The Chengdu Carrying Capacity of Water Resources Status Evaluation Based on the Variable Sets

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Abstract: Chengdu located in the western Sichuan Province, the Chengdu plain hinterland, and have the flat terrain and various river network, is the only large city in the western region. Along with the implementation of the Tianfu New Area and Eastward strategic planning and implementation, the demand for water is increasing and the water supply mainly comes from the upper Min Jiang river water in the distribution of the Du Jiang Yan irrigation system; according to many years hydrological data statistical analysis was carried out on the water resources of the upper reaches of Min Jiang river, Min Jiang river water resources quantity showed a trend of less obvious decrease; increasing water demand and water resources continue to reduce the contradiction between the increasingly prominent, need to take corresponding engineering method fundamentally resolved. The paper based on variable set theory proposed by the professor Chen shouyu, taking advantage of the water resource relevant exploitation and utilization data of Chengdu, then established the water resources carrying capacity evaluation model and evaluation system of Chengdu, and finally assessed the present situation of water resources carrying capacity of Chengdu scientifically. From the assessment we could get the main contradiction and the mining potential of Chengdu and provide some reference bases for optimizing the configuration water from the upper and middle reaches of Min Jiang river in head works of Du Jiang Yan, and helpful for the comprehensive balance of the transit water, local water and the transferred water in the process of optimizing allocation of water resources of Chengdu.

1. Introduction

From the overall point of view, carrying capacity of water resources has the subject — water resources, and the object—humans and complex social environment. In the contemporary era when global climate continues to change and human activities have an increasing effect, the mutually affected and restricted relationship between humans and nature has formed — 'human-nature' binary water cycle pattern, which has gradually become the primary basis to evaluate carrying capacity of water resources （Wang et al. 2006）. By accurately grasping the 'human-water' relationship, reasonably predicting the development demands and the main direction of human society, and changing traditional research thinking, we combine humans' survival and development with the significance of natural environment. Namely, we should keep pursuing 'mountains of gold and silver', and also protecting our 'green hills and clear waters' (Zuo et al. 2017). In such circumstances, evaluation of carrying capacity of water resources has become a key link of regional development and protection, playing the role of leading beacon.

Shi Yafeng et al., first put forward the concept of carrying capacity of water sources in the study of

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drought in Northwest China in 1995(Shi et al. 1995); Wang Jianhua et al., first discussed the concept and connotation of carrying capacity of regional water resources, and set up an evaluation index system and level. Then by using a system dynamics model, they predicted carrying capacity of years' water resources in Urumqi. What they did has provided a certain theory basis for the urban development and planning of northwest region in China (Wang et al. 1999). In 2006, by analyzing the influence of urbanization on regional water cycle, social economy and environment, Xia Jun et al. built an evaluation model for the carrying capacity of urbanized regional water resources, and further discussed the connotation and characteristics of carrying capacity of urbanized regional water resources(Xia et al. 2006); combined with the 'nature-human' binary water cycle process, Wang Hao et al. , put forward the water resource management concept — 'water consumption management as the core, and seven aspects of total amount control as constraint' , and made a new exploration of the regional water resources management in modern environment (Wang et al. 2010); in the contemporary era when computing methods and technology are developing rapidly and a variety of evaluation models emerges one after another, and the concept of global integration is deepening, a large number of outstanding achievements has been made about carrying capacity of water resources in research ideas, methods, and models(Zuo et al. 2017; Dang et al. 2015).

