



# Assessment of the water resource carrying capacity based on the ecological footprint: a case study in Zhangjiakou City, North China

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## Abstract

With the rapid economic development in the past decades, industrialization and urbanization in China has also rapidly developed and will continue in the next decades. However, the regional water shortage has posed great challenges for the sustainable development of big cities especially in north China. Here, we used the water ecological footprint model combined with the system dynamic model to assess the water resource carrying capacity and its sustainability in Zhangjiakou City, a typical water shortage city in north China. The calculated results showed that irrigation was the largest water consumer in Zhangjiakou. There existed a clear gap between water supply and water consumption in this city and such a gap is demonstrated by the high water resource pressure index. Our predicted results based on the water resource ecological footprint and the system dynamic model showed that although the improving water use efficiency has relieved the regional water shortage pressure, the efficiency gained would be to a large degree offset by increased water demands due to the increasing economic development. The annual average water shortage in Zhangjiakou in 2007–2050 would be up to  $8.53 \times 10^8 \text{ m}^3$ , nearly half of the total local average annual water resource. To deal with the severe water shortage over the next three decades, great attention should be paid to scientific water resource managements and water pollution control. This research provides a long-term view of water resource pressure and provides recommendations for a sustainable water use under the rapid regional socioeconomic development.

**Keywords** Water resource carrying capacity · Ecological footprint · Sustainability · System dynamic model

## Introduction

The contradiction between water supply and demand of water resource has become one of the most severe development problems in many developing countries around the world (Liu and Raven 2010; Pernet-Coudrier et al. 2012; Vörösmarty et al. 2010; Yu 2011). This issue particularly occurs in regions where industrialization and urbanization have increased rapidly (Wang et al. 2013; Yang et al. 2015;

Yu 2011), such as the typical example of China, the largest developing country of the world. As an important environmental conception, the water resource carrying capacity (WRCC) is defined as the maximum carrying capacity of water resource for human activities in a certain stage of the socioeconomic development without an adverse impact on the regional water environment (Song and Zhan 2011). It has been used to discuss water recourse use and sustainability for a long time (Costanza 1996; Seidl and Tisdell 1999; Wang et al. 2013; Zhang et al. 2010). The regional population size and the economic scale have been chosen as the most important indices to assess WRCC (Song and Zhan 2011; Yang et al. 2015). The ecological footprint (EF) model developed by Rees (1992) is a practical method to assess the carrying capacity of resources and the sustainability. However, due to the great variability of the water resource (for example, anthropogenic water transfer and water recycling) and land resources, the EF model is difficult to calculate WRCC accurately (Huang et al. 2008;

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Wang et al. 2013). This disadvantage has restricted its wide application to assess the WRCC. To address this limitation, based on the ecological footprint and the concept of virtual water (Allan 1998; Hester and Little 2013; Riss and Wackernagel 1996; Wackernagel et al. 1999), the water footprint (WF) (Chapagain and Hoekstra 2011; Hoekstra 2009; Zhao et al. 2009), and the water resource ecological footprint (WREF) model (Huang et al. 2008) have been proposed to assess the WRCC via measuring the water resource consumption. WF model is defined as a method to quantify human appropriation of water resource in the supply chain, which mainly focuses on water use and water resource trade (Hoekstra and Mekonnen 2012; Winnie et al. 2009). However, WF has not been widely used to evaluate the sustainability of water resource (Wang et al. 2013) due to its weakness to estimate the related environmental impacts of water consumption (Jeswani and Azapagic 2011). WREF model mainly focuses on water use by human activities and aquatic ecosystem health, and is more perfect than WF (Huang et al. 2008). It can calculate and evaluate the current regional WRCC by identifying the production capacity of water resource per capita and the quantity of the WREF per capita (Huang et al. 2008; Wang et al. 2013). Through the explanation of water resource function as both the production and the ecological protection, the WREF framework has improved the EF model developed by Rees (1992), Wackernagel and William (1998), and Wackernagel (1999). In fact, WREF can be regarded as a supplement account of water uses in the EF model, as it emphasizes the important contribution of water resource production capacity to both human and natural systems. Therefore, the meaning of WREF can be expressed in two aspects, the process of water resource consumption by human activities and aquatic ecosystem health (Huang et al. 2008). More importantly, WREF has the function to demonstrate the capacity of the water resource supply (Wang et al. 2013). Based on these advantages, WREF has been widely used to assess the WRCC (Chen et al. 2009; Tan and Zheng 2009; Wang et al. 2011). Unfortunately, in most cases, these models use static status to evaluate the WRCC via explaining the past and current water resource consumption (Chen and Chen 2013; Stoeglehner et al. 2011), and they fail to accurately predict the water resource sustainability in the future, particularly in water scarcity cities where water resource has been over exploited to meet the growing demand of population and economy. It is noteworthy that population and economic size are the main indexes of the social development and have significant effects on the natural-social system (Veldkamp et al. 2017; Wang et al. 2014; Yang et al. 2015). Thus, changes of the WREF is closely related to the regional population and GDP growth, because population and GDP growth highly depend on the water resource

(Gleick 2003; Hubacek et al. 2009; Ma et al. 2008; Wang et al. 2013). Additionally, WRCC is defined as the maximum human activities (population size and GDP growth) supported by the finite water resource in a certain stage of socioeconomic development (Song and Zhan 2011; Yang et al. 2015). Therefore, it is urgent to develop a WREF model to combine human activities and socioeconomic developments to dynamically forecast the water resource sustainability.

