Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

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Citation:
Wang D, Pei LX, Zhang LZ, *et al*. 2023. Water resource utilization characteristics and driving factors in the Hainan Island. Journal of Groundwater Science and Engineering, 11(2): 191-206.

View online: https://doi.org/10.26599/JGSE.2023.9280017

Journal homepage: http://gwse.iheg.org.cn

Research Paper

Water resource utilization characteristics and driving factors in the Hainan Island

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Abstract: The scarcity of water resources caused by the unique topography and uneven rainfall distribution in Hainan Island has become a major factor restricting local development. In order to provide effective and scientific reference basis for the overall water resource utilization status and solving this problem, this study calculated the water resource utilization situation of Hainan Island from 2017 to 2021 in detail using methods including water resource ecological footprint analysis. Furthermore, a spatial correlation analysis was conducted to examine the island’s water resource utilization characteristics, and the driving factors behind the changes in water resource utilization over the past five years were analyzed using the LMDI model. The results show that: (1) During the study period, the water resource ecological footprint in Hainan Island exhibited a slow growth trend, while the ecological carrying capacity showed a downward tendency. The per capita ecological deficit of water resources remains relatively high, and the water consumption per 10 000 yuan GDP in the whole land continues to decrease, indicating that the overall pressure on water resource demand remains high with significant regional differences accompanied by the efficiency of water resource utilization steadily improving at the same time; (2) Agricultural water use accounts for the highest proportion in the entire water use structure, while ecological water use represents the smallest share, with a year-on-year increase, indicating that Hainan Island highlights the agricultural development and is increasingly conscious of the ecological environment; (3) Significant spatial differentiation in water resource utilization characteristics exists in Hainan Island, with the western region being a hot spot aggregation area for per capita water resource ecological footprint, per capita ecological carrying capacity of water resources, water consumption per 10 000 yuan GDP, while it is a cold spot cluster area for per capita ecological deficit of water resources. The opposite holds true for the eastern region of Hainan Island; (4) Economic and technological factors have a major impact on the changes in water resource ecological footprint within the designated area. Among them, economic factors drive the growth of the water resource ecological footprint in Hainan Island, and exacerbate local water resource consumption, while technological factors negatively contribute to the amount of water resource utilization in Hainan Island, indicating that advanced technology has improved water resource utilization efficiency and significantly reduced water resource consumption.

Keywords: Ecological footprint; Ecological carrying capacity; Water consumption; Moran’s I index; Cold/hot spot analysis; LMDI model

Received: 14 Sep 2022/ Accepted: 16 Apr 2023/ Published: 15 Jun 2023

Introduction

As it is widely known, water resources play an indispensable role in the ecological environment and social production (Liang et al. 2021). Taking Hainan Island as the research subject, it is geographically separated from the mainland by the sea, making its water resources cannot be recharged in a timely manner, relying heavily on rain-

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DOI: 10.26599/JGSE.2023.9280017

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fall conditions. Despite receiving abundant rainfall and having a strong capacity to support water resources, Hainan Island faces challenges in terms of water supply capacity due to the uneven spatial and temporal distribution of rainfall, as well as the limited length and slope of its rivers, resulting from its unique geomorphology condition. These fundamental conditions result in a relatively small water storage capacity (Lu et al. 2022; Deng et al. 2019; Yang et al. 2022). With the progression of economic and social development, factors such as population growth, rapid urbanization, and tourism have exerted significant pressure on Hainan Island's water resources (Yang et al. 2022). Consequently, the shortage of water resources, as discussed in the previous paragraphs, has become a crucial constraint on the current development of Hainan Province. It significantly impacts the promising development prospect of Hainan Island and its forthcoming plan for constructing a pilot ecological civilization zone (Niu et al. 2020). Moreover, the population, economy, industry and agriculture in the region are all developing at a progressing pace, leading to an increasing demand for water resources (Xu et al. 2017). Therefore, to conduct a well-structured and systematic study on water resource utilization in Hainan Island, it is essential to objectively assessing the ecological footprint of water resources (Deng et al. 2019). Meanwhile, identifying the impacts of various economic, structural and technological factors on the water resource utilization status of Hainan Island will contribute to the scientific understanding of water resource issues, which, in turn, can provide a solid basis for the high-quality development of water resources in the region.

As a measure for the sustainability of a region, the ecological footprint estimates its use of land and water resources to support human activities and thus assesses the potential human impact on the Earth's ecosystems and environment (Dai et al. 2019; William, 1992; William et al. 1996). This method was initially proposed and subsequently refined by William and Wackernagel et al. (1992) Thereafter, Huang et al. (2008) introduced an innovative water resource model based on the ecological footprint model, offering a new quantitative evaluation method for sustainable water use. Currently, many scholars, both domestically and internationally, have carried out calculations and analyses of the ecological footprint on water resources at various scales. For instance, Gernot et al. (2011) demonstrated the applicability of the Water Supply Footprint (WSF) approach in early and strategic stages of water supply planning by using the WSF method to account for water supply in southeast Queensland, Australia. Huang et al. (2016) analyzed the ecological footprint of water resources in China from 2000 to 2010. Furthermore, he conducted in-depth researches on its dynamic change characteristics and socioeconomic impact factors. Based on the principles and methods of the ecological footprint on top of improvements, existing researches mainly focus on the ecological footprint of water resources as a comprehensive tool for measuring sustainable water resource consumption (Ouyang et al. 2023). Over the years, researchers worldwide have been improving and exploring the ecological footprint of the water resource method. For example, Xia et al. (2022) calculated the ecological footprint of water resources and ecological carrying capacity of water resources in cities located in the Poyang Lake basin using the water resource ecological footprint model, systematically assessing the ecological security of water resources in the study area. Zhu et al. (2022) analyzed the ecological footprint of water resources in Liaoning Province from 2010 to 2019 based on theoretical basis and the LMDI model. Cao et al. (2014) assessed the sustainable status of water resources in Hainan Province in 2009. Previous studies in this field primarily focused on accounting for the ecological footprint of water resources in the study area and analyzing influencing factors, with limited exploration of the linkages and differences in spatial water use of the regions in the study area.

The LMDI decomposition model was once used to analyze the drivers behind changes in the ecological footprint of water resources in Hainan Island from 2017 to 2021, while the spatial distribution of characteristics was used to further examine the socio-economic, industrial structure and technological level. This study aims to provide a reference for the sustainable utilization and scientific management of water resources in Hainan Island.

1 Study area

Located at the southern tip of China's mainland, between latitude 18°10'–20°10' N and longitude 108°37'–111°03' E, the Hainan island is widely acknowledged as the second largest island in China following Taiwan. The island is bounded by the Qiongzhou Strait to the north, separating it from Guangdong Province, Guangdong Province, while the South China Sea lies to the east and Taiwan

Province to the southeast. In addition, it has a total coastline of 1 944 km in length and an area of 33 900 km^2 in area (Fig. 1).

