Conception and evaluation methodology of water resources carrying capacity based on three-level analysis

Pengfei Lin, Jinjun You, Lin Wang, Ling Jia, Hong Gan and Yicheng Fu

ABSTRACT

In supply-oriented water development, water is a rigid constraint on sustainable development in many parts of the world, especially in arid and semi-arid areas. The water resources carrying capacity (WRCC) concept represents the maximum socio-economic scale that can be supported by water exploitation without causing an irreversible impact on the ecosystem. In this paper, three-level framework is put forward to illustrate and quantitatively evaluate the WRCC. The first level is the principal body, which focuses on the study of water resources systems. The second level is the carried object, including the socio-economic system, water ecological system, and environment system. The third level is the coupling of the principal body and carried object to calculate the WRCC. This three-level WRCC model was applied to the load conditions of the Shiyang River Basin (SRB). The results show that the SRB is overloaded, and only 1.99 million people can be carried at the modern carrying level. The WRCC could be increased by optimizing industrial structures and improving water efficiency. This method provides a tool to help policymakers develop sustainable approaches to environmental management and planning.

Key words | Shiyang River Basin, three-level model, water carrying capacity

Pengfei Lin
Jinjun You (corresponding author)
Lin Wang
Ling Jia
Hong Gan
Yicheng Fu
State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin,
China Institute of Water Resources and Hydropower Research,
Beijing 100038,
China
E-mail: *youjj@iwhr.com*

Pengfei Lin
Graduate School of Hohai University,
Nanjing, Jiangsu 210098,
China

HIGHLIGHTS

- A three-level framework is put forward to illustrate and quantitatively evaluate the WRCC.
- The WRCC could be increased by optimizing industrial structures and improving water efficiency.
- The three-level WRCC analysis method can be used to evaluate the differences in water carrying conditions.

INTRODUCTION

Water is a basic natural resource that cannot be separated from human survival and development. Societal development, progress in science and technology, and the continuous improvement in living standards has increased people's demand for water resources both qualitatively and quantitatively. Owing to the overuse and misuse of natural resources, resource scarcity has become increasingly severe and threatens China's sustainable socio-economic development (Varis & Vakkilainen 2001). Especially in inland arid areas, runoff water resources should support not only the socio-economic development of oases but also the fragile ecological environment. Previous studies have focused on how to use water resources more efficiently based on the concept of sustainability, and the water resources carrying capacity (WRCC) concept has been used to appraise the reasonable and possible scales of socio-economic activities in specific regions to direct development according to indicators from a macroscopic view (Yue *et al.* 2015).

The carrying capacity of natural resources is the maximum number of inhabitants that they can support at a

doi: 10.2166/ws.2020.149

given level of consumption without degrading the environment and therefore reducing the future carrying capacity (Abernethy 2001). The WRCC was proposed as a concept for water resources planning, development, and management. Most research on the WRCC has focused on providing analytical tools to consider the tradeoffs among water resources development, socio-economic sustainable development, and environmental and ecological protection to present suggestions for future regional planning (Jia *et al.* 2018).

Hadwen & Palmer (1992) considered the carrying capacity when studying how to control the population of reindeer introduced into Alaska. Pulliam & Haddad (1994) introduced the concept of the carrying capacity for human populations when studying sustainability and showed the relationship between population growth and ecology. Water resources are an important component of ecosystems, but there have been few studies on the carrying capacity of individual water systems. With increasing problems regarding water resources, the WRCC has become the subject of interest as a basic attribute of natural resources (Carter & Howe 2006).

Recently, more researchers have recognized the importance of the WRCC as a concept and have applied it to analyzing rational patterns of development. More research attention has been given to developing quantitative evaluation methods, such as the comprehensive evaluation model (Wang 2016), the set pair analysis method (Zhang & Li 2010), the system dynamics evaluation method (Feng *et al.* 2008), and variable fuzzy evaluation (Gong & Jin 2009). These methods were proposed from different aspects of the WRCC, according to the characteristics of the WRCC. But these methods cannot effectively study the feedback relationship between social and economic development and the WRCC.

Sustainable human-water coexistence requires the reasonable and consistent development of human society, healthy water ecosystems, and a coordinated interaction between humans and water (Ding *et al.* 2014). The WRCC is a comprehensive concept that is related to various variables. It is not easy or even possible to consider all influencing factors. Therefore, more sophisticated techniques and new analytical methods are needed to improve the computational process, especially regarding the description and analysis of rational water allocation to different users. This paper defines the WRCC by summarizing previous studies and discusses relevant influence factors before presenting a concrete computational method for its assessment based on the human-water harmony theory.

METHODS

Basis of the approach

Principal body

The principal body focuses on the study of water resources systems and evaluates the valid water resources. Valid water resources refer to water with sufficient quantity and quality to meet demand. Low-quality water is not a valid water resource and is therefore not part of the calculation of the WRCC. As a society must be able to control and exploit valid water resources, floods are not valid water resources. For sustainable development, a suitable water ecological environment and a suitable habitat environment are imperative. Therefore, a certain amount of water is reserved for ecological environmental needs. So the ecological environment water requirements are also not valid water resources.

Carried objects

Carried objects include both natural and artificial systems directly or indirectly related to water, such as humans and other creatures living in the basin, natural or cultivated plants, and industries. For water planning and management, human systems are generally considered to be a carried object because they are controllable factors. The most basic indices for assessing the scale of an artificial system are the population and economic level (Yuan *et al.* 2006). Therefore, an index that represents these two aspects can be used to assess the carrying capacity.

The concept of carried objects is related to the level of social development. The level of social development determines the productive and technological levels, of which the technological level is an important factor that influences the water consumption per unit production value. From a macroscopic view, the total water demand depends on the total economy and water consumption per unit productive value. The carried body of an artificial system is always located at some objective level that can be used to ascertain the scale of the carried body under the limitations of a definite principal body (e.g., valid water resources).

Carrying level

Both the valid water resources and social productive level are determinants for the WRCC, but both of these factors will change with socio-economic development. Therefore, to calculate the WRCC in a region, the carrying level must be determined first, to determine the valid water resources and water use efficiency. When the carrying level is determined, the water resource utilization capacity, the socio-economic level and the intensity and efficiency of water consumption can be determined. The socio-economic level is quantified by the gross domestic product (GDP) per capita, which is the key factor for calculating the amount of bearable population under a specific GDP. The level of social development basically determines different values for the water consumption per capita, where the WRCC can be computed under specific conditions for the water resources. Therefore, the carrying level is a precondition of the carrying capacity.

Fundamentally, the carrying level includes living standards, the level of economic development, and the objectives of ecological and environmental protection. When a certain carrying level is determined, the water norm, water efficiency, and ecological environmental water requirements will be determined accordingly. Although there is a competitive relationship between socio-economic and human water use, this does not affect human living conditions. Among the various influences on the carrying level, the population and economic development are the most decisive factors. These two factors represent the level of water demand from different sectors. Generally, higher living standards mean higher consumption of materials and energy, which results in a greater demand for water. However, it also represents a more developed society with higher efficiency and better management, which lowers the water consumption of per unit product. The same living standard or GDP per capita can represent different industrial structures. A higher carrying level increases the water demand despite the higher water utilization efficiency, although specific conditions differ and depend on the pattern and structure of the society and economy.

