Temporal and spatial characteristics of ecological footprint of water resources in Sichuan Province

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Abstract. In order to deeply study the sustainability of water resources in Sichuan Province, this study aims to explore the spatial distribution characteristics of the ecological footprint of water resources in Sichuan Province. Using data from the Sichuan Water Resources Bulletin and Statistical Yearbook from 2011 to 2019, the spatial and temporal distribution characteristics of the ecological footprint of water resources in Sichuan Province and its cities and states were evaluated by constructing the ecological footprint model of water resources and the three-dimensional ecological footprint model. It was found that the EFw, ECw and 10,000 yuan GDP of Sichuan Province peaked in 2011 and stabilized between 2012 and 2019; meanwhile, the WESI showed significant instability. In terms of ecological footprint distribution, Sichuan province is mainly biased towards agriculture. Chengdu city has a more significant water consumption than other cities and states due to the special characteristics of tourism and population structure. Ganzi and Aba are relatively better than other cities and states in terms of water sustainability due to geography, population and economic structure. In summary, the changes in the ecological footprint of water resources in Sichuan Province and its cities and states between 2011 and 2019 show obvious regional differences. Therefore, in order to enhance the sustainability of global water resources, in addition to the need for macro-control at the national and provincial levels, it is necessary to implement precise management strategies for individual cities and states.

Keywords: water resources; ecological footprint; ecological carrying capacity; 3D model of ecological footprint;

1. Introduction

Water resources, as a fundamental element supporting life systems, are of irreplaceable importance for human survival and development. The multifunctional nature of water allows it to play an integral role in many life processes in a variety of areas, including biological metabolism, ecosystem balance, and industrial and agricultural production [1]. However, modern technological development and increasing human activities have seriously threatened global water resources. Many precious water sources have been polluted, or gradually depleted, or even completely disappeared due to over-exploitation [2-3]. The continuation of this trend will undoubtedly pose a serious challenge to human survival and social progress [4].

Therefore, how to better protect and utilize water resources while ensuring scientific and technological progress and socio-economic development has become an important issue of concern for todays society. It is worth noting that the vulnerability and protection needs of different water sources may vary significantly depending on factors such as their geographic location, environmental conditions, and the degree of anthropogenic intervention they have received. For this reason, scientifically dividing water resources into protection classes and formulating targeted protection measures according to the different classes will be one of the effective strategies to protect water resources. We can use the water ecological footprint to distinguish different water resources.

At present, most studies on the ecological footprint of water resources in urban areas are based on industrial cities [5]. However, few people pay attention to the ecological footprint of water resources in areas rich in tourism resources and ecologically sensitive and fragile.Take the Sichuan Province in China as an example, it is a region with rich tourism resources and a unique ecological environment, but also an ecologically sensitive and fragile zone [6].

In order to assess the water resources status in Sichuan Province, this study aims to calculate and assess the water ecological footprint. We will use parameters such as water ecological stress index, water ecological footprint per million yuan of GDP, and employ 3D model (breadth and depth of water ecological footprint) [7] to analyze the ecological status of water resources. Further analyses will reveal the carrying capacity of water resources in Sichuan Province and explore the relationship between sustainable water resources development and water resources ecological surplus. The results of the study will provide an important reference for water resources management and conservation in China and other regions of the world.

2. Materials and methods

2.1 Study area

Sichuan Province is located in the southwestern part of China, between longitude 97°21" ~108°31" East and latitude 26°03" -34°19° North, with an area of 484,300 square kilometers (Fig. 1). The province has 18 prefecture-level cities and 3 autonomous prefectures. The rivers in the province belong to 7 water resource level 2 basins.

Fig. 1. Administrative regions of Sichuan Province

2.2 Data resourese

The calculated data in this paper are from the water resources bulletins and yearbooks of Sichuan Province from 2011 to 2019.

2.3 Research methods and data sources

2.3.1 Water ecological footprint

The ecological footprint of water resources (EF_W) is a measure to assess the impact of human activities on water resources and the extent of human pressure on water ecosystems. It takes into account the relationship between water supply and demand, as well as the impacts on ecosystems of different water use patterns [8]. In this paper the main water ecological footprints are the calculation of the agro-ecological footprint water ecological footprint, the industrial water ecological footprint, the domestic water ecological footprint, and the ecological footprint of the ecosystem water ecological footprint.

The formula for calculating the ecological footprint of water resources is:

$$EF_w = N\, ef_w = N\, \gamma w \left(\frac{W}{P_w}\right)$$

water resources in m^3/hm^2 [9].