China has the second largest economy in the world; however, the increasing urbanization and industrialization have caused greater demands of water resources, and have caused more severe water shortage and degradation of water quality, which in turn restricts the sustainable development of the nation (Liu and Raven 2010; Zhao et al. 2015). These problems especially occur in megacities in North China, where water scarcity is more significant than in south China (Pernet-Coudrier et al. 2012; Yu 2011). Zhangjiakou City is located in the west to Beijing, the capital city of China (Fig. 1). It has the largest natural ski resort in China and was well known as the East Davos. On the July 31, 2015, the International Olympic Committee President Thomas Bach announced that Beijing and Zhangjiakou were authorized to host the 2022 Winter Olympics ([http://www.ce.cn/xwzx/gnsz/gdxw/201507/31/t20150731\\_6100544.shtml](http://www.ce.cn/xwzx/gnsz/gdxw/201507/31/t20150731_6100544.shtml)). This special honor has attracted more population and various enterprises moving to the city. This region has become one of the most severe water scarcity areas in the whole nation (Jiang et al. 2014). Major environmental issues associated with water scarcity including soil degradation, over-extraction of groundwater and water pollution are threatening the harmony between human beings and nature systems (Lei et al. 2010; Wang et al. 2018). According to the statistical yearbook, about  $3.4 \times 10^7$  t of industrial wastewater and  $10.32 \times 10^7$  t of domestic sewage were discharged into the surface water bodies, and the wastewater discharging are increasing, leading to water quality deterioration and further aggravating the regional water resource crisis.

In this work, the future population size and the economic scale for a certain time are considered in the WREF framework to predict the future water resource pressure and provided a new perspective for regional water resource management and decision-making. The aims of this paper are to (1) analyze the WRCC in Zhangjiakou City based on the WREF and (2) forecast the changes of the WRCC and the ability of the regional sustainable development. This information is expected to address the limitation of the traditional water footprint for prediction of the regional water ecological pressures and bring a different perspective on the sustainable development in the arid and/or semi-arid regions under severe water scarcity.

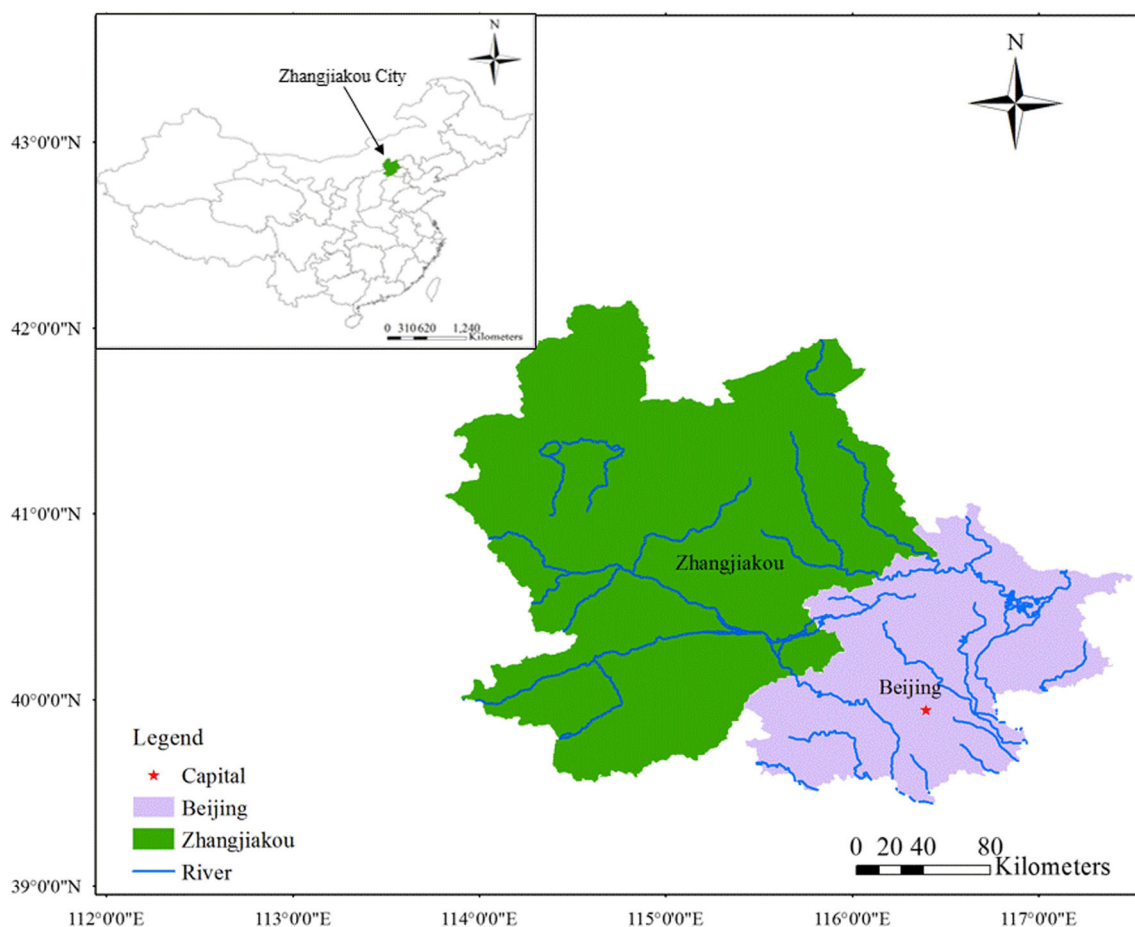


Fig. 1 Map of the location of Zhangjiakou area

## Material and methods

### Study area

Zhangjiakou City is located in the North China Plain, near Beijing (the capital city of China), with an area of 36,965 km<sup>2</sup>. It is in the arid and semi-arid region of the Hai River basin (Fig. 1). The annual average precipitation is 409 mm and 80% of the precipitation happens between June and September, while the annual average evaporation is 850–1200 mm. The total annual average water resource is 1.79 billion m<sup>3</sup> and the per capita water resource is less than 380 m<sup>3</sup>, far below the national average (2100 m<sup>3</sup> per capita). The contradiction between the regional water scarcity and the sustainable development are becoming increasingly acute in this region.

