An innovative method for water resources carrying capacity research – Metabolic theory of regional water resources

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Abstract

The shortage and uneven spatial and temporal distribution of water resources has seriously restricted the sustainable development of regional society and economy. In this study, a metabolic theory for regional water resources was proposed by introducing the biological metabolism concept into the carrying capacity of regional water resources. In the organic metabolic process of water resources, the socio-economic system consumes water resources, while products, services and pollutants, etc. are output. Furthermore, an evaluation index system which takes into the characteristics of the regional water resources, the socio-economic system and the sustainable development principle was established based on the proposed theory. The theory was then applied to a case study to prove its availability. Further, suggestions aiming at improving the regional water carrying capacity were given on the basis of a comprehensive analysis of the current water resources situation.

1. Introduction

The water resources are not only basic natural resources, but also strategic economic resources and ecological control factors. The factors constraining the availability of water have become important controlling component in restricting the development of the global economy and society in the 21st century. On March 2, 2012, the latest version of the World Water Development Report (WWDR4) was published by the United Nations in Marseille. The report warned that in times of a growing demand for water around the world, the supply of fresh water is likely to be reduced due to climate changes in many regions. The aggravating dual factors of the global climate changes and the mass economic development are making water availability become the main restriction factor for sustainable economic development. This study examines the rational utilization of water resources as a whole in context of economic and social development and the carrying capacity of the water resources. Such a harmony is essential item for the regional sustainable development.

The resource problem, due to the imbalance of supply and demand, has attracted the attention of international scientific organizations. The concept of sustainable development was first discussed by Brundtland in 1987. In the researches on sustainable development, the concept of the carrying capacity is often used in the study of the following fields: urban areas (Venkatesan et al., 2011; Wang et al., 2014); industrial structure optimization (Ren et al., 2013); land (Shi et al., 2013) and region (Chen et al., 2011). The concept of the carrying capacity originated from the science of ecology, where it is used to measure the maximum number of an individual species that can be maintained in a particular environmental area (Xu et al., 2010). Discussion on the carrying capacity of resources (World Water Resources Development Report (WWDR4)) originated from the hypothesis of Malthus on the population and grain problem in 1812 (Yue et al., 2008). Based on human ecology, the concept of the carrying capacity of the population was proposed by Parker and Burgis in 1921. It was considered that the carrying capacity of population is determined on the basis of food resources, ecological and social factors and other resources of human consumption in a particular area (Xie et al., 2011). In the late 1960s and the early 1970s, as a result of the rapid growth of the global population and the economy along with the contradiction between social development and the shortage of resources, the carrying capacity problem of the environment began to gain concern. These problems have led to extensive research on both the ecological consciousness of the ecological population and the resource consumption caused by human activities (Ehrlich and Holdren, 1971; Meadows et al., 1972). The growing contradiction between the
social development and the shortage of resources led to the concept of “resource carrying capacity”, which was proposed by UNESCO in the early 1980s. In 1989, the concept of the carrying capacity of water resources was first put forward by Xinjiang Water Resources Soft Science Project Team (1989) indirectly. In the late 1990s and the early 2000s, the concept of the carrying capacity of water resources was further studied. The conclusions of several studies considered the fact that the carrying capacity of water resources signifies that water resources are needed to sustain a healthy social system (Hunter, 1998; Ofoezie, 2002). Some other researchers thought that water resources carrying capacity is the maximum threshold of water resources to sustain human activities (Harris and Kennedy, 1999; Li et al., 2000). However, there were few studies considering water resources carrying capacity as a single study item of field. Most studies incorporated water resources carrying capacity into theory of sustainable development (Ofoezie, 2002). After the year 2000, a series of studies about the theory and calculation method of water resources carrying capacity has been conducted in China and around the world. The ecological footprint method was introduced to calculate the carrying capacity of the resources (Wackernagel et al., 1999; Stöglehner, 2003) and to evaluate the industrial sustainable development (Cerutti et al., 2010; Li & Hou, 2011) since ecological footprint had been put forward (Rees, 1992; Rees and Wackernagel, 1996). The ecological footprint method was also applied to water resources research. However, due to only consideration of the fishery function of surface water and ignorance of the other functions of groundwater and surface water, it is difficult to use the ecological footprint method to calculate the carrying capacity of the water resources. Based on the conclusions and analyses of previous studies (Xu and Zhang, 2001; Ma et al., 2005; Liu et al., 2006; Wu et al., 2006; Zhou et al., 2006), Huang et al. (2008) divided the water resources account into three secondary accounts, namely the domestic water footprint (it means urban and country domestic water), the production water footprint (it means the water used by the primary, secondary and tertiary industry) and the ecological water requirement footprint(it means the water used to support the ecological system). And the ecological footprint and the carrying capacity calculation model of ecological water were also established based on the above analysis and then applied in Jiangsu Province. However, there exist gaps between the actual values and calculation values of average output and equilibrium factors of fresh water by adopting ecological footprint method. In order to solve this limitation, Hoekstra (2003) proposed an ecological footprint simulation method focusing on water demand and water right transaction. And this method was named as water footprint by Hoekstra (2009). But Stöglehner et al. (2011) pointed out that water footprint emphasized on the consumption and transaction of water resource and had difficulty proving the abilities of the water supply. Therefore, water footprint is rarely implemented to assess the sustainability of water resources.

