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Article

Evolution of Sustainable Water Resource Utilization in Hunan Province, China

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Abstract: The demand for social and economic development has promoted research into water resources. The combined effects of natural conditions and human activities on regional water resource usage are not well understood. The sustainable utilization of water resources was assessed in terms of supply (e.g., precipitation) and demand (e.g., ecological water resources footprint (EF_w)) sides in Hunan Province, China, from 2010 to 2019. The results showed that: (1) on the supply side, water resources were increased across Hunan Province. The spatial patterns of total water resources are significantly heterogeneous, with high values in the east and south, which are mainly affected by precipitation; (2) on the demand side, evapotranspiration was great in areas with high vegetation coverage. The EF_w was high in relatively developed areas. The mean percentage of agricultural EF_w remained dominant at approximately 60% with a steady decreasing trend, while that of eco-environmental EF_w increased; and (3) the sustainable utilization of water resources in Hunan Province is generally rational. Moreover, the potential for water resource development and utilization is really significant in eastern and southern Hunan Province. The findings are beneficial in providing an important scientific basis for policymaking relating to the efficient utilization of regional water resources.

Keywords: water resources; climatic factors; human activities; Hunan Province

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1. Introduction

Water resources are essential for human survival and socio-economic development [1]. Many cities have exceeded their sustainable limits as a result of a failure to properly manage water resource systems, posing a serious social and economic dilemma [2]. This is especially true when decisions that degrade hydrological ecosystems are based on political and financial considerations rather than hydrological ones [3]. In this sense, the evolution of sustainable water resource utilization is very important for environmental and natural resource research [4,5]. This is conducive to establishing or reforming economic and environmental policy and achieving reasonable allocation and sustainable use of water resources under a changing climate.

A recent review 1 highlighted that co-evolution of human-water systems should be the focus of future hydrological research. Emphasis should be placed on understanding the combined effects of climate change and human activities on hydrological processes and water resources across temporal and spatial scales. The Intergovernmental Panel on Climate Change indicated that a global warming of 1.5 °C will be exceeded during the 21st century and that the global climate system is experiencing rapid and extensive changes [6]. Temperature plays an important role across the entire hydrological cycle [7].

The frequency and/or intensity of extreme weather, i.e., flood and drought, is expected to increase in the near future [8,9], affecting the distribution of water resources on both temporal and spatial scales [10,11]. Water resources can be directly attributable to global warming, solar radiation, and atmospheric CO_2 [12]. Furthermore, previous studies [13,14] have concluded that local water resources are influenced by tree restoration through their effects on radiation balance, infiltration and soil water storage, evapotranspiration (ET), streamflow, and precipitation. Many studies [15–17] have consistently concluded that tree planting increases annual evaporation and decreases streamflow.

The hydrological cycle is also profoundly affected by human activities and socio-economic development 1. In recent years, the rapid process of urbanization has caused some environmental problems, such as air and water pollution, land desertification, and biodiversity loss in many parts of the world, including China [18,19]. As a result of its rapid expansion and urbanization transition, China is confronted by severe water issues today, such as in the Yellow River Basin [20] and the upper Yangtze River [21]. China ranks 121st in the world in terms of per capita water resource availability, accounting for only a quarter of the global average, with insufficient water supply in over 400 cities [22]. Natural freshwater resource shortages are one of the top issues associated with the process of urbanization in two-thirds of Chinese cities [23]. Although it can be argued that there is sufficient precipitation in south China, freshwater resource trade-offs between environmental protection and development are likely to be inevitable in the future [24]. Hunan Province is such an example; it was ranked 9th among the 31 provinces of Chinese mainland in terms of gross domestic product (GDP) in 2020. The overall vegetation coverage temporal trend in this area has increased based on the Global Inventory Modeling and Mapping Studies 3 g Normalized Differential Vegetation Index [25]. The percentage of forest cover was 59.96% in 2020, up 0.06% from the previous year based on the data from Hunan Forestry Bureau (http://lyj.hunan.gov.cn/ (accessed on 10 May 2022)). The dynamics and sustainable utilization of water resources in this province are therefore worth exploring.

Many methods are available for achieving the sustainable utilization of water resources and for meeting regional water use demands, such as the analytical hierarchy process [26], data envelopment analysis [27], and evaluation index system method [28]. Fan [29] developed the water resources ecological footprint (hereafter EF_w) model to quantify water consumption by human activities based on the concept of an ecological footprint [30,31]. The EF_w model is used to calculate the human utilization of environmental resources from the demand side, and the carrying capacity of the ecological environment from the supply side (namely, the carrying capacity of water ecological resources, hereafter EC_w), and analyze the sustainable development of the ecological environment on different scales by comparing them both. This provides a reliable means for comprehensively evaluating the sustainable utilization of water resources [23]. The EF_w model has been widely used for estimating the sustainability of water resources in China, such as in Zhejiang Province [32], Shandong Province [33], and the Poyang Lake Basin [34], because it is closely related to population and economic development [35].

However, the quantitative characteristics of water resource use in a region are determined not only by anthropogenic factors, including the socio-economic development level, population size, and area of the territory served, but also by physiographic conditions, such as climate change. Their interaction determines the volume and structure of water resource use, as well as its dynamics and development patterns [36]. Therefore, both climatic and anthropogenic factors on the supply and demand sides should be considered when studying the sustainable utilization of water resources.

Against this backdrop, the objectives of this study were: (1) to explore the spatial and temporal variability of water resources on the supply side in Hunan Province, China; (2) to analyze the climatic and anthropogenic demand side of water resources in this province; and (3) to estimate the sustainability of water resources utilization in the target area. The overall findings of this study will be meaningful to deeply understand the combined effects of both climate change and human activities in terms of supply and demand sides on regional water resources utilization. The paper is structured as follows. Section 2 describes the study area, followed by data resources and methods. Section 3 introduces the results of water resource utilization in terms of both supply and demand. Discussion and Conclusion are presented in Sections 4 and 5, respectively.