The rivers of Hainan Island originate from the central mountainous and hilly areas, and flow in various directions, eventually reaching the sea. This radial water system is characterized by numerous short and steep slopes, fast-flowing rivers and limited surface water reserves (Lu et al. 2022). The island experiences a circular distribution of rainfall, with higher precipitation in the central and eastern regions, and relatively lower rainfall in the northern part and southwest. The annual precipitation ranges from 1 400 mm to 2 500 mm, with an average of 1 954 mm, this island has distinct rainy and less-rainy seasons (Xu et al. 2017). The rainy season typically lasts from May to October, contributing 70% to 90% of the annual precipitation, totaling around 1 800 mm. Conversely, the less-rainy season occurs from November to March, accounting for the remaining 10% to 30% of the annual precipitation (Xu et al. 2017; Li, 2019; Fu et al. 2022). In terms of population distribution, it shows scattered pattern, with densely populated urban areas and sparsely populated townships. The urban areas, including Haikou, Sanya, Danzhou and Qionghai, have a concentrated population. Surrounding these cities, there are industries that are less water-consuming and more profitable, along with tertiary industries (Wu et al. 2014). On the other hand, the towns with dispersed populations are dominated by agriculture and traditional water-consuming industries. For example, the central and western parts of Hainan Island, known

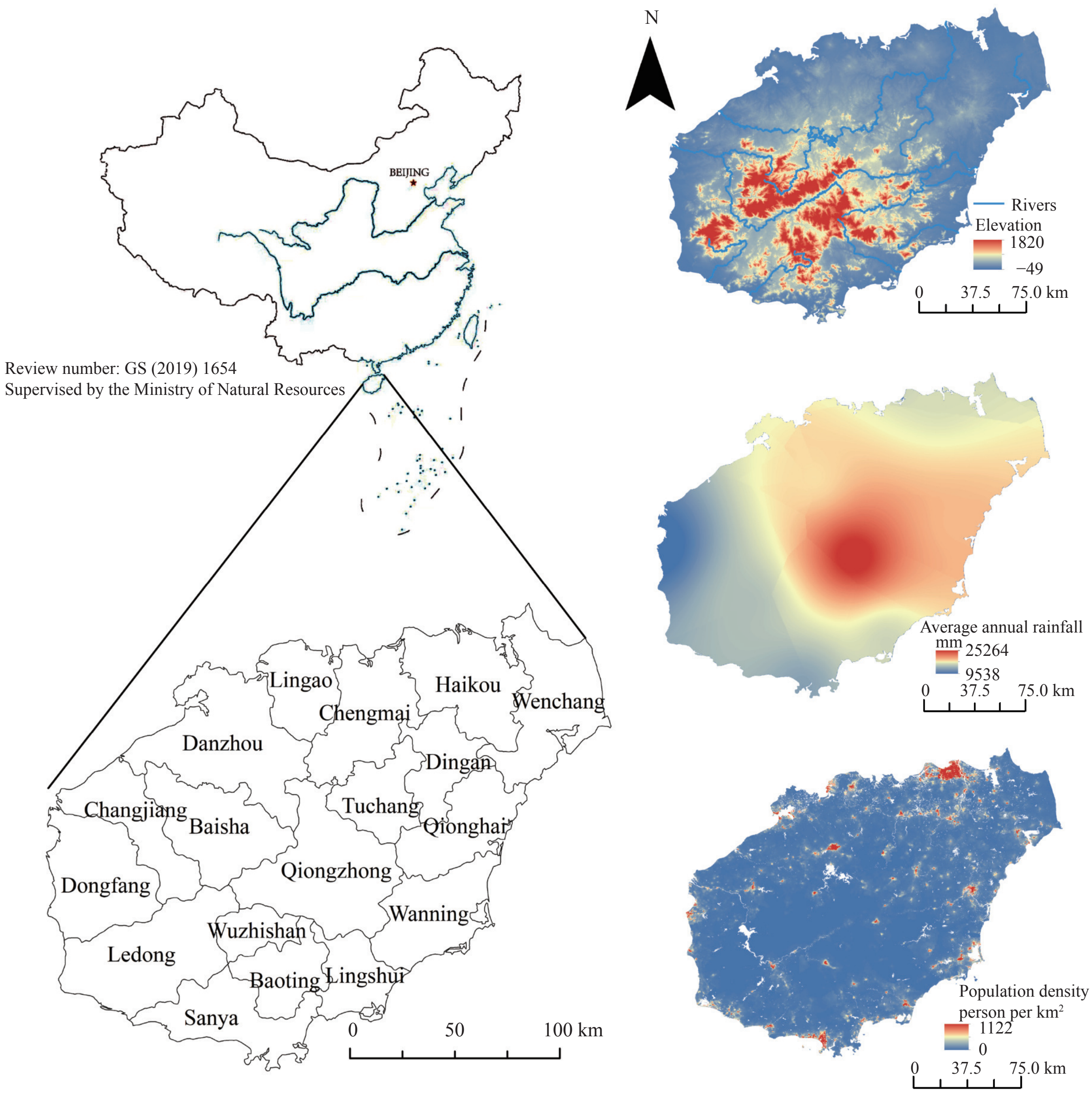

Fig. 1 Schematic diagram of the study area

for the largest area of tropical land in China, are renowned for its tropical cash crops (Li, 2019).

2 Research methodology and data sources

2.1 Ecological footprint analysis of water resources

Studies on water resource ecological footprint often focus soly on water consumption and regeneration within specific sectors of a predefined study area, overlooking the influence of external water flow into the region (Liu et al. 2011; Deng et al. 2019; Jia et al. 2019). However, Hainan Island, being a relatively enclosed study area, is not significantly impacted by external water resources. Therefore, such an ecological footprint can provide a more accurate representation of water consumption in this region (Ridha et al. 2018). Based on previous literature, four types of water use, including agricultural, industrial, domestic and ecological water use were established in the context of Hainan Island (Gernot et al. 2011; Jia et al. 2019; Lu et al. 2022; Li et al. 2023). The water resource ecological footprint and the corresponding formulas for calculating each subaccount are as follows.

2.1.1 Ecological footprint of water resources

The ecological footprint of water resources represents the amount of water resources consumed, which is converted into the land area of productive water resources corresponding to that consumption. It is then equalized to obtain an equivalent value that can be used to compare different regions on a global scale (Ouyang et al. 2023).

$$EF_w = N \cdot ef_w = N \cdot r_w \cdot (W/P_w) \tag{1}$$

Where: EF_w is the ecological footprint of water resources (hm^2); N represents the number of people (person); ef_w is the ecological footprint of water resources per capita (hm^2/person); r_w is the global water balance factor, taken as 5.19 (Huang, et al. 2008); W is the consumption of water resources (m^3); P_w is the global average production capacity of water resources (m^3/hm^2), taken as 3 140 m^3/hm^2 (Huang et al. 2008; Ouyang et al. 2023).