The variable fuzzy set theory, which was first put forward by Prof. Chen Shouyu, China's expert in hydrology and water resources (Chen 1988), has been widely used in all industries at home and abroad over the next few decades. The core idea of variable fuzzy set derives from the three basic theorems of philosophy: unity of opposites, mutual change of quality and quantity, and negation of negation. With the deepening of understanding of social environment, and by obtaining feedbacks and experience from practical application and theoretical research over many years, Professor Chen and domestic and foreign scholars have unceasingly developed and improved the variable fuzzy set theory (Chen 2010; Wu et al. 2008). In 2014, the variable fuzzy set was changed to be the variable fuzzy clear hybrid set (hereinafter referred to as the variable set). Since being proposed, the theory has been researched and studied by domestic and foreign scholars, and has been widely used currently. (Chen et al. 2014, 2013a, 2013b, 2013c)

In the paper, based on basic principle of the variable set theory, we have set up evaluation methods, corresponding index system, and evaluation standards for carrying capacity of water resources in Chengdu City. Through evaluation, we have obtained development and change trend of carrying capacity of water resources in Chengdu in recent years as well as the current state. This lays a certain foundation for the required water planning in the further sustainable development and planning of Chengdu, and also provides a reliable basis for the subsequent allocation of water resources of Chengdu and water resource utilization planning of the Min Jiang River.

2. Overview of the Research Area

Chengdu is within the Min Jiang River and the TuoJiang River system of the Yangtze river basin, with trunk streams of the two rivers to cross through. In Chengdu, area of the MinJiang River basin accounts for 70.4% of the total area, and the TuoJiang River basin for 29.6%. In the city, there are 58 rivers each of which covers a basin area of more than 50km^2, 45 rivers of more than 100km^2, 12 rivers of more than 500km^2 and 9 rivers of more than 1,000km^2. Based on the results of the Integrated Planning on Water Resources of Chengdu, for many years the city's average surface runoff is always 7.955 billion m^3, and the average groundwater resource is 3.293 billion m^3. After the repeated amount (2.641 billion m^3) of surface water and groundwater is deducted, total water resources in the city may reach 8.607 billion m^3 on average. After making analysis of water supply change in Chengdu over the past more than 10 years, we have learned about that the total amount of water collected in Chengdu from 2000 to 2007 was basically stable with little differences. Since 2008, with the speedup of economic and social development, the acceleration of urbanization, and the increase of population and machinery, water use has showed an increasing trend except that agricultural water use remains stable.

In the total water resources of Chengdu, surface water proportion is on the increase, from 94% around the year 2000 to over 99% now. Water from the Min Jiang River in the upper reaches

constitutes the main part of the surface water resources of Chengdu. However, due to climate change and human activities, rainfall runoff of the upper reaches of the Min Jiang River presents a trend of decrease year by year, which leads to a large pressure on the increase of required water for the increasing development of Chengdu.

3. Basic Principle of the Variable Set Theory

No matter natural phenomena, properties of things, contradictions in the social phenomenon, or concepts of thinking, there are always three cases below: clarity of 'either this or that', ambiguity of 'both this and that', and the dialectical unity of opposites. The degrees of opposition can be measured by the opposite measure value. They may change over time, in different spaces and conditions. However, no matter what kind of change, whether to target at clear things, phenomena, concepts or fuzzy ones, the sum of opposite measure values is equal to1, which can be described with the relative membership function:

Suppose U indicates a domain of discourse, u stands for any one of elements $u \in U$ in U (u generally refers to natural phenomena, things, social phenomena, and thinking concepts). u Opposition means the opposite attribute of phenomena and things, contradictions in the social phenomena, and opposite concepts in thinking. Whether it is opposition of clarity of 'either this or that', or ambiguity of 'both this and that', all are unified with the opposite sign $\hat{A}$ *and* $\hat{A}^c$, and assign two interval numbers 1, 0 and 0, 1 at endpoint P_l、P_r of continuum. The continuum of a pair of closed interval numbers $[1,0]$ and $[0,1]$ is formed on the number axes of 1, 0 and 0, 1. Any element u in U, has confirmed a pair of opposite measure values $\mu_{\hat{A}}(u)$、$\mu_{\hat{A}^c}(u)$ at any point of the continuum, which are called u to $\hat{A}$、$\hat{A}^c$ relative membership of opposites. Mapping:

$$\begin{aligned} &\mu_{\hat{A}}(u)、\ \mu_{\hat{A}^c}(u): U \to [0,1] \\ &u \mid \to \mu_{\hat{A}}(u)、\ \mu_{\hat{A}^c}(u) \in [0,1] \end{aligned} \tag{1}$$