2. Materials and Methods

2.1. Study Area

Hunan Province lies between 24°39′ N and 30°08′ N to 108°47′ E and 114°15′ E in south China, in the middle reaches of the Yangtze River, covering an area of 21.18 × 10^4 km^2 (Figure 1a). It is tilted from west to east, with Xuefeng Mountain to the west and Dongting Lake to the north. It has a subtropical monsoon climate, characterized by hot and wet summers, and cold and dry winters [37], with a mean air temperature of 19 °C and average annual precipitation of 1953 mm. In 2019, it had a total population of 6.9 × 10^7, a GDP of 4.05 × 10^{12} Chinese yuan (CNY), and total water resources of 2.1 × 10^{11} m^3 based on the Hunan Statistical Yearbook (http://tjj.hunan.gov.cn/ (accessed on 12 March 2022)). This province includes 14 prefecture-level cities: Changsha, Zhuzhou, Xiangtan, Hengyang, Changde, Yueyang, Yiyang, Shaoyang, Loudi, Yongzhou, Chenzhou, Zhangjiajie, Huaihua, and Xiangxi. A basic overview of these 14 prefecture-level cities is shown in Figure 1b,c. Environmental (e.g., topography and natural resources) and societal (e.g., population and technology) differences among these cities have led to unbalanced socio-economic development in this province. Changsha is the capital city of Hunan Province; its per capita GDP is several times that of other cities. Some cities in southern and western Hunan Province, such as Xiangxi, Yongzhou, Huaihua, and Shaoyang, are subject to heavy economic growth pressure.

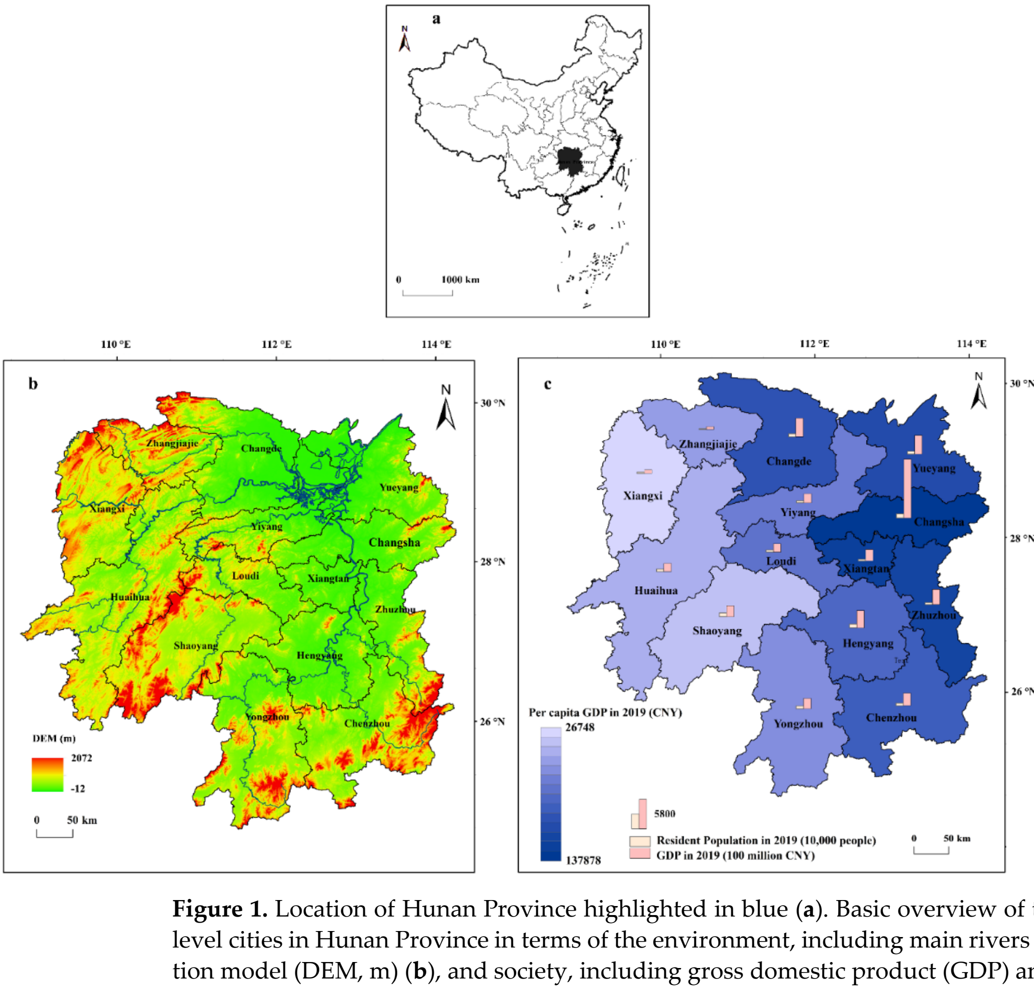

Figure 1. Location of Hunan Province highlighted in blue (**a**). Basic overview of the 14 prefecture-level cities in Hunan Province in terms of the environment, including main rivers and digital elevation model (DEM, m) (**b**), and society, including gross domestic product (GDP) and population (**c**).

2.2. Data Sources

Precipitation data for the period 2010–2019 were collected from 96 weather stations of Hunan Province, obtained from the Hunan Climate Center. Annual precipitation (mm/year) was the sum of the daily precipitation of a year at each weather station. The inverse distance weight interpolation method was used to obtain the spatial distribution of annual precipitation in Hunan Province.

