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Original Research Paper

Carrying Capacity in China: Sustainable Development and Water Resources in Yunnan Province

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ABSTRACT

Research on water resources carrying capacity provides much-needed insight for sustainable development of society and the economy. This paper reports on human carrying capacity (sustainable population) in terms of water resources in Yunnan province, China, as well as socio-economic, ecological and environmental development under selected conditions. A sustainable water resources carrying capacity model is built, with analysis and forecasts of carrying capacity in 2010, 2020, 2030 and 2050. The results indicate that Yunnan province is trending toward water stress in the long term.

INTRODUCTION

The Chinese government has greatly developed water resources in recent decades in response to population and economic growth. Water resources are, however, a source of long-term concern. The remote, mountainous, western province of Yunnan faces serious imbalances in both geographical and seasonal distribution, due to its challenging climatic, social, economic and environmental characteristics. There is water scarcity in resource-based, project-based and water quality-based aspects (Gu et al. 2007, Yang & Wang 1999, Zhao & Wang 2013). There is more water in the south-western third of the region which catches the remnants of the monsoon, and less water in the central and eastern zones. The central zone of Yunnan province around the regional capital Kunming is densely populated and industrially developed. The population and GDP here account for 63% and 82% of the whole province respectively, but it is served by 19% of the water resources. Kunming is one of the most seriously water-stressed cities in China.

Yunnan province lags behind eastern provinces in China in terms of economic development. The process of rapid economic development is over-reliant on massive exploitation of mineral resources, resulting in intense pressure on the hydrological and ecological environment in many counties. Developed areas suffer from severe water pollution and water scarcity, which restricts the sustainable and healthy development of the province's economy. In developing areas, serious problems such as the low utilization rate of water resources and wastewater are deteriorating, leading to a reduction in levels or even seasonal drying up of surface waters. This damages the ecological environment, restricts sustainable socio-economic development and could potentially impact future tourism in this stunningly attractive area of vast biodiversity.

Chinese research into water resources and their impact on carrying capacity mainly focuses on analysing and predicting maximum population, economic development and environmental protection (Xia & Zhu 2002). More emphasis is required on sustainability and coordination. Planning in areas of water stress such as Yunnan province need to aim for sustainable water management and sustainable socio-economic development in short, smart use of limited water resources. We must look to coordinate behaviors as regards: water resources management-society-economy-ecological systems.

Notably, joined-up thinking is seldom applied to the modeling of the entirety of water resources carrying capacity and whole system coordination (Satyanarayana et al. 2010, Rajamanya et al. 2011). Our research aims to effect a change in thinking in China. The various factors chosen necessarily have a complex symbiotic relationship, which opens our model up to discussion. In this study on sustainability in Yunnan province, we will analyse and quantify the factors of population, economy and ecology, and go on to predict the running and development of the whole system.

WATER RESOURCES CARRYING CAPACITY

Carrying capacity is originally used as an indicator in mechanics which represents the maximum load that an object can carry before being destroyed. In the field of ecology, it means the maximum number of individual organisms of a particular species that can survive under certain environmental conditions. Water resources are a fundamental part of the natural capital that determines carrying capacity. Much research into water resources carrying capacity and environmental systems focuses on human or broader groups of organisms (Zhu et al. 2002, Dong et al. 2007).

Chinese researchers have done much work on sustainable development in terms of the impact of water resources carrying capacity (Zhang et al. 2006, Lui & Chen 2007, Men et al. 2003, Song et al. 2011, Zhu et al. 2010). Research in China features a trend of diversification in the study of quantitative methods in this area (Wang et al. 2005, Long et al. 2004, Yao et al. 2002). However, no mature theory or all-encompassing system has yet been formed as regards content and methodology (Jiang et al. 2011, Feng et al. 2003). The purpose of this study is to coordinate and balance the development of hydrology, water resources system, human society, economy, resources and the ecological environment system. The study of water resources carrying capacity should be systemic and comprehensive. Systemic capacity refers to not only the amount of water available for use, but also the water needed to accommodate sewage and other discharges to water. Comprehensive capacity means that the carrying capacity in respect of overall resources should reflect the carrying capacity in terms of population, economic development and ecological functions. In a particular socio-economic development process, on the one hand, the largest population with limited development goals, and the economic and ecological scale should be predicted on the basis of water resources in this region; on the other hand, research on regional carrying capacity in respect of water resources cannot solely reflect the total population and the total social and economic development and structure, but should also factor in the importance of the environment so as to better explain the concept of sustainable development.

