

Spatio-temporal evolution and influencing factors of water resource carrying capacity in Shiyang River Basin: based on the geographical detector method

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ABSTRACT

In this article, the comprehensive evaluation of water resource carrying capacity (for short WRCC) in Shiyang River Basin is the objective. Based on the comprehensive evaluation model of regional WRCC, the spatial and temporal change characteristics of the WRCC in Shiyang River Basin in 2007, 2011 and 2016 have been analyzed. Moreover, the influence elements of water resource carrying capacity in Shiyang River Basin are detected by the geographical detector. The results show that: (1) In terms of the spatial dimension, water resources in Shiyang River Basin are not in accordance with the distribution of social and economic development and population distribution, presenting a prominent contradiction between supply and demand of water resources; (2) in terms of the temporal dimension, the pressure on water resources in Shiyang River Basin has gradually increased, and the area of overload, light overload and serious overload has been augmented; (3) the geographical detector indicates that the influences of the water resources system and coordinating system factors are declining, and the influences of the social economy system and ecological factor are obviously increasing. The influences of the interaction with any two factors are stronger than that of a single factor, and the synergistic influences of two factors are aggravated.

Key words | comprehensive evaluation model, geographical detector, Shiyang River Basin, water resource carrying capacity (WRCC)

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INTRODUCTION

Water resources are not only basic natural resources, but also strategic economic and social resources (Fang *et al.* 2019; Fu *et al.* 2019). The carrying capacity of water resources (WRCC) refers to the capacity of water resources to support the maximum demands of the population, social economy and ecological environment in a certain region with commitment to a certain socio-economic development level and water ecological environment (Chen & Wu 2014; Yuan *et al.* 2017; Zhang & Jin 2019). With global warming, rapid urbanization and rapid industrialization, highlighted problems are increasingly prominent in arid and semi-arid areas of China – Shiyang River Basin (Zhou *et al.* 2015), such as water resources shortage, water environment

deterioration, and water ecological imbalance. Water resources utilization in the basin approaches or even exceeds the limit of the carrying capacity, which means the carrying capacity of water resources has become the important restricting factor in the sustainable development of the river basin (Li & Li 2012; Xia *et al.* 2012). WRCC is a basic measure to evaluate the sustainable development of water resources, and it is a 'bottleneck' index to measure whether water resources can support the coordinated development of the population, economy and environment in Shiyang River Basin (Wu *et al.* 2018; Cheng *et al.* 2020). The correct evaluation of WRCC in Shiyang River Basin is not only an important aspect of the rational and full

utilization of water resources, but is also closely related to the goal of social and economic development (Brown *et al.* 2015; Xiao *et al.* 2017; Cui *et al.* 2019; Liu *et al.* 2019; Wang *et al.* 2019a). It is the focus and hotspot of water resources scientific research (Li *et al.* 2014; Guo *et al.* 2017; Wang *et al.* 2019b).

The internal elements of a water resources system are interconnected and interact with each other to form a large complex system. It is necessary to construct an index system to reflect the carrying capacity of water resources (Guo *et al.* 2017). WRCC in different regions has been evaluated by constructing index systems and multiple quantification methods in academic circles. There are two principal methods to construct the index system. One is the system analysis method. Aimed at sustainable development theory, the system is divided into subsystems composed of different levels and elements from the perspective of system theory (Su *et al.* 2019; Zhou *et al.* 2019), taking into overall consideration the complexity and systematization of water resources. The disadvantage of this method is the complex calculation and limited application (Wu *et al.* 2018). The other one is the comprehensive evaluation method, relying on the comprehensive evaluation model of WRCC by borrowing the comprehensive evaluation model of ecological carrying capacity, and setting an evaluation standard to give a comprehensive evaluation for regional WRCC. The main models include: pressure state response (PSR) model (Yan *et al.* 2008), driving state response (DSR) model (Wang & Liu 2019), driving pressure state impact response (DPSIR) model (Chen *et al.* 2004), and driving pressure state impact response management (DPSIRM) model (Guo *et al.* 2017). However, the systematicity of water resources is ignored in the study, and it is difficult to unify the index selection and evaluation criteria (Wu *et al.* 2018). The quantitative evaluation methods mainly include the comprehensive evaluation method (Liu *et al.* 2011; Zhang *et al.* 2018a), principal component analysis method (Xu *et al.* 2011; Li & Zhang 2017), multi-objective analysis method (Fu *et al.* 2011), system dynamics method (Dürr *et al.* 2006), etc.

The regional water resources composite system is a composite system which is composed of the coupling of society, economy, ecological environment and water resources (Wu *et al.* 2018). Taking two cities and five counties in Shiyang River Basin as the research objects, combining the

comprehensive evaluation method with the system analysis method, a comprehensive evaluation model is constructed of regional water resource carrying capacity which takes water resources, social economy, ecological environment and coordination system as its subsystems. The spatio-temporal pattern of water resource carrying capacity in Shiyang River Basin was analyzed by using the spatial analysis and visualization function of ArcGIS, and the factors affecting water resource carrying capacity were analyzed by geographic detector. The following problems will be solved: (1) carrying capacity and state between supply and demand of water resources in Shiyang River Basin; (2) the economic and population pressure on water resources in Shiyang River Basin; (3) the coordinated development degree of the water resources composite system; (4) factors influencing the carrying capacity of water resources. Through the above research, it is expected that a scientific basis will be provided for the sustainable utilization of water resources in Shiyang River Basin and regional coordinated development.

STUDY AREA AND DATA

Study site

The study site is located in the east of Hexi corridor of Gansu Province, west of Wushaoling Mountain and at the north foot of Qilian Mountain. It is one of the three major inland river basins in Hexi corridor, between longitudes 101°41'–104°16' and latitudes 36°29'–39°27'. In terms of administrative divisions, it involves two cities and five counties (districts), including Liangzhou district, Gulang county, Minqin county and the north of Tianzhu Zangzu Autonomous County, Yongchang county and Jinchuan district and Yugur Autonomous County of Sunan (for short Sunan county), and the total area of the basin is about 40,578 square kilometres (Yang *et al.* 2014; Guo *et al.* 2019). In regards to the climate, the region is characterized by little precipitation but strong evaporation, with the average annual precipitation reaching 213 mm (Deng *et al.* 2017; Zhang *et al.* 2017). The river basin is composed of eight major rivers from east to west, including Dajing River, Gulang River, Huangyang River, Zamu River, Jinta

River, Xiying River, Dongda River and Xida River. River water supply is an important source of mountain precipitation supply and snow melt water supply from the mountain. The basin consists of eight large and medium-sized reservoirs. The average annual water resources in the basin are 1.776 billion cubic metres, the average annual surface water resources are 1.5037 billion cubic metres, the average groundwater resources are 2,613.1 million cubic

metres, and the average per capita water resources are 734 cubic metres (Shiyang River Basin management 2018). An overview of the study area is shown in Figure 1.