Steps of the model

Based on the above definitions of the WRCC and its related parameters, the following three-level approach is proposed for quantitatively analyzing the water carrying capacity of a specific area. The first level is the principal body (i.e., valid water resources and their variability). This represents the natural attributes of water and the capacity to support socio-economic development. The second level is the object (i.e., the scale of the society and economy). This is expressed by the population and GDP. The third level is the bridge between the principal body and object (i.e., the rational water allocation from valid water resources to water users at a specific water utilization efficiency). The framework of the approach is illustrated in Figure 1.

Determining the carrying level

The carrying level is the most important factor for ascertaining the WRCC. The general criterion for classifying social development is identifying the GDP per capita. Development trends can be determined from economic predictions and population projections. The predicted economic development is the bedrock for setting the threshold value in future planning. The approximate trends of industrial changes are also available for macroscopic economic planning. The predicted economic growth curve can be used to determine the industrial structure and comprehensive water utilization efficiency at critical points (i.e., the carrying level). Based on the above analysis for the carrying level, the comprehensive water consumption per unit production can eventually be determined.

The carrying level can be classified into four levels based on the widely accepted Engel rule and living standard criteria put forward by the World Bank, as presented in Table 1. The critical value of the GDP per capita is an analytic result integrated with the realistic economic situation for China. Therefore, four critical values are chosen to estimate the WRCC. The economic status can be used to

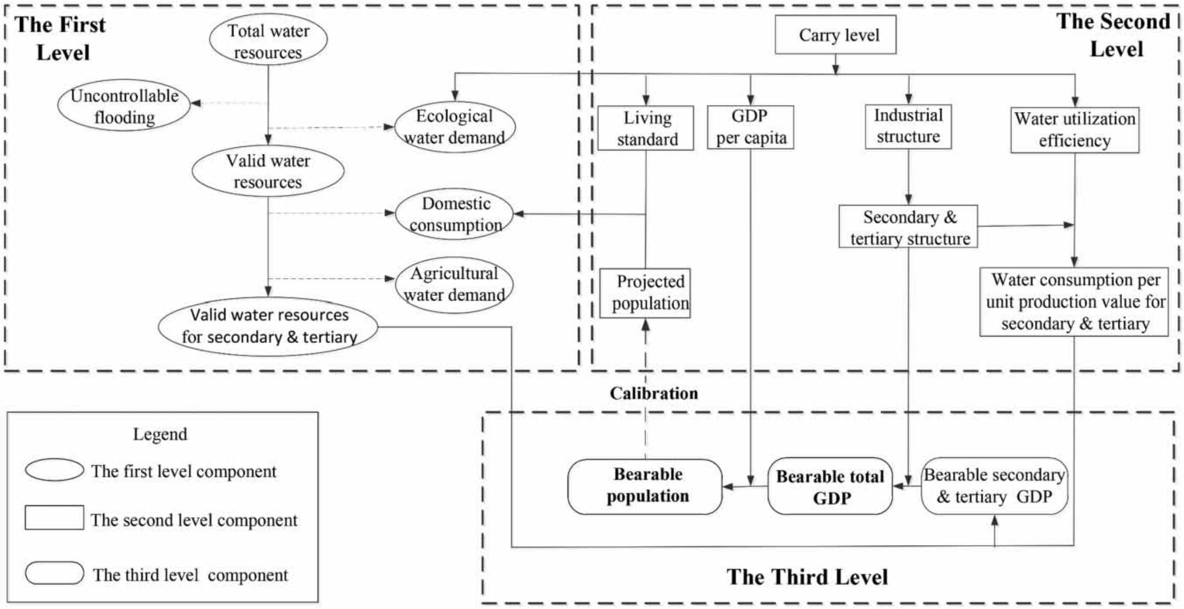

Figure 1 | Framework of the three-level water carrying capacity assessment.

Table 1 | Criteria for classifying the carrying level (GDP in CNY)

Criteria	Poor	Basic subsistence	Well off	Wealthy	Modernized
Engel's coefficient	>59%	50–59%	40–50%	30–40%	<30%
GDP per capita	<3,300 CNY	3,300–6,600 CNY	6,600–24,800 CNY	24,800–74,500 CNY	>74,500 CNY

analyze the total production value and water utilization efficiency for calculating the WRCC.

The first-level calculation

The total valid water resources represents the amount of water technically and economically usable considering ecological and environmental demands, including both surface water and groundwater. The valid water resources of a specific area can be calculated from the total water resources by subtracting the necessary ecological water demand and unmanageable floods:

$$W_v = W_s + W_g - W_e - W_f \qquad (1)$$

where W_v is the valid water resources, W_g is exploitable groundwater. W_s is the surface water resources, W_e is the ecological water demand; considering different ecological conditions, it can be taken from the minimum to the maximum ecological environment water consumption to adjust the competition between the ecological environment and other water users. W_f is uncontrollable floods. All variables are average annual values.

For the calculation of valid water resources, the major part is supplied to production sectors, which include irrigation, industries, and services. The domestic water demand should also be considered, although its amount is relatively small. The domestic water demand is obtained according to the projected population and water norm indicators at different carrying levels:

$$W_{do} = P_{fo} \times E_{do} \qquad (2)$$

where W_{do} is the domestic water demand; P_{fo} is the initial estimated population, which during the calculation process, will be optimized to the carrying population P; and E_{do} is normal domestic use. Domestic water users usually have higher priority than others, and allocated water resources are sufficient to meet future needs based on the forecast.

In general, the agriculture water consumption per unit GDP is much higher than that of other industries. If agriculture is also taken into comprehensive water consumption per unit GDP, the effect of other industries can be obscured. To reduce this adverse effect, the agricultural water demand at different carrying levels is calculated separately by the irrigated area and irrigation norm:

$$W_{ar} = A \times E_{ar} \tag{3}$$

where the W_{ar} is the agricultural water demand, A is the irrigation area, and E_{ar} is the amount of irrigation water per hectare per year. Thus, the valid water resources for production enterprises (i.e., the available economic scale calculated for a certain carrying level) is the surplus when the estimated domestic water demand and agricultural water demand are subtracted from the total valid water resources:

$$W_{ec} = W_v - W_{do} - W_{ar} \tag{4}$$

where the W_{ec} is the valid water resource for secondary and tertiary industries.

The second-level calculation

With the valid water resources and carrying level, it is feasible to compare and calculate the indices of the WRCC; that is, the bearable population and economic scale. The comprehensive water consumption per unit GDP can be obtained according to the industrial development scale, industrial structure, and water norm indicators at different carrying levels. The agricultural water demand is deducted in advance when calculating the amount of water available, so the comprehensive water consumption per unit GDP only needs to consider secondary and tertiary industries:

$$C_u = \frac{\sum k_i \sum GDP_i E_i}{\sum GDP_i} \tag{5}$$

where C_u is the comprehensive water consumption per unit GDP (except agriculture) at a given carrying level, GDP_i is the industrial added value of different sectors, mainly including secondary and tertiary industries. k_i is the industrial added value as a percentage of GDP (except agriculture), and E_i is the norm of water consumption for given industry. i represents different sectors.

