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Regional water resources security assessment and optimization path analysis in karst areas based on emergy ecological footprint

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Abstract

With the continuous growth of the world's social economy and population, problems such as water shortage and water environment deterioration need to be solved urgently. Combining the emergy carrying capacity of water resources and the emergy ecological footprint method, the water security and sustainable development status of the typical city in the karst region (Anshun City) was evaluated, and the internal driving factors and optimization suggestions were discussed. The research results of water security in Anshun City show that: The water resources carrying capacity fluctuates greatly with rainfall and is generally in a low-level surplus state. The ecological pressure index and the sustainable utilization index show a downward trend. The pressure intensity of social and economic systems on water resources is increasing, and the sustainable development of water resources is not optimistic. Water resources security is mainly affected by natural ecological mechanisms centered on mountain systems, geological structures and hydrological systems, as well as social mechanisms centered on changes in population scale, land development and utilization, and urban development. In the future, the sustainable development of water resources can be promoted by changing the mode of economic development, optimizing the allocation of water resources, and protecting the ecological environment.

Keywords Water resource security · Karst area · Carrying capacity · Emergy ecological footprint · Water resource management

Introduction

Water resources have been recognized as an indispensable natural resource for human survival. With socio-economic development, there is an unprecedented demand for water, which has given rise to a range of problems, such as water pollution, water shortage, and water resources irrational utilization (Razavi et al. 2012; Sheffield et al. 2014; White et al. 2018; Zeng et al. 2023). The UN estimates that by 2030, more than one-third of the planet's population will encounter a freshwater crisis, highlighting the need to find ways to ensure water security, improve utilization of water resources, and alleviate shortages (Abu-Zeid 1998; Bichai and Smeets 2013). At the 1973 Global Water Security Conference, the UN issued a dire warning that "water resources could trigger the next profound social crisis after the oil crisis" (Roberson and Morley 2006; Plappally and Lienhard 2012). As it receives greater concern from international agencies and national governments, scholars have defined the connotation of water security from different perspectives. For example, William Page and Rabinowitz (1993) held that water security is an integral part of urban sustainable development; Rogers (2004) pointed out that water security refers to the quality and quantity of water needed to sustain human production, living, and ecological environment. In March 2000, the Second World Water Forum and Ministerial Conference was held in the Hague, Netherlands, which proposed a concept of "water security" widely accepted by the international community, i.e., water security means access to safe water at affordable prices (Bakker 2012; Tindall and Campbell 2009; Zhao et al. 2019). Despite different starting

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points, experts and scholars share common basic requirements when defining water security. From the perspective of human needs, water security refers to the amount of water that can satisfy basic human needs; From the perspective of socio-economic development, water security refers to the amount of water that can meet the needs of all industries while ensuring social sustainability; From the perspective of ecological environment, water security refers to the amount of water that can maintain or improve environmental quality.

As a research hotspot, water security has generated a great deal of academic discussion. For example, Penn et al. (2017) used a framework for environmental security that entails four interrelated concepts: availability, access, utility, and stability of water resources, and explored the nature of water security challenges in rural Alaska. Aalirezaei et al. (2021) used gray management analysis, GM (1,1), to identify and forecast water security level, and the results are presented for a time-series analysis of the key performance indicators for a water security unit in Saskatchewan, Canada. Ali Zakeri et al. (2022) selected 8 indicators to evaluate the water security in Iran and its large watersheds over a period of 20 years based on the analytical network process (ANP) method. Aboelnga et al. (2020) developed a new urban water security assessment framework and applied the new assessment framework on the city of Madaba, Jordan, and measured urban water security using the integrated urban water security index and the analytic hierarchy process (AHP). Jabari et al. (2020) used a semi-quantitative risk-based approach to evaluate the urban water security in a severe water stress area of Palestinian. Qadeer et al. (2018) presented a fuzzy multi-criteria evaluation TOPSIS method for the water resource security evaluation. Nine provinces within the Yellow River basin were ranked for the water resources security degree based on the proposed method. These studies have adopted different perspectives to evaluate water security in different regions and made achievements. Nevertheless, given its socio-economic and ecological attributes, the evaluation of water security involves social, economic, and environmental factors. Existing evaluation methods have failed to fully take into account the objectivity, complexity, and comprehensiveness of water security. The emergy ecological footprint can compensate for the shortcomings of the above methods. In the research method, the emergy theory and ecological footprint model are combined to convert different types of energy into a unified solar energy value through solar energy conversion rate, and the ecological footprint is quantitatively analyzed and studied, which truly reflects the impact of human production and living water on the natural ecosystem. For the emergy ecological carrying capacity, only renewable water resources (groundwater, surface water, and rainwater) need to be taken into account, based on which the energy is further converted into emergy. For the emergy ecological footprint, the two parameters of energy conversion coefficient and energy conversion rate of various materials and energy consumed by human in production and life should be converted into emergy and then divided by the regional emergy density to obtain the emergy ecological footprint of the region. The method not only expands the application scope of emergy theory and ecological footprint theory and maximizes the advantages of these two theoretical models, but also enriches the research methods and means. At the same time, it also makes up for the shortcomings of the ecological footprint model to a certain extent and realizes the assessment of the strengths and weaknesses of regional water resources security. Compared with other ecological footprint improvement models, the ecological footprint assessment method based on emergy theory has more scientific, more perfect, more operational, and more practical values. The evaluation of regional water security is analyzed from the perspective of time series, and it comprehensively considers the influence of social, environmental and other factors, which can more accurately reflect the pressure of regional economic development on the ecosystem.

