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ANALYSIS

Water resources constraint force on urbanization in water deficient regions: A case study of the Hexi Corridor, arid area of NW China

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ABSTRACT

Based on analysis of water crisis during rapid urbanization especially in arid and semi-arid areas around the world, the concept of Water Resources Constraint Force (WRCF) is presented. The method utilized to identify the existence of WRCF is also introduced. After a logarithmic relationship model between urbanization level and total water utilization is established, the method to measure the WRCF on urbanization is also obtained. A case study of the Hexi Corridor, a typical arid area in NW China is presented. The results indicate that when the population, economic and urban scales approach or exceed the water resources carrying capacity, or the utilization of water resources approaches or exceeds the threshold of natural water resources, the water resources system significantly slows down the development of socio-economic systems, including the urbanization process. Furthermore, where the scarcer water resources are, the larger water resources constraint intensity (WRCI) is. In the Hexi Corridor, the WRCI is the largest in the Shiyang River Basin, in the eastern part, and where water resources are the scarcest. The WRCI in the middle and western part of the Hexi Corridor is relatively smaller because of relatively more water resources. Subsequently, areas within the Hexi Corridor should take a range of different measures to lessen the WRCF on urbanization according to their specific water resources constraint types: (1) Areas of the very strong constraint type should take emergency measures to resolve their water problems, including transferring water from other river basins, limiting the population, economic and urban scales, innovating in institution, policy and technology of water utilization, and strengthening water resources planning and management in the whole river basin; (2) areas of the less strong constraint type should avoid traditional methods of water utilization during the process of urbanization and industrialization in areas of the very strong constraint type. They should adjust the urbanization pattern and construct an intensive water resources utilization system, so that total water utilization can realize zero or negative growth and water-ecology–economy system can realize harmonic and sustainable development.

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1. Introduction

Since the Industrial Revolution of the 18th century, industrialization and urbanization have become the predominant rhythm for the socio-economic development throughout the world. The experiences of both developed and developing countries indicate that urbanization is a necessary precondition to industrialization and the eradication of poverty, as well as an important symbol to evidence the modernization of a country or a district (Qiu, 2004). In the 21st century, concurrent with the process of globalization and informationalization, city is becoming a world center and playing an ever more important role (Zhou, 2004). As urbanization progresses, a number of problems will be brought to the forefront, including such issues as population blasts, resources scarcity, and eco-environmental deterioration. A global water crisis is just one of these anticipated future problems (Biswas, 1991). Studies have shown that, global water utilization increased eight times in the 19th century and doubled in every 15 years, while water utilization for agriculture, industry and living increased 7, 20 and 12 times respectively (Liu and He, 1996). In the 20th century, while the world population doubled, the water utilization increased five times — and this despite the fact that water demand realized zero growth in some developed countries (World Water Council, 2000). Specifically, global urban water utilization for living increased over 20 times within 100 years. In 1900, it was 200×10^8 m^3. In 1950, it was 600×10^8 m^3. In 1975, it was 1500×10^8 m^3. In 2000, it was 4400×10^8 m^3. If it continues to increase at the same rate, global urban water utilization for living in the year 2050 will be equal to global water utilization at the present, and 55% of the people in the world will face a water crisis (Song et al., 2004b). In the 21st century, human beings will face a dilemma — whether to allow the water utilization level to continue increasing or to place a limit on the water demand (Malin, 1998). To lessen the loss of industrial output because of a shortage of urban water utilization, significant water resources previously utilized for agriculture are transferred to urban systems. It has much great influence on agriculture and grain production (Zhang et al., 2002). Subsequently, agricultural systems and rural areas have to transfer water from ecosystems in order to lessen their economic loss. As a result, the eco-environment gradually deteriorates due to water scarcity. Rapid urbanization has already caused serious water scarcities and drastic conflicts between water demand and supply. Water has become a key restricting factor of the urbanization process, as well as the socio-economic development (Olli and Pertti, 2001; Tomohiro et al., 2006; Guan and Hubacek, in press). Water security is an important component of food security, economic security, eco-security, social security, national security, and even human survival security, especially in arid and semi-arid areas (Knapp, 1995).

As water problems became more serious, Chinese scholars brought forth the concept of Water Resources Carrying Capacity in the late 1980s. This refers to the largest scale of population and economy in a certain area according to the total water resources, the securable technology, and the socio-economic development level within a certain period (Li and Gan, 2000). Besides, the total water resources should be rationally allocated; the socio-economic development should follow the principle of sustainable development and realize a benign circle of eco-environment. Scholars in other countries employ similar concepts to refer to this issue, including sustainable water utilization, available water resources, threshold of natural water resources, water stress index, etc. These concepts mainly refer to the utmost development of natural water resources (Long et al., 2004). In the arid area of NW China, because the existing water resources are already at a carrying capacity level, the amount of farmland, the output of industry and agriculture, and the scale of cities no longer increase when they reach a certain level (Si, 2000). While in some areas, rapid urbanization and economic reformation gradually slow down because of water scarcity, even though they obviously have not reached their largest scales. Consequently, we bring forth the concept of Water Resources Constraint Force (WRCF). This refers to the friction that water resources system gives to the socio-economic system. In other words, when the population, economic and urban scales approach or exceed the water resources carrying capacity, or the utilization of water resources approaches or exceeds the threshold of natural water resources, water resources system will be highly stressed by socio-economic system. Consequently, water resources system will slow down the socio-economic development, including the process of industrialization and urbanization.