Is called the relative membership function of opposites of $\hat{A}$、$\hat{A}^c$; the difference $D(u) = \mu_{\hat{A}}(u) - \mu_{\hat{A}^c}(u)$ is named as the relative difference function of opposites of $\hat{A}$、$\hat{A}^c$; continuum of numbers may express dynamic change of Mapping Formula (1).

Suppose the change of any element u in U is stipulated to be $C(u)$, before change, the opposite things, phenomena, and concepts of 'both this and that' or 'either this or that', will present:

$$\mu_{\hat{A}}(u) + \mu_{\hat{A}^c}(u) = 1 \tag{2}$$

After change, they will still present:

$$\mu_{\hat{A}}(C(u)) + \mu_{\hat{A}^c}(C(u)) = 1 \tag{3}$$

In continuum, there must exist:

$$\mu_{\hat{A}}(u) = \mu_{\hat{A}^c}(u) = 0.5 \quad \text{or} \quad D(u) = 0 \tag{4}$$

The tapered qualitative change points.

$0 \le \mu_{\hat{A}}(u) \le 1, \quad 0 \le \mu_{\hat{A}^c}(u) \le 1, \quad 0 \le \mu_{\hat{A}}(C(u)) \le 1, \quad 0 \le \mu_{\hat{A}^c}(C(u)) \le 1$

Formulas (1) to (4) constitute the basic theorem of variable set: unity of opposites, which is the development of Definition of opposite fuzzy set among variable fuzzy sets.

4. Evaluation Method of Variable Set for Carrying Capacity of Water Resources

Evaluation level must be confirmed for the evaluation of carrying capacity of water resources. Therefore, we introduce level variable h, $h = 1,2,\mathrm{L}\ c$ (c indicates the total number of carrying capacity

level); at first, we will grade i (*i=1, 2, …, m; m refers to the total number of indexes*) according to prepared standard interval values $[a_{ih}, b_{ih}]$. a_{ih}、b_{ih} Are respectively the upper and lower bounds for standard values of Index *i* at Level *h*. For the index (the smaller it is, the better it will be), $a_{ih} < b_{ih}$; for the index (the larger it is, the better it will be) $a_{ih} > b_{ih}$, the intersection point b_{ih} of standard interval values of adjacent two levels of index *i*, is equivalent to the tapered qualitative change point transforming from level h to level $(h+1)$ in the unity of opposites and mutual change of quality and quantity theorem; namely, the relative membership of the intersection point $\mu(b_{ih}) = \mu(a_{i(h+1)}) = 0.5$.

Suppose carrying capacity of water resources is the evaluation object *u*, based on multiple levels h and index i, we may acquire the matrix of standard interval value

$$Y = \left([a_{ih}, b_{ih}]\right) \quad i = 1,2,\mathrm{L}\ ,m; h = 1,2,\mathrm{L}\ ,c. \tag{5}$$

Second, we need to identify them. For level h and $h+1$ of the index *i*, in which the tapered qualitative change point $\mu(b_{ih}) = 0.5$ exists, based on unity of opposites, there must exist opposition of two levels on both sides of the qualitative change point; namely, levels h and $h+1$ may form opposite levels. Therefore, $\hat{A}$、$\hat{A}^c$ may be replace by ih、$i(h+1)$. In line with the theorem — unity of opposites (1), the relative membership sum of the index *i* of object *u* to levels *h*and (*h*+1) is 1.

$$\mu_{ih}(u) + \mu_{i(h+1)}(u) = 1 \tag{6}$$

Therefore, we just need to calculate $\mu_{ih}(u)$ in Formula (6).