In terms of calculation method, there emerged various approaches to quantify water resources carrying capacity. For example, the conventional trend method was used to get the population and the development scale of industry and agriculture by Shi & Qu (1992), Qu & Fan (2000) and Wang et al. (2000), based on the consideration of available water amounts, water ecological environment and water demand of national economy departments. Fu and Ji (1999), Wang et al. (2007) and Xu and Zhao (2013) used principal component analysis to convert the multiple impact variables into several comprehensive indices and obtained the classification standards and driving forces of water resources carrying capacity. Mao et al. (2012) and Xiong et al. (2012) adopted entropy weight method (it is a method for objective determining weights) to analyze and evaluate carrying capacity of water resources, and suggestions on regional sustainable development were given. Furthermore, the studies by Feng et al. (2006, 2008) and Wang et al. (2014) applied the system dynamics method to establish the regional water resources carrying capacity model. The measurement indicators of the carrying capacity of the water resources were selected to simulate the dynamic changes of the future carrying capacity of the water resources in the study area. And then recommendations for improving the carrying capacity of the regional water resources were provided. Zhang and Tan (2011) and Fu et al. (2011) respectively used the optimization model and the projection pursuit model to evaluate the carrying capacity of the water resources in the study areas. Some comprehensive evaluations were carried out on the research of the carrying capacity of the regional water resources. Li and Jin (2009), Meng et al. (2009), Wang et al. (2010) and Gao et al. (2013) applied the fuzzy comprehensive evaluation method to assess the influence factors of the carrying capacity of the water resources through establishing the fuzzy comprehensive evaluation matrix. On this basis, the factors influencing the carrying capacity of the water resources were analyzed to evaluate and predict the future carrying capacity of the water resources in the study area. In addition, other methods were also used, such as the multi-dimensional regulation (Xing et al., 2005), the multi-index evaluation model (Zhang et al., 2006), the neural network genetic algorithm (Lu et al., 2009; Chen et al., 2012) and the non-parameter analysis model (Gao et al., 2010).

Although many studies have been conducted on the carrying capacity of the water resources, there has not been an unified understanding on the definition of the carrying capacity of regional water resources both in China and internationally yet. This study considers that carrying capacity of water resources is closely connected with social, economic, ecological and technical factors. So its definition should be based on current technological and social-economic levels and its perspective relies on future technological means and social developments scale. It should also follow the principle of social sustainable development and sustainable utilization of water resources. The enhancement and the maintenance of ecological benign development, by means of the rational development and the optimized allocation of water resources, are required in order to coordinate the developmental scale between the social, economic and ecological environments being supported by the regional water resources.