Due to intense karstification, karst areas, which account for 10% of the earth's total area, suffer from severe water seepage, resulting in a fragile ecological environment and challenges in water resources development and utilization. However, previous studies have mainly focused on semi-arid and arid regions and frequently ignored water security in karst areas. In view of this, this paper conducted a case study of a typical city in the karst region. Combining water resources emergy ecological carrying capacity and emergy ecological footprint, it assessed the water security status of Anshun City by calculating the per capita water resources emergy carrying capacity, water resources emergy ecological footprint, water resources ecological surplus/deficit, water resources ecological tension, water resources sustainability index and other indicators. After analyzing the internal drivers, it proposed optimization paths for sustainability of water resources to make improvements. The research findings are expected to provide reference for regional water security evaluation and analysis and therefore have far-reaching implications for alleviating the contradiction between water resources supply and demand, forming a benign cycle of ecological environment, and promoting sustainable socio-economic development.

Theoretical framework

Water resources security is an important prerequisite for regional economic development and is closely related to regional sustainable development. On the issue of regional water resources security, the ecological footprint method is currently a relatively mature research method, which is

gradually becoming an important means of quantitative research on regional water resources security and is widely used in ecological security research at different spatial and temporal scales around the world. However, as the study progressed, it is found that there are still some controversial aspects in the ecological footprint model itself. At this time, the emergy ecological footprint model comes into being, which cleverly combines the solar energy value in the emergy theory with the ecological carrying capacity and ecological footprint indexes in the ecological footprint model to make up for the shortcomings of the ecological footprint model to a certain extent and realize the assessment of the advantages and disadvantages of the regional ecological environment. Some scholars have combined emergy theory with ecological footprint models, which have been widely applied at several research scales. On the national scale, Hong and Yamamoto (2007) used the emergy analysis method to calculate the non-renewable resources of seven countries, including Australia, the USA, and Belgium, and analyzed their ecological footprints. Pereira and Ortega (2012) proposed a method to calculate ecological footprint and ecological carrying capacity using global emergy density through an empirical analysis of Brazil, which laid the foundation for a horizontal comparative study of ecological security levels among regions. After evaluating the ecological security of Jiangsu province, Zhang et al. (2006) found that compared with the traditional ecological footprint assessment method, the emergy ecological footprint method can more truly reflect the ecological and economic environmental conditions of the region and will have a broader development prospect. On the basis of the calculation principle of the original model, Liu et al. (2008) proposed the regional emergy footprint method based on the actual situation of the region as the standard, so that the sustainable development status of the region can be evaluated more accurately. Many research results using the emergy ecological footprint model have also well verified the superiority of its evaluation effect. Therefore, using the emergy ecological footprint model and related ecological security evaluation indexes can evaluate the regional water security status more comprehensively and provide corresponding policy recommendations accordingly.

Methodology

Water resources emergy ecological footprint model

Ecological footprint is an ecological capacity evaluation method system proposed by Wackernagel et al. (1999) and Rees (1992). Ecological footprint is defined as the biological productive and mutually exclusive areas necessary to continuously provide for people's resources supplies and the

absorption of their wastes. As its basic idea, the ecological footprint theory attributes the impact of human production and consumption on the environment to the occupation of six types of ecologically productive land areas, namely water area, grassland, forest land, cultivated land, building land, and fossil energy land, which provide material and energy. Through equivalence and yield factors under the world average productivity, researchers can calculate the resource consumption and ecological carrying capacity. By comparing ecological footprint and ecological carrying capacity, they can determine whether the region is sustainable.

According to the emergy theory proposed by the American ecologist Odum (1996), since all forms of energy ultimately come from solar energy conversion, incomparable energy of different types and sources within a system can be converted to solar for quantitative analysis. Nakajima and Ortega (2016), Zadgaonkar and Mandavgane (2020) and others took the lead in combining emergy theory and ecological footprint theory and transformed various energies in the ecological economic system into solar energy values through indicators such as emergy density.

With reference to the above theories, this paper attempted to introduce emergy theory into the calculation of water resources carrying capacity, combine water resources emergy ecological carrying capacity with emergy ecological footprint, and evaluate the water security and sustainability of the study area by calculating a series of indicators, i.e., per capita water resources emergy carrying capacity, per capita water resources emergy ecological footprint, water resources ecological footprint surplus/deficit, water resources ecological tension, water resources sustainability index, and water resources carrying capacity of 10,000 Yuan GDP.