Data sources

In this study, 19 indicators were selected from the aspects of water resources, society–economy and ecological

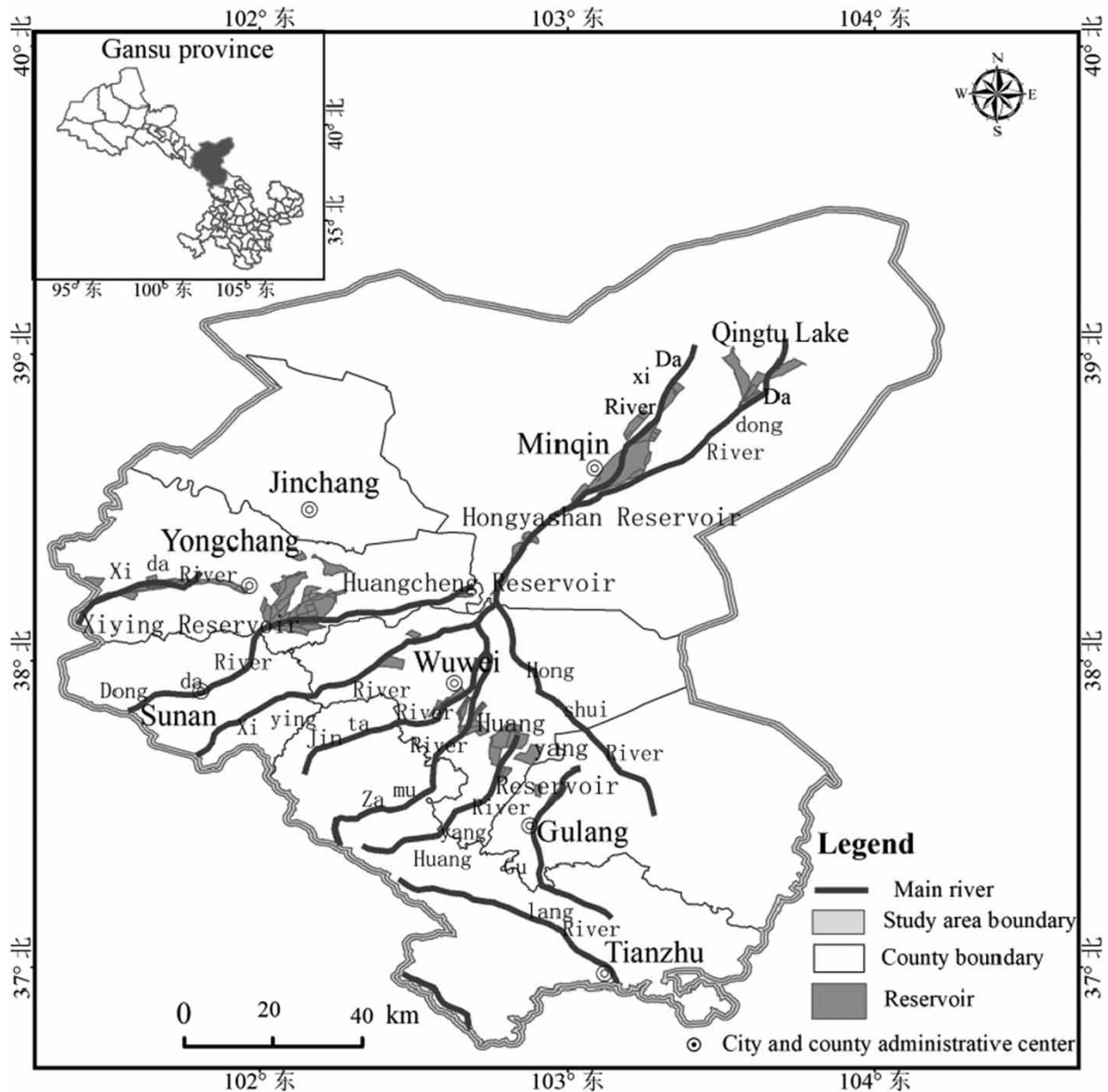


Figure 1 | The study site: geographical location, study boundaries, administrative districts, rivers, reservoirs.

environment. The data were informed from the following resources: (i) basic socio-economic data were derived from the Statistical Yearbook of China and Gansu province (2007, 2011, 2016); (ii) ecological environment data were provided by the Chinese Big Data Platform and the Data Center for Resources and Environment, Chinese Academy of Sciences (RESO); (iii) water resource utilization data were derived from Gansu Hydrologic Year Book, the Gansu Water Resources Bulletin, the Gansu Shiyang River Basin Management Bureau, water resources bulletin of Shiyang River Basin and water resources statistical bulletin of Gansu province. The groundwater-table data can be obtained from the Wuwei Hydrology Bureau and China Institute of Geo-Environment Monitoring (CIGEM).

METHODS

Comprehensive evaluation model of water resource carrying capacity

Index system design and weight calculation

The water resources system is a composite system of water resources, society, economy and ecology. In the selection of indicators, the population, resources, social, economic and ecological effects on the carrying capacity of water resources should be taken into account to truly reflect the coexistence of the components of the carrying capacity of water resources. In this study, considering principles such as the representative, comprehensive and scientific indicators and data availability, and combining the issues of Shiyang River Basin in arid and semi-arid climate features and the water resources supply-and-demand situation, 19 specific indicators from four subsystems, covering water resources, social economy, and ecology are selected (Table 1), and a water resource carrying capacity comprehensive evaluation index system in Shiyang River Basin is constructed.

Due to the different calculation units and orders of magnitude of each index, it is impossible to directly compare the indices. For the above reasons, using the extreme method for non-dimensional indicators of the

original data makes the data comparable between the indicators, and finally the purpose of scientific calculation is achieved (Li et al. 2014). The entropy value method is used to determine the weight of each indicator after water indicators of the resources composite system are standardized (Table 2 and Figure 2).

Model construction

In order to quantitatively analyze the carrying capacity of water resources, a comprehensive evaluation model of regional water resource carrying capacity will be constructed from four aspects: economic pressure, population pressure, carrying pressure and coordination level. The calculation formula is (Liu et al. 2011):

$$CI = \sqrt[3]{(\alpha E_P I + \beta P_P I) \times C_P I \times H I}$$

In this formula, CI stands for the comprehensive evaluation index of regional water resource carrying capacity; $E_P I$ and $P_P I$ for economic pressure index and population pressure index respectively; α , β for the weight of economic pressure index and population pressure index, and α and β are equal weight 0.5 (Liu et al. 2011); $C_P I$ and $H I$ for load carrying index and coordination index respectively. Specific calculation methods of each index are shown in Table 3.

This study refers to Liu et al. (2011), the comprehensive evaluation study on the carrying capacity of water resources in China which was made by Jiajun Liu. The classification standard of the comprehensive evaluation index is determined according to the actual situation of water resources, society, economy and ecology in Shiyang River Basin (Table 4).