The added value of different industries is predicted according to their respective development trends. Therefore, it is not completely independent and is limited by the historical proportional structure. Some unreasonable phenomena are expected in the process of extension, and the industrial structure can be adjusted:

$$\begin{cases} GDP_i = (1+\beta_i) GDP_{i,fo} \\ GDP_{agr} = (1+\beta_{ag}) GDP_{agr,fo} \end{cases} \tag{6}$$

where $GDP_{i,fo}$ is the initial forecast added value of different industries. $GDP_{agr,fo}$ is the initial forecast added value of agriculture. β_i and β_{ag} are the adjustment factor, which can control the changing industry added value. When the carrying level is determined, the initial projections of population and GDP per capita are fixed, so the initial forecasted total GDP is also a fixed value. When adjusting the industrial structure, it should satisfy the following constraint:

$$\sum \beta_i GDP_{i,fo} + \beta_{agr} GDP_{agr,fo} = 0 \tag{7}$$

k_i can be obtained using Equation (8):

$$k_i = \frac{GDP_i}{\sum GDP_i} \tag{8}$$

where k_i is not the industrial added value as a proportion of the total GDP, but a proportion of the sum of the secondary and tertiary added values.

The third-level calculation

The total bearable GDP at a certain level can be calculated by comparing the comprehensive water consumption per unit production and total available valid water resources:

$$E_t = W_{ec}/C_u \cdot K_{s\&t} \tag{9}$$

where E_t is the bearable economic scale at a certain carrying level, W_{ec} is the valid water resources for secondary industry and tertiary industry and $K_{s\&t}$ is the secondary and tertiary industrial added values as the percentage of GDP.

With the estimated total economic scale, the bearable population can be determined from the average GDP per capita at that carrying level:

$$P = E_t/V_p \tag{10}$$

where P is the bearable population scale at a certain carrying level and V_p is the average GDP per capita (with agriculture not included) at a given carrying level. Given the total economic scale and average GDP per capita, the other index for the WRCC (i.e., the bearable population) can be determined. When the carrying population is determined, the carrying capacity condition can be determined according to the water carrying index:

$$\delta = \frac{P_{fo}}{P} \tag{11}$$

where δ is the water carrying index. When δ is greater than 1, the predicted population is within the carrying range; when it is less than 1, the predicted population exceeds the carrying capacity. P_{fo} is the initial forecast population and P is the bearable population.

Finally, the estimated water demands should be checked against the domestic water needs from the calculated bearable population. If there is a large difference, the estimated population should be estimated again, and the whole process should be performed again. For example, if the water demand from the calculated bearable population is much higher than the estimated water demand for domestic users, this means that the estimated water resources for domestic users are too low. Hence, the estimated water demand subtracted from the total valid water resources should be increased or vice versa. When the forecasted population is changed, the forecasted GDP should change, and the water demand for agriculture should also be revised proportionally:

$$W_{ar} = \frac{P_{\mathrm{ca}}}{P_{fo}} \cdot W_{fo} \tag{12}$$

where W_{ar} is the revised agricultural water consumption. P_{ca}, P_{fo} are the revised and initial population respectively. W_{fo} is the initial forecast of agricultural water demand. After the necessary calibration and iterative checking of the pre-allocation to the domestic water demand, a rational WRCC representing the total economic scale and population can be obtained.

RESULTS AND DISCUSSION

Study area

The Shiyang River Basin (SRB) is an essential part of the Silk Road. The river flows through the eastern Hexi Corridor in northwest China, and the basin is a typical arid inland region. As shown in Figure 2, the catchment area of the Shiyang River covers about 41,600 km^2, most of which lies within Wuwei City in Gansu Province. The SRB is a typical arid region with over-exploited water resources. Agricultural oases are distributed in the SRB, and Wuwei is the main regional city. The SRB has a total of 24 reservoirs for irrigation and flood prevention purposes, although they are relatively small. The population in the SRB was 2,211,700 as of 2015. According to government statistics, the irrigated area of the SRB increased by 30% from the 1950s to 2003, and the total amount water use increased by 75% (Yao *et al.* 2017). The eight tributary rivers showed a significant reduction in the total annual runoff from 1958 to 2003 because of the influence of human activities and global climate change (Li *et al.* 2008). In recent decades, people in this region have been facing problems with overdevelopment and desertification (Su *et al.* 2018).

Huang *et al.* (2017) analyzed the water poverty index of the Hexi Corridor and concluded that the basin exhibits a relative deficiency in the distribution of water resources in various water sectors with a notable degree of water use inefficiency. Among the three basins of the Hexi Corridor, the SRB has the scarcest amount of water resources (Bao & Fang 2007). In response to the increased competition