PGESH MODEL

Model structure: The water resources system always interacts with the social, economic and ecological environment to form a complex system with multi-levels and multi-targets. In light of local circumstances here, the highly diverse geography, climate, resources, environment, society and economy in Yunnan province, we should pay close attention to the sustainability and coordination of systems involving water resources when studying carrying capacity in relation to the totality of other factors in a water-stressed environment. This obliges us to study the carrying capacity

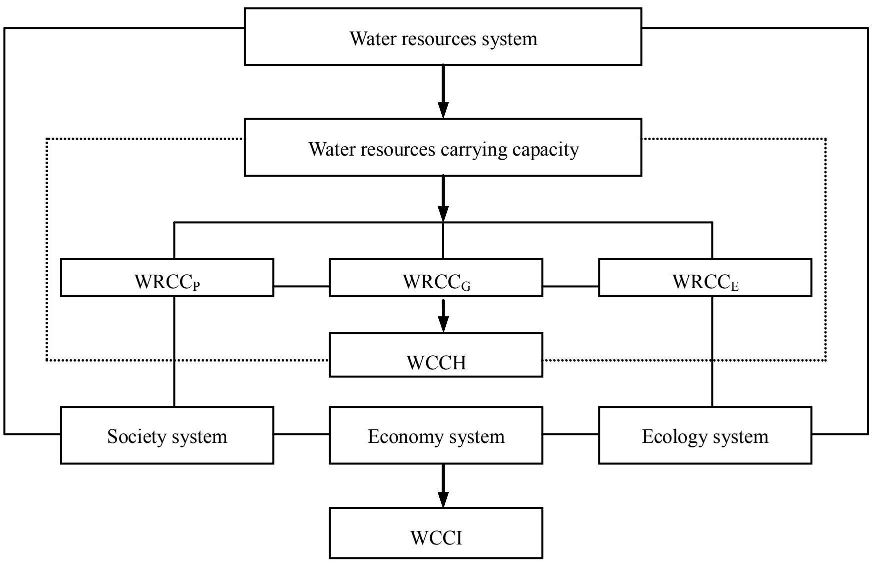

Fig. 1: Structure of water resources-society-economy-ecology-harmony.

and coordination of the system using the Population-Economy (GDP)-Ecology-Support index-Harmony model (PGESH). In this paper the term "water resources carrying capacity" refers to sustainable development capacity in terms of water resources; "carrying media" refers to the water resources system and "carrying objects" refers to social, economic and ecological systems. The structure of this model is shown in Fig. 1.

The sustainable water resources carrying capacity model (*WRCC*) of Yunnan province can be expressed as below:

$$WRCC = \{WRCC_P, WRCC_G, WRCC_g, WCCI, WCCH\} \quad ...(1)$$

Where, *WRCC* is water resources carrying capacity; $WRCC_P$, $WRCC_G$, $WRCC_e$ are respectively the carrying maximum of population, GDP, and BOD emissions (a measure of water pollution); $WRCCI$ and $WRCCH$ are respectively the support index and harmony index of water resources.

The supported population scale: The population scale supported by regional water resources is an important macro-indicator that measures water resources carrying capacity, which can be calculated through the social development level and GDP of the region, as expressed below:

$$WRCC_p = GDP/[GDP], \quad ...(2)$$

Where, $WRCC_P$ is the largest population that water resources can support for a certain level of social development; GDP is the GDP expectancy of the research year or the planning year; and [*GDP*] is the minimum per capita GDP for a certain society.