As shown in Fig. 1, during the ascending process of urbanization, the socio-economic system has its own gravitation (*G*). Correspondingly, the natural resources and environmental system gives a holding power (*N*) to it. In the direction which urbanization moves forward, a driving force (*F*) and a resisting force (f) exist (Jin et al., 2004). The driving force includes the pulling force from the demand of urbanization and the pushing force from the supply outside; the resisting force is the friction between the urbanization system, the natural resources system, and the environmental system, which can be expressed by the arithmetic product of the holding power (*N*) and the friction coefficient (u). The above forces are all composite forces. During a certain period and in a certain area, if water resources are the shortest, or other resources are much more abundant than water resources, the maximum of the holding power (*N*) will be mainly decided by the water resources carrying capacity according to the Wooden Barrel Principle (Wang, 2005). On the other hand, the pressure which urbanization system places on water resources system is tremendous when compared with the water resources carrying capacity, while the pressures that urbanization system gives to other resources system is small when compared with other resources carrying capacity. Consequently, we can consider that the friction water resources system gives to the urbanization system is by far the largest and the friction that other resources system gives to the urbanization system is near zero. Subsequently, the resisting

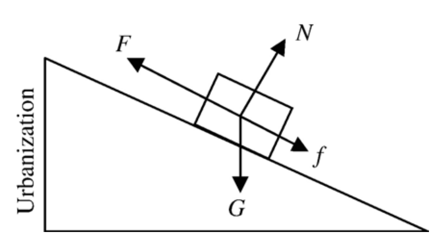

Fig. 1 – "Climbing slope" model.

force on urbanization is mainly decided by the WRCF. Therefore, to accelerate the urbanization process and realize the sustainable utilization of water resources, the system info of WRCF, including the basic theory, the quantitative method and its case study, should be constructed and perfected. In addition, its birth mechanism, influencing factors, influencing mechanism, variation law and its control should be taken as the key studies. It is considered that, during the 21st century, WRCF is one of the most important components of water security research in the world. By studying water resources carrying capacity (*N*), water resources stress (*G*) and water resources constraint force (*f*), the interaction and relationship between water resources system and socio-economic system can be precisely explained. Therefore, we put forward a method to identify the existence of WRCF and a method to measure it. Then we take the Hexi Corridor, a typical arid area in NW China as a case study to validate the methods.

2. Materials and methods

2.1. Study area

The Hexi Corridor, which is the study area, lies in the northwest of the Gansu Province and to the west of the Yellow River in China. It is a long corridor between the South Mountains (including Qilian Mountains and Aerjin Mountains) and the North Mountains (including Mazong Mountains, Heli Mountains and Longshou Mountains). It starts at Wushaoling Mountains in the east, and ends at Yumenguan (an important col in ancientry) in the west. It ranges from 92°21′ to 104°45′ E and from 37°15′ to 41°30′ N, with a total area of 27.6×10^4 km^2. The distance from north to south is 40–100 km and the distance from east to west is about 1120 km. The Badain Jaran Desert and the Tengger Desert lie in its northeast (Fig. 2).

The study area has an arid continental climate, with an average annual temperature of 5–9 °C. The annual daily mean sun duration is 2800–3300 h, and the global radiation is 140–158 kcal/cm^2. The annual precipitation is 50–150 mm, while the annual evaporation is 1500–3200 mm. It has three big river systems, including the Shiyang River, the Hei River and the Shule River from east to west. The riverheads all come from the glacier of Qilian Mountains. The average annual total water resources available are 80.31×10^8 m^3. Moreover, the surface water resources are 73.22×10^8 m^3. The unrepeated groundwater resources are 7.09×10^8 m^3(Fang et al., 2004). In 2003, the actual water utilization was 82.17×10^8 m^{3}and the utilization ratio of water resources reached 102%. The utilization ratio of water resources in the Shiyang River Basin, the Hei River Basin and the Shule River Basin reached 154%, 112% and 76.4% respectively (Chen and Hao, 2005), much higher than 40%,the internationally recognized alarm line (Malin and Carl, 1992). Consequently, eco-environmental and socio-economic problems emerged in the Hexi Corridor (Wang, 2002).

