An Analysis of Influences of Interbasin Water Transfer on Water Resources Carrying Capacity Over Dianchi-Pudu River Basin

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Abstract: This paper adopts the maximum carrying population, industrial added value and agricultural irrigation area to develop a multi-objective model of water resources carrying capacity (WRCC) in Dianchi-Pudu river basin. The model is used to calculate the WRCC for Dianchi-Pudu river basin in 2020 and 2030 respectively in terms of three different water supply schemes. Results show that except Scheme III which can basically support future socio-economic development and population increase, both Scheme I and II cannot support future socio-economic development and population increase of Dianchi-Pudu river basin. Interbasin water transfer would greatly increase the WRCC of Dianchi-Pudu river basin while efficient water saving can merely work in a limited extent. Consequently, interbasin water transfer and efficient water-saving are the necessaries to guarantee the positive balance between the exploitation of water resource and socio-economic development of Dianchi-Pudu river basin.

1. Introduction

The concept of water resources carrying capacity (WRCC) was put forward in the 20th century along with the emergence of sustainable development theory and people’s incisive understanding of close relationship between sustainable development and water resources. It is incorporated into sustainable development research in most international studies but rarely studied as a special subject. For example, Daily et al. [1] incorporated it in the sustainable development research of society and economy. The concept of WRCC was proposed by academician Shi Yafeng in 1980s in China. Later, the research on WRCC attracted great attention from academia and became the focus and hot topic in the field of water resources [2-6].

Currently, there exist many research methods on WRCC, such as fuzzy comprehensive evaluation [7], principal component analysis [8], neural network method [9], projection pursuit method [10], multi-objective decision-making and analysis [11], etc. Multi-objective feature of WRCC [12] makes the method of multi-objective decision-making and analysis have good application basis in the
researches on WRCC, so it is widely applied in the researches on WRCC. For instance, Ren [13] adopted the multi-objective random fractional goal programming model to study the economic benefits and employment population in the Shiyang river basin under different violation probabilities. Li et al. [14] analyzed the population bearing capacity of water resources in Changwu County through a multi-objective model. Xu [11] studied the influence of water-sparing time, water quantity and water-saving methods in planting industry on WRCC in the Zhangye region through multi-objective decision-making and analysis based on the scenario. Jia et al. [12] studied the scale of economy and population carried by the water resources in central Shaanxi plain in different level years and under varied development plans of water resources by building a multi-objective model. Xue et al. [15] established a multi-objective (maximum of GDP, population and grain output and minimum population load) model of Xi’an’s WRCC and calculated the social and economic development scale carried by Xi’an’s water resources in three level years of 2000, 2010, 2020.

Dianchi-Pudu river basin sits in the Centre of Yunnan province with poor natural water quality and dense population. It is severely short of water resources as its water resources quantity per capita stands only at 269m$^3$, and approximately amounts to that of Beijing-Tianjin-Tanggu region which is famous for its water shortage. Therefore, a number of cross-basin water transfer projects [16] are implemented in plans for this river basin in order to find a way out of water shortage that becomes more and more severe. Inter-basin water transfer will lead to the relocation and redistribution of water resources carrying capacity among different districts in the system of inter-basin water transfer.[17] Hence, researches on the influence of inter-basin water transfer to regional WRCC are of scientific and practical significance to realize optimal allocation of regional water resources and sustainable development. In order to provide decision basis for sustainable development of regional society, economy and environment, this thesis gives out the quantitative calculation of the social and economic development scale carried by regional water resources with or without the water supply from inter-basin water transfer projects by building a multi-objective decision-making model of WRCC in Dianchi-Pudu river basin.

2. Multi-objective decision-making model of water resources

2.1. Objective function

The stable development of regional society, sustainable development of economy and gradual improvement of environmental quality are taken as the ultimate goal, this model adopts the following objectives: maximum industrial added value ($Ind$), maximum population ($POP$), maximum agricultural irrigation area ($Area$). The objective function of multi-objective decision-making model is as follows:

$$Z = \max \{z_1, z_2, z_3\}$$

(1) Maximum $Ind$ carried by water resources:

$$z_1 = \max(Ind) = x_1 v_1$$

(2) Where $x_1$ denotes planned annual industrial water consumption, units: ten thousand m$^3$; $v_1$ denotes planned annual industrial output value of water consumption per cubic meter, units: yuan/m$^3$.