### Data collection

To evaluate the maximum population and socioeconomic scale that the water resource of the Zhangjiakou City can support, in this work, the WREF method developed by

Huang et al. (2008) and the system dynamic model (SDM) were combined to establish WRCC evaluation index system. Data of the total water resource, water consumptions, and the water use quotas in different industries, runoff yielded per unit area to calculate the WREF and WRCC were collected from the regional Water Resource Bulletin from 2007 to 2016. The precipitation and evaporation data from 1996 to 2016 were obtained from “China Meteorological Data Service Center” (<http://data.cma.cn/>). The related data (i.e., the regional birth rate, the mortality rate, the population migration, the labor force data) used in the SDM to simulate and predict the regional population and GDP were collected from the published Socioeconomic Statistical Yearbook of Zhangjiakou City from 2007 to 2016.

### The framework of water resource ecological footprint

As a supplement account in the EF model as mentioned above, WREF framework converts the water resource to a global standard biological productive land area after the fossil energy land and the arable land, the forest land, the pastureland, the construction land, and the sea space (Huang et al.

2008). In the WREF framework, water resource consumption includes household water use, production water use and the ecological water use. Thus, at a city scale, WREF contains three components, the household water ecological footprint (WEF), the production WEF and the ecological WEF, which were calculated by the following formulations:

(1) Household WEF

$$WEF_H = N \times wef_h = Nr_w(W_h/P_w)$$

where  $WEF_H$  ( $ghm^2$ ) is the total household WEF,  $wef_h$  ( $ghm^2/capita$ ) is the household WEF per capita,  $N$  is the total population of the region, and  $r_w$  is the equivalence factor of the water resource.  $W_h$  ( $m^3$ ) is the quantity of the water resource consumed in the household and  $P_w$  ( $m^3/ghm^2$ ) is the global average yield of the water resource, and  $ghm^2$  is the abbreviation of the ecological footprint unit global  $hm^2$ .

(2) Production WEF

$$WEF_P = N \times wef_p = Nr_w[(W_a + W_i)/P_w]$$

where  $WEF_P$  ( $ghm^2$ ) is the total production WEF,  $wef_p$  ( $ghm^2/capita$ ) is the production WEF per capita.  $W_a$  is the quantity of the water consumption in the agricultural activities, including irrigation, forestry, husbandry, and fishery; and  $W_i$  ( $m^3$ ) is the quantity of the water resource consumed in the industry.

(3) Ecological WEF

$$WEF_E = N \times wef_e = Nr_w(W_e/P_w)$$

where  $WEF_E$  ( $ghm^2$ ) is the total ecological WEF,  $wef_e$  ( $ghm^2/capita$ ) is the ecological WEF per capita.  $W_e$  ( $m^3$ ) is the quantity of the water resource consumed in the ecological protection.

(4) The total WREF

$$TWREF = WEF_H + WEF_P + WEF_E = N \times wef$$

TWREF is the total WREF and  $wef$  is the total WREF per capita.

(5) The WRCC

The water resource ecological carrying capacity (WRCC) is calculated as:

$$WRCC = N \times wrcc = 0.88r_w y_w Q_w / P_w$$

where  $WRCC$  ( $ghm^2$ ) is the total water resource carrying capacity,  $wrcc$  ( $ghm^2/capita$ ) is the water resource carrying capacity per capita,  $y_w$  is the regional yield factor, and  $y_w =$

$y/y_g$  and  $y$  is the quantity of the water production per area;  $y_g$  is the quantities of the global water production per area.  $Q_w$  ( $m^3$ ) is the regional total water resource quantity, and 0.88 is the compensatory coefficient of biodiversity, which is suggested by the World Commission on Environment and Development.

The water resource pressure index (WPI) for the regional sustainable development can be calculated as  $WPI = TWREF/WRCC$ .

When  $WPI > 1$ , it means that the regional water resource is unsustainable; when  $WPI < 1$ , it means that the regional water resource is sustainable; and when  $WPI = 1$ , it means that the regional water resource is in balance.

In this work, the WREF method (Huang et al. 2008) and the system dynamic model were used to calculate the WREF and assess the WRCC in Zhangjiakou City.

**Population and GDP prediction via SDM**

The SDM can well solve the high-order and nonlinear, and multi-feedback and complex time variable problems (Sterman 2010), and thus it has been widely used to simulate socio-economy, resource, and environment systems (Qin et al. 2011; Simonovic and Ahmad 2004; Winz et al. 2009). Taking consideration of the factors affecting the socioeconomic and population growth, it can well depict system behavior and predict population and GDP growth. The Vensim PLE software was chosen as the SDM platform to predict the future population and GDP.

**Population module**

The population is mainly influenced by the regional birth rate, mortality rate, and population migration. According to the previous research (Wang et al. 2014; Zhou et al. 2017), we simulated it using the following function:

$$POP = POP_{t-1} \times (1 + PBR - PDR) + PMQ_{t-1}$$

where  $POP_{t+1}$  and  $POP_t$  are the population size in the year of  $t$  and  $t-1$ , PBR is the population birth rate, PDR is the population death rate, and  $PMQ_{t-1}$  is the population migration quantity in the year of  $t-1$ .

**GDP module**

The GDP module is very important because economic growth directly relates to water consumption and environmental pressures. The Cobb–Douglas production function defines the labor force, the fixed capital stock, and the

technological advances as economic growth and these factors can be used to predict the regional economic development (Qin et al. 2011). The production function formula is:

$$\hat{R} = \frac{c + b_L \left( \frac{GL_{t-1}}{GL_t} - 1 \right) + b_k \hat{K}_t}{1 - b_L \times \frac{GL_{t-1}}{GL_t}}$$

where  $\hat{R}$  is the GDP growth rate,  $GL_t$  is the GDP per laborer in the year  $t$ ,  $\hat{K}_t$  is the growth rate of the fixed capital stock in the year  $t$ ,  $c$  is the influence index defined by the quality of the labor forces and technology-level impacts,  $b_L$  is the elastic coefficient of the labor output, and  $b_k$  denotes the elastic coefficient of the capital output. The coefficients were calculated through an optimization method based on the historical socioeconomic data (2007–2016) in Zhangjiakou area.