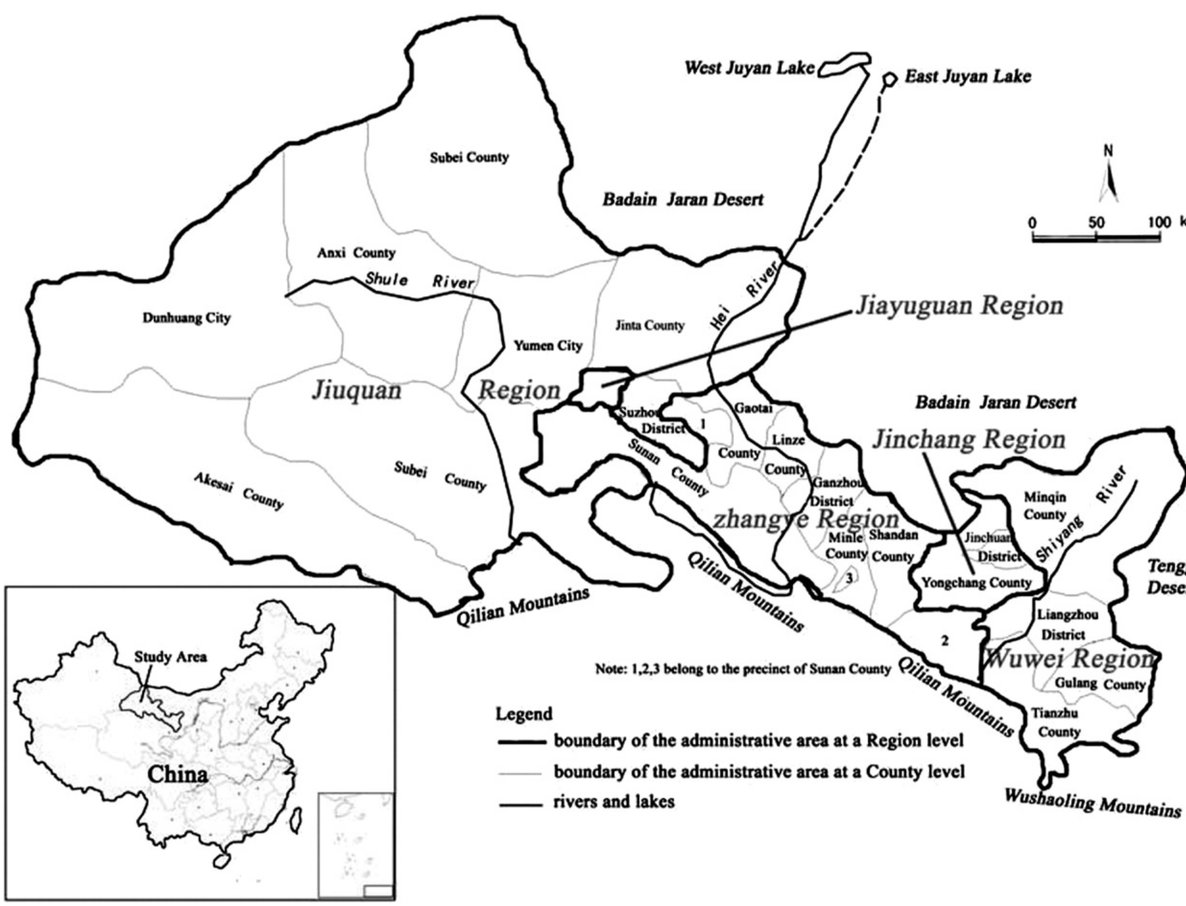

Fig. 2 – Map of the Hexi Corridor, Gansu Province, China.

The study area is an important sector of the Silk Road and the New Asia–European Railway. It is one of the key regions during the great development of West China. It has five administrative areas including Jinchang Region, Wuwei Region, Zhangye Region, Jiayuguan Region, and Jiuquan Region (Fig. 2). Table 1 shows the actual water utilization and the utilization ratio of water resources in each administrative area at the end of 2003. From Table 1, we can see that, all these five administrative areas are short of water resources. According to the international standards (UNDP, 1990), Wuwei Region belongs to the severe water deficient regions (per capita water resources between 500–1000 m^3). Jinchang Region belongs to the moderate water deficient regions (per capita water resources between 1000–1700 m^3). Zhangye Region belongs to the slight water deficient regions (per capita water resources between 1700–3000 m^3). However, Zhangye Region should transfer 9.5×10^8 m^3water resources to the lower reaches of the Hei River Basin in normal years, so total water resources available in Zhangye Region are decreased to 17.0×10^8 $m^3$and per capita water resources are decreased to 1341 m^3. Then Zhangye Region belongs to the moderate water deficient regions. The utilization ratios of water resources in Wuwei, Jinchang, and Zhangye Region all exceeded 100%. The utilization ratios of water resources in Jiayuguan Region and Jiuquan Region both exceeded 40%. All of these five administrative areas have approached or exceeded their water resources carrying capacity. During the great development of West China, the urbanization process in the Hexi Corridor will become faster. Rapid urbanization will still increase the WRCF. Consequently, it is of great importance and necessity to control the WRCF and accelerate the urbanization process in the Hexi Corridor.

Jingchang Region and Wuwei Region lie in the east of the Hexi Corridor. Of the two administrative areas, 90.4% of its area belongs to the Shiyang River Basin, and 9.6% (mainly in Tianzhu County and Gulang County) belongs to the Yellow River Basin. The Shiyang River Basin has an area of 3.87×10^4 km^2. It all belongs to Jingchang Region and Wuwei Region. Its total water resources are 17.35×10^8 m^3(82.3% of the two administrative areas). We subsequently took these two administrative areas to reflect the situations of the Shiyang River Basin and the eastern part of the Hexi Corridor.

Zhangye Region lies in the middle of the Hexi Corridor. It is the main part of the Hei River Basin — the Hei River Basin also includes Qilian County in Qinghai Province, Ejina Banner in Inner Mongolia and a part of Jiayuguan Region, Suzhou District and Jinta County in Jiuquan Region (Xu et al., 2003). The development and utilization intensity of water and land resources in Zhangye Region is the largest in the mainstream of the Hei River Basin (Zhang et al., 2004), and in the mainstream of the Hei River Basin, water utilization for production and living in Zhangye Region occupies more than 88% of the total water resources (Bao, 2004). Therefore, we took Zhangye Region to reflect the situations of the Hei River Basin as well as the middle part of the Hexi Corridor.

Jiayuguan Region and Jiuquan Region lie in the west of the Hexi Corridor. Of its total area, 88.9% lies in the Shule River Basin, and 11.1% (mainly in Jiayuguan Region, Suzhou District and Jinta County in Jiuquan Region) belongs to the Hei River Basin. The Shule River Basin has an area of 16.998×10^4 km^2. It all belongs to Jiayuguan Region and Jiuquan Region. Therefore, we took these two administrative areas to reflect the situations of the Shule River Basin and the western part of the Hexi Corridor.