2.1.2 Ecological carrying capacity of water resources

The ecological carrying capacity of water resources refers to the capacity of water resources to sustain the balanced development of ecosystems and economic systems. It requires a comprehensive assessment of both the ecological environment and the water resources needed for social production (Deng et al. 2019; Huang et al. 2019; Zhu et al. 2022).

$$EC_w = N \cdot ec_w = 0.4 \cdot \varphi \cdot r_w \cdot (Q/P_w) \tag{2}$$

Where: EC_w is the ecological carrying capacity of water resources (hm^2); N is the number of population (person); ec_w is the ecological carrying capacity of water resources per capita (hm^2/person); r_w is the water resources equilibrium factor; φ is the water resources yield factor, which is 3.73 (Liu et al. 2011; Ma et al. 2023); Q is the total amount of water resources (m^3); P_w is the world average water resources production capacity (m^3/hm^2). A factor of 0.4 is usually multiplied in the calculation because 60% is deducted in the EC_w study to maintain the ecological environment and species diversity in the region and to maintain ecological balance (Liu et al. 2011).

2.1.3 Ecological surplus/deficit of water resources

The ecological surplus or deficit of water resources is calculated as the difference between the ecological footprint of water resources within a region and its ecological carrying capacity (Liu et al. 2011; Ma et al. 2023).

$$W = EC_w - EF_w \tag{3}$$

Where: W is positive, it is an ecological surplus, indicating that Hainan Island's water resources still have potential; W is 0, demonstrating an ecological balance of water resources; W is negative, and it is an ecological deficit, indicating over-exploitation of water resources.

2.1.4 Water consumption per 10 000 yuan *GDP*

Water use per 10 000 yuan GDP is represented as the ratio of water use to 10 000 yuan GDP, with smaller values indicating more efficient water use and vice versa (Zhu et al. 2022).

$$Q = W/GDP \tag{4}$$

Where: Q is the water consumption per 10 000 yuan GDP (m^3); W is the total water consumption (m^3); GDP is the gross domestic product (10 000 yuan).

2.2 Spatial distribution pattern

When examining the spatial distribution pattern, it is crucial to consider spatial autocorrelation as a key aspect of the discussion. Spatial correlation refers to the existence of a statistical correlation observed between the values of a particular attribute in the study objects distributed in different spatial locations (Chen, 2009; Pinto et al. 2021). In this study, the global spatial autocorrelation index

(Moran's I index) was used to determine whether there is spatial clustering in the distribution of four indicators: Per capita ecological footprint of water resources, ecological carrying capacity of water resources, ecological surplus/deficit of water resources, and water consumption per 10 000 yuan GDP across different cities and counties of Hainan Island in order to determine if there is a statistical correlation in the spatial distribution of water resources (Pinto et al. 2021).

Moran's I statistic is commonly used to measure the degree of similarities between attribute values and the pattern of distribution in space. However, it has limitations in illustrating differences among spatial agglomerations with varying degrees of values, but has the potential to mask different types of spatial agglomerations (Chen, 2009; Liu et al. 2021; Sylwia et al. 2022). Therefore, a cold hotspot analysis method is necessary to identify the spatial distribution of each agglomeration type. The specific calculation equation is as follows:

2.2.1 Global spatial autocorrelation analysis

Moran's I statistic is a commonly used measure of spatial autocorrelation, primarily employed to assess the presence of spatial clustering in the distribution of geographical features or attributes (Dong et al. 2015; Pinto et al. 2021). In this study, Moran's I index was selected to evaluate the spatial relationship among water resources indicators accross different regions. It can be expressed as follows:

$$I = \frac{n}{S_0} \cdot \frac{\sum_i \sum_j W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \quad (5)$$

$$S_0 = \left(\sum_i \sum_j W_{ij} \right) \quad (6)$$

Where: n is the number of cities involved in the study, x_i and x_j represent the water resource indicators for regions i and j in the study area, and x represents the annual average of the water resource indicators. W_{ij} is an element of the spatial weight matrix W_{ij}, which represents the topological relationship between spatial units, with spatial adjacency being 1 and non-adjacency being 0. S_0 is the sum of all elements of the spatial weight matrix W, reflecting the degree of similarity of the attribute values of spatially adjacent or spatially neighboring regional units.

The Moran's I index ranges from −1 to 1. *A* value close to 1 indicates a strong positive spatial correlation, suggesting that similar water resources indicator values tend to be spatially clustered. Conversely, a value closer to −1 indicates a strong negative correlation, indicating that similar values of water resources indicator tend to be dispersed or exhibit heterogeneity (Dong et al. 2015; Pinto et al. 2021). In addition, standardized Z values were used in the calculations to assess the significance of the Moran's I index.

$$Z = \frac{I - E(I)}{\sqrt{VAR(I)}} \quad (7)$$

2.2.2 Cold/hot spot analysis method

The cold hotspot analysis method, specially the Getis-OrdGi* method, is commonly used to identify spatial clusters of low values (cold spots) and high values (hot spots) in data (Cheng et al. 2014; Sylwia et al. 2022). In this study, the cold and hotspot analysis was conducted using ArcGIS spatial statistical tools to examine the local spatial clustering of water resources use characteristics in different cities and counties in Hainan Island. Furthermore, this analysis allows for the identification of clusters with low or high values of water resources indicators in different regions using the following equations:

$$G_i = \frac{\sum_{j=1}^{n} W_{ij} X_j}{\sum_{i=1}^{n} X_i} \quad (8)$$

Where: X_i and X_j are water resource indicators for different cities and counties in Hainan Island for cities i and j, and W_{ij} is the spatial weight matrix (as above). The same Z test is performed for G_i. If $Z(G_i)$ is significantly positive, it means that high values of water resources indicators are spatially clustered, i.e. a hot spot area; conversely, it is a cold spot area. Using the natural segment point method, $Z(G_i)$ was divided into four categories: hotspot, sub-hotspot, sub-cold spot and cold spot areas.