The researchers were paying more attention to the calculation methods of water resources carrying capacity rather than the theoretical research of water resources carrying capacity in recent years. Therefore the objectives of this study are as follows. (a) Introduce the metabolism of biology into regional water resources carrying capacity and propose a new theory about water resources carrying capacity – the metabolism theory of regional water resources. (b) Set up an evaluation index system to effectively analyze the regional water resources carrying capacity on the basis of the theory. (c) Apply the method to a real-world case study to prove the validity of the regional water resources metabolism theory and evaluation index system. (d) Give some reasonable recommendations to decision makers.

### 2. Regional water resources metabolism theory

A region can be considered as a complex, open and organic dissipation system. This is similar to the metabolism of biology – a material and energy exchange process between organisms and the environment, as well as a material and energy transformation process within the organism (Song et al., 2013). As early as the 19th century, the metabolism of biology was introduced into sociology, economics and so on by Marx and other scholars to express the material exchange between human society and environment.
Regional water resources metabolism follows the substance layer, social economy system consumption layer, output layer) (Fischer-Kowalski, 1997). Similarly, this study introduced the accumulation and waste discharge (Rappaport, 1971) (i.e. input water resources input, water resources consumption, capital accumulation and waste discharge (Rappaport, 1971) (i.e. input layer, social economy system consumption layer, output layer). Regional water resources metabolism follows the substance flow analysis in materials flow analysis (Ma et al., 2007). The basic point of materials flow analysis is that the environmental influence produced by human activities has largely depended on two factors. One is the quantity and quality of natural resources and substances that enter into the economy system; the other is the quantity and quality of resources and waste materials that discharge from economy system to environment. The former would disturb the surrounding environment and result in ecological degradation, and the latter would cause environmental pollution. Starting from the quality of material object, the materials flow analysis traces the exploitation, the application and abandonment of natural resources and the material. That is, the material flow analysis can provide suggestions for the sustainable development through the process below: a) analyzing the exploitation, production, transfer, consumption circulation and abandonment of natural resources and material; b) revealing characteristics and conversion efficiency of material flow; c) finding out the direct source of the environment pressure; d) considering the pressure related factors as evaluation indexes of regional sustainable development; e) giving corresponding solutions for reducing environmental pressures based on the above evaluation, thus providing evidence for the near-term and medium-term targets of sustainable development (Chen et al., 2003a, b). So the material flow analysis can be used to study regional water resources metabolism theory. The consumption and outputs of regional water resources are considered as the mainline, and then the regional water resources carrying capacity and the situation of regional sustainable development can be obtained, which would provide basis for sustainable development planning. Fig. 1 shows the regional water resources metabolism system.

2.1. Regional water resources metabolism input layer

This paper assumed that water resources is the only input in the input layer of regional water resources metabolism. Although there are other materials (such as electric power, natural materials etc.) being consumed in the process of water consumption, this paper only selected water because this paper focuses on carrying capacity of water resources and water resources have become the “bottlenecks” of restricting region development. The first step of regional water resources metabolism is to get the water resources supply condition. The regional water resources can be divided into three broad categories: a) surface water; b) groundwater; c) reprocessed water. The water resources amount in the input layer is connected with local water resources conditions, the development and utilization of water resources and so on. A better water resources condition will result in larger water resources supply, higher water yield per unit area and stronger water supply ability. In terms of water utilization, if water resources exploitation and utilization ratio is high, the current water supply will be abundant accordingly, while the space for future improvement will be little. The different ways of the water resources exploitation will affect the available and unavailable evaporation of water directly and further affect regional water resources available for production and ecological construction.

