Environ Earth Sci (2016) 75:37
DOI 10.1007/s12665-015-4816-6

ORIGINAL ARTICLE

Assessment of water resource carrying capacity in karst area of Southwest China

Qiyong Yang[1,2,3] · Fawang Zhang[2] · Zhongcheng Jiang[2] · Daoxian Yuan[1,2] · Yongjun Jiang[1]

Received: 20 September 2014 / Accepted: 14 July 2015 / Published online: 19 December 2015

Abstract Water resources are essential for sustainable economic and social development, especially in the karst regions of Southwest China. Guizhou Province was selected as a representative area to explore water resource carrying capacity (WRCC) in karst regions. The concepts of carrying capacity of utilization amount of water resource (CCUWR) and gross amount of water resources (CCGWR) were proposed to evaluate the scales of population, agriculture and economy that local water resources can support. Results show that actual values of population and cultivated land were much larger than the CCUWR, indicating that both population and agriculture were overburdened from 1999 to 2012. However, actual values of GDP were smaller than those of CCGWR and CCUWR, suggesting that water resources were in surplus relative to economic development. In comparison between actual values and those of CCGWR, the WRCC potential for the scales of population and cultivated land is low, but the potential for the economy is high. The discrepancy between the water resources and cultivated land was most pronounced in Guizhou. This paper indicates that it is urgent to enforce rational policies to ensure utilization efficiency of water resources in karst regions.

Keywords Water resource · Carrying capacity · Karst area · Sustainable development · Southwest China

✉ Qiyong Yang
yangqiyong0739@163.com

✉ Fawang Zhang
zhangfawang@karst.ac.cn

1 Institute of Karst Environment and Rock Desertification Control, School of Geographical Sciences, Southwest University, Chongqing 400715, China

2 Key Laboratory of Karst Ecosystem and Treatment of Rocky Desertification, Institute of Karst Geology, Chinese Academy of Geological Sciences, Guilin 541004, China

3 The Collaborative Innovation Center of the Ecological Environment & Integration Development in the Xijiang River Basin, Nanning 530001, China

Introduction

Water is an indispensable and fundamental resource for regional and national socioeconomic development as well as sustainable environmental development, especially in arid and semiarid areas (Obot 1984; Meng et al. 2009). As a consequence of population growth and economic development, water scarcity has become increasingly prominent, constraining regional sustainable development (Gunasekara et al. 2014). Water resource carrying capacity (WRCC) is a new concept, first introduced by the China Xinjiang Water Resource Soft-Science Research Panel in 1985 (Song et al. 2011). There remain differing definitions of WRCC in China and other countries (Liang et al. 2002). Some consider it the capacity to maintain a sustainable and functioning society (Harris and Kennedy 1999; Ofoezie 2002; Clarke 2002; Lopes and Theisohn 2003; Feng and Huang 2008; Ubels et al. 2010), and others as a threshold of water support to human activity (Kuykendtierna et al. 1997; Hunter 1998; Falkenmark and Lundqvist 1998; Rijsberman and van de Ven 2000; Li et al. 2000; Chadenas et al. 2008; Fowler and Ubels 2010). Actually, WRCC is a concept that accounts for both nature and society but is not limited to these (Giupponi et al. 2004). Many methods have been used to assess WRCC, such as the common tendency prediction method, main component analysis model (Fu and Ji 1999), system dynamics model (Feng and Huang 2008; Zhu 2008), ecological footprint (Wackernagel and Rees 1996; Wackernagel et al. 1997), multi-objective computation model (Fang et al. 2006), artificial neural networks model (Liu and Chen 2007; Lu et al. 2009), fuzzy comprehensive assessment model (Chen et al. 2008; Gong and Jin 2009), the Pressure-State-Response framework (Wang and Xu 2015).

However, because of huge population and limited resources, the traditional methods cannot be used directly in China (Song et al. 2011). Therefore, the concept of carrying capacity of relative resources (CCRR) was proposed in 2000 (Huang and Kuang 2000) and has widely been accepted (Wang et al. 2004; Chen and Jing 2006; Jing 2006; Li et al. 2008, 2009; Ye et al. 2007; Wang and Yang 2009; Song et al. 2011). Steps used to assess CCRR flow are: (a) select one or more regions (reference zone) as a benchmark; (b) calculate the index of CCRR in a study area in accord with the possession of resources or consumption per capita in that area and the reference zone.