The MOD16 ET product was produced by the Moderate Resolution Imaging Spectroradiometer (USA) based on the improved Penman-Monteith approach by [38,39]. It showed superior performance with an 80–90% accuracy using the global measurements of FLUXNET towers [38,39]. Annual ET data with a spatial resolution of 500 m in Hunan Province were downloaded from the National Aeronautics and Space Administration MOD16A3 remote sensing dataset (https://ladsweb.modaps.eosdis.nasa.gov/ (accessed on 20 July 2021)). The Moderate Resolution Imaging Spectroradiometer Reprojection Tools were employed for extraction, format conversion, map projection transformation, and image mosaic. Image clipping in bulk using the boundary of Hunan Province was completed in ERDAS IMAGINE (USA). The MOD16 dataset uses specific values to mark areas such as cities, frozen soil, ice and snow, bare land, and water bodies, but does not calculate ET values. Therefore, these areas were excluded here by "Setting Null" in ArcGIS software. The real ET values were calculated with MOD16A3 data multiplied by the scaled factor (equaling 0.1).

The total volume of water consumption, including agricultural, industrial, domestic, and ecological water consumption, and the total amount of water resources, including surface water and ground water resources for each city were taken from the Water Resources Bulletin from each of the prefecture-level cities in Hunan Province from 2010 to 2019 (published by the Water Resources Conservancy Bureau of the prefecture-level cities). Population data and GDP were obtained from the Hunan Statistical Yearbook, published by the Hunan Provincial Bureau of Statistics.

2.3. Water Resources Ecological Footprint Model

The EF_w model is widely used to study the temporal and spatial evolution of the ecological characteristics of water resources because of its intuitive concept, and strong maneuverability and regional comparability. It can be used to objectively reveal the relationship between natural resources and economic development and describe the metabolic intensity and consumption level of regional water resources. According to the description of the water resources ecological footprint, the ecological footprint converts the amount of water resources consumed into the production area of the corresponding account and divides by the water resources land area. After balancing, it finally obtains the equilibrium value that can be compared with different cities worldwide. The calculation model of the water resources' ecological footprint can be expressed by the following formula [29,40]:

$$EF_w = \gamma * (W / P_w) \quad (1)$$

where EF_w (hm^2) is water resources' ecological footprint; γ is the global equivalence factor of water resources, divided by the average ecological productivity of various types of biological production areas worldwide. γ is the same for all countries, which was determined here as 5.19 based on the results of the World Wide Fund for Nature Earth Report (2002). W is water consumption (m^3) usually comprising four types, namely agricultural, industrial, domestic, and ecological water consumption [41]; and P_w is the average global production capacity of water resources (m^3/hm^2). Based on [40], P_w equals 3140 m^3/hm^2.

2.4. Water Resources Ecological Carrying Capacity Model

The ecological carrying capacity of water resources (EC_w) based on the ecological footprint model refers to the maximum sustainable utilization capacity of water resources that can meet the ecological water demand and maintain the limited development goal with regional socio-economic development. The water resources carrying capacity model [29] is shown as follows,

$$EC_w = \alpha * \gamma * \Phi * (Q / P_w) \quad (2)$$

where EC_w (hm^2) is the regional water resources carrying capacity, Φ is the yield factor of regional water resources, equaling the ratio of the average production capacity of regional water resources (P, m^3/hm^2) to the average production capacity of global water resources (P_w), i.e., $\Phi = P/P_w$. P is the ratio of the total amount of regional water resources in the calculation period (V, m^3) to the area of the region (S, hm^2). Q (m^3) is the total regional water resources. α is the biodiversity compensation coefficient (expressed as the amount of water resources, deducted to sustain the ecological environment and biodiversity). The empirical coefficient of 0.4 proposed by [40] showed good applicability in analyzing the sustainable utilization of water resources in humid areas at different spatial scales in China [28].

2.5. Water Ecological Pressure Index

The water ecological pressure index (WEPI) 41 was adopted to indicate the sustainable utilization of water resources. It is the ratio of the water ecological footprint to the water ecological carrying capacity, and is calculated as:

$$EC_w = \alpha * \gamma * \Phi * (Q / P_w) \quad (3).$$

The smaller the value of WEPI, the greater the profit of water resources in a certain region. A WEPI within the range of 0–0.5 indicates that the utilization of water resources is completely sustainable. A WEPI between 0.5 and 0.8 indicates a safe state and between 0.8 and 1 an unsafe state. If the WEPI is greater than 1, the utilization of water resources is unsustainable [41].

2.6. The 10,000 CNY GDP Water Ecological Footprint

The 10,000 CNY GDP water resources ecological footprint (hereafter W_{GDP}, hm^2/10,000 CNY) is an index used to evaluate the efficiency of sustainable water resource utilization. It can be expressed as [42]:

$$W_{\mathrm{GDP}} = \frac{EF_w}{\mathrm{GDP}} \quad (4)$$

where the smaller the value, the greater efficiency of water resource utilization.

3. Results

3.1. Water Resource Supply

The calculation of total water resources can reflect the supply of water resources, which is the sum of surface water and groundwater resources, and the deduction of the repeated calculation between them. The dynamic water volume of "natural runoff" such as rivers, lakes, glaciers, and other surface water bodies refers to the amount of surface water resources. The recharge of precipitation and surface water into groundwater is classed as groundwater resources. Figure 2a shows the dynamics of the annual total water resources, surface water resources, and groundwater resources of the 14 prefecture-level cities in Hunan Province from 2010 to 2019. The amount of surface water resources was significantly greater (more than three-fold) than that of groundwater resources. Surface water resources were the dominant component of the total water resources in each year. The amount of annual total water resources was between 150×10^8 m^3 and 250×10^8 m^3, with an average of 178×10^8 m^3 from 2010 to 2019. It was relatively low in 2011, 2013, and 2018, with mean values $< 100 \times 10^8$ m^3. Figure 2a reveals an increasing trend of both surface water resources and groundwater resources during this period. All three types of water resources varied within a large range in 2019, while their mean values remained stable, compared with those in other years. This indicates that there was significant spatial heterogeneity across these prefecture-level cities, rather than a dramatic increase in the whole province in this year.