2.2. *Data acquisition*

We took investigation data and statistical data as the main data sources. The statistical data are originally from the past years *Gansu Water Resources Communique*, *Water Conservancy Annals of Jinchang*, *Wuwei*, *Zhangye*, *Jiayuguan* and *Jiuquan* respectively. The socio-economic data of each administrative area are obtained in the statistical yearbooks for the years 1985 to 2003. For data gathering convenience, we took the five administrative areas as the basic study unit.

2.3. *Methods*

2.3.1. *Method to identify the existence of water resources constraint force* (WRCF)

Since the Hexi Corridor belongs to a uniform unit of nature and administration, the natural and economic conditions for the socio-economic development in the five administrative areas are similar to each other. Since 1978, China began to reform its economic system and opened its door to the world. The continuous and rapid growth of the economy offered many

Table 1 – Total water resources and their development and utilization in the Hexi Corridor

	Surface water resources (10^8 m^3)	Unrepeated groundwater resources (10^8 m^3)	Water resources available (10^8 m^3)	Actual water utilization in 2003 (10^8 m^3)	Utilization ratio of water resources (%)	Per capita water resources (m^3/person)
Jinchang Region	5.93	0.37	6.30	7.95	126	1369
Wuwei Region	13.81	0.96	14.77	20.47	139	765
Zhangye Region	24.75	1.75	26.50	29.37	111	2090
Jiayuguan Region	2.63	0.09	2.72	1.73	64	1571
Jiuquan Region	26.1	3.92	30.02	22.66	75	3107
Hexi Corridor	73.22	7.09	80.31	82.17	102	1674

opportunities for employees to get involved in non-agricultural industries. Many people could now go into urban areas to work. Therefore, like in other areas in China, the urbanization process in the Hexi Corridor is no longer restricted by national policy. However, water resources are unevenly distributed among the five administrative areas, and the unequal distribution of water resources has become the greatest difference for the urbanization process among the five administrative areas. Nonetheless, we can contrast the urbanization process, the changes of total water utilization and the degree of water shortage among the five administrative areas. If other situations are similar but the urbanization process moves slowly due to water shortage, we can conclude that water resources constraint force (WRCF) really exists. To verify the above method, we drew the scattering dot plots of urbanization level and total water utilization in the five administrative areas and the three inland river basins in the eastern, middle and western part of the Hexi Corridor from 1985 to 2003. From the changes inherent in total water utilization and the urbanization process, we can easily find whether the water resources system restricted the urbanization system.

2.3.2. *Method to measure the WRCF-indicator of water resources constraint intensity (WRCI)*

To measure the WRCF on urbanization, a model on the relationship between urbanization level and total water utilization should first be constructed.

Some scholars in China and abroad have studied the relationship between urbanization level and economic development. By analysis on the statistical data of 157 countries and districts in the world in 1977, Zhou (1995) found that the relationship between urbanization level and economic development could be expressed by a logarithmic curve (not a linear or hyperbola curve). In general, the expression goes as follows:

$$Y = c + d\ln Z \tag{1}$$

Where Y is urbanization level (%); Z is per capita GDP (yuan); c and d are simulated parameters of the regression equation.

Some scholars in China and abroad have also studied the relationship between total water utilization and economic development. Based on the historical data of GDP and water utilization in China, Song et al. (2004a,b) found the relationship between total water utilization and economic development could be expressed by a power function. In general, it can be expressed as follows:

$$X = gZ^f \tag{2}$$

Where X is total water utilization (10^4 m^3), Z is per capita GDP (yuan), g and f are simulated parameters of the regression equation.

We can get the following equation from the logarithm of the Eq. (2):

$$\ln X = \ln g + f\ln Z \tag{3}$$

From the Eqs. (1) and (3), we can obtain the following equation:

$$Y = a + b\ln X \tag{4}$$

Then a logarithmic relationship model between urbanization level and total water utilization is obtained. a and b are simulated parameters of the regression equation, and b should be above zero.

By using this model, we can forecast the total water utilization corresponding to a certain urbanization level. We can also obtain the increment of total water utilization necessary for 1% increase in urbanization level. From the logarithmic curve model, we find that, greater water supply is expected for every 1% increase in urbanization level (Fig. 3). However, as the progress of technology is limited, the repeated utilization ratio of net water resources is also limited. When the utilization of water resources has approached or exceeded the threshold of natural water resources, the net water resources are also limited. Then in the rapid urbanization, total water utilization (net water resources × the repeated utilization ratio of net water resources) cannot be increased to meet the demands of the development of socio-economic and eco-environmental systems. As shown in Fig. 3, if the urbanization level rises from Y_1 to Y_2, total water utilization should increase from X_1 to X_2 according to the normal conditions. However, because the net water resources and the repeated utilization ratio are both limited to a certain extent, total water utilization can only rise to X_2' during a certain period. Accordingly, the urbanization level can only arrive at Y_2'. Obviously, we can find that water scarcity retards the urbanization process. Consequently, in water deficient regions, to accelerate the urbanization process, the pattern of water utilization and urbanization should be adjusted. Specifically, total water utilization should realize zero or negative growth during the rapid urbanization. While in the process to compel the total water utilization to realize zero or negative growth, the logarithmic relationship between urbanization level and total water utilization will wear off. This phenomenon can be shown by the related coefficient of Eq. (4). It will become smaller while the logarithmic relationship wears off. Once total water utilization realizes zero or negative growth, the related coefficient of Eq. (4) will be very small and the logarithmic relationship model between urbanization level and total water utilization cannot pass the significance test. Therefore, the related coefficient of Eq. (4) (R) can be used as a comprehensive indicator to measure the WRCF. The smaller R is, the bigger the WRCF.