To guarantee the accuracy of the model result, some hypotheses were made in this work. The spatial scope of the model is the boundary of Zhangjiakou city and the population policy and the resident's lifestyle of the city will not change during the simulation time. The initial time of this model is 2007 and the end time is 2050. Based on detailed parameter estimations and numerical calculations of the variables in the population-GDP SDM, the uncertainty and the accuracy of the model have been improved. The diagram of population-GDP SDM is shown in Fig. 2. The main variables and expressions in the model are shown in Table 1, Fig. 2.

## Results and discussion

### Current water resource assessment in Zhangjiakou City

#### The regional water ecological footprint of different subaccounts

Based on the constructed WREF framework by Huang et al. (2008), we explored whether the water resource can meet the sustainability of the region. As shown in Fig. 3, during the year of 2007 to 2016, the agriculture had the highest WREF, accounting for 72.4% of the total WREF, much higher than the national average (62.5%; Hubacek et al. 2009). Water consumption intensity in the industrial sector was also high, consuming 13.8% of the total WREF, followed by the household sector (12.9%) due to lower per capita water consumption in this region (per capita 87.04 L/day). The ecological protection was given very low water resource. Agricultural water consumption was the largest WREF contributor in Zhangjiakou City. Due to the special climatic and geographical conditions, the double cropping system is very common in this region (i.e., winter wheat and corn). However, the average precipitation in this region is not adequate as mentioned above (“Study area” section). In this situation, the evapotranspiration of plants is much higher than the precipitation (Li et al. 2012). Thus, irrigation is necessary to maintain the stable agricultural production. The current average water consumption of the irrigated land in Zhangjiakou is 4981 m<sup>3</sup>/hm<sup>2</sup>, which is higher than the irrigation water consumption in the North China Plain (3150 m<sup>3</sup>/hm<sup>2</sup>)

**Table 1** Main variables and expressions in the population, GDP module

Name of the variables	Expression	Unit
Population birth quantity	= Population × table functions of the population birth rate	10 <sup>4</sup> people
Population birth rate	= Table functions of the population birth rate × GDP pre capital	Dimensionless
Population death quantity	= Population × table functions of the population death rate	Dimensionless
Population death rate	= Table functions of the population death rate × GDP pre capital	10 <sup>4</sup> people
Population migration quantity	= Labor migration quantity	10 <sup>4</sup> people
Population	= Population birth quantity + population migration quantity – population death quantity	10 <sup>4</sup> people
Labor demand quantity	= GDP × labor demand per unit GDP	10 <sup>4</sup> people
Labor force quantity	= Population × employment population ratio	10 <sup>4</sup> people
Labor demand per unit GDP	= 1/capital per labor GDP	Per laborer/10 <sup>4</sup> Yuan GDP
Employment population ratio	= Table functions of the employment population ratio × GDP pre capital	Dimensionless
Fixed capital stock	= Fixed investment – fixed asserts depreciation	10 <sup>8</sup> Yuan
Growth rate of the fixed capital stock	= (Fixed capital stock – Fixed capital stock in the year of $t-1$ )/(fixed capital stock in the year of $t-1$ )	Dimensionless
GDP growth	= GDP growth rate × GDP	10 <sup>8</sup> Yuan
GDP	= INTEG (GDP growth)	10 <sup>8</sup> Yuan
GDP per laborer	= Table functions of GDP per laborer × GDP pre capital	10 <sup>4</sup> Yuan/per laborer