There has been much research on CCRR in non-karst areas, but such research in the karst area of Southwest China is rare. This area covers 5.4×10^5 km^2 (Yuan 2001). Because of the unique karst topology, about 20 % of this area has severe degradation issues, such as karst rocky desertification, soil erosion, drought and shortage of water resources (Wang et al. 2002; Zhang et al. 2006). Although Southwest China has a subtropical monsoon humid climate with abundant rainfall, surface water rapidly infiltrates and supplies groundwater, because there are many fissures, gaps, sinkholes, caverns and underground streams in karst regions (Chen et al. 2010). Therefore, water resource security is a major issue and potentially a limiting factor to the socioeconomic development of karst regions and constrains the elevation of living standards. It is important to better understand WRCC in order to implement a rational water management planning so that future measurements can be implemented for rocky desertification control and ecological restoration. This paper uses a case study of Guizhou Province, a classical karst area, to explore the WRCC in the karst region of Southwest China. The objectives are to (a) reveal dynamic changes in WRCC in the province during 1999–2012 and (b) determine the spatial variability of WRCC in the province during that period.

Materials and methods

Study area

The extent of Guizhou Province is 103°36′–109°35′E, 24°37′–29°13′N, with a total area of 176,167 km^2 and nine cities/districts (Fig. 1). Carbonate rocks cover an area of 109,084 km^2 or about 61.9 % of the total area (Huang and Cai 2006). There are four topography categories in the study area: plateaus, mountains, hills and basins. The area of mountains and hills makes up 92.5 % of the total area. Topography of the study area is higher in the mid-west and lower in the east, with altitudes from 147 to 2900 m above sea level (Fig. 1). There is a subtropical monsoon humid climate with mean annual temperature of 14.8 °C and abundant but seasonally variable rainfall (Huang et al. 2012). Annual mean precipitation for the period 1958–1992 was 1300 mm.

This province was selected because it is where the most serious karst rocky desertification has occurred in Southwest China (Huang and Cai 2006). The province has a shortage of surface water resources, cultivated land and firewood and is one of the poorest areas of Southwest China. Studying the WRCC spatiotemporal pattern may

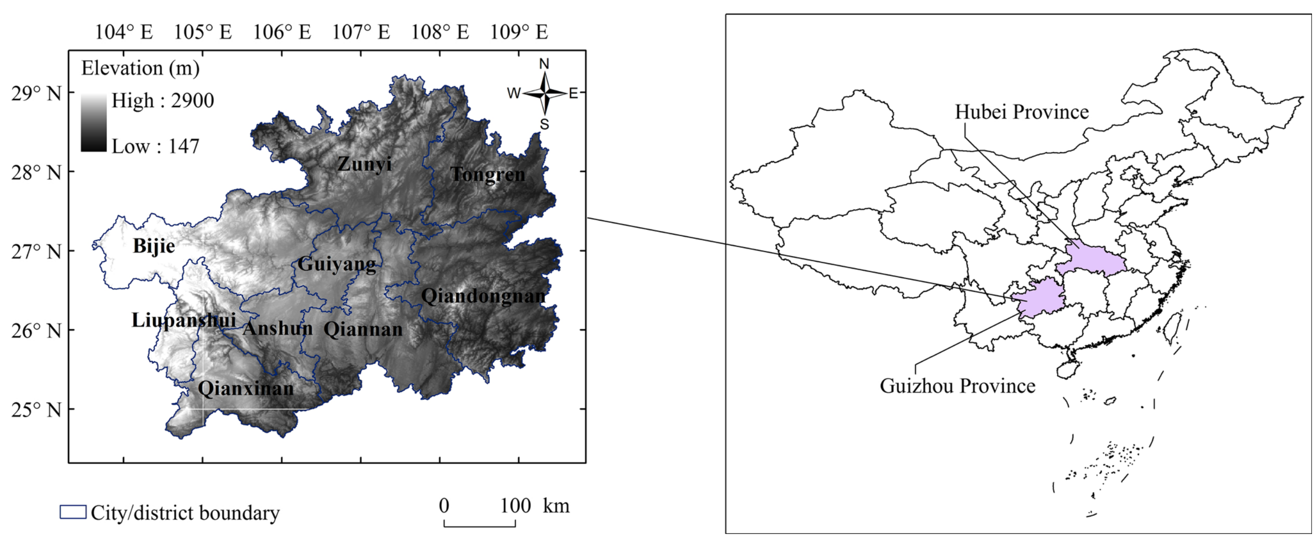

Fig. 1 Location of Guizhou Province and its nine cities/districts

help the local government develop relevant regional development policies toward improving living standards of residents and provide information for ecological reconstruction in the karst region.

Data sources

We collected time series data of population, cultivated land, GDP, gross and utilization amounts of water resources in Guizhou (including its nine cities/districts) Province, Hubei Province and all the China. Data on total population, GDP and cultivated land were obtained directly from *China Statistical Yearbook*, *Guizhou Statistical Yearbook* and *Hubei Statistical Yearbook* of the studied years. Gross and utilization amounts of water resources were from the national *Water Resources Bulletin* (1999–2012) issued by the Ministry of Water Resources, *Guizhou Water Resources Bulletin* (1999–2012) and *Hubei Water Resources Bulletin* (1999–2012). The data series for China included all provinces except Hong Kong, Macao and Taiwan.