We define water resources constraint intensity (WRCI) as the main indicator to measure the WRCF. It indicates the extent of

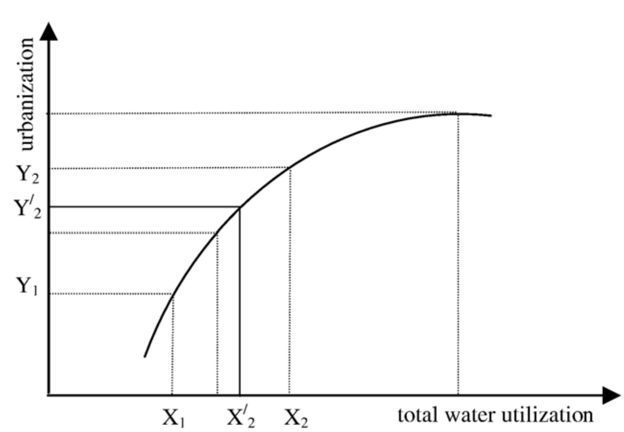

Fig. 3 – The constraint relationship between urbanization level and total water utilization.

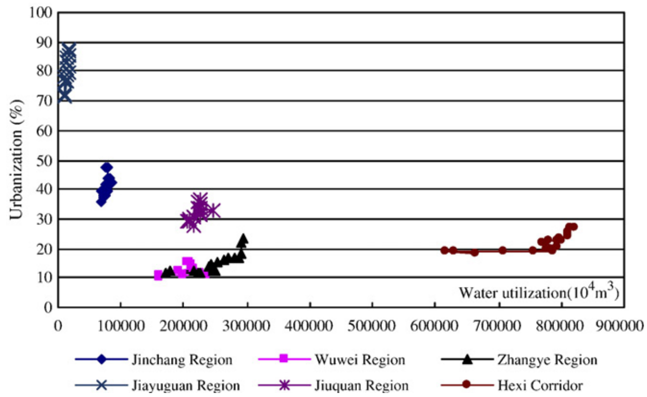

Fig. 4 – Analysis on the relationship between urbanization level and total water utilization in the Hexi Corridor.

the conflict between water resources system and urbanization system. If the WRCI is small, it means that the development between water resources system and urbanization system is coordinated, and the water resources system gives little resistance to the urbanization process. If the WRCI is large, it means that the water resources system gives heavy resistance to the urbanization process. As R^2 is called "coefficient of determination", it represents the goodness of fittest for the regression curve, or it represents how much degree X can explain Y in the regression equation. Accordingly, $1-R^2$ represents the deviation between the observation values and the fitted curve, or it represents how much degree Y cannot be explained by X based on the regression equation. When the water resources constraint intensity equals to zero, the urbanization level and the total water utilization will increase freely according to the logarithmic curve. When the water resources constraint intensity is growing, the relationship between urbanization level and total water utilization will deviate from the logarithmic curve step by step. Consequently, WRCI can be expressed by the following equation:

$$\mathrm{WRCI} = 1 - R^2 \tag{5}$$

Where R is the related coefficient of Eq. (4), and WRCI∈[0,1]. When WRCI is near zero, R is near 1 and the WRCF is small. When WRCI is near 1, R is near zero and the WRCF is large.

We define R∈[0, 0.4) as belonging to the weak correlation type, R∈[0.4, 0.6) belonging to the less strong correlation type, R∈[0.6, 0.8) belonging to the strong correlation type, R∈[0.8, 1] belonging to the very strong correlation type. Correspondingly, WRCI∈[0, 0.36) belongs to the weak constraint type. This means that water resources system gives little resistance to the urbanization process. WRCI∈[0.36, 0.64) belongs to the less strong constraint type. This means that water resources system gives a small amount of strong resistance to the urbanization process. WRCI∈[0.64, 0.84) belongs to the strong constraint type. This means that water resources system gives strong resistance to the urbanization process. WRCI∈[0.84, 1] belongs to the very strong constraint type. This means that water resources system gives very strong resistance to the urbanization process.

3. Results and discussion

3.1. *Quantitative identification of the existence of WRCF on urbanization in the Hexi Corridor*

In 2003, in the Hexi Corridor, the total population was 479.79×10^4. That was 1.26 times what it was in 1985, and the annual average growth rate was 12.9‰. The urbanization level (non-agricultural population/total population) was 27.24%, which was 8.99% larger than that in 1985. With the rapid growth of population and urbanization, total water utilization in the Hexi Corridor increased to 82.17×10^8 m^3 in 2003 from 66.47×10^8 m^3 in 1985. The annual average growth rate was 1.2%. The utilization ratio of water resources increased to 102% in 2003 from 83% in 1985. Most areas in the Hexi Corridor have to over-exploit the groundwater to keep the water utilization increasing, and the utilization of water resources has approached or exceeded the threshold of natural water resources.

As shown in Fig. 4, total water utilization in the five administrative areas all increased slowly because of water shortage. However, total water utilization in Zhangye Region increased faster than in other administrative areas while total water utilization in Wuwei Region and Jinchang Region increased rapidly at first and then decreased gradually. As the growth of total water utilization is limited, the urbanization process is also restrained. The results of Fig. 4 and the relationship between the urbanization level and the total water utilization in Wuwei Region and Zhangye Region indicate that the urbanization level and the total water utilization were both similar in 1985. While in 2003, the urbanization level and the total water utilization in Zhangye Region were both much larger than it was in Wuwei Region. From the year 1985 to 2003, the urbanization level in Zhangye Region increased by 12.4% and the urbanization level in Wuwei Region only increased by 5.2%. The total water utilization in Wuwei Region increased 7.8009×10^8 m^3 at the beginning, and then decreased 3.3081×10^8 m^3. It increased 4.4928×10^8 m^3 in total. While the total water utilization in Zhangye Region increased 7.2362×10^8 m^3 in total. It can be seen that the total water utilization and the urbanization level in Wuwei Region both increased more slowly than in Zhangye Region. Studies have