(2) Maximum $POP$ carried by water resources:

$$z_2 = \max(POP) = \frac{x_3}{D_{city}} + \frac{x_4}{D_{country}}$$

(3) Where $D_{city}$ and $D_{country}$ denote urban domestic water quota and rural domestic water quota respectively, units: L / (person. D); $x_3$ and $x_4$ denote planned annual urban domestic water consumption and rural domestic water consumption respectively, units: ten thousand m$^3$.

(3) Maximum $Area$ carried by water resources:
\[ z_3 = \max (Area) = \frac{x_2}{D_{ag}} \]  

(4)

Where \( D_{ag} \) denotes agricultural water consumption quota, units: m\(^3\)/mu; \( x_2 \) denotes agricultural water consumption quantity, units: ten thousand m\(^3\).

2.2. Constriction condition

The constrictions include four aspects including supply-demand balance of water resources, society, population and living standards, macroeconomic sector, ecological environment.

(1) Supply-demand balance of water amount.

\[ W_{zxs} = W_{zgs} \]  

(5)

Where \( W_{zxs} \) denotes total water demand, units: ten thousand m\(^3\); \( W_{zgs} \) denotes total water supply, units: ten thousand m\(^3\).

The total water demand is calculated as follows:

\[ W_{zxs} = x_1 + x_2 + x_3 + x_4 + x_5 \]  

(6)

(2) Society, population and living standard.

1) Population:

\[ P_{total} = \frac{x_1}{D_{city}} + \frac{x_2}{D_{country}} \geq P_0 (1 + t)^n \]  

(7)

Where \( P_{total} \) denotes total population carried by water resources, units: 10000 people; \( P_0 \) denotes base year annual population, units: 10000 people; \( t \), units: population growth rate, units: %.

2) Urbanization rate:

\[ \frac{x_3}{D_{city}} \geq (\frac{x_1}{D_{city}} + \frac{x_4}{D_{country}})A_{zhhl} \]  

(8)

Where \( A_{zhhl} \) denotes urbanization rate, units: %.

(2) Macroeconomy.

\[ \frac{1}{P_{total}} \frac{x_1}{D_{industry}} \geq \frac{Ind_0}{P_0} \]  

(9)

Where \( D_{industry} \) denotes the industrial water consumption quota, units: m\(^3\)/10000 yuan.

(3) Industrial water consumption.

\[ x_1 \leq W_{gy} \]
\[ x_2 \leq W_{ny} \]
\[ x_3 + x_4 \leq W_{sh} \]  

(10)

Where: \( W_{gy}, W_{ny}, W_{sh} \) denote water consumption amount at the premise of guaranteeing industrial, agricultural and domestic water consumption amount rate, among which the industrial, agricultural and domestic water consumption guarantee rate is 95%, 75% and 95% respectively.

(4) River ecological flow.

\[ (x_5 - W_{zgW}) \geq 0 \]  

(11)

Where \( x_5 \) denotes ecological water consumption of rivers; \( W_{zgW} \) denotes minimum ecological water consumption of rivers, which is 30% of the average annual flow (flood season) and 10% of the average annual flow (non-flood season).
3. Program design

According to the definition of water resources carrying capacity [18], it can be seen that water resources carrying capacity varies with different development and utilization methods of water resources in the future. Therefore, the prerequisite of researches on regional water resources carrying capacity is formulating rational schemes for developing and utilizing water resources in the future, which shall take the realities of regional water resources into account. For example, for regions seriously short of water resources, the scheme shall enhance water conservation and inter-basin water transfer based on full development of local water resources; for regions with engineering water shortage, the scheme shall strengthen the construction of water-supply projects.

Dianchi-Pudu river basin is severely short of water resources. Hence, three schemes are considered:

a) current water-saving type, i.e. maintaining the current situation of saving water while considering the development of local water resources. The water supply in every level year equals to the water supply from the current water supply facilities plus the planned water supply projects. This scheme is the water resources carrying capacity in an extensive development status of society and economy.

b) efficient water-saving type, i.e. improving water conservation and enhancing water-saving managements on the basis of the current sustainable development mode. This scheme is the water resources carrying capacity in an efficiently water-saving and intensive development status of economy.

c) water transfer from other river basins under efficient water conservation, i.e. transferring water from other river basins based on efficient water saving. This scheme is the water resources carrying capacity in an efficient water saving and intensive development status of economy while transferring water from other river basins. The water supply of three schemes in a level year is shown in table 1.

| Level year | Scheme I (billion m$^3$) | Scheme II (billion m$^3$) | Scheme III (billion m$^3$) |
|------------|-------------------------|---------------------------|---------------------------|
| 2020       | 1.112                   | 1.345                     | 1.522                     |
| 2030       | 0.767$^a$               | 1.063$^a$                 | 1.806                     |

$^a$The water supply in 2030 in Scheme I and Scheme II is less than that in 2020. The reason is that the water storage projects in this region discharge 10% ecological flow in dry season and 30% in flood season on the basis of average incoming water amount for many years in accordance with the development requirements of water ecological civilization. Ecological regression reduces the water supply of water storage projects.