Carrying capacity of relative water resources

The main sectors of the economy in Guizhou Province are agriculture and energy production. Industrial pollution is less as compared to the national average. However, soils in the province are often scarce, thin and rocky with strong permeability, which limits the amount of arable land. The conflict between population, cultivated land and water resources is great in the province. Therefore, population size, agriculture and economic scale were chosen as indices to assess provincial CCRR. Here, the theory of CCRR is used to evaluate the WRCC of Guizhou Province. CCRR was defined as the maximum bearing capacity of utilization and gross amount of water resources for human activity in a certain stage of socioeconomic development, or a certain living standard in a favorable ecological system. The former can indicate the state of WRCC and the latter its potential. The carrying capacity of relative water resources (CCRWR) was used to assess that WRCC by taking all China as the reference zone. The scales of population, agriculture and economy that local water resources could support were calculated by models of carrying capacity of utilization amount of water resource (CCUWR). Potential scales of population, cultivated land and economy that those resources could support were assessed by models of carrying capacity of gross amount of water resource (CCGWR). WRCC during 1999–2012 in Guizhou Province was selected to evaluate dynamic WRCC change in the karst region. Average WRCC from 1999 to 2012 in the nine provincial cities/districts was selected to evaluate WRCC spatial variability. Equations based on CCRWR are as follows (Tang et al. 2009; Song et al. 2011):

- Population index of the CCRWR:

$$C_{\mathrm{rp}} = I_1 \times Q_{w1} \quad (1)$$

$$I_1 = Q_{p0}/Q_{w0} \quad (2)$$

- Agriculture index of the CCRWR:

$$C_{\mathrm{rg}} = I_2 \times Q_{w1} \quad (3)$$

$$I_2 = Q_{g0}/Q_{w0} \quad (4)$$

- Economic index of the CCRWR:

$$C_{\mathrm{re}} = I_3 \times Q_{w1} \quad (5)$$

$$I_3 = Q_{e0}/Q_{w0} \quad (6)$$

Here, C_{rp}, C_{rg} and C_{re} are population size, agriculture and economic scale of CCRWR, respectively; I_1, I_2 and I_3 are the carrying indexes of relative water resources; Q_{w0} and Q_{w1} are volumes of water resources (including utilization and gross amounts of those resources) of the reference zone and study area; and Q_{p0}, Q_{e0} and Q_{g0}, are values of population, cultivated land and GDP of the reference zone.

Results

Among Chinese provinces, the area of Guizhou is nearest to that of Hubei. They both have a subtropical monsoon climate, and their precipitation and gross amounts of water resources are approximately equal. The area of Guizhou is slightly smaller than that of Hubei, by 1.0×10^4 km^2, but the gross amount of water resource in Guizhou is slightly larger, by 26.7×10^8 m^3. Guizhou Province is a representative karst area, whereas Hubei is in a non-karst area. Therefore, to address the unique characteristics of WRCC in the karst region, CCRWR in Hubei was also calculated by taking China as the reference zone (Table 1).

Dynamic changes in water resource carrying capacity in Guizhou Province

Figure 2 shows dynamic changes in WRCC in Guizhou Province from 1999 to 2012, with China as the reference zone. The trends of dynamic changes in WRCC for population, cultivated land and GDP are different in Guizhou Province in this phase. On the one hand, WRCC for population and cultivated land was stable with relatively large population and limited cultivated land. On the other, WRCC for GDP was increasing, due to the laggard economy.

During 1999–2012, population in Guizhou slowly increased to a maximum 3931×10^4 in 2005, after which it began to decrease slightly (Fig. 2a). CCUWR for population in the province first increased slightly, plateaued

Table 1 Water resource carrying capacity in Hubei Province taking China as the reference zone

Year	Carrying capacity of utilization amount of water resource			Carrying capacity of gross amount of water resource		
	Population (10^4 person)	Cultivated land (10^3 hm^2)[a]	GDP (10^8 RMB)	Population (10^4 person)	Cultivated land (10^3 hm^2)	GDP (10^8 RMB)
1999	4722.9	493.7	3135.9	5953.5	622.4	3953.0
2000	4612.5	466.8	3610.7	6236.2	631.1	4881.7
2001	2834.4	283.4	2435.3	6386.6	638.7	5487.3
2002	5252.0	521.5	4920.0	5626.7	558.7	5271.0
2003	5807.6	554.6	6104.1	5953.2	568.5	6257.1
2004	4999.5	471.0	6149.2	5686.1	535.6	6993.6
2005	4353.2	406.6	6157.0	5881.6	549.3	8318.8
2006	3319.6	307.7	5462.8	5870.2	544.2	9660.1
2007	5310.6	489.1	10,683.5	5875.2	541.1	11,819.4
2008	5005.1	459.0	11,835.8	6083.1	557.8	14,385.1
2009	7002.0	638.6	17,887.0	6540.8	596.5	16,708.7
2010	5504.5	499.3	16,482.3	6510.2	590.5	19,493.6
2011	4388.3	396.3	15,409.0	6545.7	591.1	22,984.3
2012	3732.3	335.0	14,304.1	5055.0	453.7	19,373.5