The spatial patterns of the total water resources, surface water resources, and groundwater resources of the 14 prefecture-level cities are shown in Figure 2b. It also shows that surface water resources dominated the total water resources of all cities in Hunan Province. There was an obvious spatial heterogeneity in all types of water resources in Hunan Province. The highest values were located in southern Hunan Province, such as in Yongzhou, Chenzhou, and Shaoyang. The lowest values were recorded in the central area such as Changsha, Zhuzhou, and Xiangtan. The amount of total water resources and surface water resources of most cities, i.e., Changsha, Zhuzhou, Yueyang, Changde, Hengyang, Xiangxi, and Shaoyang, fluctuated around 100 × 10^8 m^3, while that of Yongzhou, Chenzhou, and Huaihua varied over a wide range from 150 × 10^8 m^3 to 300 × 10^8 m^3, more than three-fold that of western cities, such as Xiangtan and Zhangjiajie.

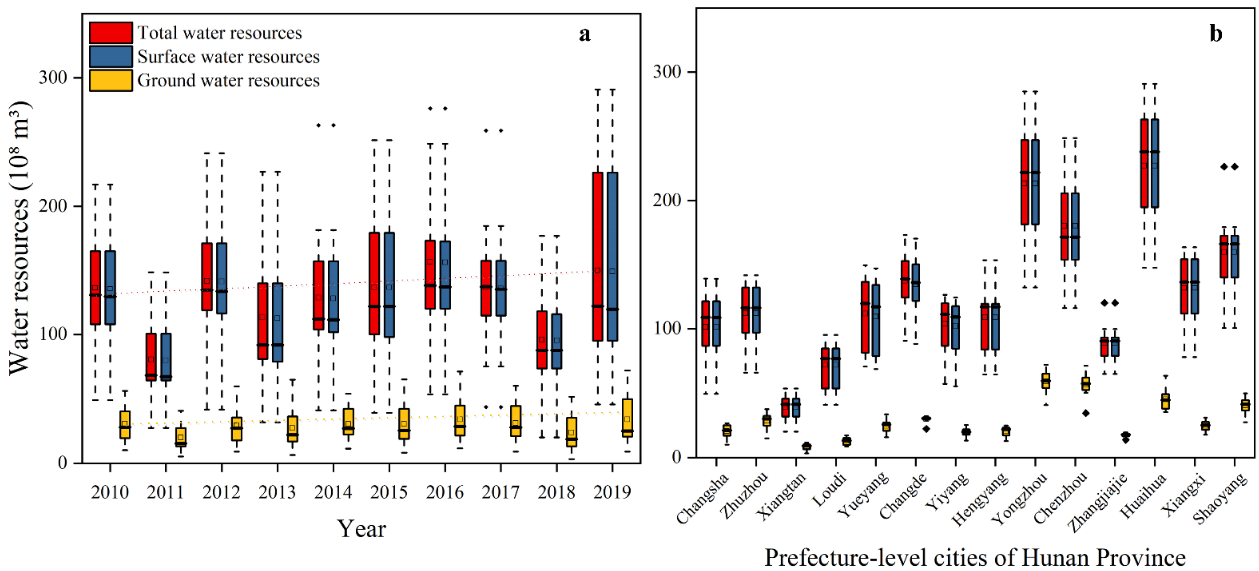

Figure 2. Temporal (**a**) and spatial (**b**) variations in total water resources, surface water resources, and groundwater resources among the 14 prefecture-level cities from 2010 to 2019. The whiskers represent the maximum and minimum values, the top and bottom of the boxes are the 25th and 75th percentiles, respectively, the median is represented by the horizontal line, and the mean by the open rectangle. The dotted lines in (**a**) are the trend lines of surface water resources in red and groundwater resources in yellow.

Precipitation is the primary source of freshwater in Hunan Province. Analyzing precipitation in terms of temporal and spatial patterns is important for understanding the variations in water resource supply in this region. The average annual precipitation in Hunan Province was within the range of 1175–1939 mm/year (Figure 3a). High values of average annual precipitation were concentrated in the south and east, with low values in the north and west. Both the lowest and the highest average annual precipitation rates were recorded in Hengyang: 1175.04 mm (weather station No. 57871 in Hengnan county) and 1938.65 mm (weather station No. 57776 at Nanyue Hengshan Mountain). Based on the DEM in Figure 1b, the spatial characteristics of precipitation were influenced by the local topography to a certain degree, with significantly higher precipitation in mountainous areas (e.g., Hengshan Mountain, Nanling Mountains in south Hunan Province, and Luoxiao Mountains in the east) than that in plain and basin areas (e.g., weather station No. 57871 in Hengyang basin). In particular, Hengyang and Shaoyang are located in

Hengyang Basin, named the drought corridor of Hunan Province [43]. Based on the results of the slope and *F* test in Figure 3b, the annual precipitation showed an insignificant increasing trend in most regions of Hunan Province, including the prefecture-level cities such as parts of Huaihua, Shaoyang, Yongzhou, Hengyang, Chenzhou, Zhuzhou, Yiyang, and Changde. There was a small part of the region located in the south of Hengyang and Huaihua that showed a significant increasing trend within a 95% confidence interval ($p < 0.05$). While the average annual precipitation in northern Hunan Province, such as in Zhangjiajie, Xiangtan, and Changsha, showed an insignificant decreasing trend.