2.2. Regional water resources metabolism consumption layer

The key to analyze regional water resources carrying capacity using regional water resources metabolism theory is the metabolic process of water resources, i.e. the social economy system consumes water resources which come from the input layer, satisfying domestic water use demand, generating value, offering service and outputting waste. Regional water resources carrying capacity is a concept with the dual characteristics of nature and society. It not only reflects the ability of water resources to satisfy the social economy system, but also shows the local water resources exploitation degree. Its value depends on many factors such as regional natural conditions, water resources amount, technology, social economic structures, driving force of carrying capacity, etc. (Wang...
et al., 2004). The ways of local social economy system consuming water resources decide regional water resources development levels, and meanwhile reflect development potential of current water resources carrying capacity. Therefore, the core of regional water resources carrying capacity is social economy system. The following factors will affect the development of social economy system. a) Ecological environment conditions—ecological water demand in fragile ecological area is higher under the same water resources conditions, so water resources available for social economy will be relatively less and thus regional water resources carrying capacity tends to be lower. b) Other resources—the development of social economy needs other natural resources such as land, minerals rather than water resources only. Forest and grass resources have a significant influence on the social economy development in oasis, especially in arid areas. c) Industrial structure and productivity levels—industrial and agricultural products of different quantities and qualities will be produced using the same amount of water under different productivity levels. It will lead to different economic development patterns. Hence, it is necessary to predict the current and future productive levels. d) Social consuming levels—different social consuming levels and structures determine different ways of life under the same productivity level. The social consuming level can carry larger population with lower standard of living and vice versa. e) Scientific development—the productivity levels determine the operation patterns of social economy system while scientific technology determines productivity levels. f) Policy—policies and regulations will affect the ways of water resources utilization, industrial structure, ways of living and so on, which will then influence the operation of social economy system.

Accordingly, social economy system is the core for the analysis of regional water resources carrying capacity using regional water resources metabolism theory. It is essential to have a clear understanding of social economy system’s structure and operation ways.

2.3. Regional water resources metabolism output layer

There are valuable output and waste discharge in the process of water resources metabolism. So positive and negative water resources metabolism efficiency are to defined in this paper. We define the ratio of input and output in the water resources (the value of per unit of water resources) as positive water resources metabolism efficiency and define discharged waste per water resources as negative water resources metabolism efficiency. The high positive water resources metabolism efficiency means a relative higher economic, social and ecological output with less water resources in the regional water resources metabolism system, indicating a water-saving and sustainable water resources metabolism system. Therefore, it's better for the output layer to generate as much value as possible. In terms of negative water resources metabolism efficiency, a small value means less waste output and consequently less oppression to ecological environmental. In regional water resources metabolism process, once the waste exceeds ecological environment tolerance capacity and surpasses the negative water resources metabolism efficiency threshold, the regional water resources metabolism will bear imbalance. As a result, serious ecological environment problems will happen.

To sum up, the output layer just focus on two aspects of the production—the value production and the waste discharge. In terms of the classification of the two kinds of production in the output layer, different indicators were selected. GDP was used to evaluate value production. Different classifications will be made in accordance with different demands in the later evaluation indexes selecting. This paper selected the quantity of wastewater effluent and COD emission as evaluation indexes to analyze water resources metabolism imbalance because of our emphasis on the water resources carrying capacity based on regional water resources metabolism theory.

3. Evaluation index system

Regional water resources metabolism evaluation index system is the evaluation basis and criterion of the harmony development of the regional water resources and social economy system. Nowadays, there exists contradiction between the burgeoning social economy system and the input water resources amount. Even worse, the burgeoning social economy system occupies ecological water use, leading to the deterioration of ecological environment. Therefore, the principle of evaluation indexes system is to fully reflect the current situation of water resources and the harmony development between water resources and social economy system. Moreover, the evaluation index system should provide guidance and supervision for water resources management under the principle of sustainable development. And the selected indexes should have clear concepts and be easily quantified.