Different levels of social development cause different consumption levels, hence the population scale supported by water resources is related to the level of social development which can be reflected by per capita GDP.

In light of Chinese socio-economic status and strategic goals as well as related foreign references, social development can be divided into six stages: food and clothing, initial well-off, middle well-off, general well-off, initial affluent and middle affluent, corresponding to per capita GDP lower limits of RMB 3000, 6300, 13000, 24000, 34000 and 62,000 respectively.

The supported economic scale: The economic scale supported by regional water resources is another macro-indicator that measures water resources carrying capacity, which can be defined as the ratio of regional GDP and water consumption per GDP:

$$E_W = GDP/W_D, \quad ...(3)$$

Where, E_W is the economic scale supported by a water unit at a certain social development stage; and W_D is the total water consumption status or planning level of social and economic system in the research year or planning year.

When water consumption equals regional available water resources, the economic scale is the largest scale that water resources can support, as expressed below:

$$WRCC_G = W_U \cdot E_W = W_U \cdot \frac{GDP}{W_D} \quad ...(4)$$

Where, $WRRC_G$ is the largest economic scale that water resources can support at a certain stage of society; and W_U is the volume of available regional water resources.

The supported pollutant scale: The supported pollutant scale reflects the maximum BOD emissions of the whole region. The maximum BOD discharge can be defined as the ultimate BOD emissions that can still ensure water quality, which satisfies national minimum standards for the living, production and ecological environment when all pollutant distributes in the available regional water resources, as expressed below:

$$WRCC_e = WRCC_{le} + WRCC_{pe} + WRCC_{ee}$$

$$= W_u \cdot (\frac{D_l}{D} \cdot q_l + \frac{D_p}{D} \cdot q_p + \frac{D_e}{D} \cdot q_e) \text{ ,} \quad ...(5)$$

Where, $WRCC_{le}$, $WRCC_{pe}$ and $WRCC_{ee}$ are respectively the largest BOD of the living, production and ecological environment; D_l, D_p, D_e and D are respectively the water demand of the living, production, ecological environment and total society at the present social stage; q_l, q_p and q_e are respectively the minimum BOD standards of the living, production and ecological environment at the present social stage.

Support index: Water resources support index is recommended descriptors of the load-bearing of the water resources system. The support index reflects the socio-economic status of water resources, which results from a comparison of the water resources system (support system of carrying capacity) and the social, economic and ecological systems that the water resources system supports (pressure system of carrying capacity).

Support of the water resource system can be reflected by six indicators: per capita water resources, water production module, per mu water resources, per capita available water, water runoff coefficient and water resources variation coefficient. Pressure of the water resources system can be reflected by seven indicators: population density, per capita GDP, living water quota, industrial water quota, agricultural irrigation water quota, and industrial water increase and farmland irrigation rate.

***Support of regional water resources*:** Supposing that the value of support media *S* (support) depends on factors $x_1, x_2, ..., x_n$, then the support $WCCS = f(x_1, x_2,..., x_n)$. Assume the property values of $x_1, x_2,..., x_n$ are respectively $v_1, v_2, \cdots, v_n$ with corresponding weights of $\omega_1, \omega_2, \cdots, \omega_m$, and then the support index can be expressed as below:

$$WCCSI = \sum_{i=1}^{n} \omega_i v_i \qquad ...(6)$$

According to the calculation results, the water resources support index can be determined by the property value and weight value of each constituent. The larger the value of $WCCSI$ is, the greater the support that water resources can provide for social, economic, ecological and other developments.