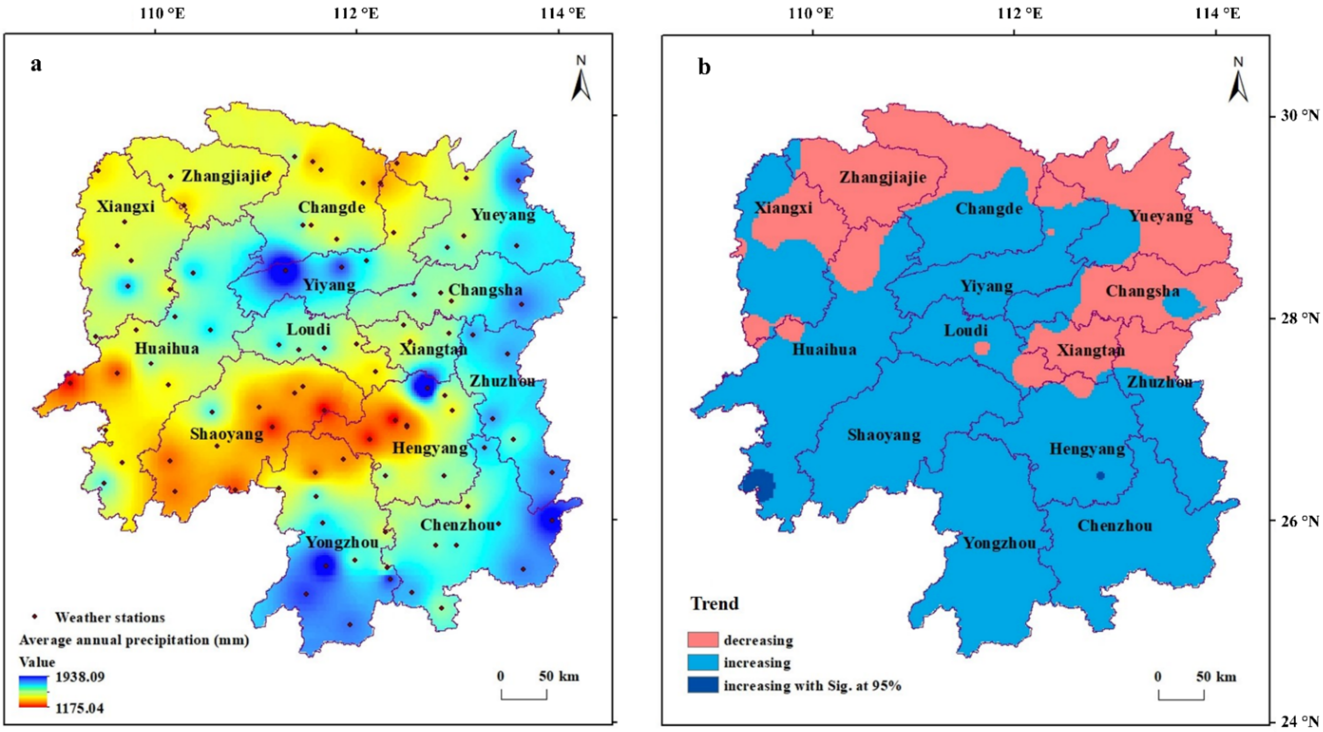

Figure 3. Spatial distribution of average annual precipitation based on data from 2010 to 2019 in Hunan Province (**a**), and the average annual precipitation trend during this period (**b**).

3.2. Water Resource Demand

The ET is a critical measure of surface water resource loss [44]. Figure 4 shows the spatial distribution of the average annual ET and its trend from 2010 to 2019 based on the MOD16 ET data from Hunan Province. The average annual ET showed a high spatial heterogeneity (Figure 4a), with low values in the Dongting Lake area and high values in western, eastern, and southern Hunan Province. The average annual ET was approximately 819. 22 mm/year during 2010 and 2019 in Hunan Province. Annual ET showed an insignificant increasing trend in most areas of Hunan Province during this period (Figure 4b).

The EF_w model is another method for estimating water resource demand regarding human activities. The dynamics of annual EF_w and average annual EF_w from 2010 to 2019 of 14 prefecture-level cities in Hunan Province are presented in Figure 5. The annual EF_w of Changsha, Hengyang, Zhuzhou, Chenzhou, and Loudi decreased during this period. In contrast, that of Yueyang, Xiangtan, and Changde showed an increasing trend. The provincial average annual EF_w was approximately 5.45×10^6 hm^2, with four prefecture-level cities (Changsha, Hengyang, Changde, and Yueyang) showing a higher EF_w than the provincial average. In contrast, cities such as Zhangjiajie, Xiangxi, and Huaihua in western Hunan Province had the lowest EF_w. Based on the GDP and population size of each city in Figure 1c, EF_w was high in the cities with a flourishing economy, indicating that economic status and population size are the main factors for such a regional water footprint disparity.

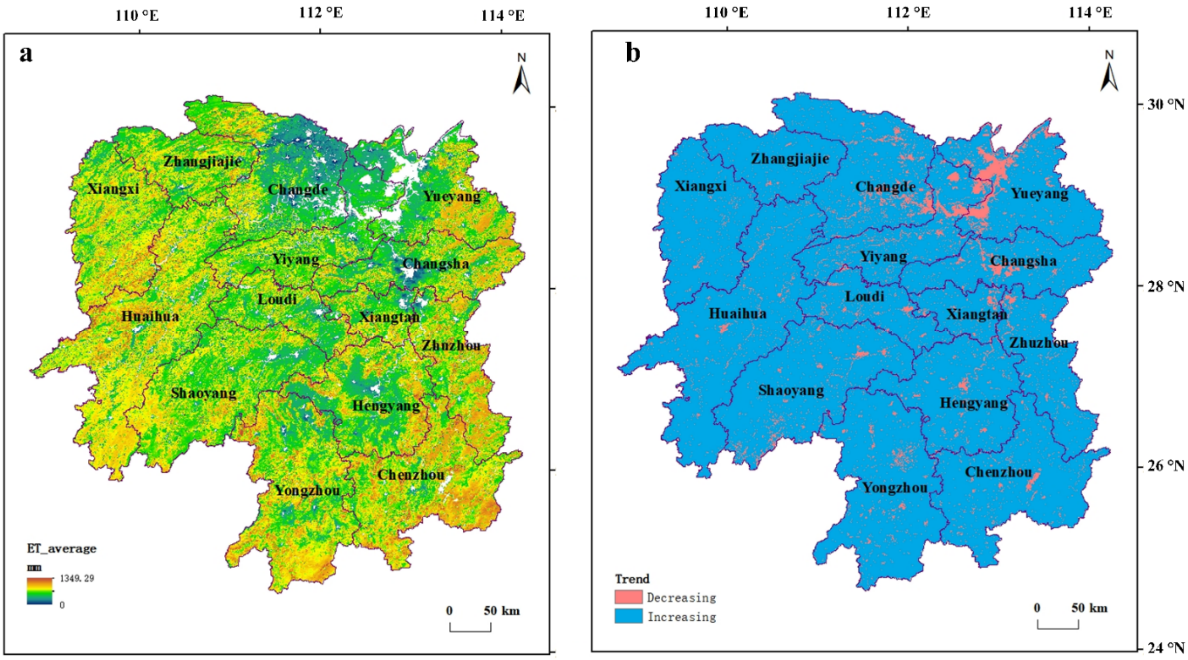

Figure 4. Spatial distribution of average annual evapotranspiration (ET) based on the data from 2010 to 2019 in Hunan Province (**a**), and its trend during this period (**b**).