2.3 Analysis of the factors influencing the ecological footprint of water resources based on the LMDI model

Numerous studies having been conducted to analyze the driving forces behind changes in water use, focusing on four key perspectives: Economic development, technological progress, industrial structure and demographic effects, which have gained a widespread recognition (Chen et al. 2022; Guo et al. 2023). The rapid economic development and advancements in production technology have led to increased water consumption, and the changes in this field will have a significant impact on water use in an era of industrialization that leads to economic development. Additionally, population growth has the potential to directly and indirectly contribute to increased water demand leading to observable changes in water use characteristics on Hainan Island (Meng et al. 2023; Zhao, 2023). To analyze the influence of each factor on water resources in Hainan Island, this study employs a log-averaged Dixie decomposition model, which considers the technological, structural, economic and demographic perspectives, to analyze the impact of these factor on water resources in Hainan Island.

The log-averaged Diese index factor decomposition method (LMDI) is a well-established approach in research applications (Pinto et al. 2021; Lu et al. 2022), which is widely used in current related research due to its advantages, such as excluding residuals and handling "0" values in the decomposition results (Chen et al. 2022). Accordingly, this study adopts the log-averaged Diese index decomposition method to analyze the drivers of changes in the ecological footprint of water resources in Hainan Island.

$$EF_W = \sum_i \frac{EF_{wi}}{EF_w} \cdot \frac{EF_w}{T} \cdot \frac{T}{P} \cdot \mathrm{P} \cdot \sum_i S_i IGP \quad (9)$$

Where: EF_W is the total ecological footprint of water resources (hm^2); i is the type of water resource ecological footprint account; EF_{Wi} is the ecological footprint of water resources used in account type i (hm^2); T is GDP; P is population; S_i is the proportion of the ecological footprint of water resources used in account type i to the total ecological footprint of water resources; I is the ecological footprint of water resources per unit of GDP, representing the water intensity of the ecological footprint of water resources; G is GDP per capita, representing the level of economic development.

Assuming 2017 as the base year, then the ecological footprints of water use in the base year and year t are EF_{wi0} and EF_{wi0} respectively, and the change in the ecological footprint of water use from the base year to year t (ΔEF_{wi}) is:

$$\Delta EF_{wi} = \Delta EF_{wit} - \Delta EF_{wi0} \quad (10)$$

$$\Delta EF_{wi} = \Delta S_i + \Delta I + \Delta G + \Delta P \quad (11)$$

$$\Delta S_i = q_i \cdot \ln \frac{S_{it}}{S_{io}} \quad (12)$$

$$\Delta I = q_i \cdot \ln \frac{I_t}{I_o} \quad (13)$$

$$\Delta G = q_i \cdot \ln \frac{G_t}{G_o} \quad (14)$$

$$\Delta P = q_i \cdot \ln \frac{G_t}{G_o} \quad (15)$$

$$q_i = \sum_i \frac{\Delta EF_{wit} - \Delta EF_{wi0}}{\ln EF_{wit} - \ln EF_{wi0}} \quad (16)$$

Where: ΔS_i is the structural effect; ΔI is the technological effect; ΔG is the economic effect; ΔP is the demographic effect; and q_i is the weighting factor. If the calculated factor decomposition effect is positive, it means that the factor effect has a pulling effect on the value of the ecological footprint of water use, which will increase the consumption of water resources; if not, it means that the factor effect has a suppressing effect on the value of the ecological footprint of water use, which is positive for the sustainable use of water resources (Meng et al. 2023).

2.4 Data

The data on water resources, water consumption, population and GDP studied in this thesis are mainly obtained from the Hainan Water Resources Bulletin (2017-2021), and the Hainan Statistical Yearbook (2017-2021).

3 Results and discussions

3.1 Temporal distribution characteristics of water ecological footprint in Hainan Island

Based on the water consumption data of various industries in Hainan Island from 2017 to 2021, the water resource ecological characteristics of Hainan Island over the past five years were calculated. The water resource ecological footprint model and water resource ecological carrying capacity model were selected as the basis for the calculation. The results are presented in this section.

According to Fig. 2, the analysis of the four accounts of water resource ecological footprint in Hainan Island from 2017 to 2021 reveals several key observations. Firstly, the agricultural water resource ecological footprint accounts for over 60% of the total footprint, and its proportion has remained relatively stable over the past five years. This highlights the importance placed on agricultural development in Hainan Island, as it is recognized as a major tropical economic crop-producing area in China, with a strong focus on ensuring food security. The per capita industrial water resource ecological footprint shows an obviously decreasing

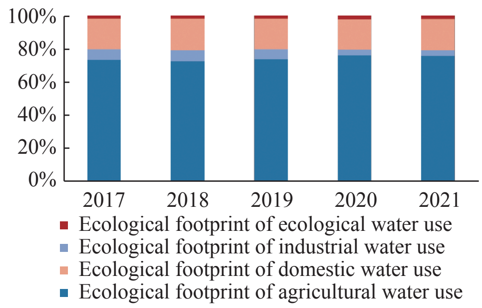

Fig. 2 Per capita ecological footprint of water resources for agricultural use, industrial use, domestic use, and ecological use in Hainan Island

trend. This suggests that Hainan Island has made significant progress in promoting water conservation measures in the industrial sector. Similarly, the per capita domestic water resource ecological footprint also shows a gradual decrease over time, which provides further evidence Hainan Island has made notable improvements in water resources utilization. On the other hand, the total ecological environment water resource ecological footprint exhibits a general increasing trend with some fluctuations, and its proportion has increased year by year. This indicates a rising focus on ecological environment construction and protection in Hainan Island which is beneficial for the development of Hainan Islands as an ecological civilization pilot zone. Considering the positive projection of the continuous increase in the ecological use of water in the near future, it is evident that Hainan Island's water resources and its society structure are showing steady improvement and advancement, which can be mainly attributed to the active adjustment in the industrial structure, optimization of the water supply system, ongoing enhancements in water resource utilization efficiency, strong emphasis on ecological environment protection, and the implementation of water-saving technologies supported by the local government.

As shown in Fig. 3, the per capita water resource ecological footprint in Hainan Island has exhibited a slowly increasing trend over the past five years, with a noticeable increase from 2020 to 2021. It indicates that as economic and living standards develop, the per capita water consumption in Hainan Island has slightly increased in the same process. However, the water resource ecological carrying capacity in Hainan Island has been decreasing during this period. Since Hainan Island is less affected by other regions for its water resources, the total amount of water resources in the region is determined by the annual precipitation, which plays a critical role in the per capita water resource ecological carrying capacity in Hainan Island. Therefore, the per capita water resource ecological carrying capacity in Hainan Island also shows significant yearly fluctuations. In those with low annual precipitation, it is necessary to continuously optimize the industrial structure, focus on water resources recycling, and improve