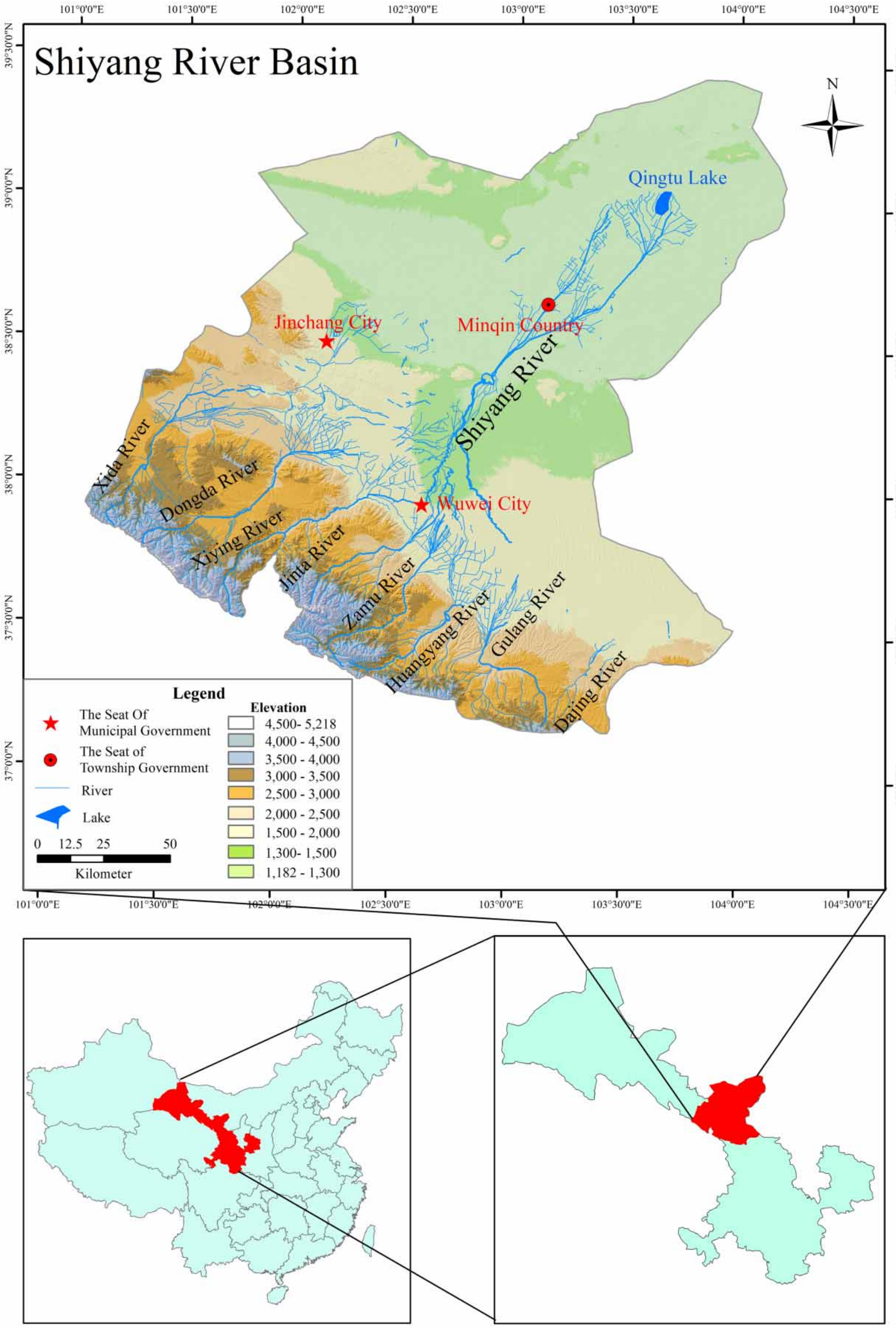

Figure 2 | River system of the Shiyang River Basin.

for water resources, many measures are being taken, such as strengthening legislation and supervision to prevent the illegal exploitation of groundwater, increasing the number of groundwater observation stations, and developing new water-saving irrigation technology (Hao *et al.* 2017). However, the ecosystem is still fragile because of excessive human activities. In order to support the construction of the Belt and Road Initiative, it is necessary to analyze the WRCC in the SRB.

Analysis of the carrying level

The years when the SRB reached the levels of basic subsistence, well off, wealthy, and modernized can be determined according to the GDP per capita and forecasted results of economic development. The GDP per capita between 1980 and 2011 in Table 2 and the predicted GDP per capita in 2020 and 2030 were used to derive the per capita GDP trend line of the SRB (Table 2). The data for the years 1980–2011 are from official statistical data. The data source of 2020 and 2030 years is the *Shiyang River River Basin Recent Integrated Management Planning*, which has been approved by the State Council of China.

Figure 3 shows that the SRB reached the basic subsistence carrying level in 1996 when the per capita GDP was 3248 Chinese yuan (CNY). The SRB reached the well-off carrying level in 2006 when the per capita GDP was 6825 CNY. The SRB is predicted to reach the wealthy carrying level in 2041 when the per capita GDP will be 24,430 CNY. The SRB is predicted to reach the modernized carrying level in 2096 when the per capita GDP will be 74,520 CNY. According to the GDP growth curve in Figure 4, the national economy will grow very slowly from 1996 to 2096 with an average GDP per capita growth rate of only 3.2%.

Table 2 | The historical and predicted population and economy data

Year	GDP (billion CNY[a])	Population (thousand)	GDP per capita (CNY)
1980	1.7	1682	989.7
1985	2.5	1784	1,373.5
1990	4.3	1932	2,224.6
1995	6.1	2079	2,955.0
2000	9.9	2105	4,688.4
2005	1.5	2143	6,975.3
2011	20.7	2197	9,421.4
2020	35.8	2672	12,041.0
2030	53.3	3006	17,721.2

[a] CNY, Chinese yuan.

Calculating valid water resources

The surface water resources in the SRB are mainly generated in the Qilian Mountains. The runoff generation area

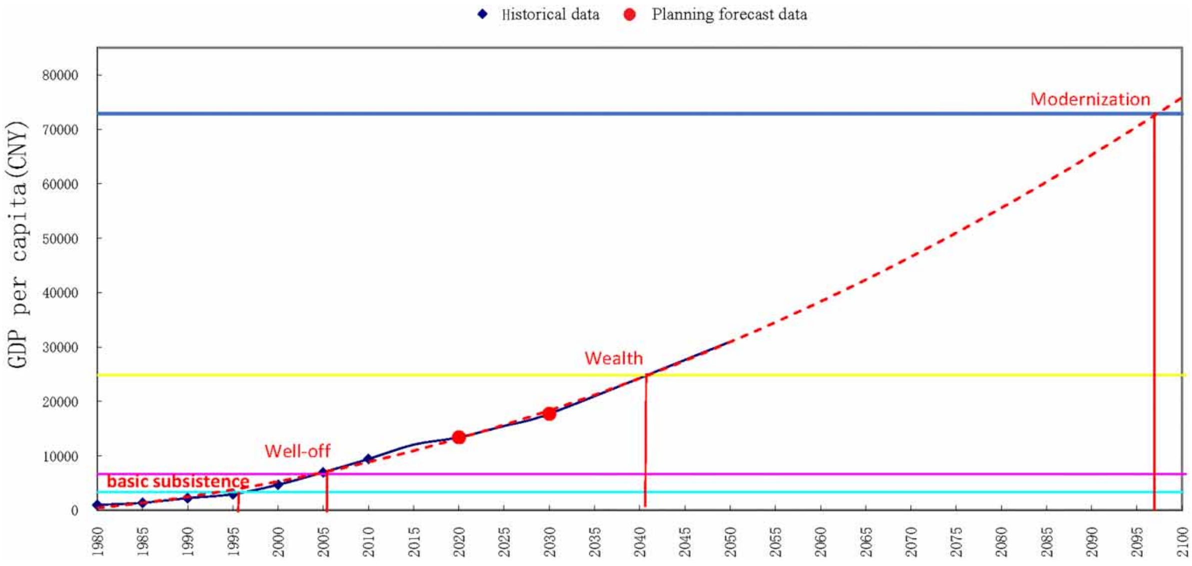

Figure 3 | Temporal changes in the gross domestic product (GDP) per capita in the Shiyang River Basin (SRB).