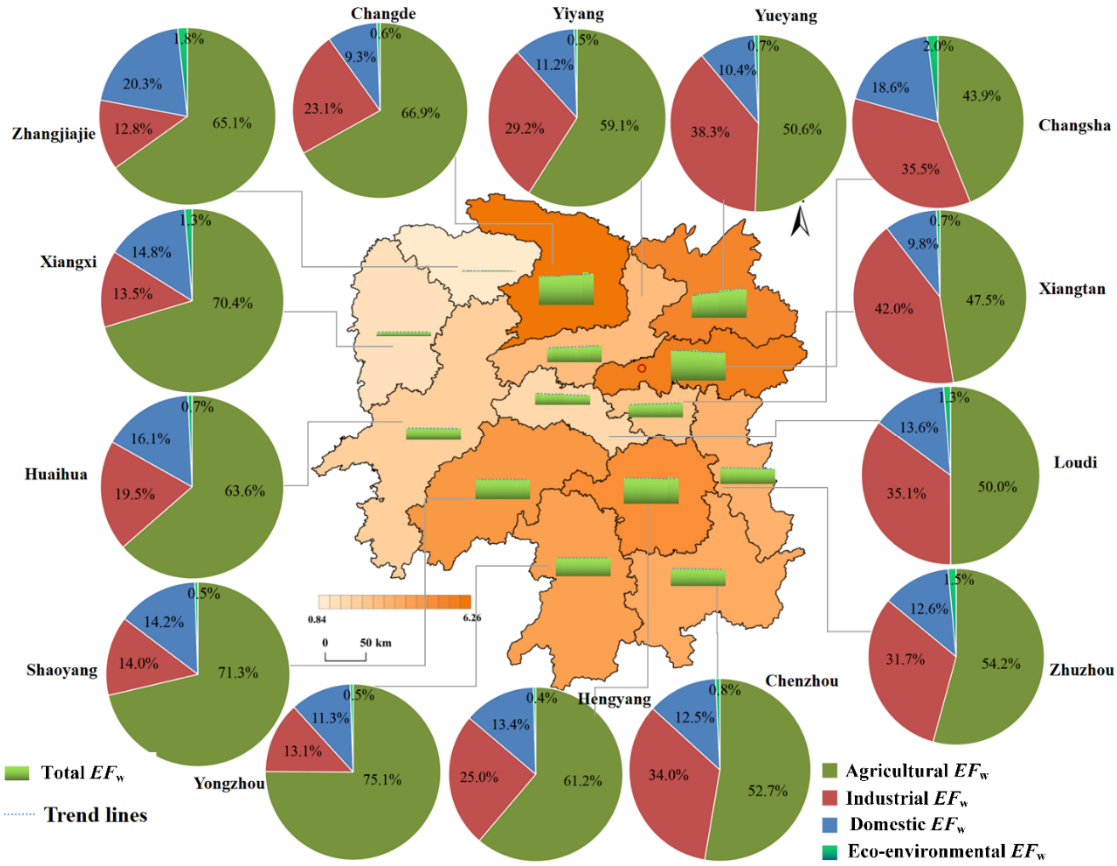

Figure 5. Regional average annual water resources ecological footprint (EF_w) (10^6 hm^2) and its components from 2010 to 2019 over 14 prefecture-level cities in Hunan Province. Dynamics of total EF_w from 2010 to 2019 of each city are shown in mini green histograms. The X-axis range of all green histograms is set as (0.76, 6.7) (10^6 hm^2).

Regarding the components of the EF_w between 2010 and 2019 (Figure 5), agricultural EF_w was the dominant one, followed by industrial and domestic EF_w. Eco-environmental EF_w showed the smallest contribution in all 14 cities. More than 50% of the total EF_w was derived from the agricultural sector in all 14 cities, except Changsha and Xiangtan, but it still comprised the largest share for these two cities. Regarding the western and southern cities, Yongzhou, Shaoyang, and Xiangxi had the highest percentages of agricultural EF_w, with values exceeding 70%. The highest percentage of industrial EF_w (42%) was recorded in Xiangtan, an old industrial city. The proportion of industrial EF_w exceeded 30% in other cities including Changsha, Chenzhou, Loudi, Yueyang, and Zhuzhou, while it was less than 15% in Zhangjiajie, Xiangxi, Shaoyang, and Yongzhou. These results correlate with the city's economic development level. Regarding domestic EF_w, there was little difference among the cities, with most of them showing a ratio between 10% to 20%. Changsha and Zhangjiajie had a high percentage of eco-environmental EF_w; 2.0% and 1.8%, respectively.

Figure 6 shows that the percentages of agricultural, industrial, domestic, and eco-environmental EF_w of all prefecture-level cities changed steadily between 2010 and 2019. The mean percentage of agricultural EF_w remained dominant at approximately 60% and showed a slight decrease, with a negative slope during this period. That of industrial EF_w showed a similar trend. The proportions of both domestic and eco-environmental EF_w showed a slightly increasing trend, with positive slope values.

