Analysis of sustainable utilization of water resources in karst region based on the ecological footprint model – Liupanshui city case

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ABSTRACT

The demand of human beings for water resources is growing strongly, causing more and more shortages of water resources. In this paper, focusing on Liupanshui city, a typical karst area, the ecological footprint and ecological carrying capacity models of water resources were established in Liupanshui city from the perspectives of the water consumption account of living, production, and ecology based on the ecological footprint theory, to estimate the ecological footprint of water resources and the ecological carrying capacity. On this basis, a variety of evaluation indicators was utilized to analyze the sustainable utilization of water resources in Liupanshui city. The results showed that water resources in this area belong to ecological surplus, while the utilization of water resources has been in a sustainable state as a whole. However, there have been great variations in the carrying capacity of water resources over different years. At the same time, the ecological water consumption and the footprint of 10,000 yuan GDP water resources are at low levels, indicating that the current water consumption ratio is not conducive to the improvement of the ecological environment. Moreover, further improvements in the efficiency of water consumption are needed.

Key words | ecological carrying capacity, ecological footprint theory, evaluate, water consumption account, water resources

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INTRODUCTION

As an important natural resource, water resource plays an irreplaceable role in human life, production activities, and maintaining the ecological environment. However, water resource scarcity has become a global issue with population and economic growth. Thus, achieving the sustainable utilization of water resources has become one of the important factors in promoting social and economic development (Haider *et al.* 2015; Giupponi & Gain 2017; Zayed & Elagib 2017; AlShalalfeh *et al.* 2018; Proskuryakova *et al.* 2018). In recent years, the sustainable utilization of water resources has also attracted more and more attention from scholars. Thus, many scholars have studied in this field. For example, Vieira (1998) proposed that the potential amount of water,

the amount usable, and water demand be compared in each basin to determine the availability indicators of water. Bossel (2000) conducted a study on the sustainable development and utilization of water resources and established an indicator system for the sustainable utilization of regional water resources to quantitatively calculate five basic directional indicators of subsistence, efficiency, freedom, safety and co-existence of water resource, social, economic and environmental subsystems. Rao (2002) utilized a combination of remote sensing and geographic information system (GIS) to evaluate the sustainable development and utilization of land resources and water resources, and also considered that the essence of evaluating

a complete and systematic sustainable development and utilization is to make a multi-objective, effective and risk analysis without considering the basic policy. Jay (2001) from South Africa pointed out that indicators of sustainable development for decision-making are difficult to measure when evaluating the interaction relationship between different basin development and resource management actions, whereas the DPSIR (Driving Forces Pressure State Impact Response) indicator framework is useful for identifying and developing indicators of sustainable development in the basin management. Hoekstra (2017) proposed a concept of water footprint that can evaluate human consumption of water resources from the perspective of water consumption. A link between resources and consumption was established to utilize the concept of an ecological footprint to the accounting of water resources. In addition, the theory of an ecological footprint was first put forward by Rees (1992) as a method of measuring humanity's utilization of natural resources and the ecological supporting capacity provided by nature, which is also one of the quantitative methods for measuring ecological sustainable development. The sustainable use of water resources based on the ecological footprint model features a specific image of the concept, an easy and convenient method and convenient comparison among areas, which is one of the most regarded evaluation methods for sustainable development. At present, studies on the ecological footprint of water resources mainly focus on arid and semi-arid areas, but few of which have been conducted on karst areas, especially on the karst mountain areas (Wu et al. 2016).

The total area of karst areas in southwest China is about 426,200 km². The surface and underground double-layer space structures formed by intensive karst lead to serious loss of surface water. At the same time, surface water resources in the karst area are mostly concentrated in deep valleys, which are inconsistent with cities and towns, mining, villages and arable lands, etc., which are distributed on the slopes and plateaus and other areas far from valleys. Thus, the contradiction between supply and demand of water resources is prominent, although precipitation in the karst area is abundant (Chen 2003; Zou et al. 2005, 2006; Li et al. 2018). In this paper, based on the analysis method of the ecological footprint model, the footprint model of water resources has been applied in the

calculation process of the ecological footprint of water resources from 2008 to 2015 in a typical karst area, Liupanshui, Guizhou, China. According to the developing trends of the ecological footprint of water resources per capita in Liupanshui city, the ecological carrying capacity per capita and ecological surplus per capita, the level of sustainable utilization of water resources in Liupanshui city has been analyzed and evaluated to improve the measures for sustainable utilization of water resources in Liupanshui city. Moreover, related studies can provide some reference for the sustainable utilization of water resources in the karst areas.

