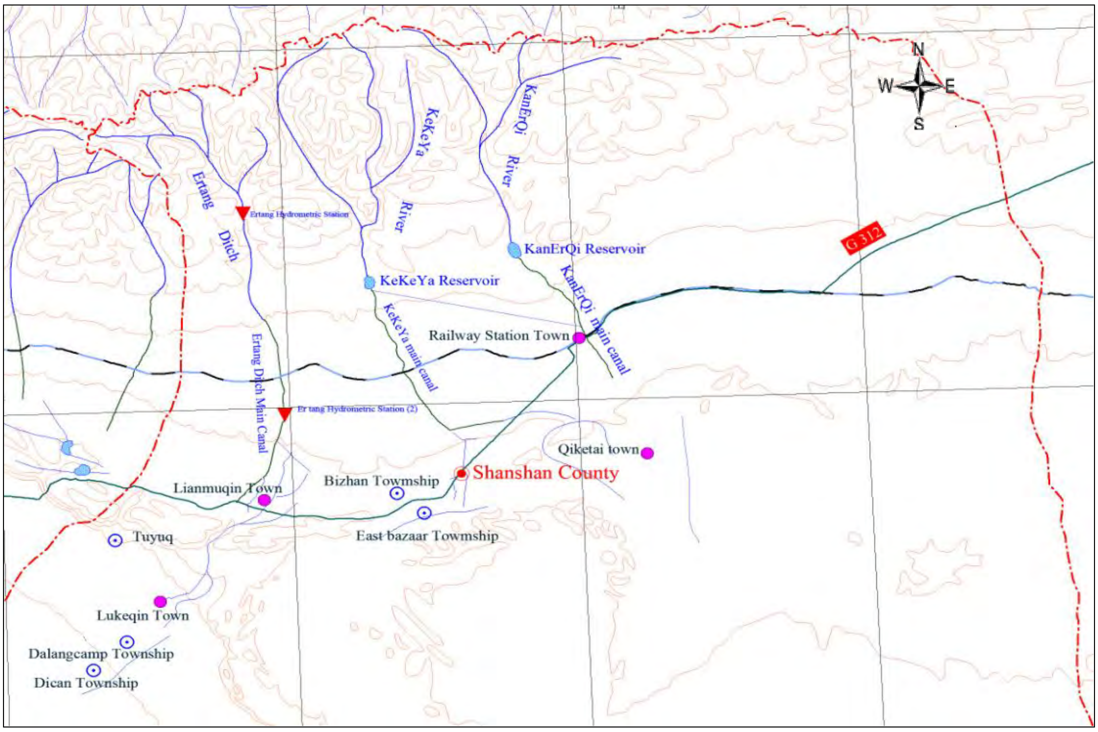

Fig. 1 Water System of Study Area

Shanshan Region is located in the east of Turpan Basin, which is between 89°20′–91°55′E and 42°17′–43°15′N (Fig. 1). Its current area is 3.83 × 104 km2. The geography of the study area varies from west to east which consists of the Ertanggou, Kekeya, and Kanerqi rivers, which are inland river of Closed intermontane basin. The distribution of rainfall is uneven in the spatial and temporal changes. The precipitation, in general, decreases from north to south and the average annual precipitation is 25 mm. Total multi-year average water resources are 3.03× 108m^3, surface water resources are 2.43× 108m^3 and ground water resources are 1.06× 108m^3. Currently(2012), the utilization rate of water resources was 171% in Shanshan Region, the groundwater of over-exploitation is amounted to 1.86× 108m^3 . The consumed-structure of water resources is unreasonable, 95% of water is used for agriculture while the contribution to the GDP of Shanshan is only about 10%. The water is diverted from ecology to agriculture, causing the depletion of karez and atrophy of Aydingkol Lake. Water shortage has become a major bottleneck to the socio-economic sustainable development in Shanshan. Therefore, a study in assessing the sustainable degree is essential to offer theoretical and technical support for the water utilization properly and comprehensive response to ecology protection of karez and Aydingkol Lake.