Geographic detector

Factor detection is used to quantitatively detect whether a certain geographical factor affects the reason for the difference in the spatial distribution of index values and its weight (Lv et al. 2017):

$$P_{DU} = 1 - \frac{1}{n\sigma_U^2} \sum_{i=1}^m n_{D,i} \sigma_{U_{D,i}}^2$$

Correct citation of Geodetector :

[1] Wang JF, Li XH, Christakos G, Liao YL, Zhang T, Gu X & Zheng XY. 2010. Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun region, China. International Journal of Geographical Information Science 24(1): 107-127.

[2] Wang JF, Zhang TL, Fu BJ. 2016. A measure of spatial stratified heterogeneity. Ecological Indicators 67: 250-256.

[3] Wang JF, Xu CD. 2017. Geodetector: Principle and prospective. Acta Geographica Sinica 72(1):116-134.

Table 1 | Comprehensive evaluation index and weights of water resource carrying capacity in Shiyang River Basin

Target layer	Criterion layer	Index layer	Meanings	Effects
Carrying capacity index	Water resources system (0.4394)	Per capita water resources (m^3/per) (0.0661)	The state of water resources shortage	Positive
		Surface water (10^4 m^3) (0.1033)	The amount of surface water resources	Positive
		Underground water (10^4 m^3) (0.1775)	The amount of groundwater resources	Positive
		Water production modulus (m^3/km^2) (0.0391)	The amount of water resources per unit area of the region	Positive
	Social and economic systems (0.1870)	Annual precipitation (mm) (0.0532)	The local water production capacity	Positive
		Population density (per/km^2) (0.0240)	Population pressure	Negative
		Per capita GDP (yuan/per) (0.0506)	The overall economic situation of the region	Positive
		Number of hospital beds (unit) (0.0223)	The relationship between water quality and human health	Negative
		Urbanization rate (%) (0.0901)	The ratio of urban population to the total population	Positive
	Ecological system (0.1607)	Ecological water use (10^4 m^3) (0.0268)	The water demand of the ecosystem	Negative
		Forest coverage rate (%) (0.0622)	The state of regional water conservation	Positive
		COD (t) (0.0269)	The chemical oxygen demand	Negative
		The rate of wastewater treatment (%) (0.0448)	The level of water conservation	Positive
		Fold purity of fertilizer (t) (0.0250)	The extent of infiltration water pollution	Negative
Coordination index	Coordinate system (0.2129)	Inter-basin water transfer (10^4 m^3) (0.0889)	The area water demand	Positive
		Irrigation rate (%) (0.0234)	The efficiency of agricultural irrigation	Positive
		Ten thousand yuan GDP water ($\text{m}^3/10,000 \text{ yuan}$) (0.0266)	The degree of coordination between water resources and economic development	Negative
		Agricultural water (10^4 m^3) (0.0247)	The dependence of agriculture on water	Negative
		Grain production (10^4 t) (0.0244)	The coordination of agricultural production and water resources	Negative

Note: The weights of 2016 are taken as an example in the table brackets.

Table 2 | The weight calculated by the entropy method

Steps	Formulas	Parameter description
(1) The index value is forward-processed, and the proportion of the evaluation index is transformed	$P_{ij} = \frac{Y_{ij}}{\sum_i^m Y_{ij}}$	P_{ij} stands for the proportion of standardized value on the j index in the i region; m for the sample area. Relevant data of Shiyang River Basin two cities and five counties are selected in this study, so $1 \leq m \leq 7$ (Wu et al. 2018)
(2) Calculate information entropy of index	$e_j = -k \sum_{i=1}^m (P_{ij} \times \ln P_{ij})$	e_j stands for the information entropy of each indicator; $k = 1/\ln m$, and m for the sample region where the index value is located (Wu et al. 2018)
(3) Determine the weight of each indicator	$W_j = \frac{1 - e_j}{\sum_j^n (1 - e_j)}$	W_j stands for the weight of each index; n for the number of indices (Wu et al. 2018)

P_{DU} stands for the detection index of the influence of influencing factors on the carrying capacity of water resources; n for the number of factors affecting water

resource carrying capacity; $n_{D,i}$ for the number of sub-level regional samples; m for the number of secondary regions; σ^2 for the variance of water resource carrying capacity in

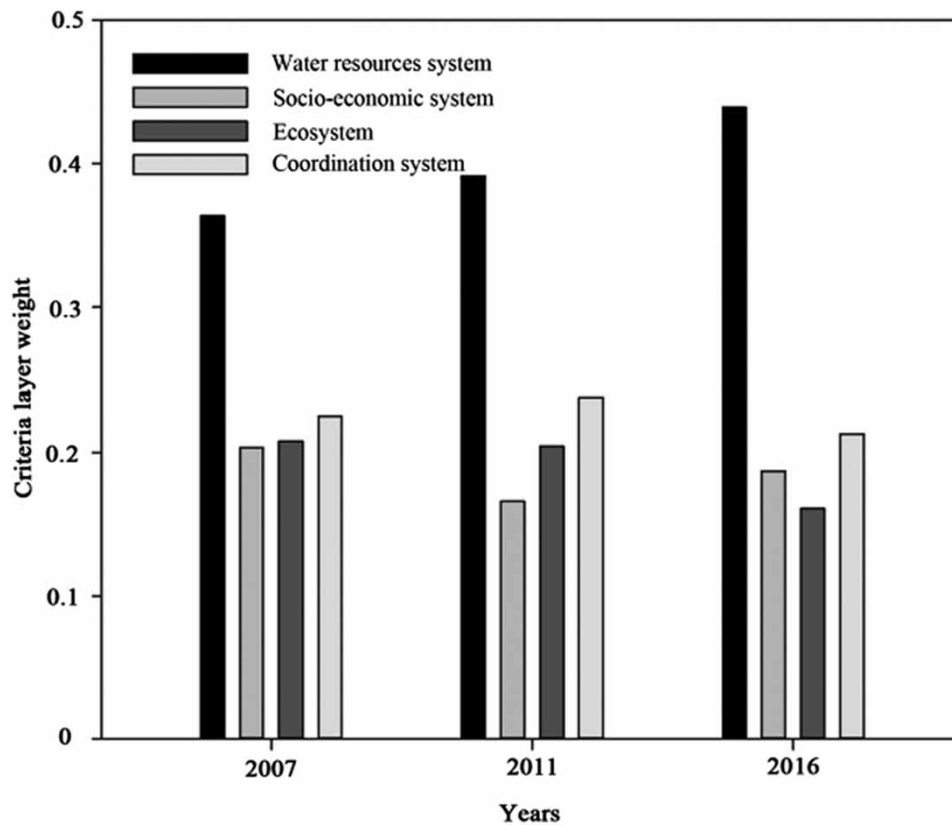


Figure 2 | The subsystem weights of water resources complex system in Shiyang River Basin: the abscissa is the research period, and the ordinate is the weight.

each research region of the city; $\sigma_{u_{D,i}}^2$ for the variance of the sub-regional water carrying capacity (Li *et al.* 2017; Lv *et al.* 2017; Wang *et al.* 2018; Zhang *et al.* 2018b).