The regional water resources carrying capacity evaluation index system is shown in Fig. 2. The evaluation index system is divided into water resources system, socio-economic system and ecosystem in accordance to the regional water resources metabolism theory. In general, the system reflects natural conditions of water resources, supply of water resources, development of socio-economic system and ecological environment. The evaluation indexes in close relation to the water resources carrying capacity and sustainable development were chosen based on previous studies (Liu et al., 2011; Zhu et al., 2002; Wang et al., 2004), the comprehensive analysis of regional socio-economic system and the connotation and features of ecological system and water resources. The detailed indexes are as follows:

3.1. Water resources system indexes

a) Water resources per unit area (10^4 m^3/hm^2). Reflect water resources availability. Water resources per unit area = mean annual water resources availability/total area of regional development of groundwater. Groundwater exploitation amount/groundwater development of regional surface water resources. Surface water exploitation rate = mean annual surface water resources exploitation amount/mean annual surface water resources amount.

e) Surface water exploitation rate (%). Reflect the potential development of regional surface water resources. Surface water exploitation rate = mean annual surface water resources exploitation amount/mean annual surface water resources amount.

f) Groundwater exploitation rate (%). Reflect the potential development of groundwater. Groundwater exploitation rate = groundwater exploitation amount/groundwater amount.

3.2. Socio-economic system

Water resources productive efficiency indexes system is to
measure the contribution of water resources subsystem to the livelihood and manufacture process in the social economy system, mainly evaluated two aspects — social subsystem and economy subsystem.

1) Social subsystem
   a) Urban population proportion (%). Reflect social development level. Urban population proportion = urban population/total population amount.
   b) Population growth rate (%). Reflect the potential development of socio-demographic scope and can be obtained from statistic data.
   c) Per capita water resource (m³/capita). Reflect supporting capacity of water resources on social population size. The average per capita water availability = water resources total amount/total population amount.
   d) Domestic water quota (m³/d·capita). Reflect population quality and water-saving condition. Domestic water quota = domestic water use/total population amount/365.

2) Economy subsystem
   a) Per capita GDP (Yuan). Reflect regional overall economic situation. Per capita GDP = total GDP/total population amount.
   b) GDP growth rate (%). Reflect regional overall development potential and can be obtained from statistic data.
   c) Water consumption per unit GDP (m³/10⁴Yuan). Reflect the coordination degree between economy development and water resources. Water use per unit GDP = total water use/total GDP.
   d) Industrial water consumption per unit GDP (m³/10⁴Yuan). Reflect industrial water use levels. Industrial water quota = industrial water use/industrial water output value.
   e) Irrigation water consumption per unit area (m³/hm²). Reflect the dependence of crops on water conditions and agriculture water-saving levels. Irrigation water quota = irrigation water amount/effective irrigation area.

3.3. Ecological system
   a) Ecological water use proportion (%). Reflect ecological water demand. Ecological water use proportion = ecological water use amount/total amount of water resources consumption
   b) Per capita public green area (m²/capita). Reflect the ecological environment of urban citizen. Per capita green area = urban public green area/urban population.
   c) Domestic sewage achieved disposal rate (%). Reflect the pressure of water environment by domestic sewage. Domestic sewage achieved disposal rate = domestic sewage achieved emissions/total emissions.
   d) Industrial wastewater disposal achieved rate (%). Reflect the pressure of water environment by industrial wastewater. Industrial wastewater disposal achieved rate = industrial wastewater disposal achieved amount/total water use.

4. Case study

The study area is Wuwei city (101°49′–104°16′E, 36°29′–39°27′N), Gansu Province, China. Wuwei city is located to the north of Qilian Mountain and south of Desert Tenggeli, with a land area of 33,238 km². Wuwei city was selected as the study area in order to introduce the regional water resources metabolism theory and the evaluation index system into a real-world case. The raw data, including hydrological data of years, the numbers of population, GDP and ecological water use amount, etc., were obtained from Statistic Yearbooks and investigation. The data in
When it comes to water resources exploitation, on the one hand, it grows very fast only 14,994. But the GDP growth ratio is 13.1%. Secondly, the economy is underdeveloped because per capita GDP was only 14,994 while the national average is 44,334. But the GDP grows very fast – GDP growth ratio is 13.1%. Secondly, the economy of Wuwei is a typically aggressive water consumption model. The irrigation water consumption is 1.07659 billion m³ (Severe water shortage condition appears when per capita water resources is less than 1000 m³ according to international standard [Chen et al., 2003a, b]). And domestic water quota is only 76 m³, which is far less than the national average standard 198 m³. In general, social scale has exceeded the carrying capacity of water resources and would continue to expand in the future.