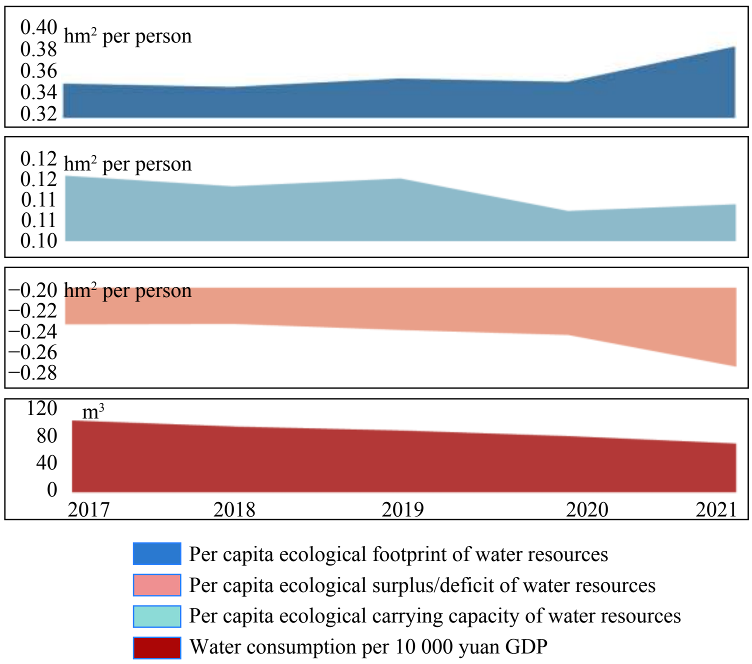

Fig. 3 Per capita ecological footprint of water resources, per capita ecological carrying capacity of water resources, per capita ecological deficit of water resources, and water consumption per 10 000 yuan GDP in Hainan Island

the water resource ecological carrying capacity. Due to the high level of initial ecological and the current large deficit status, the analysis of the water resource ecological surplus/deficit results in Fig. 3 shows that the water resource ecological deficit in Hainan Island has been increasing continuously from 2017 to 2021, indicating the growing tension between economic development and population growth on water resource demand. To some extent, this above-mentioned increase in water consumption has aggravated the ecological deficits in terms of water resources.

As shown in Fig. 3, the water consumption per 10 000 yuan of GDP in Hainan Island has been decreasing successively from 2017 to 2021. This indicates that the water resource utilization efficiency in Hainan Island has steadily improved over the past five years, which aligns well with the continuous adjustment of industrial structure and optimization of industrial development in this region. Although population and economic growth may lead to an increase in the per capita water resource ecological footprint, some other indicators may have contributed to the continuous decrease in the water consumption per 10 000 yuan of GDP, such as the optimization of industrial structure, improvement of water-saving and environmental protection technologies, enhancement of ecological awareness, and significant improvements in water use efficiency and effectiveness.

3.2 Analysis of spatiotemporal changes in per capita water resource ecological footprint of various administrative regions in Hainan Island

Based on water resource usage data collected across various administrative regions from 2017 to 2021, in this study, the author calculated various indicators including the water resource ecological footprint and ecological carrying capacity for each administrative region over the past five years using the two models - water resource ecological footprint and ecological carrying capacity.

As shown in Fig. 4, it is evident that the per capita water resource ecological footprint in Hainan Island from 2017 to 2021 was 0.356 8 hm^2/person. Five administrative regions have lower values than the island-wide average, namely Haikou (0.191 3 hm^2/person), Sanya (0.232 0 hm^2/person), Wanning (0.288 1 hm^2/person), Qionghai (0.335 6 hm^2/person), and Wenchang (0.344 1 hm^2/person), indicating relatively low per capita water consumption in these areas. In contrast, the per capita water resource ecological footprint in other administrative regions was higher than the island-wide average. Among them, Dongfang, Changjiang, and Ledong had the highest annual per capita water resource ecological footprints. These three administrative regions have placed significant emphasis on agricultural development. It is not important to ignore the significant water loss that occurs during the process of water transportation and usage, including various types of transpiration, evaporation, soil absorption, and other pathways. These alarming facts further reflect the relationship between the growth of per capita water resource ecological footprint and geographic location, economic development, and industrial patterns.

Analyzing the results in Fig. 5, the average per capita ecological carrying capacity of water resources in Hainan Island from 2017 to 2021 was 0.111 9 hm^2/person. Among the administrative regions, Danzhou, Wuzhishan, Dongfang, Dingan,

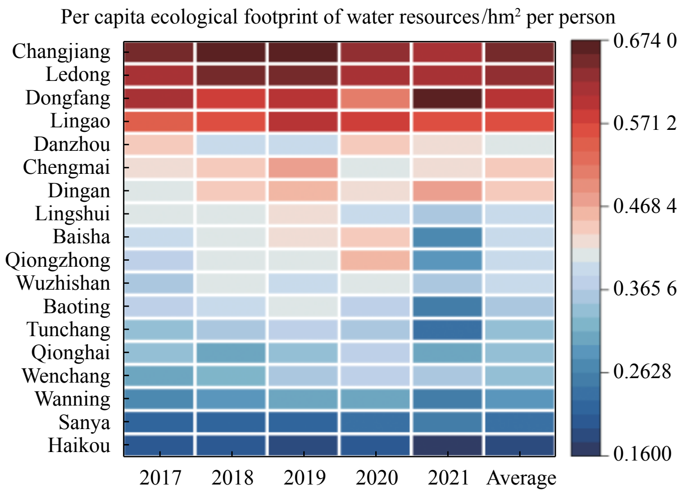

Fig. 4 Per capita ecological footprint of water resources in different administrative regions of Hainan Island

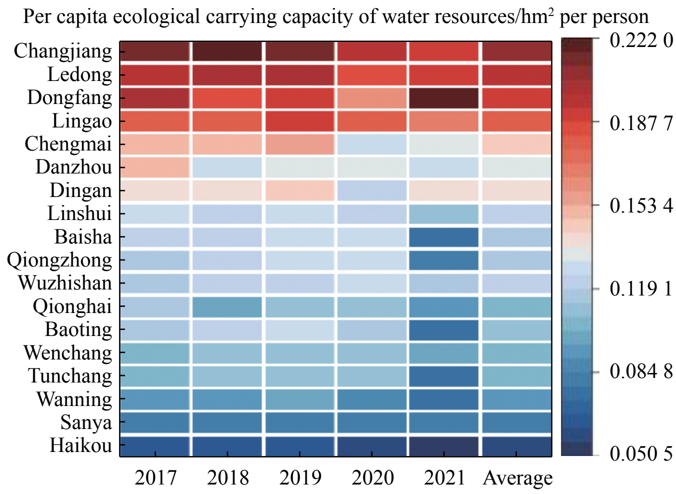

Fig. 5 Per capita ecological carrying capacity of water resources in various administrative regions of Hainan Island

Chengmai, Lingao, Changjiang, Ledong, and Qiongzhong had higher per capita ecological carrying capacity of water resources than the island's average, and the remaining eight administrative regions had lower values than the annual average of the entire island. Specifically, Changjiang had the largest per capita water resource ecological carrying capacity, while Haikou had the smallest. The difference between them was 0.146 0 hm^2/person, highlighting significant regional disparities in the per capita water resource ecological carrying capacity of Hainan Island. According to "Hainan Water Resource Bulletin", the hydrological condition of Hainan island presents significant spatial distribution differences. Rainfall is distributed in a circular pattern, with higher amounts in the middle and east, and lower amounts in the north and south. Additionally, population distribution varies across regions, with a notable coastal concentration and a circular distribution pattern. These observations indicate that the ecological carrying capacity of water resources is closely related to local hydrological conditions, population density and other factors.