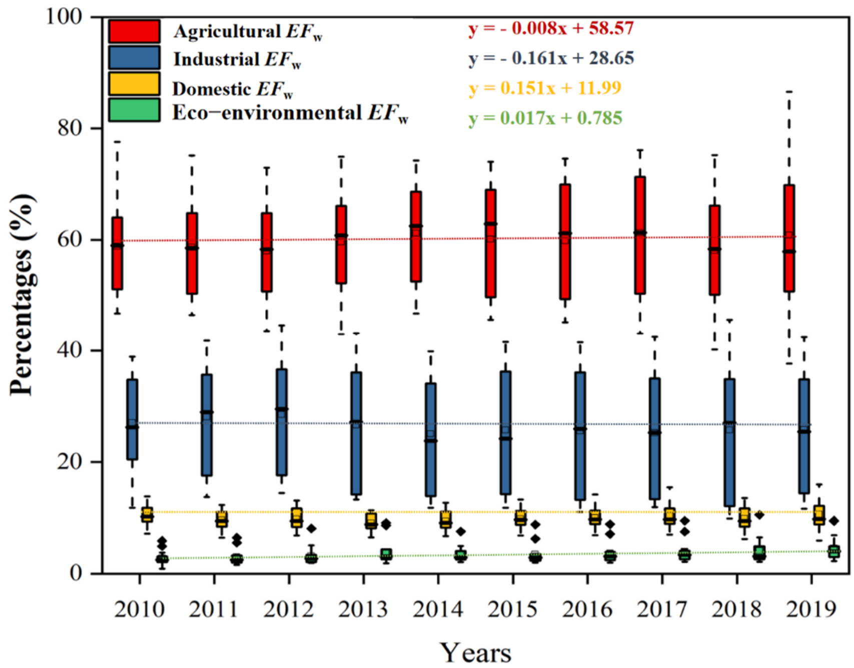

Figure 6. Change in the percentage of EF_w components from 2010 to 2019 of the 14 prefecture-level cities. Dotted lines in red, blue, yellow, and green are the trend lines of mean values of agricultural, industrial, domestic, and eco-environmental EF_w, respectively.

Figure 7 shows the spatial distribution of the average annual per capita EC_w (Figure 7a) and EF_w (Figure 7b) of the 14 prefecture-level cities. Figure 7a shows that the highest values (>6 hm^2/ per capita) of per capita EC_w in dark green were recorded in Yongzhou, Chenzhou, Huaihua, Xiangxi, Zhangjiajie, and Zhuzhou. This could potentially be explained by the large amount of water resources or the small population, or both (see Figure 1c). Hengyang had the lowest per capita EC_w with 2.49 hm^2/per capita, probably due to the low precipitation (Figure 3) and large population, ranking 3rd in Hunan Province (Figure 1c). Figure 7b shows that the relatively high values of per capita EF_w in dark orange (>1 hm^2/per capita) were found in northern Hunan Province, such as in Xiangtan, Changde, and Yueyang. Prefecture-level cities in western Hunan Province, such as

Zhangjiajie, Xiangxin, and Huaihua, had the lowest per capita EF_w, probably due to the small populations.

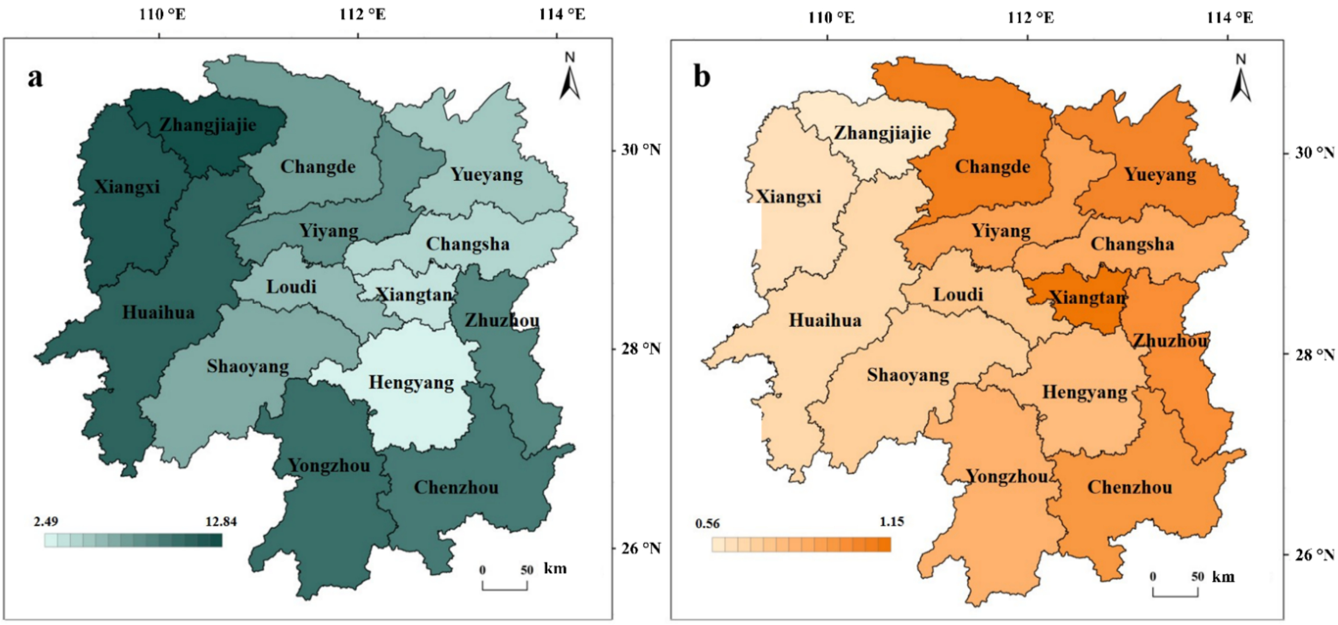

Figure 7. Average annual per capita EF_w (**a**) and EC_w (**b**) (hm²/per capita) over the 14 prefecture-level cities.