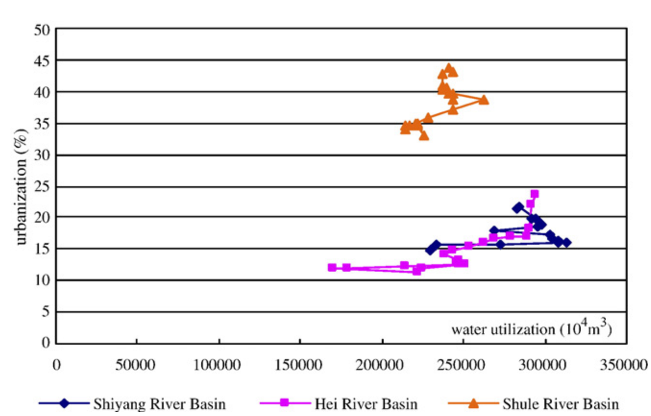

Fig. 5 – The relationship between urbanization and total water utilization in the three river basins of the Hexi Corridor.

Table 2 – The logarithmic relationship model between urbanization level and total water utilization in the Hexi Corridor

Name	Relationship model	Related coefficient (*R*)	Sig.	Significance
Jinchang Region	Y=40.851lnX−417.903	0.600	0.007	Very significant
Wuwei Region	Y=3.875lnX−34.718	0.251	0.299	Not significant
Zhangye Region	Y=16.904lnX−194.76	0.750	0.000	Very significant
Jiayuguan Region	Y=23.829lnX−147.149	0.844	0.000	Very significant
Jiuquan Region	Y=36.149lnX−412.605	0.693	0.001	Very significant
Hexi Corridor	Y=22.918lnX−288.554	0.689	0.001	Very significant
Shiyang River Basin	Y=7.8541lnX−80.425	0.325	0.175	Not significant
Hei River Basin	Y=16.904lnX−194.760	0.750	0.000	Very significant
Shule River Basin	Y=44.974lnX−517.817	0.718	0.001	Very significant

shown that the speed of the urbanization process mainly depends on the driving and resisting forces (Fang and Sun, 2005). As Wuwei Region and Zhangye Region are both typical oases in the arid area of NW China, and they both take agriculture as their main industry, have similar conditions such as population scale, economic scale, industrial structure, location situation, historical conditions and national policies, and the foundation and main driving forces of urbanization are generally similar. However, the water resources in Zhangye Region are relatively more abundant than that in Wuwei Region. Consequently, the urbanization process in Zhangye Region is relatively faster than that in Wuwei Region. In other words, Wuwei Region has larger WRCF than Zhangye Region, and then the urbanization level in Wuwei Region increased more slowly.

To identify the existence of WRCF in the Hexi Corridor, we also took the river basin as the study unit and divided the Hexi Corridor into three parts: eastern, middle and western part. Then we drew the scattering dot plots of urbanization level and total water utilization in the three parts. As shown in Fig. 5, the urbanization level and the total water utilization in the Shiyang River Basin and the Hei River Basin are similar. However, there is a significant difference in the two river basins. In 1985, the urbanization level in the Shiyang River Basin and the Hei River Basin was 14.91% and 11.34% respectively, and total water utilization in the Shiyang River Basin and the Hei River Basin was 22.9028×10^8 m^3 and 22.1293×10^8 m^3. Both the urbanization level and the total water utilization in the Shiyang River Basin were a little bigger than that in the Hei River Basin. While in 2003, the urbanization level in the Shiyang River Basin and the Hei River Basin was 21.62% and 23.67% respectively, and the total water utilization was 28.4224×10^8 m^3 and 29.3655×10^8 m^3. Both the urbanization level and the total water utilization in the Shiyang River Basin were a little smaller than that in the Hei River Basin. From 1985 to 2003, the urbanization level in the Shiyang River Basin increased by 6.71%, while the urbanization level in the Hei River Basin increased by 12.33%. Total water utilization in the Shiyang River Basin increased 5.5196×10^8 m^3, while total water utilization in the Hei River Basin increased 7.2362×10^8 m^3. Subsequently, we conclude that the urbanization process in the Shiyang River Basin was slower than in the Hei River Basin, and the total water utilization also increased at a slower rate in the Shiyang River Basin. The urbanization process in the Shiyang River Basin and the Hei River Basin were both slow compared with the average level in China, but the urbanization process in the Shiyang River Basin was slower than in the Hei River Basin because the Shiyang River Basin had a larger WRCF.

As shown in Fig. 5, the total water utilization in the Shiyang River Basin at first rose with the increase of urbanization level, but later turned downward. This phenomenon appeared not because water demand in the Shiyang River Basin rose at first and then turned down, but because the Shiyang River Basin had to reduce water utilization when the utilization of water resources approached and exceeded the threshold of natural water resources. As water utilization was reduced, the development of high water-consuming agriculture and industry were confined, and then the urbanization process in the Shiyang River Basin was also restricted.

From the above analysis, we found that whether we took the administrative area or the river basin as the basic study unit, there both exist the phenomenon that where the scarcer water resources are, the slower the urbanization process is. This indicates that WRCF really exists when the utilization of water resources approaches or exceeds the threshold of natural water resources.