In the following, based on the unity of opposites in the three fundamental theorems of variable set theory, we may derive the calculation formula of $\mu_{ih}(u)$.

The opposite thing is converted from $\hat{A}(ih)$ to $\hat{A}^c(i(h+1))$, the relative difference degrees $D_{ih}(u)$ and $D_{i(h+1)}(u)$ are 1 at the maximum. Accordingly, based on the standard interval matrix Y of level h and index *i*, we may confirm the point-value matrix K corresponding to relative difference degree $D_{ih}(u)$ and $D_{i(h+1)}(u)$ (the value of them is 1), the determination method is as follows:

Suppose level 1 $(h=1)$, we may know by the physical concept that the relative membership between upper bound a_{i1} of L1 standard value interval $[a_{i1}, b_{i1}]$ of index i to L1 is 1, and that relative membership to opposite L2 is 0, and that the corresponding relative difference degree is $D_{i1}(u) = 1$. Suppose k_{i1} is the point value of relative difference degree $D_{i1}(u) = 1$ of object *u* within the interval $[a_{i1}, b_{i1}]$ to L1, we may acquire $k_{i1} = a_{i1}$.

Suppose level c $(h=c)$, we may know by the physical concept that the relative membership between the lower bound b_{ic} of interval $[a_{ic}, b_{ic}]$ to level c is 1, and that relative membership to opposite level $(c-1)$ is 0, and that the corresponding relative difference degree is $D_{ic}(u) = 1$. Suppose k_{ic} is the point value of relative difference degree $D_{ic}(u) = 1$ of object *u* within the interval $[a_{ic}, b_{ic}]$ to level c, we may acquire $k_{ic} = b_{ic}$.

Suppose l is other level except level 1 or c, we may take the midpoint of the standard interval $[a_{i1}, b_{i1}]$ of index i and level l as the point value of level l relative difference degree $D_{il}(u) = 1$, namely, $k_{il} = \dfrac{a_{il} + b_{il}}{2}$.

Then

$$\begin{cases} k_{i1} = a_{i1} \\ k_{ih} = \dfrac{a_{ih} + b_{ih}}{2}, h = 2,3,\text{L}\ ,c-1 \\ k_{ic} = b_{ic} \end{cases} \tag{7}$$

Based on the standard value interval matrix Y and Formula (7), we may acquire the point-value mapping matrix

$$K = (k_{ih}) \tag{8}$$

Suppose the index characteristics matrix of evaluation object u is

$$X = (x_1, x_2, \text{L}\ , x_m) = (x_i)\ \ i = 1,2,\text{L}\ ,m \tag{9}$$

The characteristic value x_i of u index i falls in the point-value interval $[k_{ih}, k_{i(h+1)}]$ (the relative difference degree of characteristics value of $D_{ih}(u)$、$D_{i(h+1)}(u)$ levels h and $h+1$ index i is 1) of matrix K, and there exists $D_{ih}(u) = 0$ tapered qualitative change point b_{ih} within the interval, and so the relative difference degree $D_{ih}(u)$ between x_i to level h or $h+1$ may be calculated based on Formula (10).

$$D_{ih}(u) = \begin{cases} \dfrac{b_{ih} - x_i}{b_{ih} - k_{ih}}, x_i \in [k_{ih}, b_{ih}] \\ -\dfrac{b_{ih} - x_i}{b_{ih} - k_{i(h+1)}}, x_i \in [b_{ih}, k_{i(h+1)}] \end{cases} \tag{10}$$

Based on Formula (3), we may acquire

$$D_{ih}(u) = \mu_{ih}(u) - \mu_{i(h+1)}(u) \tag{11}$$

From Formulas (6) and (11), we may acquire

$$\mu_{ih}(u) = 0.5(1 + D_{ih}(u)) \tag{12}$$

By Formulas (10) and (12), we may acquire

$$\mu_{ih}(u) = \begin{cases} 0.5(1 + \dfrac{b_{ih} - x_i}{b_{ih} - k_{ih}}), x_i \in [k_{ih}, b_{ih}] \\ 0.5(1 - \dfrac{b_{ih} - x_i}{b_{ih} - k_{i(h+1)}}), x_i \in [b_{ih}, k_{i(h+1)}] \end{cases} \tag{13}$$