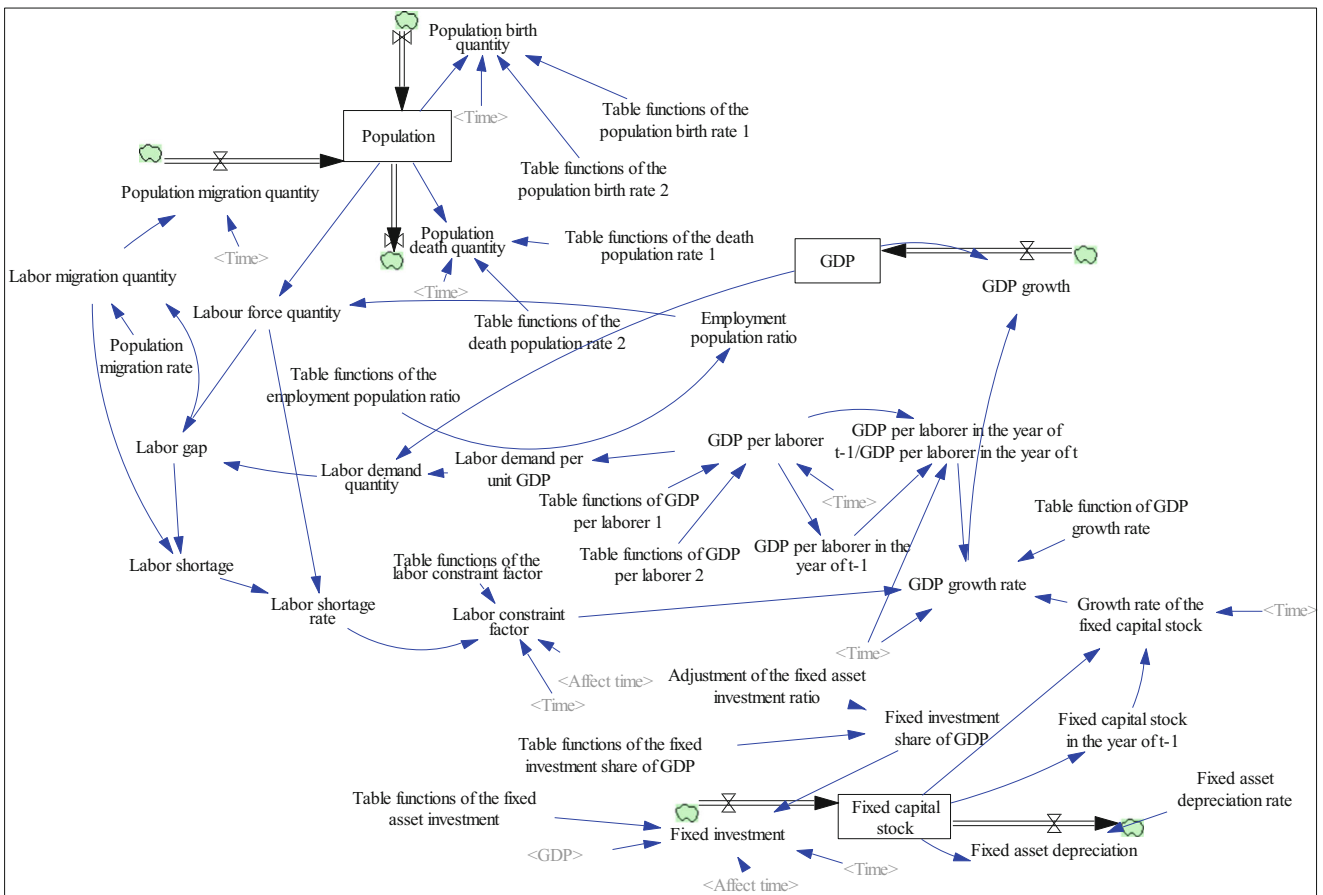
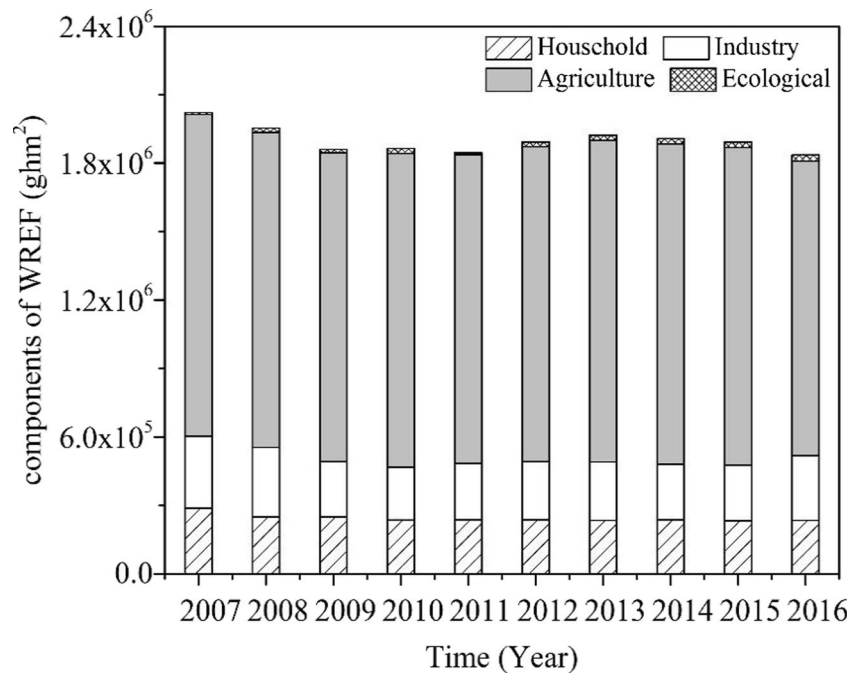


Fig. 2 SDM flow chart of the population, GDP module

Fig. 3 The components of WREF (ghm<sup>2</sup>) of Zhangjiakou



(<http://www.jsjg.com.cn/Index/Display.asp?NewsID=20209>). Studies have shown that in the North China, many rivers are drying up, not only due to long-term years of drought, but also due to the extensive water consumption for the intensified farming that largely relies on irrigation (Dalin et al. 2015; Pernet-Coudrier et al. 2012). These situations are widespread in Zhangjiakou, where the agriculture production only contributes to 16% of the GDP (2016), while the agriculture WREF exceeded 70% of the total WREF. Study has shown that irrigation in arid lands can increase soil salinity, which inhibits crop yields (Dregne 1977); in addition, the continued groundwater overdraft for irrigation can result in unsustainable socioeconomic development and ecological degradation especially in North China (Dalin et al. 2015). Therefore, currently, it is important to reduce consumption of irrigation water in this arid region by enhancing the efficiency of agriculture water utilization and improving the management of the irrigation systems.

**The regional water ecological pressure based on the WREF and WRCC**

Figure 4 showed the current total WREF, WRCC, and the water WPI of Zhangjiakou. The average mean value of the per capita WREF is 0.41 ghm<sup>2</sup>, far below the Liao River Basin (1.59 ghm<sup>2</sup>/per capita) in Northeast China (Wang et al. 2013) and the national average (1.78 ghm<sup>2</sup>/per capita) (Hubacek et al. 2009). The annual average total WREF was 1.90 × 10<sup>6</sup> ghm<sup>2</sup> in Zhangjiakou during the year of 2007–2016 and it was significantly higher than the WRCC (*p* < 0.05). The observed WPI was in agreement with this. The WPI in