Tables 2–5 present the results of water resources carrying capacity evaluation based on regional water resources metabolism theory and the established evaluation index system. Table 2 shows the values of water resources system indexes. In the aspect of water production, Wuwei is seriously lack of water resources because the water production is only 61015 m³/km², which is only a quarter of mean water production in China (241,500 m³/km², Water resources bulletin of China). In the aspect of water resources development, the water supply-demand balance index is only 1.002 (its value is very near to 1 form 2003–2011 based on the data of water resources), which means the water resources supply could merely meet the demand of city and the water resources carrying capacity of Wuwei has reached up to the maximum. In other words, the socio-economic scope has reached to the carrying limitation of water resources and the city will not function well if the demand of water resources increases in the future. Besides, water consumption rate (water consumption means the water that can’t return to the ground because of evaporation and consumption during water resources exploitation) has reached up to 69.32%, which is extremely higher than the minimum allowed value 20% (Huang and Niu, 2011). It would result in ecological problems if the rate is too high. From these we can see that water circulating system and ecological environment have suffered a certain degree of damage. Further, this situation aggravates the problem of water resources shortage and has adverse impacts on the future water production. When it comes to water resources exploitation, on the one hand, exploitation rates of surface water and groundwater have respectively reached to 88.26%, 90.92%, which also means water resources exploitation has approached to the limitation and there is no potential carrying capacity to support the expanding socio-economic scale. In addition, groundwater balance has been broken as a result of groundwater over-exploitation. On the other hand, the self-produce water utilization proportion has reached 89.94%, which suggests that the water resources condition in Wuwei could be improved by increasing external water resources amount. Considering the local conditions, water resources situation could be improved by a certain degree through water transfer projects—first-stage project of Jingdian has been put into operation and second-stage project is under construction. Overall, Wuwei is of no optimism in water production capacity and there is no potential of water resources exploitation. As a result, socio-economic development is under serious threat. Furthermore, objective of sustainable development cannot be achieved if the serious ecological problems caused by aggressive groundwater exploitation and water consumption were to continue.

Table 2 describes the economy situation in Wuwei. To begin with, the economy is underdeveloped because per capita GDP was only 14,994 while the national average is 44,334. But the GDP grows very fast – GDP growth ratio is 13.1%. Secondly, the economy of Wuwei is a typically aggressive water consumption model. The water consumption per unit GDP and industrial water consumption per unit GDP are respectively 638 m³ and 141 m³ while the national averages are 129 m³ and 78 m³. Moreover, the industrial structure is not reasonable—the industrial structure proportion (primary industry: secondary industry: tertiary industry) is 24.56:42.33:33.11, which indicates putting too much water into agriculture. The irrigation water consumption is 1.07659 billion m³ and the agricultural water consumption has reached up to 88.28%. In conclusion, there is an increasing water demand in Wuwei city due to rapid growth GDP, aggressive water consumption economic model and unreasonable industrial structure. Meanwhile, Wuwei is seriously short of water and the carrying capacity of water resources has reached up to the limits. So in order to achieve the objective of sustainable development of socio-economic system, Table 1 were obtained through the analysis and calculation of collected data. The study selected year 2011 as an example because of data integrity.

Wuwei is a developing city lacking of water resources seriously. Water resources problems has become a main factor of restricting the development of Wuwei's economy. Besides, in recent years, Wuwei city is facing a series of ecological problems, such as, the degradation of vegetation in Qilian Mountain, groundwater draw-down and land desertification, etc. So it is necessary to analyze the situation of water resources carrying capacity. It is hoped that the studied case could reveal the current situation of water resources carrying capacity and offer guidance to water resources exploitation and socio-economic development in the future.