MATERIAL AND METHOD

Overview of the study area

Located in the west of Guizhou Province in China, Liupanshui is a newly industrialized city dominated by coal, metallurgy, and building materials, whose geographical location is between north latitudes 25°19′44 to 26°55′33″ and east longitudes 104°18′204″ to 105°42′50″. Located on the slopes of the first and second terraces of the Yunnan-Guizhou Plateau, the terrain is high in the northwest and low in the southeast with the elevation being roughly between 1,400 m and 1,900 m. The total area is about 9,965 km², and belongs to the northern subtropical monsoon humid climate zone with an annual average temperature of 13 °C to 14 °C, an average temperature of 3 °C to 6.3 °C in January, average temperature of 19.8 °C to 22 °C in July and an annual rainfall ranging from 1,200 mm to 1,500 mm. As the terrain height difference is relatively large, the climatic difference in the local regional climate is obvious (Guizhou Provincial Bureau of Geology & Mineral Resources 1987). Traffic location is shown in Figure 1.

The main replenishment of water resources in the study area comes from rainfall of the atmosphere. Furthermore, surface water is mutually replenished, converted, and circulated frequently with the groundwater. A simple chemical type focusing on low-salinity bicarbonate freshwater, it is mainly applicable to water resources for industrial and agricultural production and for domestic use.
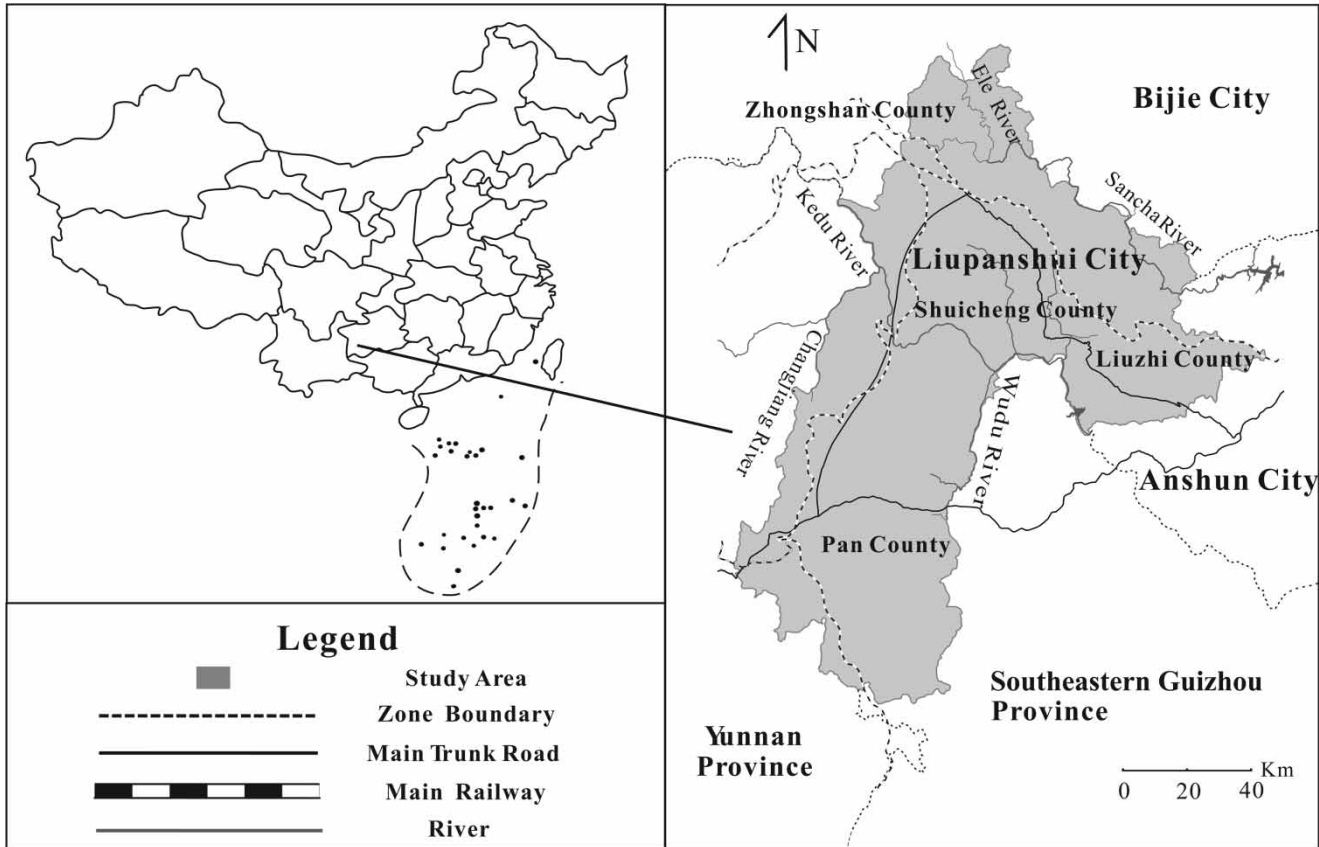
Figure 1 | Traffic and location of Liupanshui city.