Water resources emergy ecological carrying capacity

The meaning of ecological carrying capacity is the maximum amount of natural resources that can be used in a certain period of time in a certain area. In most cases, only renewable resources are considered in the calculation of ecological carrying capacity (Yang et al. 2018; Cook and Bakker 2012). In this paper, water resources are taken as renewable resources, which are rainwater potential energy, surface water chemical energy, and groundwater chemical energy. Based on emergy theory, the per capita water resources emergy ecological carrying capacity is calculated as follows:

$$\text{WEEC} = \frac{E}{\rho_1 \times N} \tag{1}$$

$$E = e_1 + e_2 + e_3 \tag{2}$$

where WEEC denotes per capita water resources emergy ecological carrying capacity (hm^2/cap); E denotes total

emery of renewable resources (sej); ρ_1 denotes global average emergy density, $\rho_1 = 3.104 \times 10^{10}$ sej/m^2; N denotes total regional population (10,000 people); $e_1, e_2,$ and e_3 denote rainwater emergy, surface water emergy, and groundwater emergy, respectively (Liu et al. 2021). According to the principle of ecological footprint calculation, the water resources carrying capacity should be deducted by 12% of the total ecological capacity to protect biodiversity.

Water resources emergy ecological footprint

Based on the ecological footprint theory, the land on earth is divided into six categories of ecological and productive land, namely cultivated land, forest land, water area, fossil energy land, grassland, and building land (Hassan et al. 2019; Sharif et al. 2020). In view of the consumption items closely related to water resources in Anshun City, crops were selected as an indicator of the cultivated land account, meat and eggs of the grassland account, gardens and fruits of the forest land account, aquatic products of the water area account, and industrial water consumption of the combined fossil energy and building land. The specific indicators of ecological footprint accounts are shown in Table 1 (Li et al. 2019; Yang et al. 2018; Zhu 2010; Odum 1996).

According to emergy theory, the per capita water resources emergy ecological footprint is calculated as follows:

(1) Calculate the per capita emergy of the ith resource and introduce the emergy conversion rate. See Table S1 (Supplementary material) for relevant energy conversion coefficients and energy conversion rates. The calculation formula is:

$$C_i = \frac{A_i \times \lambda_i \times \tau_i}{N} \tag{3}$$

where C_i denotes per capita emergy of the ith resource (sej/cap); A_i denotes raw data of the ith resource; λ_i denotes energy conversion coefficient of the ith resource; τ_i denotes emergy conversion rate of the ith

resource; N denotes total regional population (10,000 people).

(2) The regional emergy density is calculated as follows:

$$\rho_2 = \frac{E}{S} \tag{4}$$

where E denotes the total emergy of renewable resources (sej); S denotes regional land area (hm^2).

(3) The per capita water resources emergy ecological footprint is:

$$\text{WREF} = \sum_{i=1}^{n} \frac{C_i}{\rho_2} \tag{5}$$

where WREF denotes per capita water resources emergy ecological footprint (hm^2/cap); i denotes resource type.

Water security evaluation indicators

Water resources ecological surplus/deficit index

Water resources ecological surplus/deficit is the difference between regional water resources emergy ecological carrying capacity and water resources emergy ecological footprint, a measure of the sustainability of water resources (Poff et al. 2016; Howlett and Cuenca 2017). It is calculated as follows:

$$\text{WRES(WRED)} = \text{WREC} - \text{WREF} \tag{6}$$

where WRES denotes water resources ecological surplus, WRED denotes water resources ecological deficit (hm^2/cap). When WREC > WREF, the water resources are in ecological surplus, indicating that the regional natural ecosystem provides sufficient water resources for socio-economy; otherwise, the water resources are in ecological deficit.

Water resources ecological tension index

Water resources ecological tension index is the ratio of water resources emergy ecological footprint to water resources emergy ecological carrying capacity. A high ecological tension index can threaten regional water security and undermine water resources sustainability (Romeiko 2019; Lee et al. 2021). It is calculated as follows:

$$\text{WRTI} = \frac{\text{WREF}}{\text{WREC}} \tag{7}$$

where WRTI denotes water resources ecological tension index. According to the grading criteria of water resources ecological tension index levels in the study of Ren et al. (2005), the secure status can be determined from its value, as shown in Table 2.

Table 1 Ecological footprint account indicators

Accounts	Items
Grassland	Beef, mutton, eggs, pork, poultry
Water area	Aquatic products
Cultivated land	Corn, beans, wheat, potatoes, rice, oil plant, tea, vegetables, tobacco
Fossil energy and building land	Industrial water consumption
Forest land	Fruits

Table 2 Classification of water resources ecological pressure index

WETI	Status
< 0.5	Secure status
0.5–0.8	Relatively secure status
0.8–1.0	Critical secure status
> 1.0	Insecure status

Table 3 Classification of the degree of sustainable utilization of water resources

Sustainability status	WRUI	Grade
Strong unsustainability	> 0.7	4
Weak unsustainability	0.5–0.7	3
Weak sustainability	0.3–0.5	2
Strong sustainability	< 0.3	1

Water resources sustainable utilization index

Water resources sustainable utilization index is the ratio of WREF to the sum of WREF and WREC (Liu et al. 2021). It represents the extent to which the total amount of water sustainably supplied in a region can meet the needs of human socio-economic activities in a specific period, implying the coordination degree between water resources and socio-economic development. It is calculated as follows:

$$WRUI = \frac{WREF}{WREF + WREC} \tag{8}$$

where WRUI denotes water resources sustainable utilization index. When WSUI > 0.50, the water resources utilization is in danger and unsustainable; When WSUI < 0.50, the water resources utilization is in a safe state of ecological surplus and sustainable; When WRUI = 0.5, the water resources utilization is in a critical state. The greater the WRUI, the greater the conflict between social development and water resources, and the lower the degree of sustainable utilization. Based on the criteria proposed by Tang et al. (2017), water resources sustainable utilization is divided into different grades, as shown in Table 3.