***Pressure of regional water resources*:** Assuming the pressure *P* on water resources carrying objects is an objective reality then depends on the factors and thus, can be expressed as below:

$$WCCP = f(y_1, y_2, \cdots, y_m) \qquad ...(7)$$

Assume the property values of $y_1, y_2, \cdots, y_m$ are respectively $u_1, u_2, \cdots, u_m$, with corresponding weights of $\omega_1, \omega_2, \cdots, \omega_m$, and then the water resources carrying index is $WCCPI = \sum_{i=1}^{m} \omega_i u_i$: The larger the carrying index is, the greater the pressure is on the water resources system.

***Support index of regional water resources*:** The water resources support index represents the objective support capacity of the medium and can be calculated by the following formula:

$$WCCI = WCCPI / WCCSI \qquad ...(8)$$

When $WCCI > 1$, the water resources system experiences a greater pressure than it can bear, indicating the water resources system is overloading; when $WCCI = 1$, the pressure is balanced with its support, indicating that the pressure is at the upper limit; when $WCCI < 1$, the pressure is lower than its support. In order to ensure the sustainable development of society, economy and the ecological environment, the pressure of water resources should be restricted in the scope of its support, namely, the support index $WCCI \leq 1$.

Harmony index: The harmony index (*WCCH*) should reflect not only the influence of changes in water resources on the social, economic and ecological systems, but also the coordination of the whole socio-economic system with water resources. An integrated harmony index can be obtained by summing per capita arable land area, water-saving irrigation rate, water supply and demand balance index, per capita environmental water demand and river input rate after weighing them. According to the coordinated state of indicators chosen in the subsystem *WCCH*, can be calculated after normalization to the [0, 1] range, through the following formula:

$$WCCH = \sum_{i=0}^{3} \sum_{j=1}^{n} w_{ij} \cdot v_{ij} \quad i = 0,1,2,3 \; ; \; j = 1,2,\cdots,n \qquad ...(9)$$

Where, *i* is the year 2010 and the planning years of 2020, 2030 and 2050; w_{ij} is the weight of the present year or planning year; v_{ij} is the support harmony normalized property value of the present year or planning year. The greater the integrated harmony is, the better the whole system coordinates.

SUSTAINABLE WATER RESOURCES CARRYING CAPACITY

Using the PGESH model and calculation index system, this paper predicts the scale of population, economy and ecological environment supported by water resources in Yunnan province, and calculates the support index and integrated harmony index.

The supported population scale: Table 1, calculated using formula (2), shows the greatest population scale supported by water resources in the six stages: food and clothing, initial well-off, middle well-off, full well-off, initial affluent and full affluent.

As can be seen, when the society is at the food and clothing stage, the largest population supported by water resources is respectively 65.17 million, 140 million, 281.43 million and 530 million in 2010, 2020, 2030 and 2050 – far less than the maximum scale of social development. When society is at the initial well-off stage, population in all planning years never reaches the maximum scale except in 2010. If the water resources utilization of Yunnan province is sustainable, social development of Yunnan province does not reach the initial well-off stage in 2020. When society reaches the medium well-off stage, the population in 2010 and 2020 overshoots, while it does not in 2030 and 2050, which indicates that the population will not overshoot before 2030, when society is below the middle well-off stage. When society reaches the full well-off stage, the population overshoots in 2010, 2020 and 2030, but not in 2050, which indicates that the population will not overshoot before 2050 when society is below the full well-off stage. When society is in the initial affluent or full affluent stage, the population supported by water resources overshoots in all research years. Otherwise, in light of the part below the dotted line of the table, it can be seen that the population is in the sustainable range in all planning years.

Table 1: Greatest population scale supported by water resources in Yunnan province.

Planning year	Population /10,000	Maximum population supported/10,000					
		Food and clothing	Initial well-off	Middle well-off	Full well-off	Initial affluent	Full affluent
2010	4288	6517	3103	1504	815	575	315
2020	4707	14000	6667	3231	1750	1235	677
2030	5140	28143	13402	6495	3518	2483	1362
2050	5386	53000	25238	12231	6625	4676	2565

Table 2: Maximum economic scale supported by water resources in Yunnan province.