Data and methods

Data sources

Data on the development and utilization of water resources in the study area was obtained according to the 'Liupanshui Water Resource Bulletin' (Water Conservancy Bureau of Liupanshui City 2008–2015) and 'Liupanshui Statistical Yearbook' (Liupanshui Statistical Yearbook Editorial Board 2008–2015). The data included, for example, various types of water consumption, total amount of water resources, area of administrative district, population, economic development, etc. Then, the data were collated and Table 1 was obtained.

Study methods

(1) The ecological footprint model of water resources: The purpose of calculating the ecological footprint of water

resource is to convert the amount of water resources consumed into land used for water resources, and obtain equilibrium values that can be used for comparison between different regions of the globe (Hoekstra 2017). The formula can be expressed as:

$$EF_W = N \cdot ef_w = N \cdot A = N \cdot r_w (W/P_W) \tag{1}$$

where, EF_w is the ecological footprint of water resources (hm^2); $ef_w = A$, is the ecological footprint of water resources per capita (hm^2/person); N is population; r_w is global equilibrium factors of water resources; W is the consumption of water resources (m^3); P_w is the global average productivity of water resources (m^3/hm^2).

According to the consumption of water resources in the study area, the ecological footprint of water resources is mainly divided into three aspects, that is, the ecological footprint of water for production, the

Table 1 | Water resources utilization data of Liupanshui city

Year	Average annual rainfall (mm)	Total amount of water resources (10^8 m³)	Total population (ten thousand people)	Total production water (10^8 m³)	Total domestic water (10^8 m³)	Total ecological water (10^8 m³)	GDP (100 million yuan)
2008	1,352.1	62.807	298.17	4.74	1.71	0.01	384.27
2009	1,081.9	41.884	298.34	5.219	2.052	0.015	433.46
2010	1,175.1	36.65	285.118	7.882	1.259	0.078	500.64
2011	802.2	26.26	285	7.18	1.51	0.02	613.39
2012	1,197.6	44.88	285.9	7.26	1.53	0.02	753.65
2013	1,005.2	25.31	287.45	6.165	1.214	0.044	882.11
2014	1,467.9	59.16	288.2	6.373	1.346	0.065	1,042.73
2015	1,256.2	52.388	289.5873	6.28	1.48	0.07	1,201.08

ecological footprint of water for living, and the ecological footprint of ecological water. The corresponding calculation models are presented as follows:

$$EF_{pw} = N \cdot ef_{pw} = N \cdot r_w \cdot (W_i/P_w) \qquad (2)$$

$$EF_{lw} = N \cdot ef_{lw} = N \cdot r_w \cdot (W_l/P_w) \qquad (3)$$

$$EF_{ew} = N \cdot ef_{ew} = N \cdot r_w \cdot (W_e/P_w) \qquad (4)$$

where, EF_{pw} is the ecological footprint of water for production (hm²); ef_{pw} is the ecological footprint of water per capita for production (hm²/person); W_i is the consumption of water for production (m³); EF_{lw} is the ecological footprint of water for living (hm²); ef_{lw} is the ecological footprint of water per capita for living (hm²/person); W_l is the consumption of water for living (m³); EF_{ew} is the ecological footprint of ecological water use (hm²); ef_{ew} is the ecological footprint of ecological water use per capita (hm²/person); and W_e is the consumption of ecological water use (m³).

(2) The model of water resources carrying capacity: The carrying capacity of water resources refers to the maximum sustainable utilization of water resources provided for the economic, environmental, and social development of a region within a specific period of development in a region (Zhang *et al.* 2014), whose formula can be expressed as:

$$EC = N \cdot G = (1 - 0.6) \cdot \varepsilon \cdot r_w (Q/P_w) \qquad (5)$$

where, EC is water resources carrying capacity (hm²); G is water resources carrying capacity per capita

(hm²/person); ε is regional water resources yield factors; and Q is yield of water resources (m³).