Analysis of per capita ecological surplus/deficit of water resources in various administrative regions from 2017 to 2021 in Fig. 6 shows that the ecological deficit of water resources in administrative regions represented by Haikou and Sanya has consistently increased over the years. This indicates the pressure imposed by economic development and rapid population growth in terms of water resource demand. The ecological deficits of water resources in administrative regions represented by Dongfang City, Changjiang County, and Ledong County have remained relatively stable, but the high initial degree of ecological deficit suggests that water supply and demand conflicts

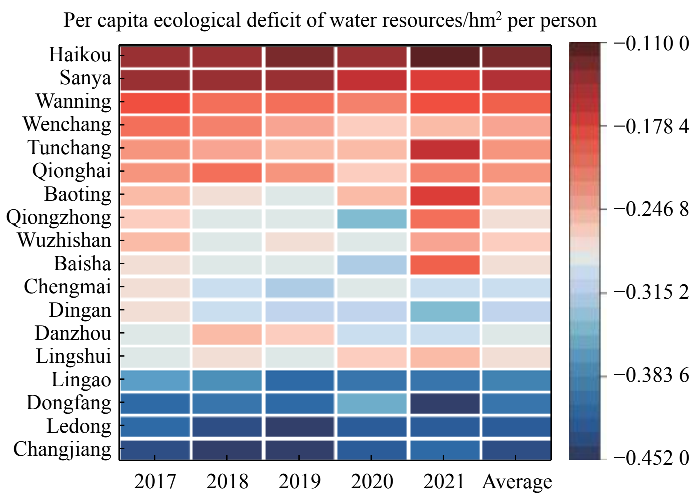

Fig. 6 Per capita ecological deficit of water resources in different administrative regions of Hainan Island

still persist in these areas. On the other hand, the administrative regions represented by Lingshui County and Baoting County exhibit a fluctuating downward trend in the ecological deficit of water resources, suggesting that the water supply and demand conflicts in these regions have been gradually reduced, and the structure of water supply and demand has been optimized continuously. It can be seen that the per capita ecological deficit of water resources is related to geographical location, population size, and industrial structure to a certain extent. Generally, agriculturally developed areas in central Hainan Island consume a significant amount of water resources, leading to water scarcity and prominent water supply and demand conflicts, resulting in substantial ecological deficits in water resources. This situation hinders the sustainable utilization and development of water resources in those areas. On the contrary, the northeast and southeast regions of Hainan Island, which rely mainly on the tertiary industry with low water consumption, experience smaller ecological deficit, and have a lower impact on the sustainable development and utilization of water resources. However, it is crucial to acknowledge that with the ongoing economic development and rapid population growth, the per capita ecological deficit of water resources continues to increase. Therefore, appropriate attention should be given to address this issue effectively.

The analysis of per 10 000 yuan GDP water consumption in various administrative regions, as shown in Fig. 7, reveals that a significant decreasing trend across all administrative regions of Hainan Island, indicating an overall improvement in the utilization rate of water resources in the region. Although population and economic growth may lead to an increase in per capita ecological footprint of water resources, the optimization of industrial structure, improvement of water-saving and environmental protection technologies, and enhancement of ecological awareness have greatly contributed to water use efficiency, resulting in a continuous decrease in per 10 000 yuan GDP water consumption. The disparity in water resource production efficiency between regions such as Wuzhishan, Dongfang, Dingan, Lingao, Baisha, Changjiang, Ledong, Baoting, Qiongzhong and Haikou, Sanya, and other regions, can be primarily attributed to their agricultural nature, characterised by high water consumption but low production efficiency. Conversely, areas like Haikou, Sanya, and others mainly focus on secondary and tertiary industries with low water consumption and high production efficiency, which is the main reason for the regional disparities observed.

3.3 Spatial distribution characteristics of water resource utilization in Hainan Island.

During the research period, the Moran's I index of per capita ecological footprint, per capita ecological carrying capacity, and per capita ecological surplus/deficit of water resources in Hainan Island showed a slight decreasing trend, indicating that the spatial correlation gradually weakened. However, by comparing the z-score and p-value of the Moran's I index, it was found that the three indicators of per capita ecological footprint, per capita ecological carrying capacity, and per capita ecological deficit showed distinct clustering trends, indicating a significant correlation with geographical location. The Moran's I index of water use per 10 000

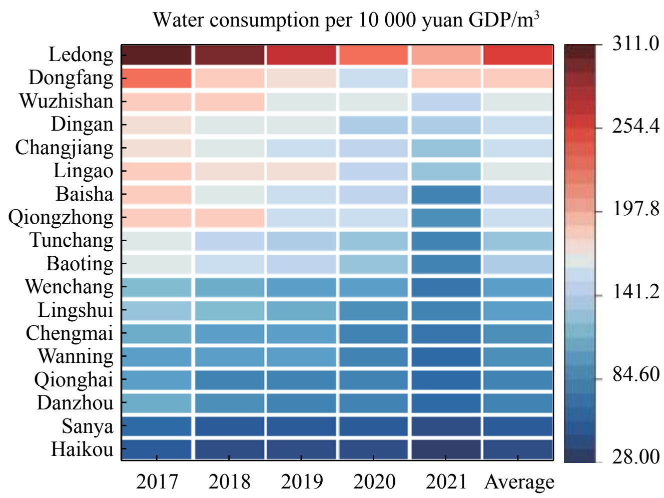

Fig. 7 Water consumption per 10 000 yuan of GDP in different administrative regions of Hainan Island

yuan GDP in Hainan Island showed a trend of first decreasing and then increasing, and after reaching −0.003 59 in 2019, it rapidly increased to 0.111 384 in 2021, indicating a relatively small correlation due to its high volatility. The Moran's I index and related test indicators are shown in Table 1.