Water resources carrying capacity of 10,000 Yuan GDP

Water resources carrying capacity of 10,000 Yuan GDP is the ratio of water resources carrying capacity to GDP in a period of time. It provides an objective measure of water resources utilization efficiency (Yang et al. 2019). The smaller the value, the higher the water resources utilization efficiency; otherwise, the lower the water resources utilization efficiency. It is calculated as follows:

$$WGDP = \frac{WREC \times N}{GDP} \tag{9}$$

where WGDP denotes water resources carrying capacity of 10,000 Yuan GDP (hm^2/cap); GDP is calculated at current year prices, so it is nominal GDP.

Study area and data

Overview of study area

Located in central Guizhou Province, China, Anshun City is situated at 105°07′ ~ 106°07′E and 25°21′ ~ 26°38′N, as shown in Fig. 1. Anshun covers an area of 9267 km^2, of which 6627 km^2, or 71.52%, are karst outcropped. Among the karst area, stony desertification covers 2969 km^2, accounting for 32.04% of the city's total area, making it a typical concentrated area of karst landform in the world. Located at the watershed between Wujiang River Basin of Yangtze River system and Beipanjiang River Basin of Pearl River System, the city has a typical plateau humid subtropical monsoon climate with abundant rainfall, averaging 1360 mm a year. Despite their large volume, Anshun's water resources are unevenly distributed in time and space, with low utilization efficiency. They come mainly from atmospheric precipitation, characterized by the replenishment, conversion and frequent alternation between surface and groundwater.

Anshun, located in a karst landform area, has special geological and climatic conditions. With a dual structure of surface and underground, it is known for severe surface water infiltration, difficulty in forming sustained catchments and poor storage capacity. In case of seasonal drought, some rivers will dry up without replenishment. High elevation difference poses challenges for the development and utilization of surface water resources. Although large in volume, the groundwater is deeply buried and complex in form, implying high engineering costs for water extraction. Besides, the city suffers from engineering and seasonal water shortages. As China's development center shifts westward, Anshun has seen rapid population and economic growth, highlighting the conflict between water supply and demand. Because of such natural and social factors, the city's water resources face sustainability challenges. In this regard, the evaluation and analysis of water security in Anshun will assist the government in developing targeted water resources management policies to address the supply–demand conflict and promote sustainable development.

Fig. 1 Geographical location of Anshun City
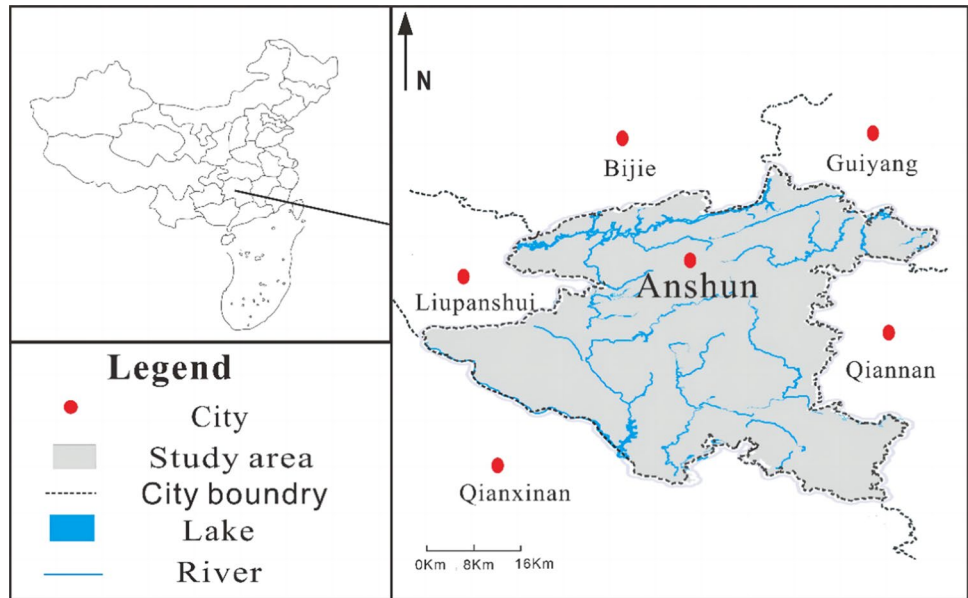
Data sources

This paper compiles and collects the relevant data of Anshun City from 2012 to 2019. Data on average annual rainfall, surface water, groundwater, and rain are from the *Anshun Water Resources Bulletin* (Anshun Department of Water Resources 2012–2019); data on population, GDP, beef, mutton, eggs, pork, poultry, aquatic products, corn, beans, wheat, potatoes, rice, oil plant, tea, vegetables, tobacco, industrial water consumption, and fruits are from the *Anshun Statistical Yearbook* (Anshun Bureau of Statistics 2012–2019).

Results and analysis

Water security analysis

Analysis of water resources carrying capacity

According to the per capita water resources carrying capacity in Table S3 (Supplementary material) and the average annual rainfall data of Anshun City from 2012 to 2019 in Table S2 (Supplementary material), the researcher made a change curve of the per capita water resources emergy carrying capacity and average annual rainfall, as shown in Fig. 2.