(3) Indicators evaluating the sustainable utilization of water resources:

   (1) *Ecological surplus of water resources*: The ecological surplus of water resources is used to judge whether the utilization of water resources in the study area is in a stage of sustainable development, represented by *ED*; that is, the difference between the ecological footprint of water resources per capita and the water resources carrying capacity per capita (Li *et al.* 2016). Its formula can be expressed as:

$$ED = G - A \qquad (6)$$

where, if $A > G$, it indicates that water resources per capita is in ecological deficit, going against the sustainable development; if $A < G$, it indicates that water resources per capita is an ecological surplus, being conducive to sustainable development; if $A = G$, it indicates that the utilization of water resources is in the critical state of sustainable development.

   (2) *The ecological stress index model of water resources*: Ecological surplus of water resources per capita can neither be an index to evaluate the comparison of sustainable utilization of water resources among different regions, nor reflect the relative magnitude of the stress intensity borne by the ecological environment. However, the

ecological stress index of water resources, defined as the ratio of the ecological footprint of water resources of a country or a region and the ecological carrying capacity of water resources, can well solve the problem (Zhao *et al.* 2007). It can be expressed in the following formula:

$$EP = EF_w/EC \qquad (7)$$

where, *EP* is the ecological stress index of water resources. Based on the grading standard proposed by Ren *et al.* (2005), when *EP* <0.5, it indicates that the development and utilization of water resources in the area is in a completely safe state; when $0.5 \leq EP$ <0.8, it is in a safe state; when $0.8 \leq EP \leq 1$, it is in a critical state; when *EP* > 1, it is in an unsafe state.

(3) *The ecological footprint of water resources of 10,000 yuan GDP:* The water resources ecological footprint of 10,000 yuan GDP can measure the utilization efficiency of water resources in the region. The ratio between the ecological footprint and GDP is the ecological footprint of 10,000 yuan GDP water resources. The lower ratio values mean a higher efficiency of water resources utilization while the higher values result in a lower efficiency of utilization. The index can roughly reflect the economic growth pattern in a certain area (Gui *et al.* 2014). Its formula can be presented as follows:

The ecological footprint of water resources of 10,000 yuan

$$GDP = \frac{EF_W}{GDP} \qquad (8)$$

(4) Determination of main parameters: The global equivalence factor of water resources is the average ecological productivity of a certain kind of biological production area worldwide divided by the average ecological productivity of all kinds of biological production areas worldwide. Considering the difficulty of producing statistics on all types of biomass worldwide, the equivalence factor value of water resources $r_w = 5.19$

determined according to WWF 2002 (World Wide Fund for Nature 2002) was adopted in this paper. The water yield per unit area is the average water producing modulus of water resources. Thus, the average water productivity of water sources in the study area was calculated as 4,382 m^3/hm^2 based on the area of the total amount of annual average water resources in the study area from 2008 to 2015. The regional water resources yield factor can be obtained through the average yield capacity of the regional amount of water resources amount divided by the productivity of water resources worldwide. Taking the water yield per unit area worldwide as 3,140 m^3/hm^2, it can be obtained that the yield factor of water resources was 1.3955, together with the water yield per unit area in the study area.

RESULTS AND DISCUSSION

According to the ecological footprint models of water resources (Equations (1)–(8)) established above, the ecological footprint and the ecological carrying capacity of water resources in Liupanshui city from 2008 and 2015 are calculated. Results are presented in Table 2.

(1) Analysis of the ecological footprint of water resources: Figure 2 illustrates the variation curves for the footprint of water resources per capita for production, living, and ecology according to consumption of water resources.