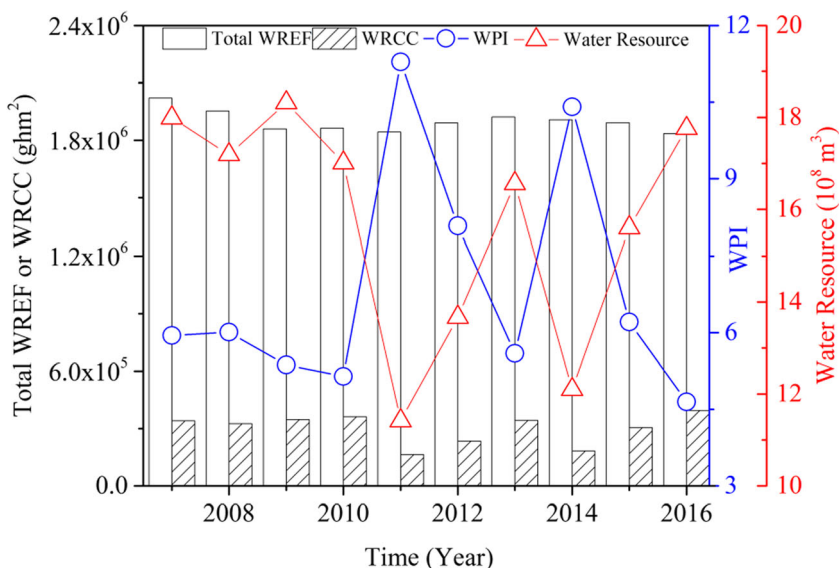
Zhangjiakou during the year of 2007 to 2016 was higher than 4, with an average of 6.87, indicating severe water stress in this region. In addition, the WPI reached the peak in the year of 2011 and 2016. This is mainly because the precipitation in these 2 years was relatively low, resulting in a decrease of the regional water production, and then leading to the lower water resource and the higher WPI (Fig. 4). More importantly, the WPI of Zhangjiakou was much higher than many cities in the Liao River Basin in Northeast China (Wang et al. 2013), further evidencing terribly unsustainable condition of water resource in this region. The high WPI also indicates that the WRCC of Zhangjiakou is overloaded, which would become the dominate pressure for the socioeconomic sustainable development without any urgent and effective measures. Therefore, it is imperative to improve the water use efficiency, especially for the agricultural water use, to relieve the water resource pressure in Zhangjiakou.

**Projected change of the regional water resource pressure in the following decades**

**Population and GDP prediction**

To identify the sustainability of the regional water resource, the future population size and the economic scale are considered to calculate the regional WREF and the water WPI in dynamic status. In the SDM model, the socioeconomic data from 2007 to 2012 were chosen to calibrate the population and GDP modules parameters (Fig. 2), while data from 2013 to 2016 were used to verify the validity of the simulation results. Table 2 showed that the relative error of the calibration and the

**Fig. 4** The total WREF, the WRCC, the water resource, and the WPI of Zhangjiakou



**Table 2** Error analysis in the SDM of Zhangjiakou (unit: %)

Population				GDP			
Time	Relative error	Time	Relative error	Time	Relative error	Time	Relative error
2007	0.004	2012	0.689	2007	-0.006	2012	-4.312
2008	0.497	2013	0.630	2008	-4.806	2013	-0.811
2009	0.559	2014	0.517	2009	4.076	2014	2.026
2010	1.275	2015	0.813	2010	-0.862	2015	3.964
2011	1.840	2016	1.079	2011	-5.785	2016	-2.335

validation results for both the population and GDP from 2007 to 2016 were below 10%. The results indicated that the population and GDP tendency simulated by the SDM could well reflect the socioeconomic development in Zhangjiakou City, as shown in Fig. 5. The simulated result of the population and GDP development in the next decades is shown in Fig. 6 and we used this result to further predict the future WRCC.

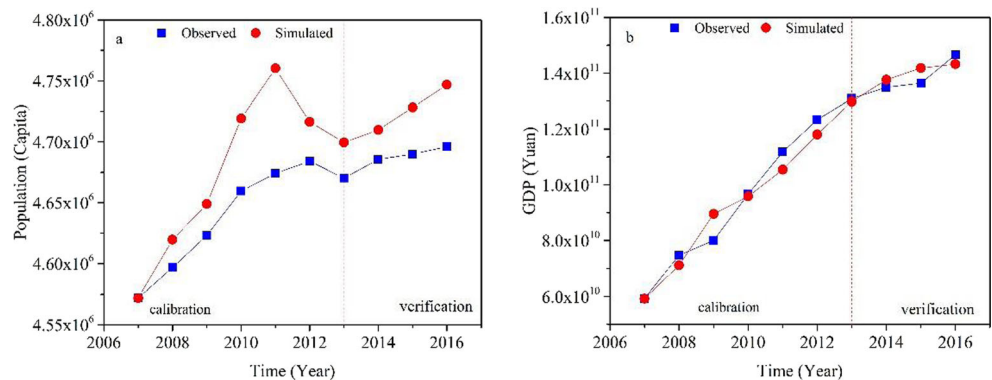
**The future sustainability of the regional water resource**

Since the regional precipitation and evaporation had no significant change during the past two decades ( $p < 0.05$ , Fig. 7), we assume that the total amount of water resource in this region generally keep stable. Therefore, we consider that the average annual water resource in this region and the mean value of the WREF per capita are constants. These assumptions have been adopted to further explore the long-term sustainability of the water resource and its effects on the socioeconomic development in Zhangjiakou City from 2017 to 2050 with the predicted population and GDP.