4. Calculation results and analysis of multi-objective decision-making model

The population, industrial added value and agriculture irrigation area carried by Dianchi-Pudu river basin under different development and utilization methods of water resources are calculated based on the above models.

4.1. Scheme I (current water-saving level)

It can be seen from table 2 that under the current water-saving level and on the basis of the full development and utilization of local water resources (Scheme I), the WRCC is a population of 4.37 million, an industrial added value of 156.61 billion RMB, and an agricultural irrigation area of 471.3 thousand mu in Dianchi-Pudu river basin in 2020. By 2030, the bearable population, industrial added value and agricultural irrigation area of scheme I is 4.46 million, 213.69 billion RMB, and 428.2 thousand mu respectively. Bearable development value (WRCC) of water resources is smaller than the planned development value (see details in table 2), indicating that the water resources in Dianchi-Pudu river basin in 2020 and 2030 are insufficient to support its social and economic growth and population increase.

Through further comparing water resources carrying capacity with planned development value in Dianchi-Pudu river basin in every level year, it can be found that regional water resources are increasingly overloaded (planned development value exceeds water resources carrying capacity). The overload of regional population, industrial added value and agricultural irrigation area is 10.3%,
37.0% and 28.1% respectively in 2020. By 2030, the overload of these three indexes will increase to 17.8%, 78.8% and 59.6% accordingly. It shows that under this scheme, the water resources in Dianchi-Pudu river basin couldn’t support its planned development scale but will be more and more overloaded. As a result, water resources and ecological environment will constantly deteriorate.

| Level year | Bearable development value (WRCC) | Planned development value |
|------------|----------------------------------|--------------------------|
|            | POP (million people) | Ind (billion RMB) | Area (thousand mu) | POP (million people) | Ind (billion RMB) | Area (thousand mu) |
| 2020       | 4.37 | 156.61 | 471.3 | 4.82 | 214.60 | 603.9 |
| 2030       | 4.46 | 231.69 | 428.2 | 5.26 | 414.30 | 683.6 |

4.2. Scheme II (Efficient water-saving level)

As can be seen from table 3, the water resources carrying capacity rises when local water resources are fully developed and utilized and the water-saving level continuously improves (Scheme II). The bearable population and social economy scale of water resources (WRCC) are 4.49 million people, 160.81 billion RMB, 502.7 thousand mu, and 4.67 million people, 266.44 billion RMB, 478.1 thousand mu in 2020 and 2030, respectively. However, through comparing WRCC with planned social development value in this region (see details in table 2), it can be concluded that regional water resources still couldn’t prop up its social and economic development and population increase. In 2020, regional population, industrial added value and agricultural irrigation area will separately be overloaded by 7.4%, 33.5% and 20.1%. By 2030, these three indicators will be overloaded by 12.7%, 55.5% and 43.0%.

Table 3. WRCC under the scheme II

| Level year | POP (million people) | Ind (billion RMB) | Area (thousand mu) |
|------------|----------------------|-------------------|--------------------|
| 2020       | 4.49                 | 160.81            | 502.7              |
| 2030       | 4.67                 | 266.44            | 478.1              |

In order to study the influence of efficient water saving on regional water resources carrying capacity, the water resources carrying capacity with and without efficient water saving in Dianchi-Pudu river basin are compared with each other. As can be seen from figure 1, compared with Scheme I, the population, industrial added value and agricultural irrigation area carried by regional water resources (Scheme II) increase by 2.7%, 2.7% and 6.7% respectively. With more water saved in 2030, these three indexes will rise evidently, up by 4.5%, 15.0% and 11.7% respectively.