[a] 1 hm^2 = 0.01 km^2

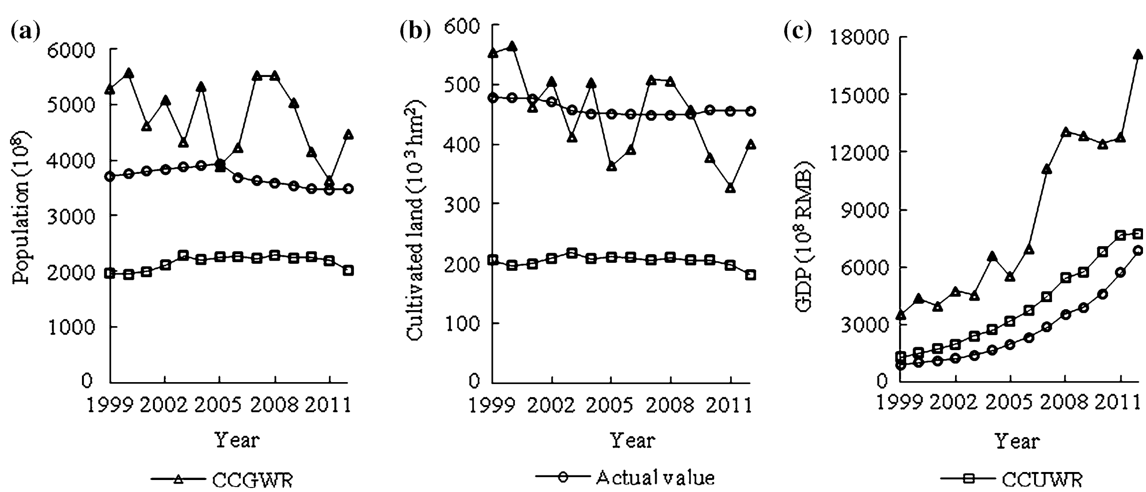

Fig. 2 Population (**a**), cultivated land (**b**) and GDP (**c**) of CCRWR in Guizhou Province relative to all China

from 2003 to 2010, and then decreased (Fig. 2a). CCGWR for population decreased with fluctuation (Fig. 2a). Cultivated land initially declined slightly, dropping to a minimum 448.5 × 10^3 hm^2 in 2008, and then began to increase slowly (Fig. 2b). CCUWR for cultivated land first increased slightly (2000–2003), stabilized at 208.0 × 10^3 hm^2 from 2003 to 2010, and then began to decrease (Fig. 2b). CCGWR for that land had reduced volatility (Fig. 2b). One exception to the trend of cultivated land was in 1999. Figure 2c shows that both actual GDP and CCUWR for population increased continuously from 1999 to 2012. However, CCGWR for population had elevated volatility (Fig. 2c).

State of water resource carrying capacity from 1999 to 2012 in Guizhou Province

The curve of actual population was above that of CCUWR for population, but below that of CCGWR for population (Fig. 2a). This means that actual values of population were larger than corresponding values of CCUWR, but smaller than those of CCGWR over 1999–2012 (Fig. 2a). Therefore, for the utilization amount of water resources, the population in Guizhou Province was overburdened, but for the gross amount of water resources, those resources are relatively surplus. One exception was in 2005 for CCGWR (Fig. 2a), which was slightly larger than the actual population value. The potential of WRCC for population was limited, especially in years with low CCGWR, such as 2003, 2005, 2010 and 2011. Figure 2b shows that actual values of cultivated land were larger than those of CCUWR, meaning that this land in the province was overburdened. However, the curve of CCGWR for this land fluctuated relative to actual values (Fig. 2b), indicating that in some years the gross amount of water resources was deficient and in other years they were in surplus. The potential of WRCC for cultivated land was very low. Both CCGWR and CCUWR for GDP were larger than corresponding actual values of GDP from 1999 to 2012 (Fig. 2c). This indicates that economic development of Guizhou was at a very low level in this period, and water resources were in surplus during that development. The potential of WRCC for GDP was relatively high. Therefore, taking Guizhou Province as a whole, the discrepancy between the water resources and cultivated land was most pronounced from 1999 to 2012.

Spatial variability of water resource carrying capacity in Guizhou Province

To investigate WRCC spatial variability in Guizhou Province, mean values of the time series data of population, GDP, cultivated land, gross and utilization amounts of water resource were calculated for the nine cities/districts in the province and China. China was chosen as the reference zone to calculate average WRCC in those cities/districts. Actual values larger than those of WRCC signified an overburden, which is shown by a+ symbol in Table 2. This table shows that it is population which overburdened the WRCC. Along with the population growth, climate change and increasing urbanization, many cities, especially in developing countries, are facing water-related problems including pollution, eutrophication and scarcity of clean water (Anthonj et al. 2014). Therefore, sustainable water management will become even more urgent in Guizhou Province.