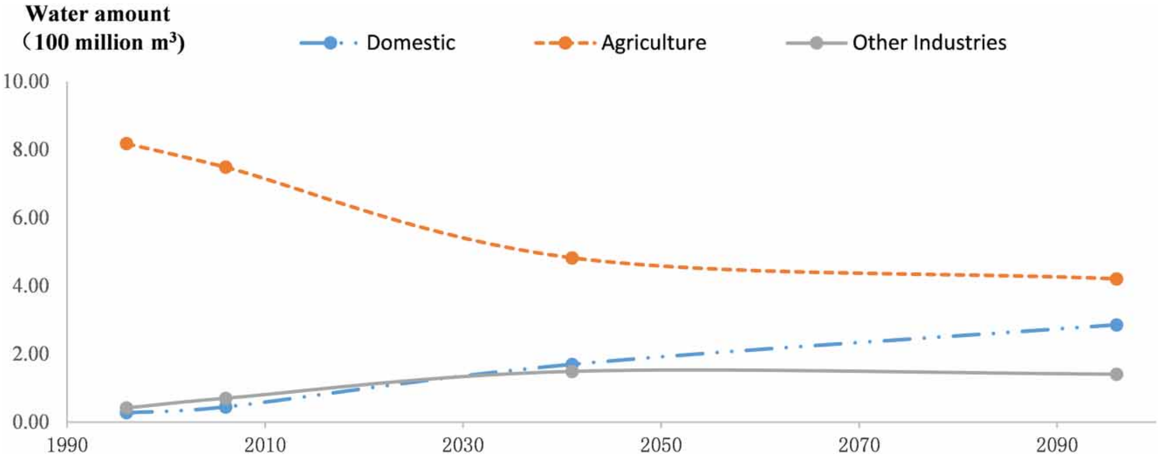

Figure 4 | Water consumption trends for different carrying levels.

is 11,100 km^2, and the volume of surface water resources is 1.56 billion m^3. Owing to the impact of climate change on the water cycle, the mean monthly streamflow of the SRB is predicted to increase 3.7% in 2041–2070 and 4.9% in 2070–2100 at the Zamu gauging station (Wang *et al.* 2012). The predicted amount of surface water resources based on this trend is 1.62 billion m^3, when the wealthy carrying level is reached (i.e., 2041) and 1.64 billion m^3, when the modernized carrying level is reached (i.e., 2096). Owing to the construction of water conservation facilities, uncontrollable floods will be reduced and so the rate of regulated water in the basin will increase from 63.3% to 70% as the carrying level increases. The non-duplicate groundwater resource was 99 million m^3, including the recharged water from precipitation and condensation (43 million m^3), the lateral recharge water from desert areas (49 million m^3), and the lateral recharge water from the Qilian Mountains area (7 million m^3). The ecological water demand outside the river is mainly for urban water use and anti-sand forest irrigation. With the development of urban green areas and increase in anti-sand forest areas, eco-water demand will increase in the future, and there will be less valid water resources for the economy and the population, as indicated in Table 3.

Determining social and economic indicators

Equation (5) was used to calculate the comprehensive water consumption per unit GDP. The historical data and comprehensive planning of the Shiyang River resources were used with trend analysis to predict the added value and water norm of different industries at different carrying levels. In order to improve the accuracy of the calculated results, calculations were carried out according to the sub-industry. Secondary industries include the energy industry, heavy industry, and light industry. Tertiary industry mainly includes construction, transport, and services.

Table 4 indicates that, at the basic subsistence carrying level, the comprehensive water consumption per unit GDP is 146.4 m^3/10,000 CNY. At the modernized carrying level, it is reduced to 10.5 m^3/10,000 CNY. As the carrying level increases, the water norm of various industries decreases,

Table 3 | Valid water resources for different carrying levels (unit: 100 million m^3)

Carrying level	Surface water	Utilization ratio (%)	Available surface water	Exploitable groundwater	Eco-water demand	Valid water resources
Basic subsistence	15.6	**63.3**	**9.87**	0.99	2.0	**8.86**
Well off	15.6	**65.0**	**10.14**	0.99	2.5	**8.63**
Wealthy	16.2	**68.0**	**11.02**	0.99	4.0	**8.01**
Modernized	16.4	**70.0**	**11.48**	0.99	4.0	**8.47**

and the water efficiency increases; therefore, the comprehensive water consumption per unit GDP decreases.

Analysis of preliminary carrying conditions

The first step to calculating the carrying capacity was to determine whether the water demand at the predicted carrying level could be guaranteed to be met. The population could be predicted based on population development rate. Then, the amount of domestic water demand at different carrying levels was determined from the projected population and norm for the per capita domestic water use. As indicated in Table 5, the predicted socio-economic development caused the total water demand to exceed the valid water resources. This implies that the SRB will be overloaded at any carrying level. This result is consistent with Professor Zhao's evaluation of the SRB (Zhao et al. 2009). He also found that the WRCC of the SRB will be overloaded in the future. Bao & Fang (2007) indicate that the use of water resources approaches or exceeds the threshold of natural resource in the SRB. In particular, groundwater resources are in a serious state of over-exploitation. According to the *Water Resources Bulletin for the Shiyang River Basin in 2015*, actual groundwater extraction was 767 million m^3 in 2015, but its exploitable capacity was only 99 million m^3. The development model of the SRB is unsustainable under the present situation; therefore, it is necessary to analyze the factors affecting the WRCC and determine the reasonable development mode and scale.

Analysis of carrying capacity

According to Equations (4)–(10), all parameters of the carried body are dynamically correlated based on per capita GDP. When predicting population adjustment, the total GDP can be obtained based on per capita GDP. If the economic structure and water efficiency of the carrying level remain unchanged, the GDP and water consumption of different production sectors will be adjusted. When the available water resources are quantitative, the carrying capacity is a constant value, and so the relationship between socio-economic factors and carrying capacity can be quantitatively analyzed. For each calculation process, the bearable population was compared with the projected population; if

Table 4 | Comprehensive water consumption per unit gross domestic product (GDP) for different carrying levels[a]

Carrying level		Basic subsistence (1996)	Well off (2006)	Wealthy (2041)	Modernized (2096)
Agricultural	Added value (100 million CNY)	23.3	37.5	123.1	260
Energy industry	Added value (100 million CNY)	0.7	1.4	6.5	15.0
	Water norm (m^3/10,000 CNY)	902.4	742.7	270.0	70.0
Heavy industry	Added value (100 million CNY)	17.4	35.4	171.8	340.0
	Water norm (m^3/10,000 CNY)	396.6	326.3	117.3	55.0
Light industry	Added value (100 million CNY)	8.9	17.8	83.7	280.0
	Water norm (m^3/10,000 CNY)	39.7	32.9	12.3	10.0
Construction	Added value (100 million CNY)	5.1	14.8	59.5	174.0
	Water norm (m^3/10,000 CNY)	6.5	4.9	1.5	0.5
Transport	Added value (100 million CNY)	3.0	5.3	27.2	65.0
	Water norm (m^3/10,000 CNY)	8.0	6.8	2.4	2.3
Services	Added value (100 million CNY)	20.1	49.3	211.6	1,350.0
	Water norm (m^3/10,000 CNY)	7.0	6.8	0.5	0.5
GDP (100 million CNY)		**78.5**	**161.5**	**683.4**	**2,484**
Total added value (except agriculture) (100 million CNY)		**55.2**	**124**	**560.3**	**2,224.0**
Comprehensive water consumption per unit GDP (except agriculture) (m^3/10,000 CNY)		**146.4**	**109.8**	**41.4**	**10.5**

[a]CNY, Chinese yuan.