### Table 1

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<tr>
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<th>MAWA 10³m³</th>
<th>MAUA 10³m³</th>
<th>WRC 10³m³</th>
<th>SWA 10³m³</th>
<th>MSWEA 10³m³</th>
<th>MSWA 10³m³</th>
<th>GEA 10³m³</th>
<th>GA 10³m³</th>
<th>IWU 10³m³</th>
</tr>
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<tbody>
<tr>
<td>WRUA 10³m³/km²</td>
<td>61015</td>
<td>1.002</td>
<td>69.32</td>
<td>89.94</td>
<td>88.26</td>
<td>90.92</td>
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Note: MAWA: Mean annual water resources availability; MAUA: Mean annual water use amount; WRC: Water resources consumption; SWA: Self-produce water amount; MSWEA: Mean annual surface water resources exploitation amount; MSWA: Mean annual surface water resources amount; GEA: Groundwater exploitation amount; GA: Groundwater amount; IWU: Industrial water use; WRUN: Ecological water use amount; DWU: Domestic water use; IWOV: Irrigation water amount; i: Total population amount; IWG: Industrial water output value; UPG: Urban pubic green area; EIA: Effective irrigation area.

### Table 2

<table>
<thead>
<tr>
<th>WRUA 10³m³/km²</th>
<th>WSBI</th>
<th>WCR</th>
<th>SWUP</th>
<th>SWER</th>
<th>GWER</th>
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<tr>
<td>6.1015</td>
<td>1.002</td>
<td>69.32</td>
<td>89.94</td>
<td>88.26</td>
<td>90.92</td>
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</table>

Note: WRUA: Water resources per unit area; WSBI: Water resources supply-demand index; WCR: Water consumption rate; SWUP: Self-produce water utilization proportion; SWER: Surface water exploitation rate; GWER: Groundwater exploitation rate.
than the demand of constructing ecological area, which is 33.33% seen that ecological water use ratio is only 4.46% and it is far less capita public green area is only 5.8 m²/capita at present while the purifying capacity of water environment. This is because the per ment ratio. Furthermore, the ecological water should be guaranteed environment can be reduced by improving the wastewater treat-
aggravation of water shortage. In the future, the pressure of water resources carrying capacity has been seriously weakened owing to occupa-
tion of ecological water and discharge of large amounts of sewage into water environment. Therefore, a rigorous water situation will appear in the future if these tendencies continue. In other words, the socio-economic development at present has exceeded the carrying capacity of water resources and the situation is going to aggravate in the future. On the purpose of achieving sustainable development, some recommendation are given. (1) Improve water resources carrying capacity and groundwater situation by increasing the external water amount and reducing over-exploitation of underground water. (2) Slow down the speed of urbanization, adjust the industrial structure and develop watersaving economic pattern. (3) Increase ecological water proportion to improve the purifying capacity of water environment. The pressure of water environment can be relieved by increasing the wastewater treatment rate.

6. Conclusion

Water resources play an increasingly important role in the social and economic development of a regional, especially in the arid and semi-arid regions. Water resources have significant impacts on a regional sustainable development. However, researchers are paying more attention to the calculation methods of water resources carrying capacity than the theoretical research of it. Therefore, in this paper, regional water resources metabolism theory was put forward and the evaluation index system was established based on the theory. A real-world study was applied based on the above theory and evaluation index system.

The water resources metabolism theory developed in this study has a number of advantages, which are listed as below.

- Decision makers can get a more comprehensive and accurate water resources carrying capacity situation than other methods because it focus on the whole water consumption system rather than parts of water consumption system (such as only agricultural water sector or only industrial water sector, etc.)
- It can directly access water resources use efficiency because this study put forward the positive water resources efficiency.
- It not only focuses on value production, but also reflects the waste discharge to ecological environment, in the output layer of water resources metabolism process.
- The decision makers can get the relationship between economic development model and water resources based on the results of the evaluation index system.
- It can give the decision makers suggestions about the water resources utilization policies and the social-economic development in the future.

There is much space for the development of regional water resources metabolism theory in the future, such as introducing some other theories like the energy flow theory, etc.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.11.033.
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