The levels of WRCC of the nine cities/districts were classified into low, moderate and high levels according the numbers of + (Table 2). Figure 3 shows WRCC patterns of the province, portrayed according to Table 2. In general, WRCC was higher in the southeast and lower in the middle and northwest of the study area. Therefore, WRCC was not balanced between the nine cities/districts in the province.

Figure 4 shows average WRCC in the nine cities/districts of Guizhou Province from 1999 to 2012, taking China as the reference zone. Actual population of all the cities/districts was larger than corresponding values of CCUWR (Fig. 4a), indicating that populations in these cities/districts were overburdened (Table 2). The potential of WRCC for

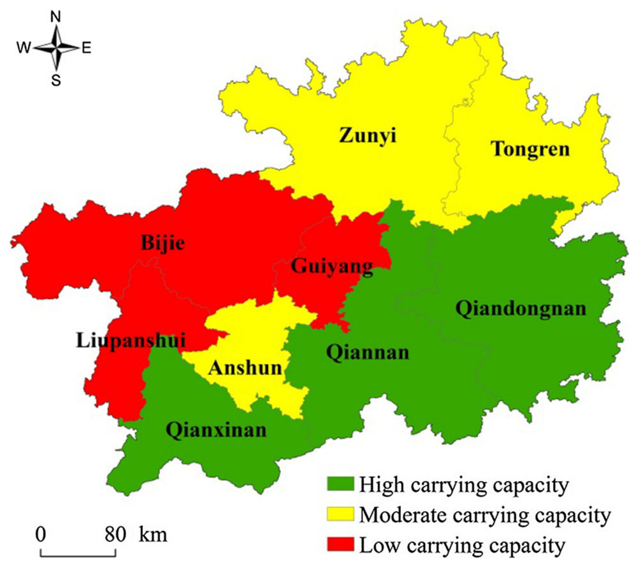

Fig. 3 Spatial distribution of water resource carrying capacity in Guizhou Province

Table 2 State of water resource carrying capacity in the nine cities/districts in Guizhou Province

City	Gross amount of water resource			Utilization amount of water resource			Level
	Population (10^4 person)	Cultivated land (10^3 hm^2)	GDP (10^8 RMB)	Population (10^4 person)	Cultivated land (10^3 hm^2)	GDP (10^8 RMB)	
Anshun	+			+			M[a]
Bijie	+	+		+	+	+	L[b]
Guiyang	+		+	+		+	L[b]
Liupanshui	+		+	+		+	L[b]
Qiandongnan				+			H[c]
Qiannan				+			H[c]
Qianxinan				+			H[c]
Tongren				+	+		M[a]
Zunyi	+			+	+		M[a]

[a] M = moderate, [b] L = low, [c] H = high, sign + means overloaded

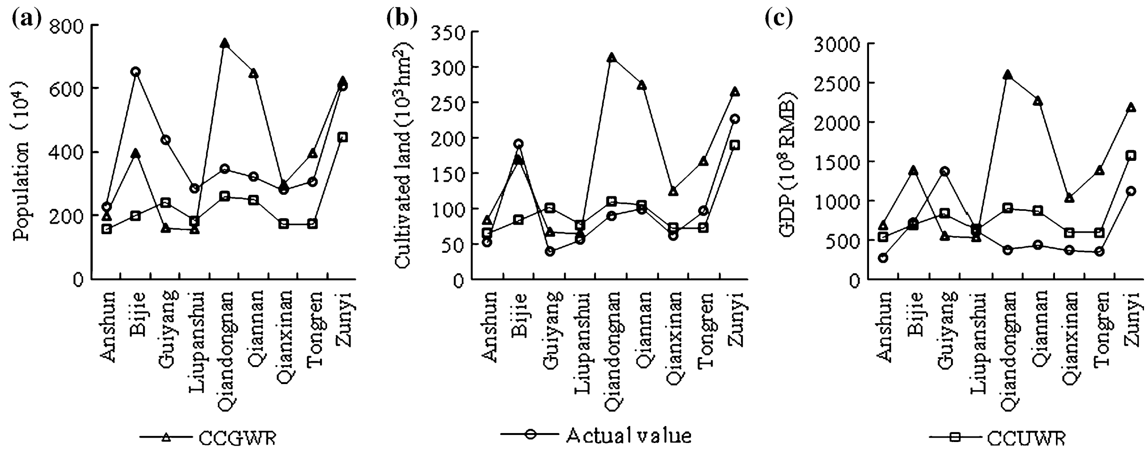

Fig. 4 Average CCRWR for population (**a**), cultivated land (**b**) and GDP (**c**) in cities/districts of Guizhou Province from 1999 to 2012 taking China as the reference zone

population in Qiandongnan and Qianxinan (Fig. 3) was high, and their gross amounts of water resources were in surplus. This potential in the other cities/districts was very low, with insufficient water resources.