The current water resource assessment as mentioned above showed that the water resource and water consumption in Zhangjiakou is far from balance. Based on the total WREF and WRCC formulas (“The framework of water resource ecological footprint” section), from a macroscopic perspective, we choose the average annual water resource ( $17.90 \times 10^8 \text{ m}^3$ ) and WREF (0.41  $\text{ghm}^2/\text{per capita}$ ) as constants to

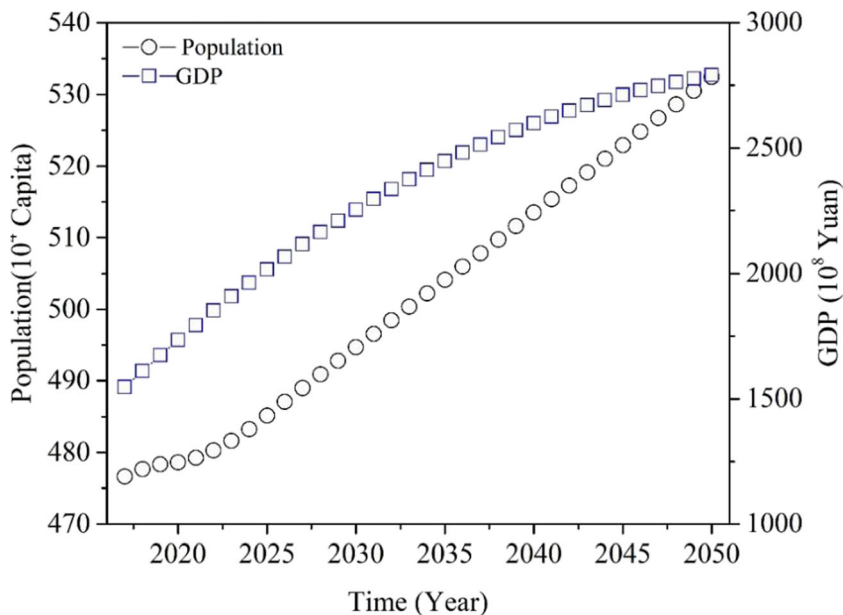
reveal the long-term trend of the WREF and the water resource WPI. As shown in Fig. 8a, the total WREF increased from  $1.91 \times 10^6 \text{ ghm}^2$  in 2017 to  $2.13 \times 10^6 \text{ ghm}^2$  in 2050. Meanwhile, compared with 2007, the water resource WPI will increase up to 5.39 by 2050. This indicates that the water use far exceeds sustainable limit and the water resource in Zhangjiakou is unsustainable to support the local development. However, the average WREF per unit GDP (10,000 Yuan) shows decrease through years (Fig. 8b), indicating that the utilization level of the water resource gradually improved. During 2007–2016, the average WREF per unit GDP (10,000 Yuan) decreased sharply with a decreasing rate of  $0.020 \text{ ghm}^2/\text{year}$ , and while during 2017–2050, it would decrease more slowly with a decreasing rate of  $0.001 \text{ ghm}^2/\text{year}$  (Fig. 8b). The difference of decreasing rates indicates that although the improved water use efficiency has alleviated the regional water resource pressure, the efficiency gained would be largely offset by the increased water demand due to the continued economic development (Fig. 6). In addition, the total amount of water resource in the region would not increase because of the relatively constant regional precipitation and evaporation in the long term (Fig. 7). Therefore, the space to increase the water resource is hardly feasible, and to improve the efficiency of water resource, utilization becomes urgent. Thus, the water shortage will become more severe and the restriction of water resource for the socioeconomic

**Fig. 5** Comparison of observed and simulated values (a population, b GDP)





**Fig. 6** The predicted population and GDP of 2017–2050 via SDM



development will become more and more prominent over the next three decades, and this will in turn restrain the future GDP growth rate.

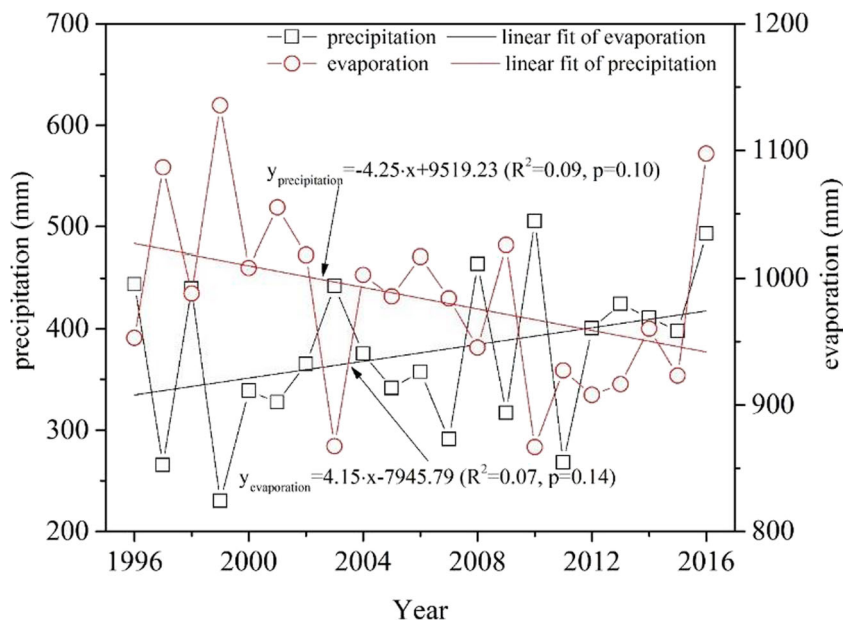
In general, the increased demand for water resource is the main reason for the continuously increasing of the total WREF. Even though the utilization level of the water resource has been improved based on the decreased WREF per unit GDP (10,000 Yuan), the sustainable development in the city could not be supported by the limited water resource (Fig. 8). We believe that without effective

managements for the available water resource supplement, this adverse effect will last long even until the year of 2050.