It can be seen from Figure 2, in three accounts of the ecological footprint of water resources, the footprint of water for production has the largest proportion of the ecological footprint of water resources per capita, accounting for about 70% with a water consumption footprint presenting as a rising and then falling trend, of which it rises at the fastest speed from 2009 to 2010; and water for production begins to decrease somewhat in 2011. The ecological footprint of water for living accounts for about 25% of that of water resources per capita; and its water consumption footprint is relatively stable as a whole. Consumption of ecological water occupies the lowest proportion, and the change of the footprint of water

Table 2 | Ecological footprint and ecological carrying capacity of water resources in Liupanshui city, 2008–2015

Indicators		Year							
		2008	2009	2010	2011	2012	2013	2014	2015
The ecological footprint of water resources per capita/(hm^2·person^{-1})	Total water	0.2566	0.2892	0.383	0.362	0.365	0.3059	0.3199	0.3202
	Production water	0.1883	0.2072	0.3274	0.2984	0.3008	0.254	0.2619	0.2568
	Domestic water	0.0679	0.0815	0.0523	0.0628	0.0634	0.05	0.0553	0.0605
	Ecological water	0.0004	0.0006	0.0032	0.0008	0.0008	0.0018	0.0027	0.0029
Water resources carrying capacity per capita/(hm^2·person^{-1})		1.3926	0.9282	0.8498	0.6092	1.0378	0.5821	1.3571	1.196
Ecological surplus of water resource/(hm^2·person^{-1})		1.136	0.6389	0.4669	0.2472	0.6729	0.2763	1.0372	0.8758
The ecological footprint of water resources of 10,000 yuan GDP/(hm^2·person^{-1})		0.1991	0.1991	0.2181	0.1682	0.1385	0.0997	0.0884	0.0772
The ecological stress index of water resources	Production	0.1352	0.2232	0.3853	0.4898	0.2898	0.4364	0.193	0.2148
	Domestic	0.0488	0.0878	0.0615	0.103	0.0611	0.0859	0.0408	0.0506
	Ecology	0.0003	0.0006	0.0038	0.0014	0.0008	0.0031	0.002	0.0024
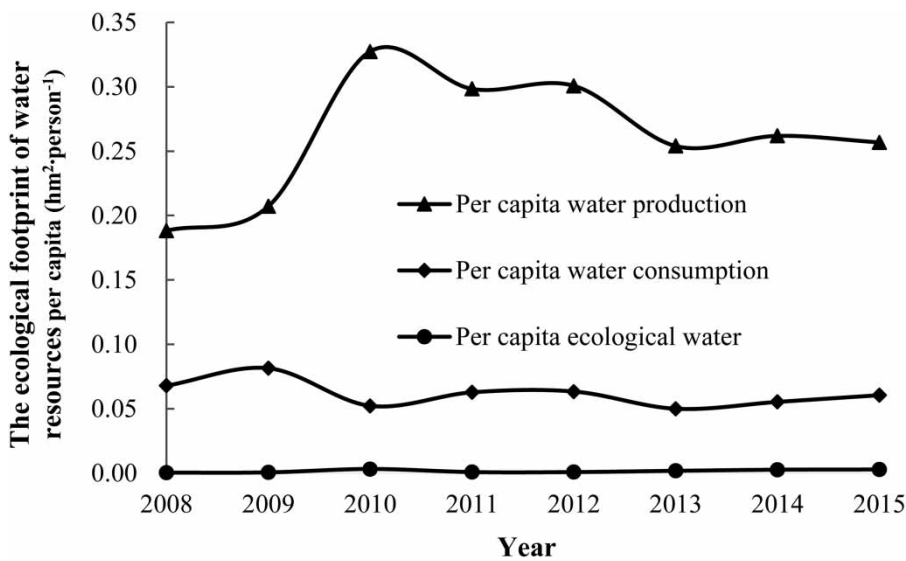
Figure 2 | Water resources per capita for production, consumption, and ecology from 2008 to 2015 in Liupanshui city.

consumption is not obvious, presenting a slightly upward trend as a whole.

(2) Analysis of water resources carrying capacity: Figure 3 illustrates the variation curve of the ecological carrying capacity per capita according to the calculated data of the ecological carrying capacity of water resources per capita in Liupanshui city from 2008 to 2015.

It can be seen from Figure 3 that the water resource carrying capacity varies greatly. High variations occur in 2008 and 2014, reaching 1.3926 hm^2/person and 1.3571 hm^2/ person, respectively; while low variations occur in 2011 and 2013, reaching 0.6092 hm^2/person and 0.5821 hm^2/ person, respectively. Combined with Table 1, it can also be found that the variation law of water resource carrying capacity is consistent with that of water resource amount.