Actual cultivated land in Bijie, Tongren and Zunyi was larger than that of CCUWR for cultivated land (Fig. 4b), demonstrating that cultivated lands in these three cities/districts were overburdened (Table 2). Actual cultivated areas in Anshun, Bijie, Guiyang and Liupanshui were similar to those of CCGWR (Fig. 4b), meaning that the water resources for cultivated land in these cities/districts were approaching a critical state. Water resources of the other cities/districts showed a surplus for cultivated land.

Figure 4c and Table 2 show that water utilization for economic use in Bijie, Guiyang and Liupanshui was critically high. The potential of WRCC for economy in these cities/districts was limited. On the contrary, water resources in other cities/districts were in surplus for economic development (Fig. 4c).

It is evident from the above analysis that the discrepancy between water resources and population was most pronounced in the nine cities/districts, which was inconsistent with the discrepancy taking Guizhou Province as a whole from 1999 to 2012. The reason may be the irregular distribution of cultivated land in the province. Therefore, a small scale can reflect more detail of WRCC in this province.

Discussion

Impact of precipitation on water resource carrying capacity

The gross amount of water resources has significant correlation with precipitation in Guizhou Province (Fig. 5). Therefore, that amount is remarkably affected by the

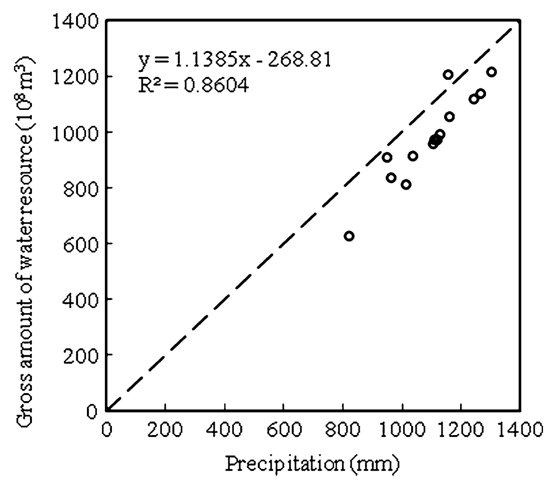

Fig. 5 Relationship between gross amount of water resource and mean precipitation from 1999 to 2012 in Guizhou Province

precipitation. However, average annual precipitation does not match average annual evaporation, which is 1220 mm. So, water received is rapidly lost and the amount of available water resources is small. Because of the subtropical monsoon climate, precipitation varies greatly, e.g., 820–1242 mm with mean 1097 mm in Guizhou Province during 1999–2012. The gross amount of water resource therefore also greatly varies, with a minimum in that period of 626×10^8 m^3 in 2001 and maximum 1217×10^8 m^3 in 2000. This significant variation of precipitation strongly influences the CCGWR. In 2005 and 2011, there were precipitation deficits and CCGWR for population and cultivated land was very small (Fig. 2a, b).

Precipitation also varies across the nine cities/districts of Guizhou Province, so water resources in some of them are surplus and in others they are insufficient. Topology affects precipitation, which alters the distribution of WRCC in the province. In the study area, WRCC was higher in the

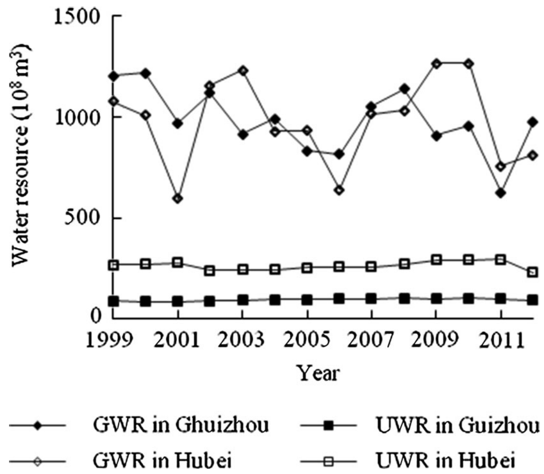

Fig. 6 Comparison of gross (GWR) and utilization (UWR) amounts of water resource between Hubei and Guizhou provinces

southeast portion at low elevation and lower in the middle and northwest at high elevation (Figs. 1, 3).

Impact of karstification on water resource carrying capacity

As stated above, Guizhou Province is a karst region and Hubei Province non-karst. Although the gross amount of water resource in the two provinces is nearly equal, utilization of that resource in Hubei is two to three times that in Guizhou (Fig. 6). This results in a low CCUWR in Guizhou (Fig. 2) and high CCUWR in Hubei (Table 1). Given the unique two-dimensional hydraulic structure resulting from long-term strong karstification, precipitation in the area tends to infiltrate rapidly (Song et al. 2006; Peng et al. 2012). Furthermore, caverns, fissures, gaps, underground streams, sinkholes and channels enlarged by solution in the underlying bedrock facilitate rapid transport of surface water to groundwater (Chen et al. 2010). Therefore, WRCC in the karst region is lower than that in a non-karst one.