$\mu_{i(h+1)}(u)$ is determined by the unity of opposites. By the physical concept, the relative membership of index i of the level less than h and more than $(h+1)$ should be 0, namely,

$$\begin{cases} \mu_{i(<h)}(u) = 0 \\ \mu_{i(>(h+1))}(u) = 0 \end{cases} \tag{14}$$

From this, we may acquire the relative membership matrix of characteristic value x_i of object u and index i to indexes at levels h

$$\mu(u) = (\mu(u))_{ih}\ \ i = 1,2,\text{L}\ ,m; h = 1,2,\text{L}\ ,c. \tag{15}$$

Due to different importance of index i, we may suppose the index weight vector

$$\vec{w} = (w_1, w_2, \text{L}\ , w_m) = (w_i)\ ,\ \sum_{i=1}^{m} w_i = 1 \tag{16}$$

Available vector of comprehensive relative membership of u to level h

The Formula

$$v(u) = (w_i) \circ (\mu(u))_{ih} = (v_h(u)) \tag{17}$$

Is confirmed. Apply the level characteristics value calculation formula of the variable set theory

$$H(u) = \sum_{h=1}^{c} v_h(u) \cdot h \quad \text{h=1,2,L ,c} \tag{18}$$

We make evaluation of carrying capacity of water resources in line with the level characteristics value.

5. Evaluation of Carrying Capacity of Water Resources in Chengdu City

5.1 Evaluation Index and Standard

We have taken into account of the following aspects: characteristics of carrying capacity of water resources, difficulty degree and reliability level of obtaining required index data in the evaluation process, and actual needs and requirements of evaluation results. Based on the evaluation index system for supply and demand analysis of water resources nationwide, combined with experts' advice, we have selected 7 evaluation indexes including per capita water resource quantity, and water utilization rate. Furthermore, on the ground of degree of correlation between carrying capacity of water resources and evaluation indexes, we have classified evaluation results into three levels — excellent, good, and poor, specifically as shown in Table 1 below.

Tab 1 Water Resources carrying capacity evaluation indexes and the classification standard

No	Indexes	Poor（LI）	Good（LII）	Excellent（LIII）
1	per capita water resource quantity (m^3）	<1500	1500-3000	>3000
2	water utilization rate（%）	>75	75-50	<50
3	Ecological water use rate（%）	<1	1-5	>5
4	Water supply modulus（$10^4m^3/km^2$)	>15	1-15	<1
5	The annual per capita net income of farmers (￥）	<2800	11000-2800	<11000
6	population density（person/km^2）	>30	5-30	<5
7	The rate of irrigation（%）	>60	20-60	<20

Among the three-level evaluation indexes, Level III (LIII) is regarded as Excellent, and it has the following requirements: carrying capacity of water resources is good and has great potential; demand of water resources may be guaranteed to some extent; the overall supply of regional water resources is fairly optimistic. Level II (LII) is regarded as Good, and it indicates that water supply and development capacity are nearly close to the limit of carrying capacity, and that capacity for sustainable use is low, while certain development potential still exists, and that supply and demand of water resources can guarantee the basic development of social economy in the region. Level I (LI) is regarded as Poor, specifically, carrying capacity of water resources is poor as a whole, and close to saturation with little development potential; water resources have become the main bottleneck restricting social and economic development; continued development will lead to serious shortage of water resources, so some measures should be taken to solve the problem.