(3) Analysis of dynamic indexes of water resources:

  (1) *Analysis of water resources stress index*: The ecological footprint of water resources was divided into three aspects, including water for production, living, and ecological water. The corresponding
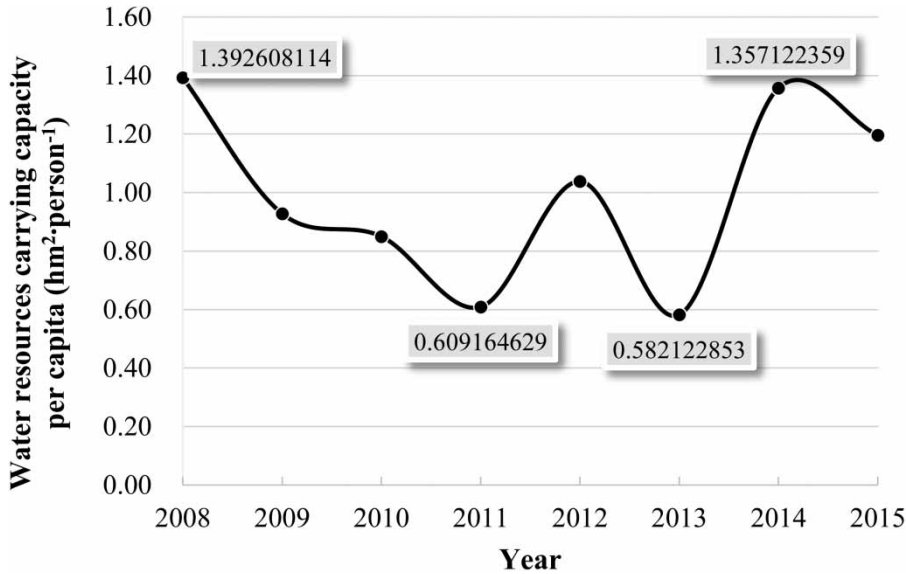
Figure 3 | Varations in water resources carrying capacity per capita from 2008 to 2015 in Liupanshui city.

variation curves of water resources stress indexes were obtained according to the calculated data.

It can be seen from Figure 4 that the stress indexes of water resources for ecology, living, and production are between 0 and 1, as well as less than 0.5. Water for production, fluctuating greatly, is much higher than other indicators. The maximum stress index of water resources for production is in 2011, reaching 0.4898. The stress index of ecological water resources is the smallest, showing a slight upward trend. The stress index of water for living fluctuates smoothly and is roughly around 0.06.

(2) *Analysis of ecological surplus*: It can be seen from Table 2 that the city's water resources belong to ecological surplus; the carrying capacity of per capita ecological water resources is greater than the ecological footprint of per capita water resources. The largest surplus is 1.1360 hm²/person in 2008, with the total water resources of
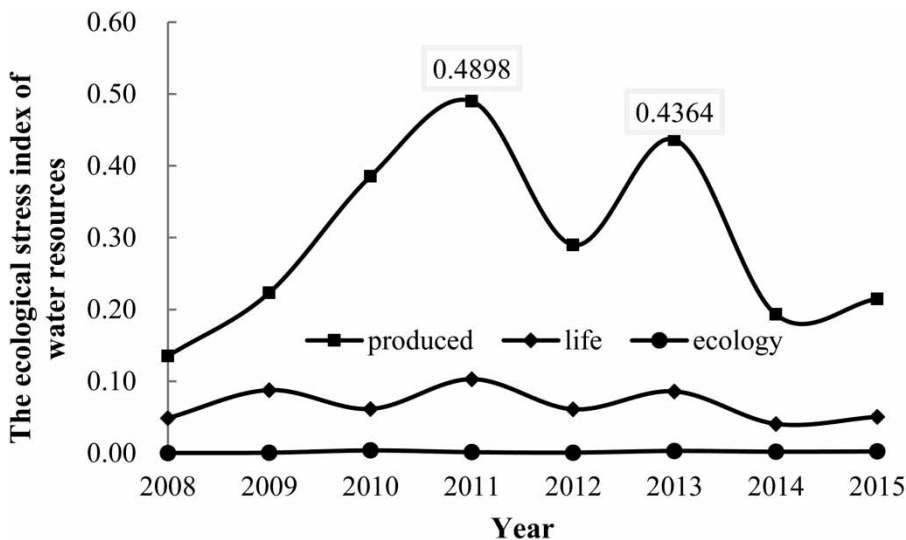

Figure 4 | Variations in water resources stress indexes from 2008 to 2015 in Liupanshui city.

up to one year, reaching 6.2807 billion m^3; while the smallest surpluses include 0.2472 hm^2/person in 2011 and 0.2763 hm^2/person in 2013, whose corresponding water resources are 2.626 billion m^3 and 2.531 billion m^3, respectively.