3.2. *Analysis of WRCI on urbanization in the Hexi Corridor*

3.2.1. *Logarithmic relationship model between urbanization level and total water utilization in the Hexi Corridor*

Based on the statistical data of urbanization level and total water utilization from 1985 to 2003, the logarithmic relationship model between urbanization level (*Y*) and total water utilization (*X*) in the five administrative areas and the three inland river basins in the eastern, middle, and western part in the Hexi Corridor are calculated. The results are shown in Table 2.

Table 3 – Water resources constraint intensity on urbanization in the Hexi Corridor

	Jinchang Region	Wuwei Region	Zhangye Region	Jiayuguan Region	Jiuquan Region	Hexi Corridor	Shiyang River Basin	Hei River Basin	Shule River Basin
WRCI	0.640	0.937	0.438	0.288	0.520	0.525	0.894	0.438	0.484
Constraint type	Strong	Very strong	Less strong	Weak	Less strong	Less strong	Very strong	Less strong	Less strong

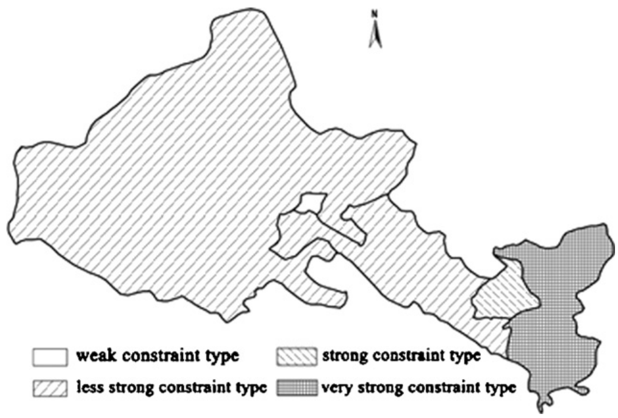

Fig. 6 – Water resources constraint intensity on urbanization in the five administrative areas in the Hexi Corridor, NW China.

From Table 2, we found that, if we took the administrative area as the study unit, all the logarithmic relationship models between urbanization level and total water utilization can pass the significance test except in Wuwei Region. This indicates that the urbanization level and the total water utilization level have a significant relationship. When the urbanization level increases, total water utilization also increases. The sequence of the significance between urbanization level and total water utilization in the five administrative areas goes as follows: Jiayuguan Region (0.844)>Zhangye Region (0.750)>Jiuquan Region (0.693)>Hexi Corridor (0.689)>Jinchang Region (0.600)>Wuwei Region (0.251). This sequence is almost in accordance with the sequence of the utilization ratio of water resources (Table 1). If we took the river basin as the study unit, all the logarithmic relationship models between urbanization level and total water utilization can pass the significance test except in the Shiyang River Basin. The related coefficients in the Hei River Basin and the Shule River Basin are 0.750 and 0.718 respectively. This indicates that the urbanization level and the total water utilization have a significant relationship in the Hei River Basin and the Shule River Basin.

From the logarithmic relationship model, we can calculate total water utilization corresponding to a certain urbanization level. Taking the whole Hexi Corridor as a case study, when the urbanization level was 10% ($Y=10$), total water utilization would be 45.30×10^8 m^3; when the urbanization level was 20% ($Y=20$), total water utilization would be 70.07×10^8 m^3; when the urbanization level was 30% ($Y=30$), total water utilization would be 108.40×10^8 m^3, much greater than its average annual total water resources available (80.31×10^8 m^3). As the urbanization level and the total water utilization are not perfectly related, there exist definite errors between the real conditions and the results we obtained from the logarithmic relationship model. Nevertheless, a trend exists that, as the urbanization level increases, more water will be required for every 1% increase in urbanization level. If total water utilization still increases according to the logarithmic relationship model, the urbanization level in the Hexi Corridor will hardly keep on increasing because the utilization of water resources has exceeded the threshold of natural water resources. Therefore, the traditional mode of urbanization and economic development should be adjusted. Total water utilization should realize zero or negative growth. In conclusion, the Hexi Corridor should construct an intensive water resources utilization system in order to lessen the WRCF on the urbanization process.

3.2.2. *WRCI on urbanization in the Hexi Corridor*

Based on the logarithmic relationship model between the urbanization level and the total water utilization in the five administrative areas and the three inland river basins in the eastern, middle and western part in the Hexi Corridor, and according to the method to measure the WRCF, the WRCI on urbanization in the Hexi Corridor is obtained as Table 3. From Table 3, we can see that, Wuwei Region belongs to the very strong constraint types. It indicates that Wuwei Region is the shortest of water resources and the water resources system gives very strong resistance to the urbanization process. Jinchang Region belongs to the strong constraint type. It indicates that Jinchang Region is the second shortest of water resources and the water resources system gives strong resistance to the urbanization process. Jiuquan Region and Zhangye Region belong to the less strong constraint type. It indicates that Jiuquan Region and Zhangye Region are less short of water resources and the water resources system gives a little resistance to the urbanization process. Jiayuguan Region belongs to the weak constraint type. It indicates that Jiayuguan Region is the most abundant of water resources and the water resources system gives the least resistance to the urbanization process. The results accord with the real conditions in the Hexi Corridor. In the eastern part (the Shiyang River Basin), including Wuwei Region and Jinchang Region, water resources are the shortest and the utilization ratio of water resources is the biggest, then the WRCI is the biggest. In the middle part (the Hei River Basin), the utilization ratio of water resources is the second biggest. However, we only took Zhangye Region to reflect the conditions of the Hei River Basin. As Zhangye Region robbed some water resources from the lower reaches of the Hei River Basin, water shortage was reduced to some extent, and then the WRCI is not the second biggest. Jiayuguan Region belongs to the weak constraint type not because its water resources are very abundant, but