Methods

Multi-objective WROA Model

To realize sustainable utilization of regional water resources, to improve water use efficiency, and to promote the harmonious development of the economy, society and environment, the water resources optimal allocation multi-objective programming model for Shanshan region was developed based on the system analysis and sustainable development principle according to many related studies. The multi-objective WROA model includes two important parts: objective function and constraints.

This study has three objectives: maximum water resources carrying capacity, maximum GDP per capita, maximum ecological water utilization, representing the extent of socio-economic development, environment and ecology condition, and impact on social stabilization. Each detailed formulation was shown as follows.

$$\begin{cases} Objiective = a_1 \bullet f_1(x) + a_2 \bullet f_2(x) + a_3 \bullet f_3(x) \\ \min\ f_1(x) = Q - \sum_{t=1}^{T} \sum_{j=1}^{J} Q_{tj} \\ \min\ f_2(x) = \sum_{j=1}^{J} (c_j A_j + d_j I_j) \\ \min\ f_3(x) = \sum_{j=1}^{J} e_j E_j \end{cases} \quad . \tag{1}$$

Where Q refer to the water resources of regional carrying capacity; Q_{tj} is the regional water supply; A_j, I_j and E_j refer to the agriculture, industry and ecology water shortage rate of jth sub-unit, respectively; $a_1, a_2, a_3, c_j, d_j, e_j$ are the weight coefficients; Min means to minimize the value.

Four constraints were set for the multi-objective WROA (MWROA) objective functions for Shanshan region. They were water resources balance between water supply and water demand, social–economic development and its structure balance, ecology protection and other basic constraints, non-negativity which were expressed by the following equations.

a. The water resources balance between the water supply and water demand constraint is written as:

$$\begin{cases} \forall t, \sum_{j=1}^{J} S_{jt} \le S_t \\ \forall t, \sum_{j=1}^{J} P_{jt} \le P_t \\ \forall t, \sum_{j=1}^{J} T_{jt} \le T_t \end{cases} \quad . \tag{2}$$

where S_{jt} , P_{jt} and T_{jt} refer to the whole surface water , groundwater and recycled water used of the national economy and ecology in tth period, respectively; St is the maximum surface water resources available volume in tth period ; Pt is the regional groundwater available volume in tth period; T_t is the amount of waste-water treatment in tth period.

b. The social–economic development and its structure balance constraint are written as:

$$\begin{cases} \sum_{j=1}^{J} A_j \le A \\ \sum_{j=1}^{J} EI_j \ge EI_{\mathrm{p}} \end{cases} . \tag{3}$$

Where A_j is the irrigation area of jth sub-unit, A is the total cultivated area. Where EI_j is the industrial water efficiency per unit of jth sub-unit ; EI_{p} is the planned industrial water efficiency per unit in this region .

c. The ecology and environment protection constraints are written as:

$$Q(l) \ge Q_{\min}(l) . \tag{4}$$

Where $Q(l)$ is the measured flow of lth river, $Q_{\min}(l)$ is the minimum flow for the ecology need of lth river.

d. Other basic constraints: Mainly includes the equilibrium constraints of node, reservoirs and sub-unit; the flow capacity constraints of rivers, channels and pipes; the variable nonnegative constraints, etc.

Fuzzy Comprehensive Evaluation Method

In this study, the fuzzy comprehensive evaluation is the base of the computation of WROA, and many model variables and initialization values were developed in this section. The fuzzy comprehensive evaluation method has been refined into five steps, and their detailed explanation is given below.

Determination of an evaluation index system

The first step was to structure an index system and identify the indices. For this purpose, ‘‘m’’ indices are assumed in the index system, and the index system is given as:

$$X = \{x_1, x_2, \cdots, \mathrm{x_m}\} . \tag{5}$$

The index system for sustainable evaluation included three layers. The topmost layer of the index system was the goal of the sustainable evaluation.