From 2012 to 2019, the per capita water resources carrying capacity of Anshun City showed large fluctuations. It grew by about 7% during the study period yet remained at a low level. In 2014 and 2015, the city had a high per capita water resources carrying capacity of 3.08 and 3.05 hm²/cap, corresponding to an average annual rainfall of 1328.8 and 1328.5 mm, making them wet years. In 2013, its per capita water resources emergy carrying capacity reached
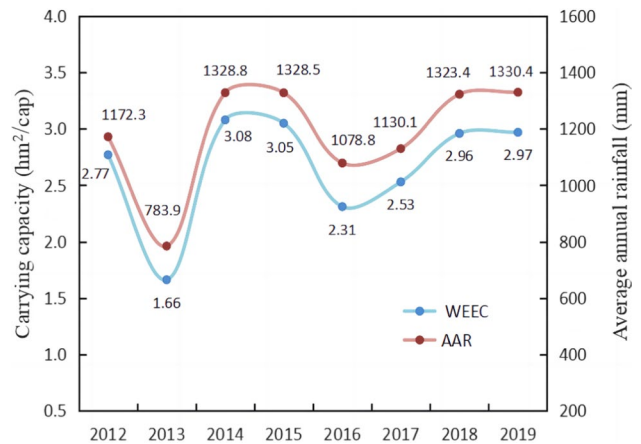

Fig. 2 Changes of per capita water resources emergy carrying capacity and average annual rainfall of Anshun City from 2012 to 2019

the bottom of 1.66 hm²/cap, corresponding to an average annual rainfall of 783.9 mm, making it a dry season. The difference between the maximum and minimum years of per capita water carrying capacity was 1.4 hm²/cap; the difference in their rainfall was 544.9 mm. The annual change rule of the city's water resources emergy carrying capacity was closely related to that of average annual rainfall. The total water resources increased with the increase of rainfall, and the carrying capacity of water resources increased with the increase of total water resources. Due to its location in the monsoon climate zone, there were obvious interannual differences in precipitation in Anshun, with large fluctuations in water resources carrying capacity. On the one hand, this implies the city's weak ability in self-regulating water

resources carrying capacity and its heavy dependence on atmospheric precipitation. On the other hand, social progress boosts human activities, such as accelerated industrialization, urbanization and deforestation. These have led to problems such as water area pollution and water resources overuse, which reduce water resources available to human beings and further damage the city's water resources carrying capacity. In a word, water resources security was closely related to the change of water resources emergy carrying capacity. The greater the emergy carrying capacity of water resources, the safer the water resources.

Analysis of water resources emergy ecological footprint

According to the calculation results of water resources ecological footprint in Table S4 (Supplementary material), the researcher made a change curve of the water utilization accounts of fossil energy and building land, cultivated land, grassland, forest land and water area, as well as their per capita water resources emergy ecological footprint, as shown in Fig. 3.

Among all ecological footprint accounts, the fossil energy and building land account had the largest impact on water resources ecological footprint, with an average contribution of 59%. As can be seen, the energy production water and human domestic water in Anshun turned into a large amount of water resources emergy ecological footprint. The grassland and cultivated land accounts had moderate contribution rates of 26% and 10%, respectively. The cultivated land account had a low water resources emergy ecological footprint, mainly due to the severe stony desertification in Anshun (2969 km^2, accounting for 32.04% of the city's area). The forest land and water area accounts assumed only 3 and 2% of water resources emergy ecological footprint, respectively. Except for the fossil energy and building land, which had a decrease in water resources ecological footprint,
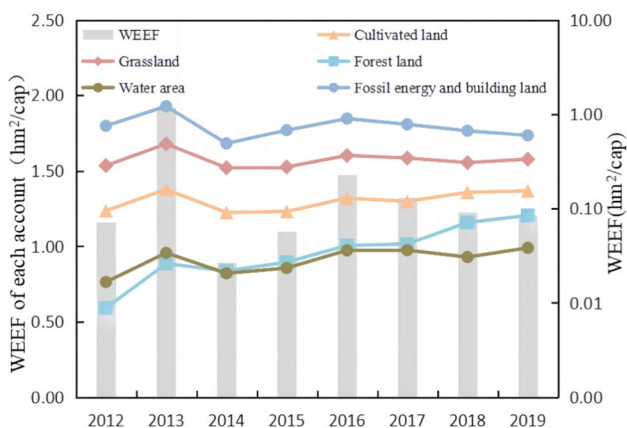
the footprint of other accounts all increased slightly during the study period. The decrease in water resources ecological footprint of the fossil energy and building land account resulted primarily from the "energy saving and emission reduction" policy introduced in Anshun in recent years, which optimized the industrial structure of water resources consumption and reduced industrial water consumption and wastewater discharge. The increase in water resources ecological footprint of the grassland and forest land accounts was mainly attributed to the local government's continued control of soil erosion and desertification, as well as the "closing hillsides to facilitate afforestation" policy. During the study period, the per capita water resources ecological footprint of Anshun increased from 1.16 to 1.21 hm^2/cap, a growth rate of about 4.31%. There were notable fluctuations in the process, such as in 2013 and 2016, which were associated with a decrease in water resources as a result of the year's significant drop in rainfall. Overall, due to greater consumption of water resources brought about by population growth and economic development, the per capita water resources ecological footprint of the city was on the rise. In a word, water resources security was closely related to the change of water resources emergy ecological footprint. The larger the emergy ecological footprint of water resources, the more insecure the water resources are.