According to Moran's I index, there is a certain spatial autocorrelation within these four indicators of per capita ecological footprint of water resources, ecological carrying capacity of water resources, ecological surplus/deficit of water resources, and water consumption per 10 000 yuan GDP in Hainan Island from 2017 to 2021. In order to further explore the local agglomeration characteristics of water resource utilization in Hainan Island, the method of hot/cold spot analysis was used to reveal the cold spot and hot spot areas of water resource utilization from 2017 to 2021, as shown in Fig. 8, Fig. 9, Fig. 10, and Fig. 11.

In summary, there is an agglomeration phenomenon in the distribution of the four water resource utilization indicators. The per capita ecological footprint of water resources in Hainan Island is concentrated in the southwest, including Baisha, Changjiang, Dongfang and other areas where agriculture is well developed and water consumption is

Table 1 Moran's I statistics for water resource utilization characteristics in Hainan Island from 2017 to 2021

Hainan Island	Per capita ecological footprint of water resources				Per capita ecological carrying capacity of water resources			
	I	Variance	Z(P)	P	I	Variance	Z(P)	P
2017	0.464 75	0.043 157	2.520 29	0.011 726	0.483 192	0.043 320	2.604 172	0.009 210
2018	0.352 48	0.042 888	1.986 04	0.047 028	0.377 248	0.042 965	2.103 786	0.035 397
2019	0.340 11	0.043 020	1.919 32	0.054 944	0.374 435	0.043 278	2.082 648	0.037 283
2020	0.292 56	0.042 488	1.704 68	0.088 253	0.358 527	0.042 292	2.029 424	0.042 415
2021	0.339 53	0.044 180	1.895 22	0.058 063	0.378 596	0.043 108	2.106 775	0.035 137
Hainan Island	**Per capita ecological surplus/deficit of water resources**				**Water consumption per 10 000 yuan GDP**			
	I	**Variance**	**Z(P)**	**P**	**I**	**Variance**	**Z(P)**	**P**
2017	0.450 41	0.043 128	2.452 11	0.014 202	0.091 243	0.040 106	0.749 344	0.453 650
2018	0.337 28	0.042 883	1.912 78	0.055 776	0.008 160	0.039 355	0.337 650	0.735 627
2019	0.321 33	0.043 154	1.829 99	0.067 252	−0.003 590	0.040 476	0.274 547	0.783 664
2020	0.256 90	0.042 665	1.528 52	0.126 383	0.028 143	0.042 166	0.423 516	0.671 919
2021	0.317 40	0.044 551	1.782 48	0.074 671	0.111 384	0.041 865	0.831 860	0.405 488

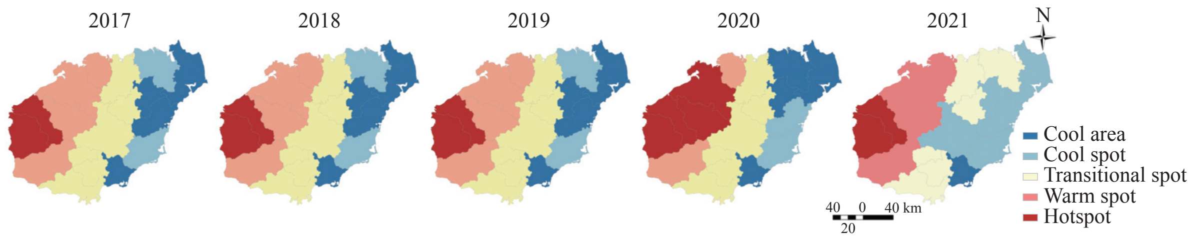

Fig. 8 Spatial distribution of hot and cold spots for per capita water resource ecological footprint in Hainan Island from 2017 to 2021

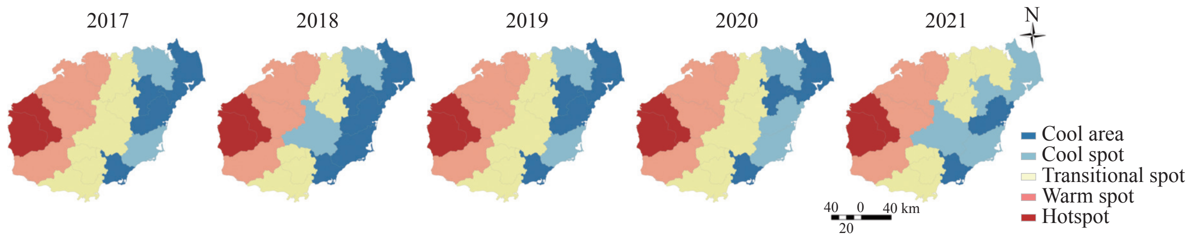

Fig. 9 Spatial distribution of hot and cold spots for per capita water resource ecological carrying capacity in Hainan Island from 2017 to 2021

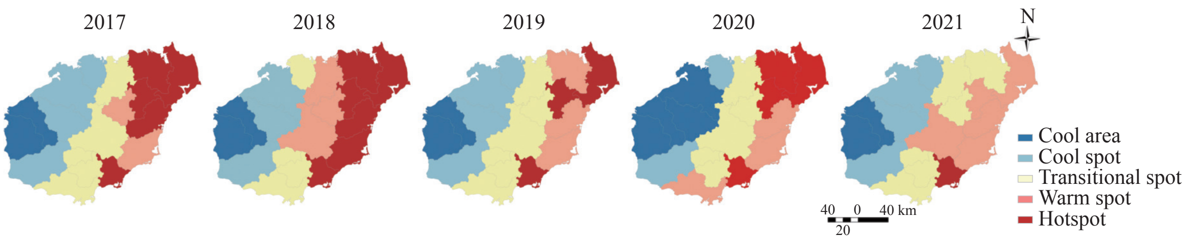

Fig. 10 Spatial distribution of hot and cold spots for per capita water resource ecological deficit in Hainan Island from 2017 to 2021

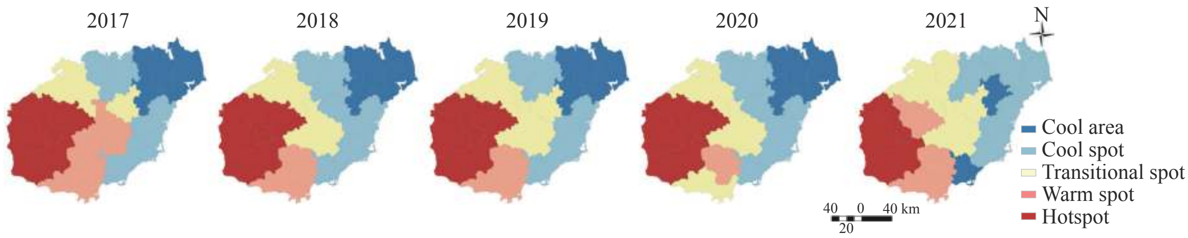

Fig. 11 Spatial distribution of hot and cold spots for water consumption per 10 000 yuan GDP in Hainan Island from 2017 to 2021

relatively high. Additionally, these areas have lower the industrial production technology level, making them the hot spot aggregation areas in the spatial distribution map of water consumption per 10 000 yuan GDP in Hainan Island, indicating that the amount of water resources consumed per 10 000 yuan GDP in theses areas is significantly higher than other areas. Based on the population density, economic development situation, industrial structure distribution, as well as the climate and hydrological conditions of Hainan Island, the reasons for these observations were thus analyzed. The eastern and northern parts of Hainan Island are mainly dominated by industries and tertiary industries with lower water consumption and higher profits, such as Haikou and Sanya. On the other hand, the central and western regions receive relatively less rainfall and are mainly dominated by agriculture and traditional industries with higher water consumption. These factors contribute to spatial and temporal variations in the ecological footprint of water resources across Hainan Island.