(3) *Analysis of the ecological footprint of 10,000 yuan GDP water resources*: According to data in Table 2, the variation curve for the ecological footprint of water resources from 2008 to 2015 in Liupanshui city was obtained, as shown below.

It can be seen from Figure 5 that the ecological footprint of water resources of 10,000 yuan GDP presents a stable declining trend after a slight rise from 2008 to 2010, which is at a low level in general. It indicates that there is a large capacity in the sustainable use of water resources in Liupanshui city.

CONCLUSION

In this paper, the ecological footprint was utilized to establish ecological footprint models in Liupanshui city, a typical karst area, to calculate dynamic indexes such as the water resources ecological footprint, water resources carrying capacity, and water resources ecological stress index from 2008 to 2015 in Liupanshui city. Considering population, economy, and utilization status of water resources of the city, the following conclusions can be drawn:

(1) The law of change in rainfall and total water resources was basically the same. At the same time, there was a positive correlation between the total water resources, water resources carrying capacity and ecological surplus, and a negative correlation with the pressure index of water resources. The change in total water resources caused by rainfall played a key role in the sustainability of water resources in Liupanshui city.

(2) From 2008 to 2015, the water resource account per capita in Liupanshui city was in surplus, the water supply was greater than the demand, and the ecological, life, and production water resources pressure index values were all less than 0.5, reflecting that the water resources development and utilization in Liupanshui city was in a safe state as a whole and belonged to the sustainable range.

(3) In the three accounts of the water resources ecological footprint of Liupanshui city from 2008 to 2015, the production water footprint accounted for the largest proportion of the per capita water resources ecological footprint, and the production water consumption was large. In the future, the water use efficiency of industrial water needs to be increased. The ecological water footprint was the least, and at a low level, which is detrimental to the improvement of the ecological environment. In addition, the inter-annual change of water resources carrying capacity was large, and sustainability was in a relatively unstable state.
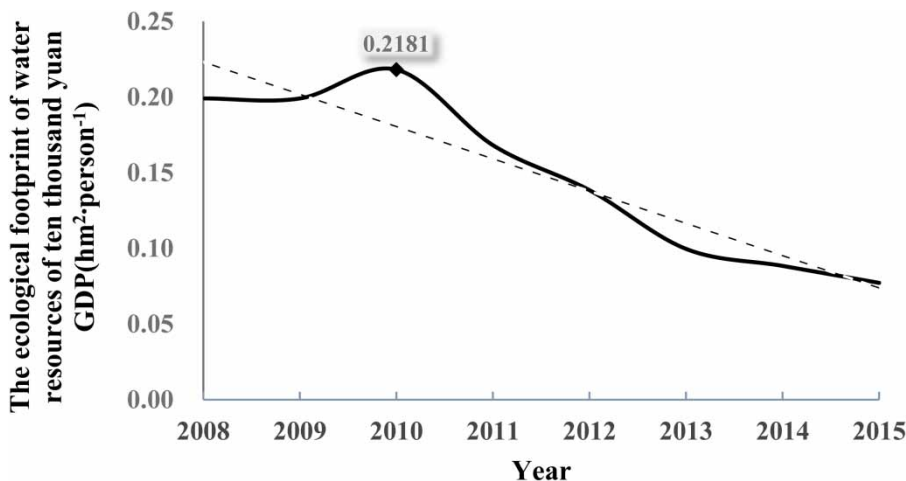

Figure 5 | Variations in the footprint of 10,000 yuan GDP water resources from 2008 to 2015 in Liupanshui city.

(4) The model of the water resources ecological footprint and ecological capacity provides a quantitative tool for assessing the state of sustainable use of regional water resources. It can effectively reflect the trends of various indicators related to the sustainability of water resources; however, the current research period on the theory and model of ecological footprint of water resources is short. With further in-depth research, more water accounts can be added to evaluate the sustainability of water resources from a more comprehensive perspective.

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REFERENCES

Alshalalfeh, Z., Napier, F. & Scandrett, E. 2018 Water nakba in palestine: sustainable development goal 6 versus Israeli hydro-hegemony. *Local Environment* **23** (1), 117–124.

Bossel, H. 2000 The human actor in ecologica1-economic models: policy assessment and simulation of actor orientation for sustainable development. *Ecologica1 Economics* **34**, 337–355.

Chen, M. X. 2003 *Karst Water Resources and the Treatment of Karst Rocky Desertification in Karst Areas of Southwest China*. Study on Karst Underground and Rocky Desertification in China. Guangxi Science-Technology Press, Nanning (in Chinese).