Conclusions

Water resources are particularly important in karst areas. In this paper, the WRCC in a representative karst region (Guizhou Province) was assessed using CCRWR theory. The main conclusions are as follows:

(a) Taking China as a reference zone, WRCC of the karst region was very low, and WRCC potential was also limited. This potential was relatively high in a non-karst region with similar gross amount of water resource.

(b) Water resources were in surplus for the GDP scale, because the economy in the province was laggard from 1999 to 2012. The WRCC associated with population and agriculture was overburdened and near a critical state.

(c) WRCC in the province had strong spatial variation and was higher in the southeast portion and lower in the middle and northwest. Therefore, environmental determinants should be assessed in more detail.

Acknowledgments This research was supported by the Ministry of Science and Technology of China (No. 2010BAE00739), the Remote Sensing Survey and Ground Monitoring on Karst Rocky Desertification in Southwest China (No. 1212011220958) and the Ministry of Water Resources of China (No. 2005SBKK05). We acknowledge all the reviewers and editors of the journal for their valuable comments, suggestions and revisions on this paper, which greatly improved the original manuscript.

References

Anthonj C, Beskow S, Dornelles F, Fushita AT, Galharte CA, Galvão P, Gatti Junior P, Gücker B, Hildebrandt A, Karthe D, Knillmann S, Kotsila P, Krauze K, Kledson Leal Silva A, Lehmann P, Moura P, Periotto NA, Rodrigues Filho JL, Lopes dos Santos DR, Selge F, Silva T, Soares RM, Strohbach M, Suhogusoff A, Wahnfried I, Zandonà E, Zasada I (2014) Water in urban regions: building future knowledge to integrate land use, ecosystem services and human health. German National Academy of Sciences Leopoldina, Brazilian Academy of Sciences, German Young Academy, Halle/Saale

Chadenas C, Pouillaude A, Pottier P (2008) Assessing carrying capacities of coastal areas in France. J Coast Conserv 12:27–34

Chen YZ, Jing YJ (2006) Study on comparative bating capacity of resource and sustainable development in Jilin Province. Popul J 1:41–45

Chen NX, Ban PL, Zhang WB (2008) Fuzzy evaluation of the water resources carrying capacity based on the maximum entropy theory. J Irrig Drain 27(2):57–60

Chen HS, Zhang W, Wang KL, Fu W (2010) Soil moisture dynamics under different land uses on karst hillslope in northwest Guangxi, China. Environ Earth Sci 61:1105–1111

Clarke AL (2002) Assessing the carrying capacity of the Florida keys. Popul Environ 23:405–418

Falkenmark M, Lundqvist J (1998) Towards water security: political determination and human adaptation crucial. Nat Resour Forum 21:37–51

Fang GH, Hu YG, Xu Y (2006) Research on the multi-objective evaluation model of regional water resources carrying capacity and its application. Water Resour Protect 22(6):9–13

Feng LH, Huang CF (2008) A risk assessment model of water shortage based on information diffusion technology and its application in analyzing carrying capacity of water resources. Water Resour Manage 22:621–633

Fowler A, Ubels J (2010) The multi-faceted nature of capacity: two leading frameworks. In: Ubels J, Fowler A, Acquaye-Baddoo N-A (eds) Capacity development in practice. Earthscan, London

Fu X, Ji CM (1999) A comprehensive evaluation of the regional water resources carrying capacity—application of main component analysis method. Resour Environ Yangtze Basin 8(2):168–173

Giupponi C, Mysiak J, Fassio A, Cogan V (2004) Mulino-DSS: a computer tool for sustainable use of water resources at the catchment scale. Math Comput Simulat 64(1):13–24

Gong L, Jin CL (2009) Fuzzy comprehensive evaluation for carrying capacity of regional water resources. Water Resour Manage 23:2505–2513

Gunasekara NK, Kazama S, Yamazaki D, Oki T (2014) Water conflict risk due to water resource availability and unequal distribution. Water Resour Manage 28:169–184

Harris JM, Kennedy S (1999) Carrying capacity in agriculture: global and regional issues. Ecol Econ 29:443–461

Huang QH, Cai YL (2006) Assessment of karst rocky desertification using the radial basis function network model and GIS technique: a case study of Guizhou Province, China. Environ Geol 49:1173–1179

Huang NS, Kuang YQ (2000) The carrying capacity of resources and the problems of sustainable development in Guangdong Province. Econ Geogr 20(2):52–56 **(in Chinese)**

Huang M, Qi SZ, Shang GD (2012) Karst landslides hazard during 1940–2002 in the mountainous region of Guizhou Province, Southwest China. Nat Hazards 60:781–784

Hunter C (1998) Perceptions of sustainable city and implications for fresh water resources management. Int J Environ Pollut 10:84–103