Table 5 | Carrying conditions for predicted development levels[a]

Carrying level		**Basic subsistence**	**Well off**	**Wealthy**	**Modernized**
Agricultural	Arable land (ha)	228,000.1	232,666.8	194,000.1	194,000.1
	Irrigation norm (m^3/ha)	6975.0	6240.0	3,870.0	3615.0
	water demand (100 million m^3)	15.9	14.5	7.5	7.0
Other industries	Added value (100 million CNY)	55.2	124.0	560.3	2,224.0
	Comprehensive water consumption per unit GDP (m^3/10,000 CNY)	146.4	109.8	41.4	10.5
	Water demand (100 million m^3)	0.8	1.4	2.3	2.3
Life	Population (10,000)	220.1	236.2	323.9	324.6
	Domestic water norm (L/p·d)	65.0	100.0	224.0	400.0
	Water demand (100 million m^3)	0.5	0.9	2.6	4.7
Total water demand (100 million m^3)		17.2	16.7	12.5	14.1
Valid water resources (100 milliom^3)		8.9	8.6	8.0	8.5
Overload (Y/N)		Y	Y	Y	Y

[a]CNY, Chinese yuan; GDP, gross domestic product.

the error was large, adjustments were continued. The results obtained by trial and error for the predicted economic structure and eco-environmental water consumption are presented in Table 6. The bearable population is much lower than the predicted population, and hence, the carrying conditions are not optimistic. At the modernized carrying level, the carrying index is 1.72, indicating that 39% of the projected population does not have access to reliable water resources.

The local economic development level has important implications for water and ecological sustainability (Pan & Xu 2018). The bearable GDP gradually increases with an increasing carrying level. Socio-economic development optimizes the industrial structure and continuously increases the water use efficiency. Therefore, the output value per unit of water resources and the bearable GDP both increase. However, when the carrying level increases, the population does not show a single upward trend. At the well-off carrying level, the bearable population is below those of other carrying levels. The per capita GDP and water efficiency have a significant impact on the bearable population. Increasing the per capita GDP reduces the bearable population, but the increased water efficiency increases the bearable population.

When the carrying level was increased, the per capita GDP and water use efficiency increased, which had an opposite effect on the carrying capacity. From the basic subsistence to the well-off carrying levels, the per capita GDP growth was more significant than water efficiency improvement, so the bearable population decreased. However, from the well-off to the modernized carrying level, the water efficiency improvement was more significant than the per capita GDP growth, so the bearable population increased.

Figure 4 shows the water consumption trends of different water users on different carrying levels. The consumption of domestic water increased gradually with the increase in carrying level, and after the level of wealthy, it began to exceed the water consumption of the secondary and tertiary

Table 6 | Calculation results for the carrying capacity at different carrying levels[a]

Carrying level	**Year**	**Bearable GDP (100 million CNY)**	**Bearable population (10,000)**	**Projected population/bearable population**
Basic subsistence	1996	40	124	1.71
Well off	2006	83	122	1.93
Wealthy	2041	451	185	1.79
Modernized	2096	1484	199	1.72

[a]CNY, Chinese yuan; GDP, gross domestic product.

industries. A suitable proportion of domestic water consumption to the total water consumption was calculated to be 0.03–0.34 from the basic subsistence to the modernized carrying levels. Although the bearable population on the basic subsistence carrying level is more than when for the well off owing to its poorer living conditions, the domestic water consumption is relatively small. The consumption of water for agriculture will continue to decline but will fall less and less as the carrying level increases. However, it is still the largest water user in the SRB. With the increase of the carrying level, the added values of secondary and tertiary industries gradually increased. Thanks to the continuous improvement in water use efficiency, water consumption gradually stabilized. The proportion coefficient of water used for industrial development was set at 0.66 on the modernized carrying levels of the SRB.

Relationship between eco-environment water and WRCC

From the perspective of the whole water-resources system, there are coupling evolution processes and internal feed-in relationships between water, people, social economy, and ecological environment. The development and utilization of water resources should be based on maintaining the benign development of the ecological environment, and the needs of ecological water should be taken into account while supporting the scale of socio-economic development. Therefore, when calculating the carrying capacity of water resources, it is necessary to guarantee a suitable environment with a pre-set ecological water demand. In order to analyze the relationship between the ecological environment water consumption and the WRCC, the change in the carrying capacity can be analyzed by adjusting the size of the reserved ecological water volume. In this study, the predicted water demand for the ecological environment is taken as the maximum water reserve, and the proportion of water demand for the ecological environment is considered to change the water reserve for the ecological environment. Table 7 shows that with a reduction in the proportion of eco-environment water consumption, the bearable population and bearable GDP will increase accordingly in the study area, but they are disproportionate. At the modern carrying level, when eco-environment water is reduced by 50%, the population carrying level can increase by only 20%. Although the ecological environment has been severely damaged, the resulting population benefits are not obvious. Compression of the eco-environment water is not a sustainable development method and is not recommended.

Relationship between industrial structure and WRCC

According to Equation (5), the comprehensive water consumption per unit GDP is greatly influenced by the industrial structure. Therefore, at the same carrying level, adjusting the industrial structure will have a major impact on the WRCC. The industrial structure at the carrying level year is predicted based on historical data. The GDP increment of different industries is not completely independent, and they are constrained by the current economic structure. By adjusting the predicted industrial structure, we analyze the corresponding load-carrying capacity changes and determine the impact of the industrial structure on the carrying capacity. Zhang *et al.* (2018) pointed out that agriculture is a significant factor to solve the gap between supply and demand in northwest China. Therefore, this

Table 7 | WRCC on different proportions of eco-environment water demand[a]

	Bearable population (10,000)				Bearable GDP (100 million CNY)			
Proportion	Basic	Well off	Wealthy	Modernized	Basic	Well off	Wealthy	Modernized
25%	151	148	248	259	49	101	606	1,927
50%	144	140	226	235	47	95	551	1,751
75%	136	131	203	211	44	89	496	1,575
90%	132	126	190	197	43	86	464	1,470
100%	124	122	185	199	40	83	451	1,487

[a]CNY, Chinese yuan; GDP, gross domestic product.

study mainly focuses on the active adjustment of agricultural factors, while other industries are passively adjusted according to the predicted structure. When the proportion of agriculture in the industrial structure is reduced, qualitative analysis will lead to a reduction in agricultural water consumption, and hence, the amount of water available for other industries will increase. According to Equation (7), the relationship between the industrial structure and the carrying capacity is quantitatively analyzed using β_i. The horizontal coordinate of Figure 5 is the agriculture industrial structural adjustment coefficient; when this value gradually increases, it implies that agriculture accounts for an increase in the proportion of the industrial structure. When the value of the adjustment coefficient is negative, it means the adjusted agricultural proportion of total GDP is lower than the predicted structure, but on the contrary, the adjusted agricultural proportion of total GDP is higher than the predicted structure. The main longitudinal coordinate is the load-carrying population, and the secondary vertical coordinate is the load-bearing GDP.

Figure 5 shows that the larger the proportion of agriculture in the industry structure, the smaller the population and GDP that can be carried on the same carrying level year. Therefore, industrial structural optimization can be considered if the WRCC of a region needs to be increased. When $\beta_{\text{agriculture}}$ changes from 0.2 to -0.2, the variation in

Figure 5 | Trends for the bearable gross domestic product (GDP) and population with the agriculture industrial structural adjustment coefficient.