Interactive detection was used to identify the combined actions of different driving factors on the explanatory power of the analysis variables (Wang & Xu 2017). In the following rules (Table 5) the symbol ‘ \cap ’ means that the X_i and X_j are taken together (or, the conjunction of X_i and X_j). The $q(X_i)$ and $q(X_j)$ denote the effect of the explanatory variables X_i and X_j , respectively, on soil heavy metal accumulation, and the $q(X_i \cap X_j)$ denotes the q -statistic of the joint (interactive) effect of X_i and X_j . Specifically, the characterization ‘nonlinear-weaken’ indicates a small interactive effect of X_i and X_j compared with their effects considered separately; the term ‘uni-weaken’ suggests a mild interactive effect that lies between the separate effects of X_i and X_j ; the term ‘bi-enhance’ indicates that the interactive effect of X_i and X_j is bigger than each one of the separate effects of X_i and X_j ; the characterization

‘independent’ means that the interactive effect is equal to the sum of the separate effects of X_i and X_j ; and the term ‘nonlinear-enhance’ indicates that the interactive effect of X_i and X_j is stronger than the sum of their separate effects (Yang *et al.* 2019).

RESULTS AND DISCUSSION

Comprehensive evaluation and analysis of water resource carrying capacity

Economic pressure index analysis of water resources

The economic pressure on water resources carried in the Shiyang River Basin is relatively large and increasing, with significant spatial differences (Figure 3 and Table 6). In terms of temporal dimension, the annual average value of the economic pressure index of water resources in Shiyang

Table 3 | Specific calculation methods of correlation index of the comprehensive evaluation model

Index	Formula	Parameter description
Economic stress index	$E_p I = \frac{GDP}{E_m}$ $E_m = \frac{GDP_d}{W} \times W_u$	<p>$E_p I$ stands for the economic pressure index; GDP for the current size of the domestic economy; E_m for the maximum economic scale that water resources can carry. The larger the $E_p I$, the greater the economic pressure</p> <p>GDP_d for the economic scale of water consumption W; W for the total water consumption in the socio-economic system; W_u for the total water resources (Wei & Tang 1997)</p>
Population pressure index	$P_p I = \frac{P}{P_m}$ $P_m = \frac{GDP}{GDP_c}$	<p>$P_p I$ stands for the population pressure index; P for the current population; P_m for the maximum population that the water resources can carry (Su et al. 2019). The larger the $P_p I$, the greater the population pressure</p> <p>GDP_c stands for the lower limit of GDP per capita in a certain social stage (Liu et al. 2011)</p>
Comprehensive carrying pressure index	$C_p I = \frac{PI}{SI}$ $PI = \sum_i^n P_i Y_i$ $SI = \sum_i^n S_i Y_i$	<p>$C_p I$ stands for the comprehensive bearing pressure index; PI and SI for the pressure index and support index of the water resources composite system respectively (Liu et al. 2011)</p> <p>PI stands for the pressure index of the water resources composite system; P_i and Y_i for the weight and standardized value of the index in the social, economic and ecological environment system respectively; n for the number of indices (Liu et al. 2011)</p> <p>SI stands for the support index of the water resources composite system; S_i and Y_i for the weight and standardized value of the index in the water resource system respectively; n for the number of indices (Liu et al. 2011)</p>
Coordinated pressure index	$HI = \sum_i^n W_i Y_i$	<p>HI stands for the agreement pressure index; W_i and Y_i for the weight and standardized value of the index in the coordination system respectively; n for the number of indices. The larger HI is, the higher the coordinated development degree of the composite system of social, economic, ecological and water resources is (Liu et al. 2011)</p>

Table 4 | Classification standard of comprehensive evaluation index of water resource carrying capacity

CI	0.00–0.20	0.21–0.30	0.31–0.50	0.51–0.7	> 0.7
Carrier level	Surplus	Bearable	Close to overload	Light	Serious
Carrier status	Abundant	Coordination	Minor discordance	Shortage	Serious shortage

Table 5 | Interaction model of independent variables

Criterion	Interaction
$q(X1 \cap X2) < \min(q(X1), q(X2))$	Nonlinear weakening
$\min(q(X1), q(X2)) < q(X1 \cap X2) < \max(q(X1), q(X2))$	Single factor nonlinear weakening
$q(X1 \cap X2) > \max(q(X1), q(X2))$	Two-factor enhancement
$q(X1 \cap X2) = q(X1) + q(X2)$	Independence
$q(X1 \cap X2) > q(X1) + q(X2)$	Nonlinear enhancement

River Basin is 0.691, which indicates it has borne great pressure. During the period of 2007–2016, the economic pressure of water resources in Jinchang city and Wuwei

city increased significantly, from bearable to greater, while other cities and counties did not change significantly. In terms of spatial dimension, the economic pressure index of water resources in Sunan county is the lowest in the Qilian Mountain area, where the multi-year average is 0.0191. The next is Tianzhu (0.1896). The economic pressure index of these two places is much lower than the average of the river basin (0.691), which shows that the water demand is far lower than the water supply, so it is a relatively abundant water area. The economic pressure of water resources in Wuwei city is the largest, where the multi-year average of economic stress is 1.21, 63 times more than that of Sunan. The second is Jinchang city

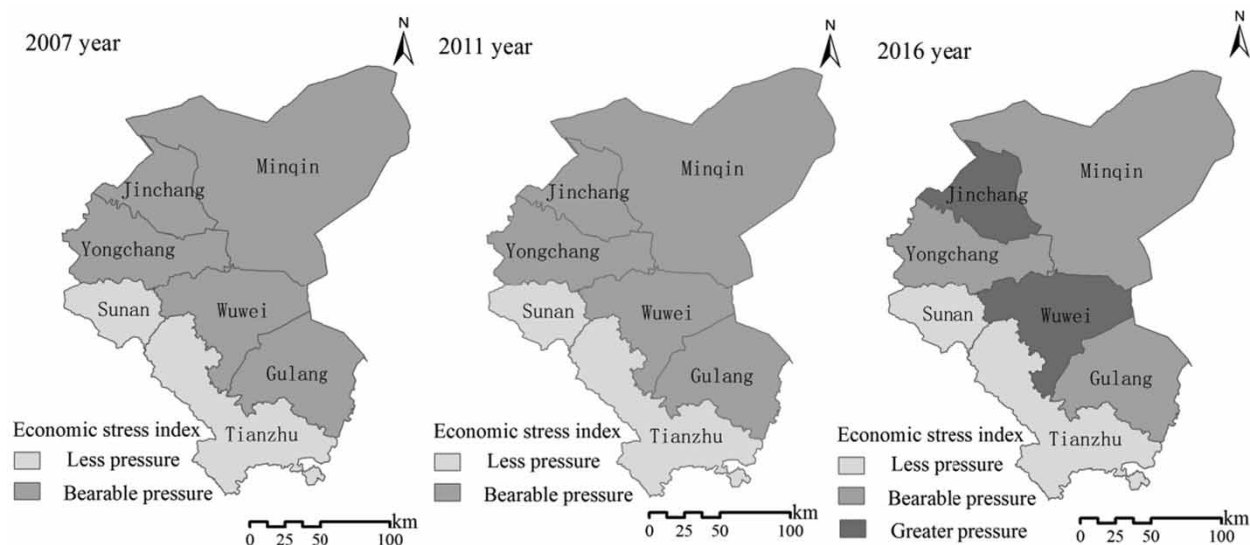


Figure 3 | Economic pressure index of water resources in Shiyang River Basin.