3.4 Analysis of ecological footprint drivers of water resources in Hainan Island

In this study, the LMDI decomposition method was utilized to analyze the ecological footprint drivers. 2017 was taken as the base year, and a structural analysis was conducted to examine the factors influencing the ecological footprint of water resources in Hainan Island from 2017 to 2021. The analysis focused on four aspects: Technology, structure, economy and population, aiming to determine the impact of each factor on the water resources of Hainan Island. The results, as depicted in Fig.12, indicate that the economic and technological factors had the most significant influence on the change of ecological footprint of water resources in Hainan Island during the study period. The contribution of structural and population factors was relatively minor and had less interference compared to the former two factors.

It is revealed that economic and demographic factors had positive effects on the growth of the ecological footprint of water resources in Hainan Island. However, these factors also contributed to increased water resource consumption, which is not favorable for the sustainable use and development of water resources in Hainan Island. Among the analyzed factors, economic factors were identified as the primary drivers influencing the growth of the ecological footprint of local water resources. From 2017 to 2020, the economic factors exhibited an overall slow decline, followed by an overall high growth pattern after 2020. This can be attributed to the implementation of various measures, such as the development of the free trade port, which has a notable impact on the reduction of the ecological footprint of water resources in Hainan Island.

From 2017 to 2020, the population factor exhibited a gradual increase, which contributed to the growth of the ecological footprint of water resources in Hainan Island and intensified the water resource consumption in the region. However,

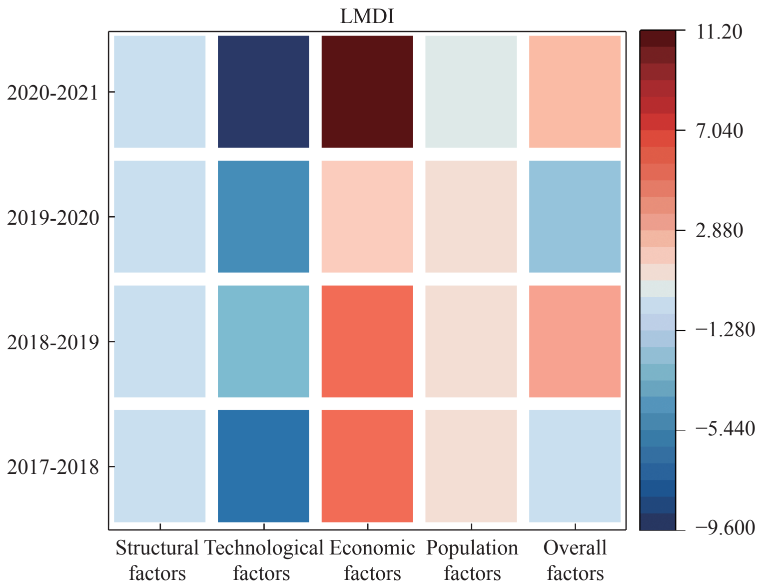

Fig. 12 Decomposition effect of water resource ecological footprint factors in Hainan Island

from 2020 to 2021, the population factor displayed a downward trend, thus playing a negative role in restraining the growth of the ecological footprint of water resources, while enormously enhancing the sustainable use and development of water resources in Hainan Island. Overall, the population factor had minor fluctuations, indicating that its influence on the ecological footprint of water resources was not significant during the study period.

The technology factor had a negative value in the research years, manifesting that the application of advanced technology means can effectively restrain the growth of the ecological footprint of water resources, reduce the rate of water consumption, and play a positive role in the sustainable use and development of water resources in Hainan Island. It is evident that the technological effect is a key factor to in mitigating the rapid growth of the ecological footprint of water resources in Hainan Island. Compared with the other three factors, the structural factor was close to "0", indicating its stability and limited influence on the ecological footprint of water resources in Hainan Island. With the establishment of the pilot ecological civilization zone in Hainan Island and the active development of green sustainable industries, the structural factors also have a positive impact. It is expected that with the development of technology and effective adjustment of industrial structure, it will significantly support the sustainable use and development of water resources in Hainan Island.

4 Conclusions

(1) This study developed calculation models for water resource ecological footprint, water resource ecological carrying capacity, and water resource ecological surplus/deficit of Hainan Island to assess the overall water resource utilization of Hainan Island as well as its various sub-regions. The results showed that the proportion of agricultural water use in the overall water use structure of Hainan Island ranked the highest, while the proportion of ecological water use was the lowest, although it displayed a significant increase over the years. The ecological footprint of water resources on the island showed a relatively slow growth trend, yet the ecological carrying capacity of water resources remains significantly deficient at the current stage. The water consumption per 10 000 yuan GDP across the entire island has been consistently decreasing over time. (2) The spatial distribution pattern of water resources utilization characteristics in Hainan Island has been identified and divided separately. In the western part of the island, there is a notable aggregation of hot spots in terms of per capita water resource ecological footprint, ecological carrying capacity, water consumption per 10 000 yuan of GDP. Conversely, it is characterized by a cluster of cold spot in terms of per capita water resource ecological deficit. On the other hand, the eastern part of Hainan Island exhibits the opposite pattern. (3) The LMDI index decomposition method indicates that the utilization of water resources was influenced by four dominant factors: Economy, population, technology, and structure. Among these factors, the first two (economy and population) have a promoting effect on the growth of the ecological footprint of water resources in Hainan Island,

leading to intensified water resource consumption. In contrast, technological factors played a crucial role in inhibiting the growth of water ecological footprint and slowing down the consumption of water resources. Structural factors had a relatively minor impact on the ecological footprint water resources in Hainan Island. Furthermore, the economic factors are the primary driving force behind the growth the water resource ecological footprint in Hainan Island.

Acknowledgements

This work was funded by Guangxi Karst Science and Technology Innovation Fund (KFKT2022001) and China Geological Survey Program (DD20230416).

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