The purpose of sustainable evaluation is to enable the water resources to future generations and to enable the planned and sustainable use of these resources in a manner that is suitable for their potential. The selection of an index should consider the carrying capacity of and the natural characteristics of the water resources. Additionally, human and economic factors regarding the subsequent use of water resources should also be considered. Lastly, environment and ecology condition should also be considered. Hence, the second layer of the index system is divided into three groups: carrying capacity, socio-economic and ecological environment.

In addition, the selection of evaluation indices by this method followed four principles: (1) Representativeness – Indices should have a significant impact on sustainable development. (2) Comparability – assess achievement of requirements and comparable among sustainable development; (3) Quantitativeness – data are reliable and can be cost-effectively collected; (4)

Conservation priorities – ensure environment and water resources are not damaged. To avoid excessive complexity of the index system, typical indices or easily obtain indices were selected [5-7]. The third layer of the index system, which explains the concrete meaning of the second layer, was determined following the checklist given in Table 1.

Weights of indices

The weights of the indices were obtained using the AHP method. The priorities of each index were determined according to experts' opinions. The elements of a particular layer were compared pairwise with respect to a specific element in the layer above.

Determination of the evaluation criteria

The evaluation criteria employed in this study were determined according to the reference [8] and expert consultation. The checklist was given in following Table 1.

Tab. 1 the Index System and Criteria for the Sustainable Development

Goal	Sub-system	index	Criteria	
			0	1
Sustainable degree	Carrying capacity	The modulus of water supply [10000m^3*km^2]	≤ 40	≥ 100
		water use efficiency[%]	≤ 20	≥ 60
		irrigation rate [%]	≤ 20	≥ 60
	Socio-economic	The output of GDP per unit of water[Yuan/m^3]	≤ 56	≥ 634
		water per person [m^3/ person]	≥ 3000	≤ 1000
		The extent of exploitation and utilization of water resources[%]	≤ 30	≥ 70
	Ecological environment	Eco-environmental water proportion[%]	≥ 5	≤ 2

1) Determination of the fuzzy relationship matrix

Fuzzy theory is introduced to address the ill-defined and imprecise index system. A fuzzy set has elements with membership falling in the range [0, 1]. Intermediate cases of membership (above 0 and below 1) indicate uncertainty or incompleteness of membership information. The fuzzy relationship matrix is ascertained as:

$$R = \left(r_{ij}\right)_{m\times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}. \tag{6}$$

R indicates the membership of the ith index belonging to the jth rank. The membership function is established according to the characteristics of the index system. When sustainable evaluation is positively correlated with values of these indices, the fuzzy set function is selected as:

$$r_{ij} = \begin{cases} 0, & x_{ij} \ge s_{is} \\ \dfrac{x_{ij} - s_{is}}{s_{ib} - s_{is}}, & s_{is} < x_{ij} < s_{ib} \\ 1, & x_{ij} \ge s_{ib} \end{cases} . \tag{7}$$

When sustainable evaluation is negatively correlated with values of these indices, the fuzzy set function is selected as:

$$r_{ij} = \begin{cases} 0, & x_{ij} \geq s_{ib} \\ \dfrac{x_{ij} - s_{ib}}{s_s - s_{ib}}, & s_{is} < x_{ij} < s_{ib} \\ 1, & x_{ij} \leq s_{is} \end{cases} \quad . \tag{8}$$

2) Determination of comprehensive evaluation

This paper set the relative membership grade of the jth actual parameter values to the extreme point as u_j, the objective function based on the minimum square sum of weighted Euclidean distances is established:

$$\min F(u_j) = D_{yj}^{\,2} + D_{gj}^{\,2} = u_j^{\,2} \bullet \sum_{j=1}^{p} \left[w_i \left(r_{ij} - 1 \right) \right]^2 + u_j^{\,2} \bullet \sum_{j=1}^{p} \left[w_i \left(r_{ij} - 0 \right) \right]^2 \quad . \tag{9}$$

Take the derivative of $F(u_j)$, we could get the sustainable degree:

$$u_j = \left[1 + \frac{\sum_{j=1}^{p} \left[w_i \left(r_{ij} - 1 \right) \right]^2}{\sum_{j=1}^{p} (w_i r_{ij})^2} \right]^{-1} \quad . \tag{10}$$