(0.93), which indicates that Wuwei city and Jinchang city have great economic pressure on water resources, and the water demand far exceeds the water supply of the region. The economic pressures of water resources in Yongchang county, Minqin county and Gulang county have always been bearable, and water resources can basically support economic development.

The analysis of population pressure index

The population pressure on water resources in Shiyang River Basin is relatively less, and the trend is downward with obvious spatial differentiation (Figure 4 and Table 6). In terms of temporal dimension, the water resource population pressure in Shiyang River Basin has decreased from 2007 to 2016, especially in Wuwei city and Minqin county, but in Jinchang city, Tianzhu county, Wuwei city, Gulang county and Yugu Autonomous County of Sunan, the water resource population pressure has remained stable. In terms of space dimensions, water resource population pressure is greater in Wuwei city and Gulang county, and the multi-year average of the population carrying stress index is 0.2276 and 0.3357 respectively; Sunan county and Jinchang city maintain a relatively low level of water resource population pressure, while Tianzhu county has always been in a bearable state; Yongchang county gradually changed from

greater to lesser, and Minqin county changed from a bearable state to a lower pressure state. The water resource population pressure index of Minqin county decreased from 0.1158 in 2007 to 0.0618 in 2016. With urban and rural integration development being implemented in Wuwei city, some areas of Wuwei city and Gulang County have entered the accelerated urbanization stage together with the implementation of the ‘four downs and four advances’ ecological immigration policy. Those measures have led to the population density of Wuwei city and Gulang county becoming higher, and the population pressure on water resources becoming larger.

The analysis of comprehensive carrying pressure

The data of 2007, 2011, and 2016 shows that the water resources support force in Shiyang River Basin is low, while the pressure on the development of the social and economic environment is high. Hence, the comprehensive carrying pressure of water resources is large and increasing, and the spatial and temporal differences are obvious (Figure 5 and Table 6). In the basin, the average values of the carrying pressure index in 2007, 2011 and 2016 are 2.2, 3.1 and 3.1, which shows that the water resource demand of water is greater than supply, and water shortage is serious, and carrying pressure increases significantly. The

Table 6 | The calculation results of water resource carrying capacity on index

Index	Economic stress index			Population pressure index			Carrying pressure index			Coordination index			Comprehensive Index (CI)		
	07	11	16	07	11	16	07	11	16	07	11	16	07	11	16
Sunan	0.016	0.020	0.021	0.255	0.110	0.065	0.600	0.669	0.521	0.108	0.155	0.111	0.207	0.189	0.136
Wuwei	0.939	0.943	1.748	0.295	0.235	0.153	0.270	0.351	0.282	0.155	0.112	0.112	0.296	0.285	0.311
Tianzhu	0.402	0.089	0.090	0.302	0.178	0.104	2.106	2.406	2.075	0.102	0.078	0.108	0.423	0.293	0.273
Yongchang	0.827	0.918	0.970	0.249	0.140	0.096	2.334	2.321	3.594	0.083	0.110	0.086	0.472	0.475	0.449
Gulang	0.588	0.707	0.944	0.468	0.326	0.213	2.328	1.538	1.178	0.118	0.135	0.133	0.526	0.513	0.547
Jinchang	0.829	0.958	1.002	0.030	0.034	0.048	4.846	5.577	5.723	0.096	0.110	0.110	0.585	0.673	0.693
Minqin	0.930	0.862	0.720	0.115	0.112	0.062	2.942	9.125	8.475	0.156	0.132	0.159	0.621	0.838	0.807

comprehensive carrying pressure of water resources in Yongchang county and Minqin county increased significantly, and the carrying pressure index of Yongchang county increased from 2.32 in 2011 to 3.59 in 2016. The pressure of water resources in Minqin county increased from 2.94 in 2011 to 9.13 in 2016. This data indicates that the water carrying pressure index increased significantly, and water pressure significantly greater than its support, and the demand is much greater than the supply. Hence, there is serious shortage of water. The carrying pressure of water resources in Jinchang area remains at 4–6, which shows an increasing trend (4.85–5.58–5.72), and the water pressure is far greater than the support. The carrying pressure index of Gulang county and Tianzhu county has always been at the level of 1–3, and the average C_pI is 1.68, 2.2 respectively. It indicates that water resources, social economy, and ecology have reached a state of mutual restraint and stability, the pressure of water resources is greater than the supporting force, and demand is greater than supply. For Sunan county and Wuwei city, the C_pI is less than 1, and the multi-year average respectively is 0.5968, 0.3011, which indicates that the water resource pressure in Sunan county and Wuwei city is less than the supporting force, and water resource supply is greater than demand.

The analysis of coordination index

In 2007, 2011 and 2016, the coordination degrees of the water resources composite system in Shiyang River Basin are low, with a trend of first rising and then falling (0.117–0.118–0.117), with obvious spatial difference (Figure 6 and Table 6). The average annual values of the water resource carrying coordination index of Minqin county, Gulang county, Wuwei city, Sunan county, Jinchang city, Tianzhu county and Yongchang county respectively are 0.15, 0.13, 0.13, 0.12, 0.11, 0.1, 0.09, all of which are at the lower level. Relatively speaking, the coordination index of water resource carrying capacity in Minqin county is higher, because of the development of water-saving agriculture and the improvement of people's awareness of water-saving, which make the water resource utilization in this area highly coordinated. The coordination index HI of Gulang county, Jinchang city and Minqin county shows