2.3.2 Water ecological carrying capacity

The ecological carrying capacity (EC_w) of water resources is the population, socio-economic and ecological environment that can be carried by the water resources of a given study area under the established economic level and technological conditions, and that can achieve the largest mutually coordinated sustainable development [10]. The utilization rate of water resources should not be higher than 40% to develop the most basic ecological environment stability in a region.

The formula of ecological carrying capacity of water resources is as follows:

$$EC_w = N\, ec_w = 0.4\, \varphi\, \gamma w (\frac{Q}{P_w})$$

In the formula: EC_w is the ecological carrying capacity of water resources in hm^2; N is the population size; ec_w is the ecological carrying capacity of water resources per capita in hm^2/person; φ is the production factor of water resources; γw is the global equilibrium factor of water resources; Q is the total amount of water resources in m^3; and P_w is the global average production capacity of water resources in m^3 /hm^2 [11].

2.3.3 Water ecological carrying capacity

The Water Ecological Stress Index (WESI) is the ratio of the water footprint to the ecological carrying capacity, with smaller indices indicating lower stress and larger indices indicating higher stress [7].

Water Ecological Stress Index's formula is:

$$WESI = \frac{EF_w}{EC_w}$$

In the formula, EF_w is the ecological footprint of water resources and EC_w is the ecological carrying capacity [11].

2.3.4 Ten thousand yuan GDP water ecological footprint

Ten thousand yuan GDP is used to measure the use of water resources by regional economic development, and its value change has a negative relationship with water resources use efficiency [12].

Ten thousand yuan GDP water ecological footprint formula is:

Ten thousand yuan GDP water ecological footprint = $\frac{EF_w}{GDP}$

Where the smaller the calculation result is, the higher efficiency of water use is.

2.3.5 Three-dimensional modeling of the ecological footprint

The depth of the ecological footprint of water resources characterizes the level of human consumption of water resources stock capital, and the breadth of the ecological footprint of water resources characterizes the level of human occupation of water resources flow capital. The formula is:

$$EF_{depth} = 1 + \frac{ES}{EC_w}$$

$$EF_{\text{□□□□}} = min[EC_w, EF_w]$$

Where: EF_{depth} is the depth of water resources ecological footprint, EFSize is the breadth of water resources ecological footprint (hm^2). When $EF_w \leq EC_w$, the ecological footprint depth of water resources is the natural depth $EF_{depth} = 1$, because human demand for water resources can be satisfied only through the consumption of flow capital, the larger the EF_{depth}, the greater the regional consumption of water resources stock, the greater the ecosystem hazard to water resources. Due to the rational basis of ecological footprint, the upper limit of natural capital flow that can be provided by the biosphere is the biological carrying capacity, and the upper limit of flow capital that can be provided by water resources is the ecological carrying capacity of water resources.

3. Results and analysis

3.1 Characteristics of Ecological Footprint Distribution of Water Resources in Sichuan Province

The distribution of ecological footprints for each year is almost similar, with agriculture occupying the most, followed by industry, and ecology occupying the least (Table 1). Except for 2012, when agriculture and industry are almost identical. Ecology not only occupies the smallest share, but also has a large difference of only 2% on average. EFw, ECw and ten thousand yuan GDP reached their maximum values in 2011 and plateaued from 2012 to 2019. WESI is very unstable, sometimes large and sometimes small, but the values are between 1 and 2, suggests Sichuan is struggling to maintain a balance between ecological consumption and ecological capacity. The indicator peaked in 2017, suggesting that unsustainable practices may have become more prevalent that year, possibly due to external factors such as economic pressures, lax regulation or even changes in global demand. indicating that EFw was large and ECw was small in that year.

Table 1. Distribution characteristics of ecological footprint of water resources in Sichuan Province from 2011 to 2018

	2011	2012	2013	2014	2015	2016	2017	2018	2019
Agricultural	127.2	216.26	139.41	145.37	156.7	155.86	160.42	156.6	154.53
industry	64.56	216.26	58.254	44.73	55.37	55.83	51.37	42.47	37.94
live	38.25	27.16	10.64	42.55	48.31	49.81	50.81	54.4	54.09
ecology	2.22	2.5	4.69	4.21	5.13	5.75	5.8	5.46	5.88

3.2 Differences in the distribution of water resources among cities in Sichuan Province

The trend of change over the years is about the same for all provinces (Fig. 2). Agriculture had the lowest overall share in 2011, peaked in 2012, and then did not change significantly. The composition of domestic water was relatively high in 2011, fell off a cliff in 2012, rebounded a bit in 2013, fell again in 2014, and was at a plateau in the subsequent think. Developed cities such as Chengdu will have a higher percentage than others, and less developed cities such as Liangshan will have a lower percentage. This may be due to the fact that cities like Chengdu have a more developed tourism industry and the wealth of their people. So residents will also have relatively higher water consumption for living in these cities. There doesnt seem to be much of a pattern to the share of industry, it jumps around a lot.