Jing YJ (2006) Dynamic analysis of bearing capacity of relative resources in Northeast China. Jilin Univ J Soc Sci Ed 46(4):104–110 **(in Chinese)**

Kuykendtierna JL, Bjorklund G, Najlis P (1997) Sustainable water future with global implications: everyone's responsibility. Nat Resour Forum 20:181–190

Li LJ, Guo HC, Chen B (2000) Water resources supporting capacity of Chaidamu Basin. Environ Sci 21(1):20–23 **(in Chinese)**

Li ZH, Guo WJ, Dong SC (2008) Empirical analysis on carrying capacity of relative resources based on harmonious development between population and economy: a case study of Hubei Province. Areal Res Dev 27(3):83–87

Li ZH, Dong SC, Gao D (2009) Model modification and application on carrying capacity of relative resources. Chin Popul Resour Environ 7(2):19–26

Liang F, Zhang X, Liu JM (2002) Sustainable use of water resources in the region and evaluation index system. Northwest Univ Agric For Sci Technol J 20(6):119–122

Liu SF, Chen JH (2007) Water resources carrying capacity based on the theory of ANN. Res Sci 29(1):99–105

Lopes C, Theisohn T (2003) Ownership, leadership and transformation. Can we do better for capacity development?. Arthscan, London

Lu F, Xu JH, Wang ZY (2009) Application of GA optimized wavelet neural networks for carrying capacity of water resources prediction. In: 2009 international conference on environmental science and information application technology, pp 308–311

Meng LH, Chen YN, Li WH, Zhao RF (2009) Fuzzy comprehensive evaluation model for water resources carrying capacity in Tarim River Basin, Xinjiang, China. Chin Geogr Sci 19(1):89–95

Obot JU (1984) The spatial perspective of water resource management and economic development in Nigeria. GeoJoumal 4:369–376

Ofoezie IE (2002) Human health and sustainable water resources development in Nigeria: schistosomiasis in artificial lakes. Nat Resour Forum 26:150–160

Peng WX, Song TQ, Zeng FP, Wang KL, Du H, Lu SY (2012) Spatial distribution of surface soil water content under different vegetation types in northwest Guangxi, China. Environ Earth Sci 69:2699–2708

Rijsberman MA, van de Ven FHM (2000) Different approaches to assessment of design and management of sustainable urban water system. Environ Impact Asses Rev 3:333–345

Song TQ, Peng W, Yi W, Xiao R, Wang J, Li S, Luo W (2006) Defensive effects of three representative biological measures on seasonal drought in tea plantation in subtropical red soil hilly region. J Soil Water Conserv 20(4):191–194 **(in Chinese)**

Song XM, Kong FZ, Zhan CS (2011) Assessment of water resources carrying capacity in Tianjin City of China. Water Resour Manage 25:857–873

Tang XL, Liu YL, He Y (2009) Analysis on the relative carrying capacity of water resources of Shihezi. J Shihezi Univ (Nat Sci) 27(4):490–494

Ubels J, Fowler A, Acquaye-Baddoo N-A (eds) (2010) Capacity development in practice. Earthscan, London

Wackernagel M, Rees WE (1996) Our ecological footprint: reducing human impact on the earth. New Society, Gabriola Island

Wackernagel M, Onislo L, Bello P (1997) Ecological footprints of nations. International Council for Local Environmental Initiatives, Toronto

Wang TX, Xu SG (2015) Dynamic successive assessment method of water environment carrying capacity and its application. Ecol Ind 52:134–146

Wang CW, Yang SJ (2009) Research on water resource relative carrying capacity in Jining City. J Univ Jinan (Soc Sci Ed) 19(2):66–68 **(in Chinese)**

Wang ZM, Song KS, Zhang B, Liu DW, Li XY, Ren CY, Zhang SM, Luo L, Wang SJ (2002) Concept deduction and its connotation of karst rocky desertification. Carsologica Sin 21:101–105 **(in Chinese)**

Wang ZM, Zhang B, He YF (2004) Analysis of dynamic changes of relative carrying capacity of resources in Jilin Province. J Arid Land Resour Environ 18(2):5–10

Ye HR, Wang SL, Yang JZ (2007) Tempo-spatial analysis on the dynamics of the relative carrying capacity of resources in southeastern of Fujian Province. Econ Geogr 27(2):265–274

Yuan DX (2001) On the karst ecosystem. Acta Geol Sin 75:336–338 **(in Chinese)**

Zhang PJ, Li LQ, Pan GX, Ren JC (2006) Soil quality changes in land degradation as indicated by soil chemical, biochemical and microbiological properties in a karst area of Southwest Guizhou. China Environ Geol 51(4):609–619

Zhu YZ (2008) Assessment of water resources carrying capacity: a case study of Zhangye in China. In: 3rd IASWE/WSEAS international conference on water resources, hydraulic and hydrology, UK, pp 145–150