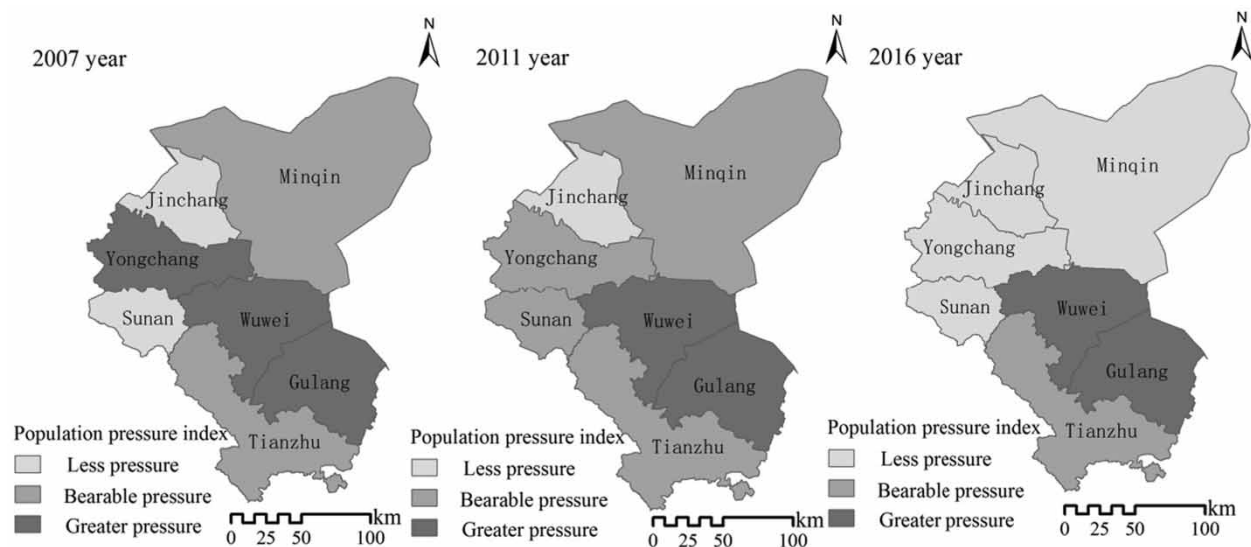


Figure 4 | Population pressure index of water resources.

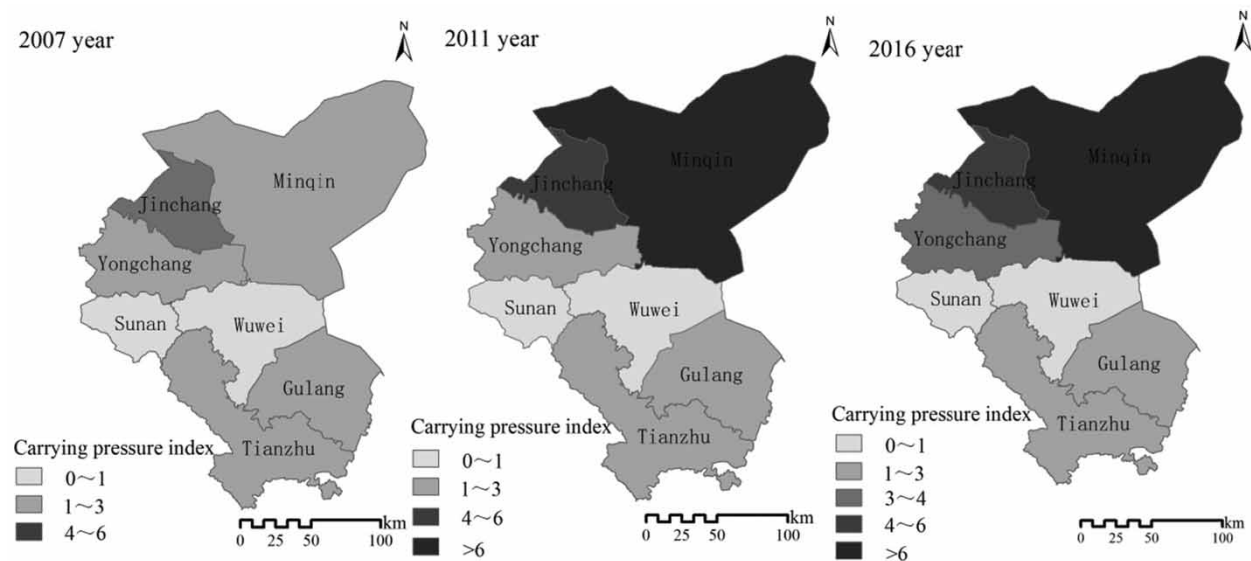


Figure 5 | Comprehensive pressure index of the complex water resources system in Shiyang River Basin.

an increasing trend. The *(HI)* coordination index of Gulang county, Jinchang city and Minqin county shows an increasing trend, indicating that there is a better utilization of water resources due to public policies, and water conservancy infrastructure construction, investment in supporting irrigation areas and water-saving transformation improve the agricultural irrigation methods and water resource

utilization level. The water resources coordination index of Wuwei city is obviously reduced, and the level of water resources utilization is reduced. The water resources coordination index of Yongchang county and Sunan county shows a trend of first rising and then falling, and the utilization capacity of water resources shows a volatile decline. The water resources coordination index in Tianzhu county

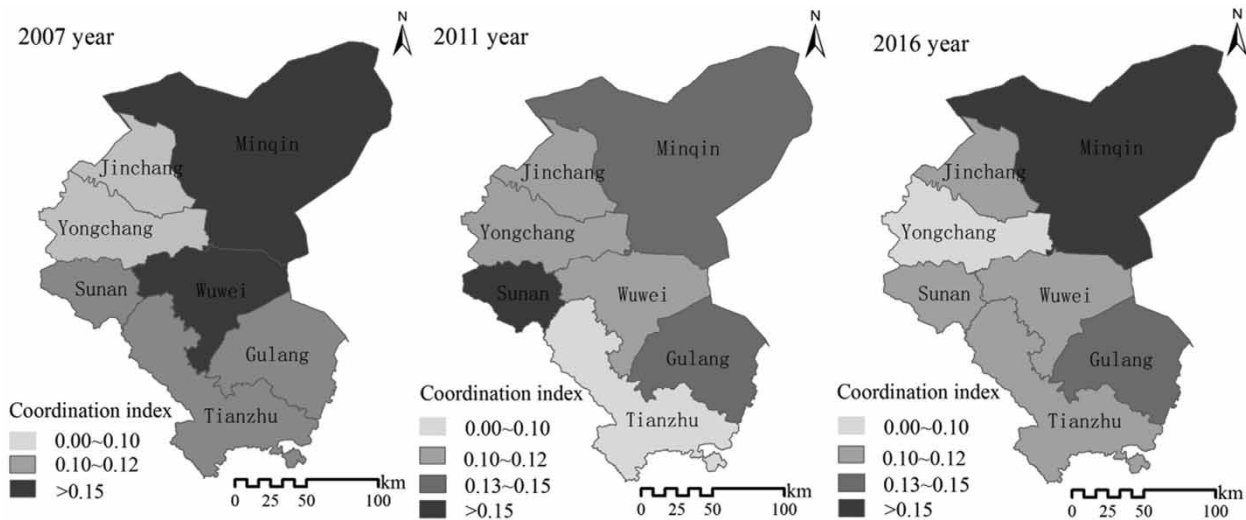


Figure 6 | Coordination index of the complex water resources system in Shiyang River Basin.

reduces first and then increases to the original level (0.10–0.07–0.10), and its utilization capacity of water resources remains at a low level.