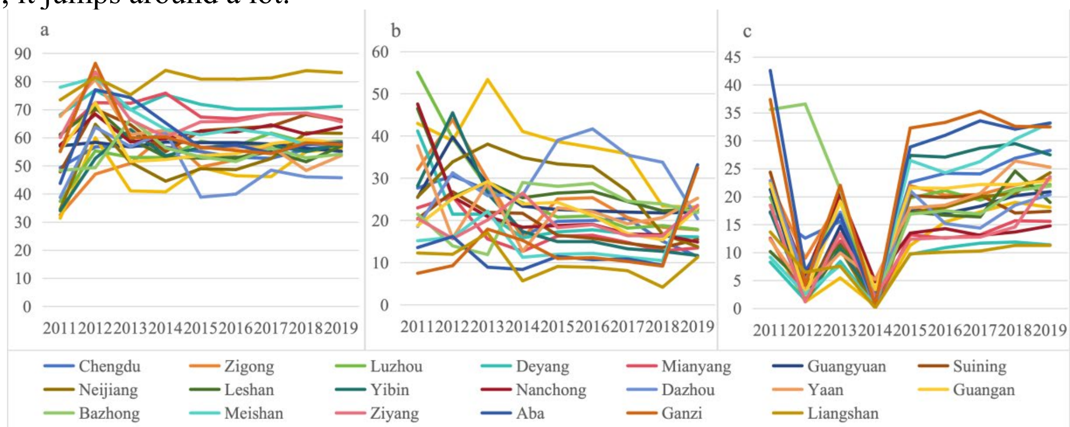

Fig. 2. Contribution to the ecological footprint of water resources by administrative. a: Agriculture, b: Industry, c: Live

The ecological footprint and average ecological footprint characteristics of water resources in each administrative region of Sichuan Province from 2011 to 2019 are shown in Fig. 3 and Fig. 4. Efw is about the same in each province from year to year, except for 2011 in Chengdu, where it was very large, and ECw is very different and variable. But except for Ganzi, Liangshan and Aba the rest are almost unchanged from 2011 to 2019. For WESI, Ganzi, Aba, Chengdu, Dazhou, and Yibin have significant changes, while the rest of the cities are in a steady state. Ganzi, Aba and Chengdu all have particularly high values in 2011, and level off in the other years.Chengdus ten thousand yuan GDP is very high in 2011, and stabilizes in the same range in the other years. Ganzis ten thousand yuan GDP is the highest of all provinces in almost every year, followed by Aba and Liangshan. Several other provinces have stabilized their GDP per million in each year without much fluctuation. Based on EFw, ECw, WESI and ten thousand yuan GDP, something must have changed in 2011 to make these values very significantly higher in 2011. The population in 2011 was higher than in any other year, probably as a result of Chinas childcare policies.

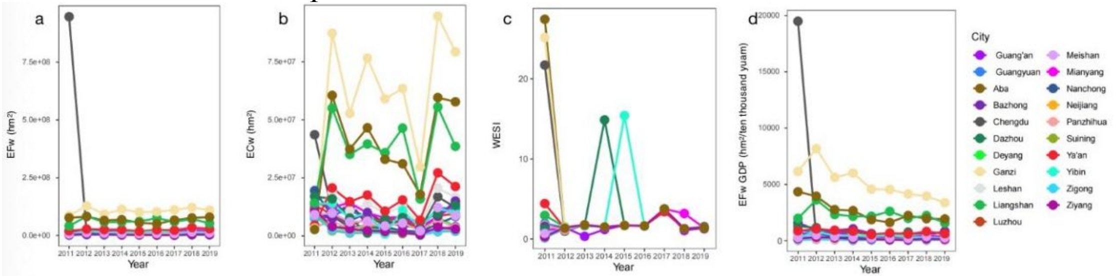

Fig. 3. The ecological characteristics of water resources in each administrative region of Sichuan Province from 2011 to 2019.