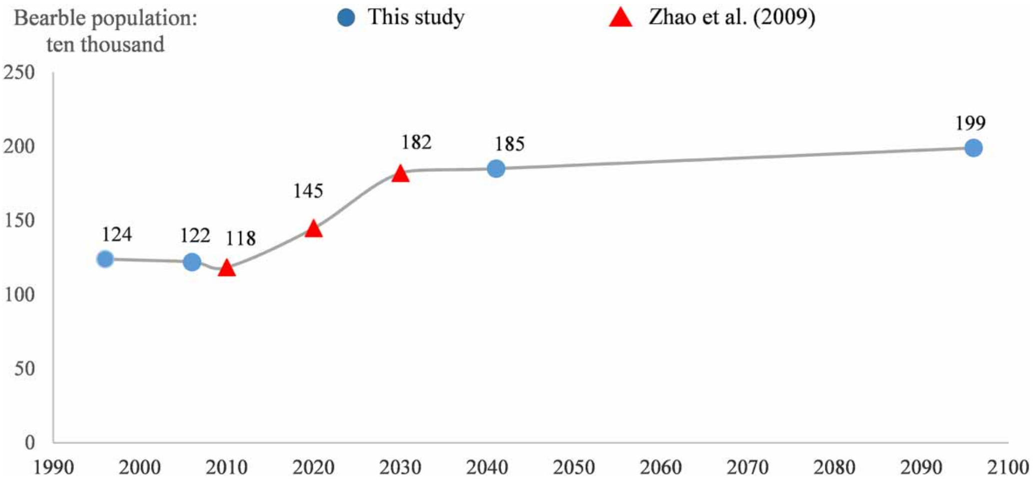

Figure 6 | Comparison of evaluation results between this study and that of Zhao *et al.* (2009)

the carrying capacity in higher carrying level years is smaller than that in lower carrying level years. Optimizing the industrial structure can increase the regional WRCC in the low carrying level years. In the high carrying level years, the industrial structure is already sufficiently optimized. It is more difficult to adjust the industrial structure, and it has less potential to increase the WRCC. The projected population at the modernized carrying level is 3.25 million; and agricultural water will need to be compressed by 80% to carry this population. This proportion will lead to the total destruction of agricultural production and will not guarantee effective food production. Therefore, the population size must be controlled, or water diversion projects need to be considered to increase the amount of water available.

DISCUSSION

Many studies have considered how to calculate the WRCC. Zhang & Li (2010) established the model using a set pair analysis based on entropy weight. Xu & Zhao (2013) calculated the WRCC based on the principal component analysis method and entropy method. Gong & Jin (2009) used fuzzy comprehensive evaluation to evaluate the WRCC of Lanzhou city. The core of these methods is to convert multiple indicators into one comprehensive indicator by constructing an indicator system and determining weights, so as to evaluate the WRCC based on the comprehensive indicator. These methods can be very effective in evaluating the water load in a region, but the comprehensive indicator usually has no physical significance. The calculation method of the WRCC based on the three-level analysis proposed here, transforming the most intuitive GDP and population as the ultimate carrying capacity evaluation indicator, can quantitatively analyze the balance relationship between water resources and social economy in a region. Moreover, the carrying population and GDP are dynamically related through the per capita GDP. There will be no reduction in per capita domestic water even if the economic water consumption increases. This method not only evaluates the carrying state of water resources, but also informs decision makers about the extent to which the population and GDP can be carried and how they can be adjusted based on full consideration of the ecological water.

Zhao *et al.* (2009) also analyzed the carrying capacity of the SRB based on the calculation methods of both water quantity and quality for the years 2010, 2020 and 2030. Zhao *et al.*'s projected population and socio-economic data for 2020 and 2030 were also based on the *Shiyang River Basin Recent Integrated Management Planning*, and used roughly the same amount of water resources. Although the years used for the calculation are different, the results can be compared based on relatively close years and trends (Figure 6). According to the results of this study, the bearable population for 2006 is 1.22 million; according to the results of Zhao *et al.* (2009), the bearable population in 2010 is 1.18 million. Thus, the results using the different methods are relatively close for 2006 and 2010. According to Zhao *et al.* (2009), the bearable population will be 1.82 million in 2030, which is close to values found for 2041 in this study. Although the two time nodes differ by 11 years, the trends are the same. Zhao *et al.* (2009) also calculated the WRCC of the SRB in terms of water quality, according to the river self-purification capacity, but bearable population by water quality is much higher than water quantity, so the main constraint on the WRCC is the water quantity in the SRB. Moreover, Zhao *et al.* (2009) also clearly showed that water resources in the SRB have been in a state of overload for a long time; this is consistent with the results of our study.

The WRCC encompasses a large complex system, including society, economy, environment, ecology and resources. In this system, both the natural and human-based factors (e.g., social, economic, cultural, and others) affect the WRCC. According to our results, the WRCC in a region is dynamic. With the development of the economy and technology, the efficient utilization of water resources can be improved; this improvement is further helped by water conservation measures, and can thus increase the carrying capacity of each unit of water. Although this uncertainty increases the complexity of regional WRCC calculation, it provides decision makers with the rationale to adjust water resources planning and socio-economic development trends. For the SRB, it is necessary to improve the efficiency of water resources utilization with the help of advanced science and technology, speed up the adjustment of the industrial structure, and gradually reduce the over-exploitation of groundwater to ensure an efficient utilization model of water resources. Water diversion at an appropriate scale or planned migration could also alleviate the water crisis in the basin.

CONCLUSIONS

The WRCC is a valid index for identifying the supportable socio-economic scale based on water resources at certain living standards in a specific region or basin. It is expressed by the bearable economic scale and population for a specific socio-economic standard called the carrying level. This paper establishes a three-level WRCC model from two selected indices for the principal body and objects. The population size and GDP per capita were chosen to represent both the scale and level of socio-economic development at different carrying levels. The established model was used to evaluate the WRCC of the SRB. According to the predicted development trend, the total water demand will exceed the amount of water resources available, and the SRB is already overloaded. Optimizing the industrial structure and improving water efficiency would increase the carrying capacity. However, even with improved efficiency, the population is still above the WRCC.

Through qualitative and quantitative analysis of the regional WRCC under the influence of various factors, the following measures can be considered to improve the regional WRCC:

(1) Restructuring of socio-economic development: The structure of socio-economic development needs to be matched with the local water resources conditions. The WRCC is related not only to the GDP but also to the economic structure. For regions with poor water resources, appropriate policies are needed to guide the development of low-water-consuming industries. The water resources in the SRB do not match the current socio-economic structure, which will leads to serious ecological environment problems. Therefore, it is necessary to gradually reduce the proportion of agricultural development and develop other industries with higher added value.