Analysis of water resources ecological surplus/deficit and water resources ecological tension

According to the calculation results of water resources ecological surplus/deficit and water resources ecological tension index in Table S5 (Supplementary material), the researcher made a change curve of the water resources ecological surplus/deficit and water resources ecological tension index, as shown in Fig. 4.

Except for 2013, when there was a water resources ecological deficit, Anshun had a water resources surplus in all the remaining years. The maximum surplus occurred in 2014, with a value of 2.18 hm^2/cap; the minimum surplus occurred in 2016, with a value of 0.83 hm^2/cap; the maximum deficit occurred in 2013, with a value of -0.26 hm^2/cap. According to the grading criteria of the water resources ecological tension index, the city has seen large fluctuations in its water resources ecological tension index from 2012 to 2019. It was 1.16 in 2013, suggesting unsafe development and utilization of water resources, 0.64 in 2016 and 0.52 in 2017, suggesting safe development and utilization, and the same was true in the remaining years. On the whole, the water resources in Anshun were in a safe state (Fig. 5).

A water resources ecological deficit was frequently accompanied by greater water resources ecological tension; at water resources ecological surplus, the water resources ecological tension decreased with the increase of surplus.
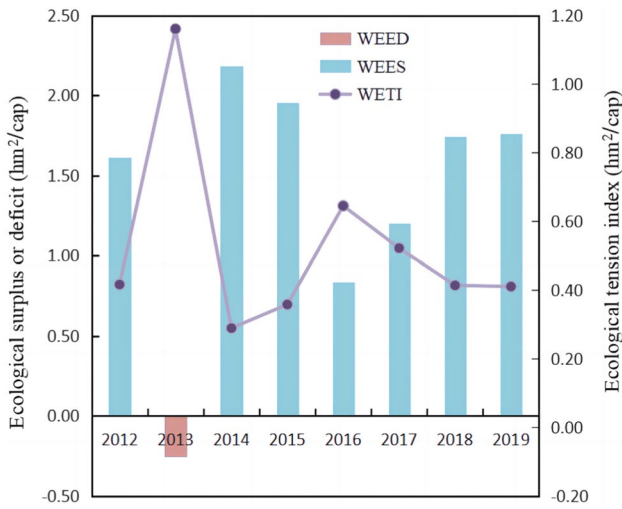

Fig. 3 Changes of water use accounts and per capita water resources ecological footprint of Anshun City from 2012 to 2019

Fig. 4 Changes of water resources ecological surplus/deficit of Anshun City from 2012 to 2019

Similar to water resources carrying capacity, the changes in water resources ecological surplus and ecological tension roughly corresponded to changes in rainfall. The ecological deficit in 2013 was mainly due to the low average annual rainfall in that year. The decrease in per capita water resources emergy carrying capacity and the increase in per capita water resources emergy ecological footprint triggered water resources ecological deficit and led to an increase in water resources ecological tension. In 2016, there was a sudden drop in water resources surplus in Anshun, which was due to a major decrease in the total amount of water resources while the consumption of each account grew much higher than in 2014 and 2015, leading to greater water resources ecological tension. In general, Anshun's water resources were in surplus and safe, with its natural ecosystem providing water that basically covered

local economic, ecological and environmental needs. The city's water resources ecological surplus/deficit and water resources ecological tension were closely related to its rainfall. At smaller rainfall, there could be a water resources ecological deficit or a small water resources ecological surplus, thus increasing water resources ecological tension and water security concerns. In a word, when water resources were in an ecological deficit, water resources were unsafe. The ecological tension index of water resources became larger as the ecological surplus of water resources decreased, and the larger the ecological tension index of water resources, the more unsafe the water resources were.

Analysis of water resources carrying capacity of 10,000 Yuan GDP

According to the GDP of Anshun from 2012 to 2019 in Table S2 (Supplementary material) and the water resources carrying capacity of 10,000 Yuan GDP in Table S5 (Supplementary material), the researcher made a change curve of the water resources carrying capacity of 10,000 Yuan GDP, as shown in Fig. 6.

From 2012 to 2019, Anshun's water resources carrying capacity of 10,000 Yuan GDP was on the decline, with a decrease of about 55.56% from 0.18 hm^2/cap in 2012 to 0.08 hm^2/cap in 2019. As for the reasons, on the one hand, rapid economic development boosted the city's GDP. On the other hand, the water resources consumption of each account increased with population growth. In general, the decrease of carrying capacity can be divided into two stages. The first is the rapid decline in water resources carrying capacity of 10,000 Yuan GDP from 2012 to 2014, thanks to the "Western Development Strategy" and the resulting economic takeoff and large consumption demand for water resources. The dramatic decline from 2012 to 2013
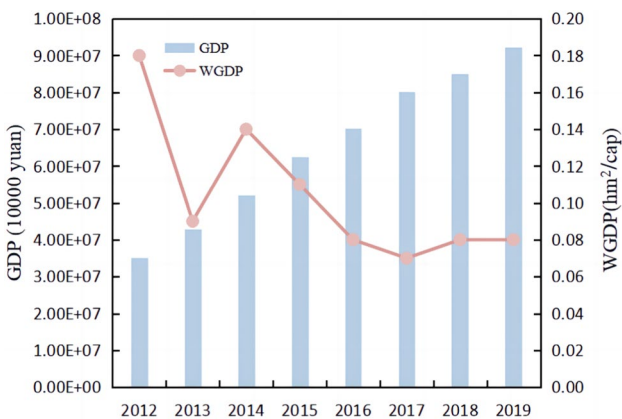