5.2 Evaluation Data

Evaluation indexes for carrying capacity of water resources in Chengdu are chosen from the data obtained during the 8 years of 2008-2015. Data about per capita water resource quantity, water utilization rate, and ecological water consumption comes from 2008-2015 Bulletin of Chengdu Water Resources. Water supply modulus is calculated from the statistics of water consumption in Chengdu in the Bulletin of Water Resources and the land area of Chengdu in 2008-2015 Statistical Yearbook of Chengdu. Data about the farmers' annual per capita net income, population density, and land irrigation rate comes from 2008-2015 Statistical Yearbook of Chengdu., as shown in Table 2 below.

Tab 2 Water Resources carrying capacity evaluation indexes characteristic value of Chengdu

Indexes	2008	2009	2010	2011	2012	2013	2014	2015
per capita water resource quantity (m^3)	804.0	557.0	855.9	899.9	698.9	855.0	606.4	540.0
water utilization rate（%）	59.76	90.99	62.05	57.49	78.57	53.19	69.11	79.08
Ecological water use rate（%）	13.45	6.12	13.79	15.65	8.90	16.08	8.77	6.83
Water supply modulus（$10^4m^3/km^2$)	43.6	47.6	50.4	49.7	53.2	44.6	42.5	43.3
The annual per capita net income of farmers (￥)	6481	7129	8205	9895	11501	12986	14478	17690
population density（person/km^2）	903	934	944	954	964	974	989	1006
The rate of irrigation（%）	79.8	75.1	73.5	87.4	85.4	85.9	87.0	88.0

5.3 Index Weight

Firstly, in line with actual experience in evaluation and the correlation between evaluation indexes and carrying capacity of water resources, on the advice proposed by personnel and experts related to the basin department, by referring to national evaluation standard of carrying capacity of water resources, we assign the weight of seven evaluation indexes, and acquire the index weight matrix $w_1 = (0.1,\ 0.2,\ 0.1,\ 0.2,\ 0.1,\ 0.2,\ 0.1)$; secondly, excluding non-difference of indexes and the influence of other human factors, we consider that the 7 indexes are equally important. After the equal weight is objectively evaluated, we acquire the index weight matrix $w_2 = (0.14,\ 0.14,\ 0.14,\ 0.14,\ 0.14,\ 0.14,\ 0.14)$. The carrying capacity of water resources in Chengdu under two weights is respectively calculated and analyzed through comparison.

5.4 Evaluation of Carrying Capacity of Water Resources in Chengdu City

In the light of the basic steps for evaluation methods of carrying capacity of water resources as a variable set, we first set up the interval value matrix of the three-level index for the evaluation of carrying capacity of water resources in Chengdu

When weight is $w = w_1$, $H_1 = (1.53, 1.31, 1.54, 1.65, 1.4, 1.75, 1.49, 1.4)$

When weight is $w = w_2$, $H_2 = (1.59, 1.44, 1.62, 1.73, 1.57, 1.82, 1.64, 1.57)$

Evaluation results above show that since 2008, carrying capacity of water resources in Chengdu has changed to some extent with the change of water resource quantity and water consumption, but it is relatively stable as a whole, without remarkable change; evaluation levels of all the year are between LI and II, which is good but slightly poor. In 2013 with abundant rainfall, carrying capacity was on a noticeable increase and thereafter, it was on a continuous decrease. When equal weight and expert consultation weight are adopted, the evaluation results of carrying capacity of water resources in Chengdu are generally similar, yet the evaluation result under equal weight is larger.

6. Conclusion and Analysis

From the evaluation results of carrying capacity of water resources in Chengdu in recent 8 years, we know that carrying capacity of water resources of Chengdu is between LI and LII as a whole, nearly in a state of saturation, with less potential for further development and utilization, and it presents an unsustainable development trend. Therefore, the whole city confronts an obvious water shortage. Even in 2013 with abundant rainfall, carrying capacity was still unable to reach LII, let alone other dry or normal years. This fully shows that Chengdu's current water resources are still not enough to support the current and future urban social development needs, and necessary measures should be taken immediately.

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