Figure 1. The enhancement of WRCC under the scheme II contrary to that under scheme I (a POP, b Ind, c Area)

The above analysis shows that efficient water saving (full exploitation of the potential in this region) can improve the water resources carrying capacity in Dianchi-Pudu river basin, but it can’t help to support its planned development scale. This region lacks water resources, so inter-basin water transfer shall be considered to further improve its water resources carrying capacity.
4.3. Scheme III (water transfer from other river basins under efficient water conservation)

As can be seen from table 4, implementation of inter-basin water transfer on the basis of full exploitation of the potential in this region (efficient water saving) will greatly raise the water resources carrying capacity in Dianchi-Pudu river basin, which will be close to planned development value of regional society and economy (see details in table 2). In 2020, the population, industrial added value and agricultural irrigation area carried by regional water resources are lower than the planned development values respectively by 0.4%, 0.5% and 9.7%. By 2030, as the quantity of water transfer becomes larger, these three indexes are only lower than the planned development values respectively by 0.2%, 0.3% and 0.9%. It shows that under this scheme, the water resources carrying capacity in Dianchi-Pudu river basin can support its planned development scale. In this scenario, the regional water supply can realize a virtuous circulation in which the society and economy develops in a sound environment.

Table 4. WRCC under the scheme III

| Level year | POP (million people) | Ind (billion RMB) | Area (thousand mu) |
|------------|----------------------|------------------|-------------------|
| 2020       | 4.80                 | 213.58           | 559.1             |
| 2030       | 5.25                 | 405.91           | 680.0             |

Similarly, in order to study the influence of water transfer from outer river basins on regional water resources carrying capacity, the water resources carrying capacity with and without water transfer in Dianchi-Pudu river basin is compared with each other. As can be seen from Figure 2, water transfer from outer river basins plays an important role to improve water resources carrying capacity in Dianchi-Pudu river basin. In 2020, the population, industrial added value and agricultural irrigation area carried by regional water resources with water transfer are higher than those without water transfer by 6.9%, 32.8% and 8.5%. By 2030, these three figures rise to 12.5%, 52.3% and 42.2% accordingly.

![Figure 2. The enhancement of WRCC under the scheme III contrary to that under scheme II (a POP, b Ind, c Area)](image)

4.4. Integrated analysis of carrying capacity of water resources in different schemes

From calculation results of multi-objective decision-making models, it can be concluded that except Scheme III which can basically support future social and economic development and population increase, both Scheme I and II cannot support future social and economic development and population increase. It shows that for Dianchi-Pudu river basin which is seriously short of water resources, rational development of regional water resources, efficient water saving and cross-basin water transfer shall be concurrently implemented so as to ensure benign development of regional society, economy and ecological environment.

Scheme III figures out that the bearable population of the water resources in Dianchi-Pudu river basin in 2020 is 4.80 million, including 4.14 million people in Dianchi lake river basin and 0.66 million people in Pudu river basin. Sheng et al. [19] also believes that the bearable population of Dianchi lake river basin with the help of water transfer is 4.2345 million in 2020 from the perspective of water environmental capacity in Dianchi lake river basin. Although studied from different
perspectives, the results of these two researches are basically identical so that they can mutually verify the rationality of their results.

5. Conclusion
The maximum of population, industrial added value and agricultural irrigation area carried by water resources are taken as objectives, this thesis builds a multi-objective decision-making and analysis model for water resources carrying capacity in Dianchi-Pudu river basin and calculates the water resources carrying capacity under three types of schemes: current water-saving type (Scheme I); efficient water-saving type (Scheme II); water transfer from outside river basins under efficient water conservation (Scheme III). The following is the conclusion:

(1) Due to severe shortage of water resources in Dianchi-Pudu river basin, water resources may not support future socio-economic development and population increase until full exploitation of water resources in this region, efficient water saving and inter-basin water transfer are carried out simultaneously, namely Scheme III. Under Scheme III, bearable population, industrial added value and agricultural irrigation area reach 4.80 million, 213.58 billion RMB and 559.1 thousand mu respectively in 2020; by 2030, these three values stand at 5.25 million, 405.91 billion RMB and 680.0 thousand mu, basically approximate to planned regional development scale.

(2) Both water transfer from other river basins and efficient water saving can improve the water resources carrying capacity in Dianchi-Pudu river basin, and the former is the most effective and fundamental method while efficient water saving can merely work in a limited extent. Comparing with the condition of no water transfer, the bearable population in case of water transfer will increase by 6.9% and 12.5% respectively in 2020 and 2030, industrial added value 32.8%, 52.3%; agricultural irrigation area 8.5%, 42.2%. Efficient water saving can raise bearable population by 2.7% and 4.5% respectively in 2020 and 2030; industrial added value 2.7%, 15.0%; agricultural irrigation area 6.7%, 11.7%.

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