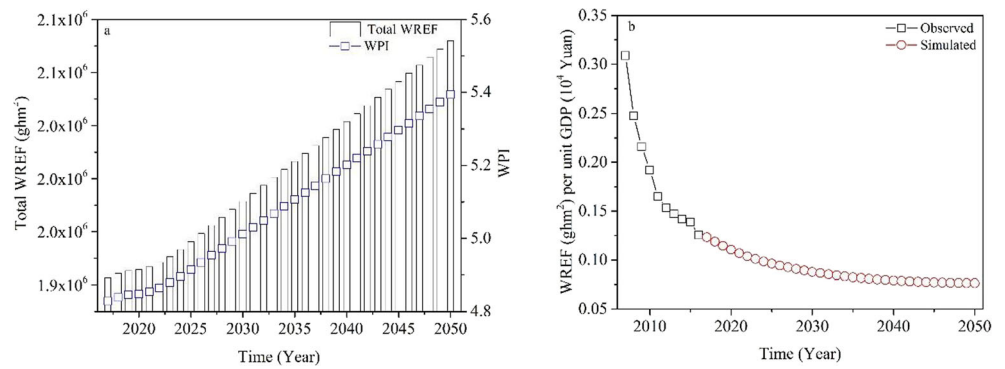
**Environmental implications**

According to our calculated result, the annual water shortage in Zhangjiakou during 2007–2050 would be up to  $8.53 \times 10^8 \text{ m}^3$  (Fig. 9), nearly half of the total local annual average water resource ( $17.90 \times 10^8 \text{ m}^3$ ), and thus, severe

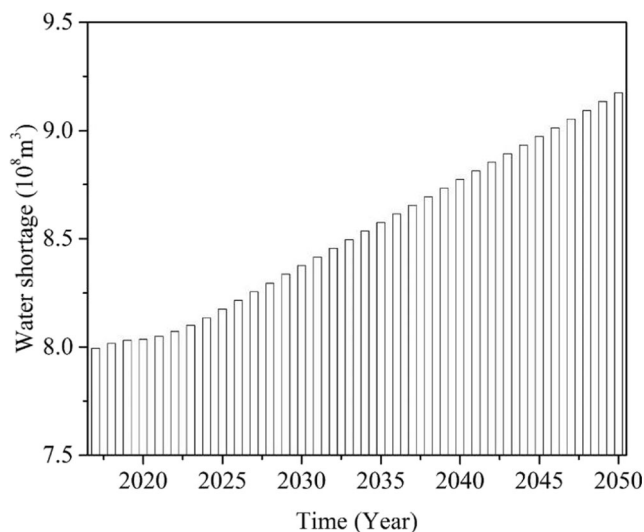
**Fig. 7** Long-term variation of precipitation and evaporation in Zhangjiakou City (the statistical analysis indicated that both the precipitation and evaporation had no significant change over the past two decades. Note that the year of 1999 saw the extreme dry year in north China)



**Fig. 8** The sustainable development trend of the WREF and the WPI (a) and changes of the WREF (ghm<sup>2</sup>) per unit GDP (10<sup>4</sup> Yuan) (b) in Zhangjiakou



water scarcity will exist for long-term in Zhangjiakou. Under this circumstance, there is growing competition between domestic water demand and the expanding industrial development. In the severe cases of water scarcity, such as extreme drought, the household water use must be given priority, and then the process water will be restricted, which would further intensify the regional unsustainability of local economic development. More importantly, though the precipitation and evaporation in Zhangjiakou had no significant change (Fig. 7), the global climate models have predicted that climate warming will reinforce the drought trend in the North China (the Yellow and the Hai River Basins) (Chen and Sun 2015; Xia et al. 2012). In fact, water resources in this area are highly sensitive to the climate change, because the increased temperature will result in decreased runoff (Xia et al. 2012). In this condition, the actual regional water resource yield would decrease, which will produce a great impact on the WREF result. Thus, the effects of climate change on WREF will be the focus of future studies.



**Fig. 9** The tendency of the water shortage in Zhangjiakou

### Recommendations to alleviate the regional water ecological pressure

The big challenge for Zhangjiakou is to achieve its economic growth and at the same time, to tackle the increasing water resource pressure. The key to solve the contradiction between economic development and water shortage requires multi-pronged approaches. Since irrigation is the largest water consumer in this region, irrigation system and agricultural management should be improved in this region. Specifically, the city need to reduce the irrigation land and/or increase the efficiency of irrigation water and encourage the development of high-tech industries with low water consumption and pollution, which have a significant effect on the WPI alleviation. Considering the adverse effects of climate change for the yield of the water resource, the city can increase the water supply through long-distance water diversion, i.e., the national South-to-North Water Transfer Project via the regional cooperation. Furthermore, the environmental pollution has put extra burden to the water scarcity in this region since there were no adequate waste-handling facilities (Guo et al. 2008). A successful alleviation strategy for the regional WPI therefore also includes long-term pollution controlling programs for the rivers and groundwater. These strategies may well benefit the water resource sustainability in this arid region in the near future. Further studies should focus on the sensitivity of water resource to climate change, and on the new technology related to maintain the sustainable socioeconomic development.

### Conclusions

This work provides a long-term recognition of the water resource sustainability of Zhangjiakou City in north China

based on the water ecological footprint model combined with the system dynamic model. The analytical results showed that:

- (1). The irrigation was the dominant water resource consumer in Zhangjiakou, accounting for 72.4% of the total water resource. There exists a clear gap between water supply and water consumption in this city and the gap is evidenced by the high WPI values with an average of 6.87. The current regional WRCC is overloaded, and this is the major limitation to the sustainable socioeconomic development if no effective measures are taken.
- (2). The predicted results based on the WREF and the SDM model showed that although the improving water use efficiency has mitigated the regional water shortage pressure due to the decreased WREF per unit GDP, the efficiency gained would be to a large degree offset by the increased demand for water resource because of the economic and population growth. The annual average water shortage in Zhangjiakou in 2007–2050 would be up to  $8.53 \times 10^8 \text{ m}^3$ , nearly half of the total local average annual water resource, which will bring a great challenge for the regional sustainable development.
- (3). The effective water management practices must be given priority in Zhangjiakou region. Otherwise, the severe water shortage will restrict the socioeconomic development in the next decades. Our findings provide important insights to policy-makers on how to balance the economic growth and the harmony of the human-natural system in the water scarcity regions.

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