Planning year	Total water demand/$10^8 m^3$	GDP expectation/ 10^8 Yuan	Maximum economic scale/10^8 Yuan
2010	197	1955	8923
2020	223	4200	16990
2030	247	8443	30785
2050	269	15900	53183

Table 3: Pollutant content contained by water resources in Yunnan province.

Planning year	Total population /10^4	BOD expectation /10^4kg	Maximum supported BOD/ 10^4kg10^8Yuan
2010	4288	45567	84620
2020	4707	43209	82202
2030	5140	41588	80395
2050	5386	39608	78612

Table 4: Support index and harmony index of water resources in Yunnan Province.

Planning year	Support	Pressure	Support index	Harmony index
2010	0.9647	0.5523	0.5725	0.8746
2020	0.9265	0.5985	0.6459	0.8189
2030	0.8908	0.6793	0.7625	0.7219
2050	0.8788	0.8597	0.9783	0.6946

The supported economic scale: Table 2 shows the economic scale supported by water resources which can be calculated from formulas (3) and (4). It can be seen that the maximum economic scale supported by water resources is more than the GDP expectation in all the planning years, indicating that the water resources are not overloaded.

The supported pollutant scale: The pollutant scale by water resources can be calculated according to formula (5) as given in Table 3. Along with increased environmental awareness among the general population, the maximum BOD discharge supported by water resources will decrease gradually, so that in all planning years the pollutant scale supported by water resources is within the range that water resources can support.

Support index and integrated harmony index: Using normalized indicators, a discriminant matrix can be constituted, and the entropy weight is assigned by the entropy method. For calculating support indicators, the entropy and weight are respectively: H_j = (0.8759, 0.9700, 0.9927, 0.8675, 0.8738, 0.9995),w_j = (0.2951, 0.0713, 0.0173, 0.3151, 0.3002, 0.0011); for calculating pressure indicators, the entropy and weight are respectively: H_j = (0.9579, 0.9132, 0.9930, 0.9657, 0.9954, 0.9804, 0.9873), w_j = (0.2035, 0.4192, 0.0340, 0.1656, 0.0223, 0.0945, 0.0611); for calculating integrated harmony indicators, the entropy and weight are respectively: H_j = (0.9840, 0.9922, 0.9768, 0.9896, 0.9122), w_j= (0.1103, 0.0536, 0.1595, 0.0718, 0.6050). Thus, the support indicators and pressure indicators of water resources can be calculated using formulas (6), (7) and (8), and the support index and harmony index can be obtained by a further calculation.

Table 4 shows the support index and harmony index of water resources in Yunnan province. In 2010, 2020, 2030 and 2050 no sustainable water resources support is overloaded, but in 2050 the water resources support index is 0.9783, very close to the overload alert value 1. Support of water resources becomes smaller year by year, but the carrying pressure of water resources increases year by year, so that the support index also increases year by year to the overload limit. Moreover, the continuous decrease in the harmony index indicates that the overall system of water resources-society-economy-ecological environment is deteriorating. Unless appropriate measures are taken, the model shows that after 2050 Yunnan province will be in a critical situation where regional water resources can no longer maintain sustainable development in the region.

CONCLUSIONS

This study creates a new model to quantify and assess the long-term sustainability and coordination of water resources carrying capacity in Yunnan province in light of several factors like level of population, economy, ecological environment and system operation. The calculation results of the population scale, the economic scale and the pollutant carrying capacity by water resources are all within the sustainable range in 2010, 2020, 2030 and 2050, but the water resources support index and harmony index keep decreasing, and come close to the warning line in 2050. Research into water resources carrying capacity is a complex multi-target, multi-attribute decision-making process; it must consider system support and coordination of water resources-society-economy-ecological environment factors, and focus on healthy operation of the overall system and sustainable development of society. Water resources carrying capacity modeling lends important insight into sustainable use of water resources and should form the basis for regional socio-economic development planning.

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