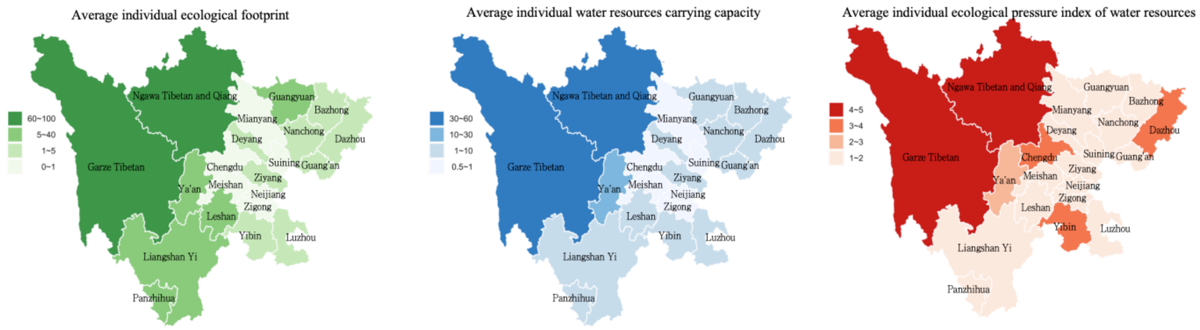

Fig. 4. The average ecological characteristics of water resources in each administrative region of Sichuan Province from 2011 to 2019.

3.3 Three-dimensional modeling of the ecological footprint of water resources in Sichuan Province

In the 3D model (Fig. 5), there are three types of data variations, depth, size, and final 3D. In the chart for depth, 2012 has the largest values for Aba, Ganzi, and Chengdu which are all over 20. 2014 Dazhou and 2015 Deyang also have relatively large values, and the other years as well as provinces are similar. depth greater than 1 means consumption of is greater than production. Almost all of the values are greater than 1, which means that water resources in Sichuan Province are always being consumed and are overloaded. For size, except for Ganzi, Aba, Yanan, and Liangshan, the values are regionally stable. In 2012 and 2018, Ganzis values were high, and in 2017, Ganzi and Abas values were the lowest they have been in years. larger size means more sustainability. Aba and Ganzi are more sustainable and the others are less so because of the geography of Aba and Ganzi. 3D data Ganzi is the largest Aba is second and Liangshan and Luzhou are next The rest of the provinces have similar data.

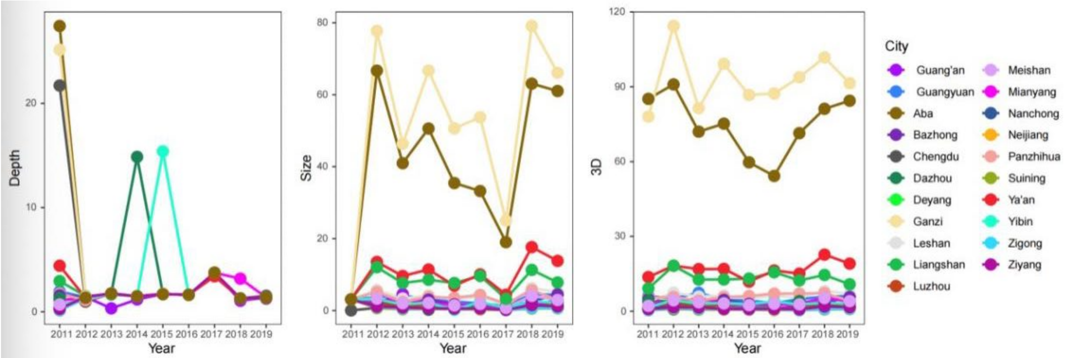

Fig. 5. Three-dimensional modeling of the ecological footprint of water resources in Sichuan Province.

4. Conclusion

The distribution of ecological footprints in Sichuan province has been skewed towards agriculture, except in 2012, when agriculture and industry were almost equal, and the values of EFw, ECw and GDP leveled off between 2012 and 2019, with the WESI index suggesting an imbalance between EFw and ECw, especially in 2017.The apparent changes in ecological and economic indicators in the provinces in 2011 coincided with a population boom, which may be related to Chinas childcare policy, with developed cities such as Chengdu exhibiting higher water use due to factors such as wealth and tourism. In the three-dimensional model of water resources in Sichuan Province, water use peaked in 2012 in Aba, Ganzi, and Chengdu; most regions consistently use more water than they produce, with the unique geographic location of Ganzi and Aba making them more sustainable, as reflected in their scale values and their leading position in the three-dimensional data.

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