The analysis of comprehensive evaluation index

Basing on the comprehensive index *CI* of water resource carrying capacity (Table 2) and the comprehensive evaluation index of water resource carrying capacity in Shiyang River Basin (Figure 7), the spatial-temporal

characteristics of the comprehensive carrying capacity of water resources in Shiyang River Basin is analyzed. In the spatial dimension, the distribution of water resources in Shiyang River Basin is uneven, and the contradiction between supply and demand of water resources is prominent. Even more, the dependence of human production and life on water resources far exceeds the carrying capacity of the water resources. There is extreme shortage of water resources in Minqin county, where the water resource carrying capacity is seriously overloaded, and

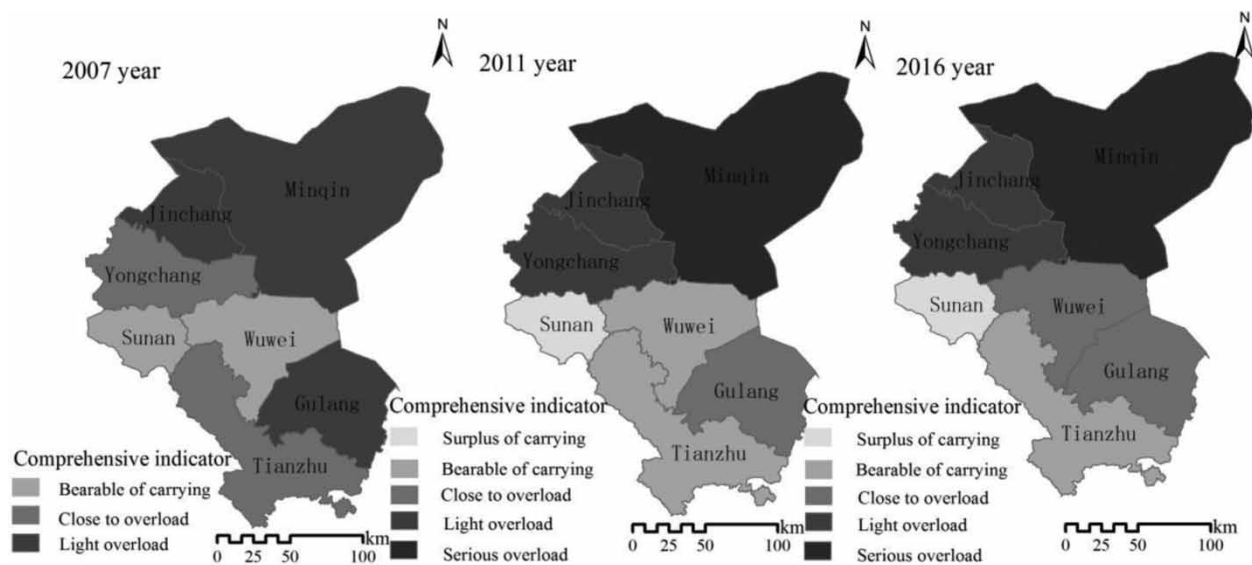


Figure 7 | Comprehensive evaluation index of water resource carrying capacity in Shiyang River Basin.

the water resource problem has become the restraining factor for sustainable development; Wuwei city and Gulang county in the oasis area of the middle basin have a concentrated population and rapid economic development, while their water resources are less and there is a mildly discordant use of water resources. Hence, it belongs to the area where water resource carrying capacity is on the verge of overload and the area of mild overload. The carrying capacity of water resources in Yongchang county and Jinchang city is slightly overloaded; Tianzhu county belongs to the bearable area, because its social and economic development is coordinated with the utilization of water resources with relatively low pressure; Sunan county belongs to the surplus area, because its supply of water resources is larger than the demand of social and economic development, with a low pressure.

In terms of temporal dimension, the carrying pressure of water resources in Shiyang River Basin has gradually increased. Meanwhile, the area of overload has increased. Minqin county, Yongchang county and Wuwei city are all in the state of intensified water shortage. The carrying pressure of water resources in Sunan, Gulang and Tianzhu counties has decreased slightly, and the water shortage has improved. The water carrying pressure in Jinchang city is always in a state of slight overload. Minqin county has

changed from a state of light overload to serious overload; Yongchang county changed from overloaded to lightly overloaded, and water resources utilization is not coordinated; Wuwei city changed from bearable to overloaded, and the water resources are in the state of slight uncoordination; Sunan county changed from bearable to surplus; Gulang county has changed from slight to overloaded; Tianzhu county has changed from an overloaded area to a bearable area.

Analysis of influencing factors of water resource carrying capacity

Factor detection results of geographical detector

There is a close correlation between the carrying capacity of water resources and the indices of the water resources composite system. Therefore, geographical detector is applied to detect 19 indicators of the water resources composite system and get the explanatory power of each indicator factor of water resource carrying capacity (Zhang *et al.* 2018b). The factors with significant verification and high explanatory power (>0.5) are selected as the main influencing factors of water resource carrying capacity in three periods (Table 7).

Table 7 | The q values of influencing factors

System factors	Impact factor	07(q)	Influencing factor	11(q)	Influencing factor	16(q)
Water resources system	Water production modulus	0.964	Water production modulus	0.987	Underground water	0.943
	Underground water	0.929	Underground water	0.789	Per capita water resource	0.749
	Surface water	0.857	Surface water	0.789	Annual precipitation	0.732
	Annual precipitation	0.857	Annual precipitation	0.776	Water production modulus	0.598
	Per capita water resource	0.536				
Social and economic systems	Number of hospital beds	0.804	Urbanization rate	0.772	Per capita GDP	0.866
			Number of hospital beds	0.507	Urbanization rate	0.713
					Number of hospital beds	0.541
Ecological system	Ecological water use	0.571	COD	0.757	COD	0.857
	COD	0.631	Fold purity of fertilizer	0.618	Wastewater treatment rate	0.68
	Fold purity of fertilizer	0.631	Ecological water use	0.547	Forest coverage rate	0.627
					Fold purity of fertilizer	0.584
					Ecological water use	0.507
Coordinate system	Irrigation rate	0.857	Irrigation rate	0.759	Inter-basin water transfer	0.512
	Grain production	0.631	Inter-basin water transfer	0.579	Irrigation rate	0.508
	Inter-basin water transfer	0.571				

Detection results (Table 7) show that although there are temporal differences in the influencing elements of water resource carrying capacity in Shiyang River Basin, the background of water resources still is the main factor of the water resource carrying capacity. The impact on water resources systems and coordination system factors is declining, the impact of socio-economic and ecological factors on the water resource carrying capacity of the basin is significantly enhanced, most of the ecological factors are related to human activities (such as ecological water use, wastewater treatment rates and folding purity of chemical fertilizer, etc), which indicates that the root factor of water resources is the sustained supporting force of water resources in Shiyang River Basin, and the socio-economic development and human activities have an increasing impact on water resources carrying capacity. Shiyang River Basin belongs to an arid and semi-arid climate with a shortage of water resources. The water resources in the basin mainly derive from atmospheric precipitation on Qilian Mountain and the snow melt water from alpine snow and ice, and its surface water resources, annual precipitation, water production modulus and groundwater are the main forces of the water resources supply in the basin. With the socio-economic development of the basin area, the improvement of urbanization level and the implementation of green development strategy, the influence of socio-economic and ecological environmental factors on water resource carrying capacity increases significantly. In addition, inter-basin water transfer is a crucial measure to solve the contradiction between supply and

demand of water resources in the river basin, and the inter-basin water diversion projects, such as the Liuhuanggou area–Jinchang city water diversion project, and Datong River–Xida River water diversion project, are the reserve force of basin water resources.