Giupponi, C. & Gain, A. K. 2017 Integrated spatial assessment of the water, energy and food dimensions of the Sustainable Development Goals. *Regional Environmental Change* **17** (7), 1881–1893.

Gui, G. N., Wang, X., Xu, L. Y., Zhang, J. & Yu, B. 2014 An improved method for evaluating ecological suitability of hydropower development by considering water footprint and transportation connectivity in Tibet, China. *Water Science & Technology* **70** (6), 1099–1107.

Guizhou Provincial Bureau of Geology and Mineral Resources 1987 *Regional Geology of Guizhou Province*. Geological Press, Beijing (in Chinese).

Haider, H., Singh, P., Ali, W., Tesfamariam, S. & Sadiq, R. 2015 Sustainability evaluation of surface water quality management options in developing countries: multicriteria analysis using fuzzy UTASTAR method. *Water Resources Management* **29** (8), 2987–3013.

Hoekstra, A. Y. 2017 Water footprint assessment: evolvement of a new research field. *Water Resources Management* **31** (10), 3061–3081.

Jay, J. 2001 Framework for measuring sustainable development in catchment systems. *Environmental Management* **29** (2), 195–206.

Li, Y. J., Lu, H. J. & Pu, P. 2016 Analysis of sustainable utilization of water resources in Zhejiang Province based on ecological footprint. *Yangtze River Scientific Research Institute* **33** (12), 22–26 (in Chinese).

Li, B., Zeng, Y. F., Zhang, B. B. & Wang, X. Q. 2018 A risk evaluation model for karst groundwater pollution based on geographic information system and artificial neural network applications. *Environmental Earth Sciences* **77**, 344, https://doi.org/10.1007/s12665-018-7539-7.

Liupanshui Statistical Yearbook Editorial Board 2008–2015 *Liupanshui Statistical Yearbook*. China Statistics Press, Beijing (in Chinese).

Proskuryakova, L. N., Saritas, O. & Sivaev, S. 2018 Global water trends and future scenarios for sustainable development: the case of Russia. *Journal of Cleaner Production* **170**, 867–879.

Rao, D. P. 2002 A remote sensing-based integrated approach for sustainable development of land water resources. . *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews* **31** (2), 207–215.

Rees, W. E. 1992 Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization* **4** (2), 121–130.

Ren, Z. Y., Huang, Q. & Li, J. 2005 Quantitative analysis of dynamic change and spatial difference of the ecological safety: the case of Shanxi Province. *Acta Geographica Sinica* **60** (4), 597–606.

Vieira, V. P. P. B. 1998 Water resources in Brazil and the sustainable development of the semi-arid north east. *Water Resources Development* **14**(2), 183–189.

Water Conservancy Bureau of Liupanshui City 2008–2015 *Liupanshui City Water Resources Bulletin*. (in Chinese).

World Wide Fund for Nature 2002 Living Planet Report 2002 (in Chinese).

Wu, Q. Z., Su, X. J. & Long, L. L. 2016 Analysis of sustainable utilization of water resources in Guizhou Province based on ecological footprint model. *Journal of North China University of Water Conservancy and Hydroelectric Power* **37** (3), 36–40. (in Chinese).

Zayed, I. S. A. & Elagib, N. A. 2017 Implications of non-sustainable agricultural water policies for the water-food

nexus in large-scale irrigation systems: a remote sensing approach. *Advances in Water Resources* **110**, 408–422.

Zhang, J., Zhou, D. N. & Zhang, R. Z. 2014 Dynamic characteristics of water resources ecological footprint in Shule river basin during 2003–2010. *Energy Education Science and Technology Part A: Energy Science and Research* **32** (6), 8359–8366.

Zhao, X. G., Ma, C. H. & Gao, L. F. 2007 Regional ecological security assessment at different scales based on ecological pressure index. *Chinese Journal of Eco-Agriculture* **15** (6), 135–138 (in Chinese).

Zou, S. Z., Zhang, W. H., Liang, B., Chen, H. F. & Liang, X. P. 2005 A discussion of the assessment of ground water vulnerability in epikarst zone of the karst area, Southwest China. *Earth Science Frontiers* **12** (S1), 152–158.

Zou, S. Z., Zhu, M. Q., Tang, J. S. & Xia, R. Y. 2006 Water resources security in karst area of southwest China: problems and countermeasures. *Acta Geologica Sinica* **80** (10), 637–642 (in Chinese).