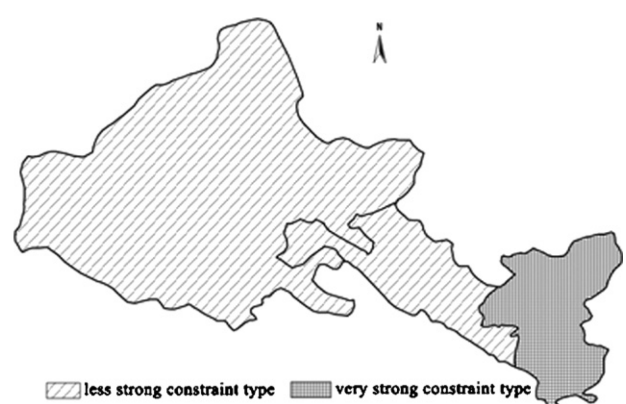

Fig. 7 – Water resources constraint intensity on urbanization in the three inland river basins in the Hexi Corridor, NW China.

because it is an important industrial city in China and its water resources should be first guaranteed. If the western part (the Shule River Basin), including Jiayuguan Region and Jiuquan Region are both very short of water resources in a certain year, some water resources will be transferred from Jiuquan Region to guarantee the industrial development in Jiayuguan Region. Then water resources system gives the least resistance to its urbanization process.

From Figs. 6 and 7, it is much more clear that the WRCI on urbanization in the Hexi Corridor is different in spatial scale. Most areas in the Hexi Corridor belong to the less strong constraint type. If we take measures as soon as possible to adjust the pattern of water utilization and urbanization in these areas, sustainable development in the Hexi Corridor can still be realized. As the Shiyang River Basin belongs to the very strong constraint type, shortage of water resources has caused serious problems, including socio-economic and eco-environmental problems, such as water quality deterioration, soil salinization, vegetation degeneration, land desertification, frequent disaster, ecological refugee and slow development of economy and urbanization. Then emergency measures should be taken in this area. First, water should be transferred from other river basins (mainly from the Yellow River Basin and the Yangtze River Basin). Second, the urban scale should be limited according to the water resources carrying capacity. Third, institution, policy and technology of water utilization should be innovated in. Besides, water resources planning and management in the whole river basin should be strengthened.

4. Conclusions

(1) As the water crisis during rapid urbanization becomes more serious, especially in arid and semi-arid areas around the world, we put forward the concept of Water Resources Constraint Force (WRCF). In water deficient regions, when the population, economic and urban scales did not approach or exceed the water resources carrying capacity before, water constraint force on the socio-economic development was not so great. However, when the utilization of water resources has approached or exceeded the threshold of natural water resources nowadays, WRCF will become the key resisting force to slow down the growth rate of economy and the process of industrialization and urbanization. It will do bad to transform the rural population to citizens, and aggravate the eco-environment and the poverty in rural areas. The WRCF has become one of the important exogenic forces of economic growth. Consequently, most traditional economic growth theory models (Good and Reuveny, 2006) and traditional resource and environmental economics (Matthias, 2006) should be adjusted. WRCF is one of the key components of water security research. Through the study of water resources carrying capacity, water resources stress, and water resources constraint force, the interaction and relationship between water resources system and socio-economic system can be quantitatively explained. At present, the system info of WRCF, including the basic theory, quantitative method, and its case study, should be constructed and perfected. Specifically, its birth mechanism, influencing factors, influencing mechanism, variation law, and its control should be taken as the key studies. Additionally, the integration study between WRCF and other domains in water sciences should also be emphasized.

(2) According to the scattering dot plots of the urbanization level and the total water utilization in the five administrative areas and the three inland river basins in the eastern, middle, and western part of the Hexi Corridor from 1985 to 2003, we found that whether we took the administrative area or the river basin as the basic study unit, there both exists the phenomenon that the scarcer the water resources are, the slower the urbanization process is. This indicates that WRCF really exists when the utilization of water resources approaches or exceeds the threshold of natural water resources.

(3) According to the logarithmic relationship model between urbanization level and total water utilization, we found that, urbanization level and total water utilization level have a significant relationship. As the urbanization level increases, more water will be required for 1% increase in urbanization level. If total water utilization still increases according to the logarithmic relationship model, the urbanization level in the Hexi Corridor will hardly keep on increasing because the utilization of water resources have exceeded the threshold of natural water resources. Therefore, the traditional mode of urbanization and economic development should be adjusted, and the total water utilization should realize zero or negative growth.

(4) According to the WRCI on urbanization, we found that, Wuwei Region belongs to the very strong constraint type. Jinchang Region belongs to the strong constraint type. Jiuquan Region and Zhangye Region belong to the less strong constraint type. Jiayuguan Region belongs to the weak constraint type. Most areas, including the Hei River Basin and the Shule River Basin belong to the less strong constraint type. The Shiyang River Basin belongs to the very strong constraint type. Areas within the Hexi Corridor should take a range of different measures to lessen the WRCF on urbanization according to their water resources constraint types. Specifically, areas of the very strong constraint type should take emergency measures to resolve their water problems, including transferring water from other river basins, limiting the population, economic and urban scales, innovating in institution, policy and technology of water utilization, and strengthening water resources planning and management in the whole river basin, etc. However, areas of the less strong constraint type should avoid traditional methods of water utilization during the process of urbanization and industrialization in areas of the very strong constraint type. They should adjust the urbanization pattern and construct an intensive water resources utilization system, so that total water utilization can realize zero or negative growth and the water-ecology–economy system can realize harmonic and sustainable development.

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