The socio-economic development of the Shiyang River Basin relied on the local water resources. At the cost of the ecological environment, it is not a better development mode in which the social economy is not coordinated with water resources and the ecological environment. What we should do is to rationally plan the sustainable utilization of water resources in the basin, and to pay attention to the research on water resource carrying capacity. That is how we can avoid water resources overload and ecological environmental damage caused by social and economic development.

Interaction of influencing factors on water resource carrying capacity

The regional water resources composite system is a complex, giant system that is composed of society, economy, ecological environment and water resources. The intensity of the subsystem factors will have a profound impact on the WRCC.

Taking 2016 as an example year, 36 factor pairs are obtained through interactive detection of the nine factors (the influence q -value of these factors is greater than 0.5). The result shows that the influence of the pairwise interaction of each factor is more than 0.5, indicating that the two factors of enhancing pairs have the stronger synergistic effect. It is

Table 8 | The dominant interactions between two covariates of water resource carrying capacity

	X1	X2	X3	X4	X5	X6	X7	X8	X9
X1									
X2	0.9877								
X3	1	1							
X4	1	0.9877	1						
X5	1	0.9508	0.9877	1					
X6	1	1	1	0.6926	0.9877				
X7	1	0.9877	1	0.9877	1	1			
X8	0.8893	0.9508	1	1	0.8361	0.9877	1		
X9	0.8893	1	0.9508	0.8033	0.9877	1	1	0.8893	

Notes: 1. X1,X2,X3,X4,X5,X6,X7,X8,X9 represent per capita GDP, urbanization rate, groundwater, water production modulus, annual precipitation, forest cover, COD, wastewater treatment rate and per capita water resources. 2. It only selects the factor interactions of the first nine q -values in the table.

indicated from Table 8 that the combination of per capita water resources, groundwater resources, water production modulus and annual precipitation in the water resources system has a positive effect on WRCC and that the water resources system factor plays a positive role in the whole composite system. Among ecosystem factors, chemical oxygen demand (COD) and other factors form negative effective pairs, while forest coverage rate, wastewater treatment rate and other factors form positive pairs. In the socio-economic system, when the per capita GDP and urbanization rate interact with other factors, a negative effect of WRCC will be formed. It shows that the main consumption of water resources comes from groundwater, surface water and precipitation in the process of the social, economic and urbanization development of Shiyang River Basin. At the time, we should pay close attention to water quality safety and ecological protection of water resources. The sustainable utilization of water resources should be rationally planned during social and economic development. Attention should be paid to water resources bearing capacity, to avoid sacrificing the ecological environment for quick economic benefits.

CONCLUSIONS

In this research, the data of water resources and socio-economics from the years 2007, 2011 and 2016 is used to analyze the spatial and temporal evolution characteristics of water resource carrying capacity in Shiyang River Basin, a comprehensive evaluation model of regional water resource carrying capacity is constructed, and the geographical probe method is applied to detect the factors that affect the carrying capacity of water resources. The results show the following:

- (1) In the spatial dimension, the distribution of water resources in Shiyang River Basin is uneven, and does not match the economic development and population distribution. The contradiction between the supply and demand of water resources is prominent, and the dependence of human production and life on the water resources far exceeds the water resource carrying capacity. Sunan and Tianzhu county belong to the surplus or bearable carrying area of water resources, and are located in the upstream of the basin with less

population and abundant water resources. The water resource carrying capacity of oasis areas, including Yongchang county, Jinchang city, Gulang county and Wuwei city, is on the verge of overload and a slightly overloaded city in which the economy develops rapidly with large population, but with less water resource. Minqin county belongs to the serious overload, which is far away from water sources and near desert with extreme shortage of water resources.

- (2) In terms of temporal dimension, the water pressure in Shiyang River Basin gradually increases, and the areas on the verge of overload, and of slight overload and severe overload increase. The shortage in Minqin county, Yongchang county and Wuwei city worsens. Minqin county changes from a light overload area to a serious overload area, Yongchang county changes from an overload area to a light overload area, and Wuwei changes from a bearable area to an overload area. The carrying pressure of water resources in Sunan, Gulang and Tianzhu counties decreases slightly, among which Sunan county changes from a bearable area to a surplus area, and Gulang county changes from a light overload area to an overload area. Tianzhu county, which used to be on the verge of overload, has become a bearable area.
- (3) The results of geographical detector indicate that the influencing factors of water resource carrying capacity in Shiyang River Basin are different in time, and the root factor of water resources is the sustained supporting force, that the factors of the water resources system and coordination system have weaker influence while the socio-economic and ecological factors are significantly enhanced, and the influence of human activities is enhanced. The interactive results further reveal that the interaction of any two factors is stronger than that of a single factor, and two-factor enhanced pairs have the strongest synergistic effect.

The research area has its particularities including desert, oasis plain and mountain range, which is the ecological barrier area in northwest China. Shiyang River is a typical arid inland river, in which water resource shortage and overload is becoming more and more serious. Strengthening the efficient utilization of water resources, the implementing of the inter-basin water transfer project and storage project

will be beneficial for alleviating these problems in Shiyang River Basin. The utilization coefficient of the canal system should be improved and the traditional irrigation method should be ameliorated in the oasis agriculture area. The water resources in upstream water areas (Sunan county and Tianzhu county) are in surplus. Due to the complex topographic and geomorphic conditions, the protection of water resources and the ecological environment would be strengthened to realize the sustainable development of water resources and the social economy in Shiyang River Basin. (I) The study applied geographical detector to detect the factors that affect the carrying capacity of water resources. Furthermore, the WRCC in the study area was analyzed more precisely, but the influence factors were not analyzed in other studies microscopically. (II) This paper analyzed the WRCC from the perspectives of socio-economy, coordination, water resources and ecology. In particular, ecology was first studied as an independent indicator. This study has a certain reference value for the WRCC in the Shiyang River Basin and its sustainable utilization in the future. Although the study analyzes the WRCC in the Shiyang River Basin from a macroscopic perspective, the balance between supply and demand of water resources is not analyzed from a microscopic perspective (such as water footprint). Hence, further exploration is needed in the future.

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