(2) Improving the water efficiency: Improving the water efficiency can increase the bearable population and GDP. Basic measures to improve water efficiency, including economic, technical, and regulatory policies and public participation, are a comprehensive and systematic exercise. Examples include reforming water prices to stimulate water use efficiency; developing new technologies, equipment, and new techniques to save water; strengthening water management; and educating the public about water conservation.

(3) Improving water resource utilization: To maximize water resource utilization, the complementary use of surface water, groundwater resources and unconventional water sources is essential. The utilization of water resources requires full consideration of the water needs of the ecological environment, to ensure the sustainable development of water resources. In addition, a greater degree of inter-basin water transfer is required to achieve sustainable water resource utilization, especially in dry areas.

(4) Ensuring good water quality: Water quality is also a determinant of carrying capacity, and only qualified water can be regarded as the valid water resources. Therefore, while developing the social economy, sewage treatment capacity building should be strengthened.

The results of the model for the SRB are satisfactory and should help policymakers to develop sustainable approaches to environmental management and planning. The three-level WRCC analysis method can not only be used for the overall basin, but also could also be used to evaluate the differences in water carrying conditions between different regions within a basin or city. In future work, it will be necessary to normalize and simplify the method, and create a visual model with information technology tools to makes the calculation of the WRCC more convenient and universal.

ACKNOWLEDGEMENTS

This work was supported by the National Key Research and Development Programme of China (2017YFC0404405, 2018YFC0407705, 2016YFC0401301); the National Natural Science Foundation of China (71774172, 51279210); and the Consulting Project of the Academy of Engineering (2020-XY-41).

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Abernethy, V. D. 2001 Carrying capacity: the tradition and policy implications of limits. *Ethics in Science and Science and Environment Politics* **1**, 9–18.

Bao, C. & Fang, C. L. 2007 Water resources constraint force on urbanization in water deficient regions: a case study of the Hexi corridor, arid area of NW China. *Ecological Economics* **62** (3-4), 508–517. doi:10.1016/j.ecolecon.2006.07.013.

Carter, J. & Howe, J. 2006 The water framework directive and the strategic environmental assessment directive: exploring the linkages. *Environmental Impact Assessment Review* **26** (3), 287–300. doi:10.1016/j.eiar.2005.05.001.

Ding, Y. F., Tang, D. S., Dai, H. C. & Wei, Y. H. 2014 Human-water harmony index: a new approach to assess the human water relationship. *Water Resources Management* **28** (4), 1061–1077. doi:10.1007/s11269-014-0534-1.

Feng, L. H., Zhang, X. C. & Luo, G. Y. 2008 Application of system dynamics in analyzing the carrying capacity of water resources in Yiwu City, China. *Mathematics and Computers in Simulation* **79** (3), 269–278. doi:10.1016/j.matcom.2007.11.018.

Gong, L. & Jin, C. 2009 Fuzzy comprehensive evaluation for carrying capacity of regional water resources. *Water Resources Management* **23** (12), 2502–2513. doi:10.1007/s11269-008-9393-y.

Hadwen, S. & Palmer, L. J. 1992 *Reindeer in Alaska, Bulletin No. 1089*. US Department of Agriculture: Washington, DC, USA, pp. 1–70.

Hao, Y., Xie, Y., Ma, J. & Zhang, W. 2017 The critical role of local policy effects in arid watershed groundwater resources sustainability: a case study in the Minqin oasis, China. *Science of The Total Environment* **601–602**, 1084–1096. doi:10.1016/j.scitotenv.2017.04.177.

Huang, S., Feng, Q., Lu, Z., Wen, X. & Deo, R. C. 2017 Trend analysis of water poverty index for assessment of water stress and water management polices: a case study in the Hexi Corridor, China. *Sustainability* **9** (5), 756. doi:10.3390/su9050756.

Jia, R. N., Jiang, X. H., Shang, X. X. & Wei, C. 2018 Study on the water resource carrying capacity in the middle reaches of the Heihe River based on water resource allocation. *Water* **10** (9), 1203. doi:10.3390/w10091203.

Li, Z. L., Xu, Z. X. & Li, Z. J. 2008 Shift trend and step changes for runoff time series in the Shiyang river basin, northwest China. *Hydrological Processes* **22** (23), 4639–4646. doi:10.1002/hyp.7127.

Pan, H. L. & Xu, Q. 2018 Quantitative analysis on the influence factors of the sustainable water resource management performance in irrigation areas: an empirical research from China. *Sustainability* **10** (1), 264. doi:10.3390/su10010264.

Pulliam, H. R. & Haddad, N. M. 1994 Human population growth and carrying capacity concept. *Bulletin of the Ecological* **9**, 141–157.

Su, F., Saikis, U. & Hay, I. 2018 Relationships between livelihood risks and livelihood capitals: a case study in Shiyang River Basin. *China. Sustainability* **10** (2), 509. doi:10.3390/su10020509.

Varis, O. & Vakkilainen, P. 2001 China's 8 challenges to water resources management in the first quarter of the 21st century. *Geomorphology* **41** (2–3), 93–104. doi:10.1016/s0169-555x(01)00107-6.

Wang, K. F. 2016 Evaluation of the water resources carrying capacity of Shandong peninsula. *China. Journal of Groundwater Science and Engineering* **4** (2), 120–130.

Wang, Z. G., Ficklin, D. L. & Zhang, Y. Y. 2012 Impact of climate change on streamflow in the arid Shiyang River Basin of northwest China. *Hydrological Processes* **26** (18), 2733–2744. doi:10.1002/hyp.8378.

Xu, Y. Y. & Zhao, Q. L. 2013 Water resources carrying capacity based on principal component analysis. *2013 21st International Conference on Geoinformatics*. doi:10.1109/geoinformatics.2013.6626084.

Yao, L. Y., Zhao, M. J. & Xu, T. 2017 China's water-saving irrigation management system: policy, implementation, and challenge. *Sustainability* **9**, 2339. doi:10.3390/su9122339.

Yuan, Y., Gan, H. & Wang, Z. J. 2006 Discussion on progress and development trend of the research on water resources carrying capacity. *Journal of China Institute of Water Resources and Hydropower Research* **4** (1), 62–67 (in Chinese).

Yue, C., Cui, Y. L., Rao, R. & Dong, X. 2015 Evaluation on water resources carrying capacity of Changchun-Jilin region. *Journal of Groundwater Science and Engineering* **3** (2), 164–169.

Zhang, X. & Li, N. 2010 Research on water resources carrying capacity based on set pair analysis evaluation model. In: *2010 3rd International Conference on Information Management, Innovation Management and Industrial Engineering*, Kunming, China, 26–28 November 2010; IEEE: Piscataway, USA, pp. 350–353.

Zhang, H., Jin, G. & Yu, Y. 2018 Review of river basin water resource management in China. *Water* **10** (4), 425. doi:10.3390/w10040425.

Zhao, J. S., Wang, Z. J., Gan, H. & Li, H. H. 2009 Computable model for carrying capacity of two dimensional water resources and its application. *Journal of Hydroelectric Engineering* **28** (3), 167–180.

First received 22 January 2020; accepted in revised form 26 June 2020. Available online 9 July 2020