Fig. 5 Changes of water resources carrying capacity of 10,000 Yuan GDP of Anshun City from 2012 to 2019
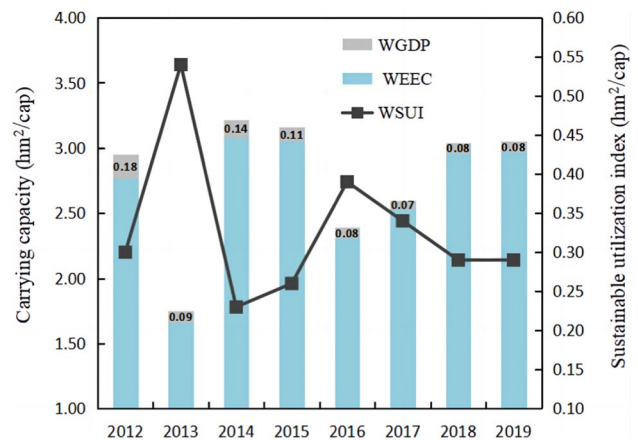

Fig. 6 Changes of water resources emergy carrying capacity and sustainable utilization index of Anshun City from 2012 to 2019

was attributed to the significant decrease in average annual rainfall in that year. The second stage was from 2014 to 2019, when the water resources carrying capacity of 1000 Yuan GDP dropped steadily. With the introduction of water conservation and green economy policies, the consumption structure of water resources was optimized and the efficiency of water resources utilization was improved. Nevertheless, there was a significant decrease in the rate of decline of water resources carrying capacity of 10,000 Yuan GDP at this stage, hinting at the constraints of internal factors and rainfall on the city's water security and, more importantly, its limitations in sustainable development and utilization. In a word, the smaller the water resources carrying capacity of 10,000 Yuan GDP, the more the utilization efficiency of water resources, the safer the water resources.

Analysis of water resources carrying capacity and sustainable utilization index

According to the calculation results of per capita water resources carrying capacity in Table S3 (Supplementary material) and water resources sustainable utilization index in Table S5 (Supplementary material), the researcher made a change curve of the water resources emergy carrying capacity and sustainable utilization index, as shown in Fig. 6.

From the grading criteria of the water resources sustainable utilization index in Table 3, it can be seen that the water resources sustainable utilization index of Anshun fluctuated sharply from 2012 to 2019, with a trend roughly the same as that of the water resources ecological tension index. In 2014, 2015, 2018 and 2019, the city had highly sustainable water resources utilization and per capita water resources carrying capacity was higher, which was in a safe state of ecological surplus; in 2012, 2016 and 2017, it had weakly sustainable water resources utilization and per capita water resources carrying capacity was relatively low, which was in a safe state of ecological surplus; in 2013, it had a weak and unsustainable sustainable water resources utilization and per capita water resources carrying capacity was the lowest, which was in danger of ecological deficit. After 2016, the city's sustainable utilization index for water resources declined slowly overall, showing a good sustainability trend. In a word, the greater the sustainable utilization index of water resources, the smaller the carrying capacity of water resources, the more unsustainable the utilization of water resources, and the less secure the water resources.

Drivers of water resources sustainability and optimization paths

As the analysis of Anshun's water security situation shows, the city had highly sustainable water resources in ecological surplus in recent years. According to the change curve, however, the sustainability of its water resources was constrained by rainfall and internal factors, suggesting a possibility that future water resources carrying capacity might not be able to sustain social development. Hence, this paper analyzed the internal driving mechanisms of water resources sustainability in Anshun from the perspective of natural ecological and social factors and proposed suggestions for optimization.

Natural ecological mechanism

Located in a typical karst landform area, the soil matrix of Anshun's mountainous system is heavily depleted by gravity and the soil water content is rapidly declining, leading to severe stony desertification and an extremely fragile ecological environment. With a dual structure of surface and underground, the karst landform is known for severe surface water infiltration, convergence toward deep canyons, and enormous development and utilization challenges. Although large in volume, the groundwater is deeply buried and unevenly distributed in time and space, resulting in water extraction difficulties and surface drought. As shown in the analysis above, due to the city's efforts in stony desertification management in recent years, its erosion and stony desertification area has been gradually reduced. As a result, its water resources carrying capacity is generally on the rise.