Results and Discussion

The Results of WROA

Tab. 2 The Results of Scenario II

the results of Scenario II	2013	2020	2030
population [10^4 person]	24.75	27.43	33.08
land [km^2]	437	437	437
irrigated area [km^2]	324	239	225
GDP[10^4 yuan]	2947000	3702000	5087000
the water used in ecology[$10^4 m^3$]	3310	2662	2618
the total water supply[$10^4 m^3$]	40978	32815	31209
manageable water[$10^4 m^3$]	32503	27538	26892
water resources [$10^4 m^3$]	30303	30303	30303

Based on the aspects of economic development, water resources exploitation, and environment protection, the following three scenarios were established in this study: Scenario I, Scenario II and Scenario III. For example, Scenario I addressed the concern for economy development with high speed, high water resources exploitation level, and low ecology and environmental protection level. Scenario II addressed the concern for economy development with high speed, high water resources exploitation level, and high ecology and environmental protection level. Scenario III addressed the concern for economy development with low speed, low water resources exploitation level, and high ecology and environmental protection level. Using the simulation of optimal water allocation model, we get the results of the three scenarios. The result of recommended scenario is showing in table 2. Combined with the results, we get the sustainable development indicators values, as shown in table 3.

Tab. 3 The Index Value

index value	2013	2020	2030
The modulus of water supply [10000m^3*km^2]	94	75	71
water use efficiency [%]	107.3	90.9	88.7
irrigation rate [%]	74.21	54.68	51.52
The output of GDP per unit of water [yuan/m^3]	72	113	163
water per person [m^3/ person]	1656	1196	943
The extent of exploitation and utilization of water resources [%]	135.2	108.3	103
Eco-environmental water proportion [%]	8.1	8.1	8.4

Fuzzy Comprehensive Evaluation

Combined with the above results, the normalized indicator values are obtained as follows:

r2013=(0.896,1,1,0.03,0.672,1,0);r2020=(0.585,1,0.867,0.1,0.902,1,0);r2030=(0.524,1,0.788,0.19,1,1,0)

Basing the Fuzzy dual contrast method, we get the index weight as follows:

w= (0.137, 0.244, 0.113, 0.124, 0.143, 0.101, 0.143)

Put into the formula of sustainable degree, we get the planning years sustainable degree of Shanshan region, respectively:

u2013=0.72; u2020=0.73; u2030=0.74

The result showed that the policy of economic development with rapid growth and better environmental protection may achieve the best sustainable development for Shanshan region in the future. In 2030, the sustainable degree is 0.74, which basically achieve the higher the degree of sustainable development. At the same time, the degree of water resources utilization arrives medium above .The exploitation and utilization of water resources is increasing sophistication. The way of using water changed from comsuming to saving and ecological environment benign development.

Conclusion

According to the relationship of sustainable development and the optimal allocation of water resources, the evaluation system based on sustainable development of optimal allocation of water resources was established in respect of the index system water resources carrying capacity, and the social economic and ecological environmental. The index system is comprehensive considered form the connotation of sustainable development in time and space scales. Based on engineering fuzzy set theory, this paper puts forward the method of the membership degree to describe the sustainable degree evaluation.

The sustainable degree is increasing gradually in the planning years, which implies that the results of the optimization allocation of water resources in the study area are feasible. Within the water resources carrying capacity, adjust the structure of socio-economic. On the basis of ensuring national food security, construct modern facility agriculture, water-saving measures and reduce the excessive demand for agriculture. Then taking the replaced water from the agriculture used for the ecological environment and industry cross-cutting development is feasible. This study examined the case of Shanshan region, but the general framework presented here is transferable to other locations and can be used to assess the sustainable degree .Moreover, the index system we constructed for this paper is suitable for typical arid areas in China. However, we did not claim that this method is either conclusive or exhaustive. With the development of socio-economic, further research should be conducted in the future.

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