Social mechanism

As the main effect of social mechanism, it increased Anshun's water resources ecological footprint and decreased its water resources carrying capacity during the study period, thus lowering its water resources ecological surplus. First, the city embraced rapid urbanization from 2012 to 2019, accompanied by population growth from 2,283,400 to 2,363,600, as well as increasing demand for industrial, agricultural, domestic and ecological water. This was particularly true during 2016 and 2019, when the increased water resources consumption resulted in a per capita water resources ecological footprint that was consistently greater than 1.20 hm^2/cap. Second, in terms of land development and utilization, Anshun is located in a mountainous karst area, and the increase in population exacerbated the reclamation of sloping land. Long-term deforestation led to soil erosion, severe stony desertification and ecological degradation, which undermined the city's water resources carrying capacity.

Optimization paths for water resources sustainability

Optimization path for water resources sustainability: combining the current status of water resources, effectively improve and optimize the systems and methods of water resources management, utilization and protection to ensure the security and sustainable use of water resources in the future. Based on the drivers and status quo of water resources development and utilization, this paper proposed the following optimization paths to ensure the sustainable development of water resources in Anshun:

(1) Strengthen policy orientation and focus on developing a green and low-carbon economy. As economic and population growth inevitably brings about a large consumption of water resources, water resources ecological footprint increases with socio-economic development. A favorable economic development model can improve the efficiency of resource utilization, reduce resource loss, and ease ecological tension. In view of this, Anshun should uphold the concept of "ecological priority and green development" to adopt a green and low-carbon circular economy model, including reducing water resources input and wastewater discharge in agricultural, industrial and service production, and improving the recycling rate of water resources.

(2) Adjust the supply and demand structure of water resources and optimize the allocation of water resources. Given the large proportion of industrial water in Anshun's water resources utilization, the government should carry out macro adjustment of the supply–demand structure and optimize the allocation of water resources in time and space. There should be optimization of the industrial structure, including fostering industries that drive economic growth with low water consumption, upgrading industries that contribute much to economic aggregate with large water consumption, and transferring or eliminating industries that contribute little to economic growth with large water consumption, so as to ensure the sustainability of the city's water resources. Other measures include further promoting the concept of water conservation, implementing a tiered water price, improving the water resources consumption structure, and increasing water resources utilization efficiency.

(3) Protect ecological environment and improve water resources utilization rate. In light of the characteristics of Anshun's natural ecological mechanism, the government should give priority to stony desertification control, constantly promote the return of farmland to forest, increase forest coverage, and avoid soil erosion, thereby improving the ecological environment and enhancing the self-cleaning and repairing capacity of

water resources. It should also guide water resources development and utilization through supply regulation, increase investment in water construction, and upgrade the development and utilization of surface and transit water resources.

Discussion and conclusion

(1) During the study period, the per capita water resources carrying capacity of Anshun slowly increased yet remained at a low level, sharing a similar trend with the average annual rainfall. Among the city's ecological footprint accounts, the fossil energy and building land account contributed the most to water resources ecological footprint, while the forest land and water area accounts contributed less. The per capita water resources ecological footprint of Anshun increased from 1.16 to 1.21 hm^2/cap during the period, a growth rate of 4.31%. In summary, the per capita water resources carrying capacity has risen slowly, and the per capita water resources ecological footprint has shown a rapid upward trend. The amount of water resources may not be enough to support regional economic development and the load of the ecological environment in the future. In addition to the ecological deficit of water resources in 2013, water resources were surplus in all other years; and the surplus of water resources increased year by year from 2016. The water resources carrying capacity of 10,000 Yuan GDP dropped from 0.18 to 0.08 hm^2/cap, a decrease of about 55.56%. To sum up, the overall water resource was in an ecological surplus state, and the utilization efficiency of water resources has been improved. The existing amount of water resources can support the regional economic development and ecological environment load in a short period of time. However, the sustainable development of water resources was constrained by internal factors and the amount of rainfall. With the gradual increase of the pressure intensity of the socio-economic system on water resources in Anshun City, the water resources ecological tension index and sustainable utilization index may show an upward trend. Therefore, there can be a decrease in water resources ecological surplus or an ecological deficit in the near future, and water resources may become unsustainable and the future water resources security is threatened.

(2) The sustainable development of water resources in Anshun is under the dual influence of natural ecological mechanisms and social mechanisms. In terms of natural ecological mechanisms, the fragile ecological environment of the karst mountains leads to severe soil erosion,

while the highly permeable hydrogeological structure weakens the surface water storage capacity and results in surface water scarcity. In terms of social mechanism, due to greater water resources demand arising from increasing population and urban expansion, and ecological degradation because of land overload, Anshun has greater water resources ecological footprint and lower water resources carrying capacity. To ensure the sustainability of its water resources, the city is recommended to strengthen policy orientation and develop a green and low-carbon economy, adjust the supply and demand structure of water resources and energy structure, optimize the allocation of water resources; protect the ecological environment and improve the utilization rate of water resources.

(3) This paper improved the ecological footprint model and innovatively combined it with emergy theory to establish an emergy ecological footprint model. The scope of application of the two theoretical models was expanded: the advantages of the two theoretical models were brought into full play, and the research methods and means of water resource security were enriched. In this paper, the researcher combined water resources emergy ecological carrying capacity and emergy ecological footprint to evaluate the water security in karst areas and analyze its sustainability, with a view to providing inspiration for water security studies in similar regions. The account indicators were selected based on their relevance to water resources consumption and the availability of data. Follow-up studies are expected to improve the account indicator system through further data source mining, so as to assess the regional water security situation in a more accurate and reasonable manner.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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