3.3. Evolution of the Sustainable Water Resource Utilization

Based on the WEPI results in Figure 8, the water resource status across Hunan Province is generally secure with a WEPI < 0.5 between 2010 and 2019. In this period, the WEPI in most cities did not vary significantly. The lowest WEPI was recorded in the western cities, followed by the southern cities. Values of WEPI in Xiangtan, Changde, and Yueyang increased over the past 10 years. Two probable reasons for the high WEPI in Xiangtan are the high industrial EF_w (Figure 5) and the decreasing precipitation trend (Figure 3b). The most likely explanation for Changde and Yueyang is the shrinking tendency of Dongting Lake [45], resulting in reduced water resource supply for these cities. The WEPI in Yongzhou and Chenzhou slightly increased, probably due to its increasing precipitation trend (Figure 3b). The average WEPI showed significant spatial heterogeneity across Hunan Province (Figure 8d). There was no water resource pressure in the west and south with WEPIs < 0.3. In comparison, cities in central and northern Hunan Province, such as Yueyang, Changsha, Xiangtan, and Hengyang, were under relatively high-water resource pressure.

Table 1 shows that Changsha had the lowest 10,000 CNY GDP water resources ecological footprint (W_{GDP}) each year, with a relatively advanced economic development. The mean value was 0.082 hm²/10,000 CNY from 2010 to 2019, less than half of that of the whole Hunan Province (0.203 hm²/10,000 CNY). Only two cities, Changsha and Zhuzhou, had a lower W_{GDP} than that of the whole Hunan Province. Relatively high values (>3.0 hm²/10,000 CNY) were recorded in Shaoyang, Yongzhou, and Xiangxi, indicating that natural resources and economic development widely varied among these cities. The W_{GDP} steadily declined annually in all prefecture-level cities. For most cities, it decreased by more than 50% from 2010 to 2019. This demonstrates that total water resource use efficiency improved for all cities to varying degrees during this period. The GDP growth for the whole of Hunan Province is based on an efficient economic development model, not on high water resource consumption, which is important for achieving sustainable economic development and building a resource-conserving and environment-friendly society.

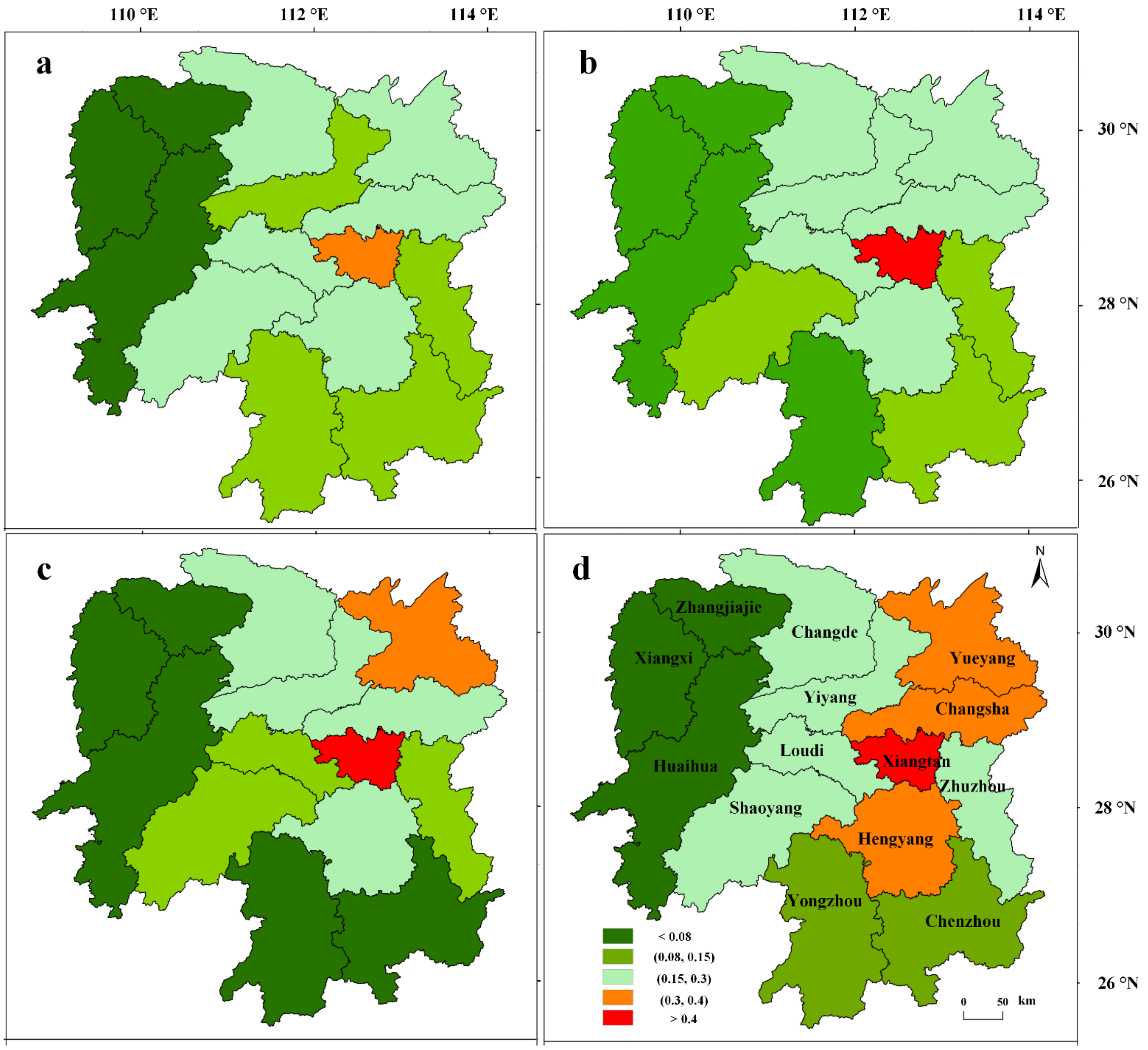

Figure 8. Spatial patterns of per capita water ecological pressure index (WEPI) in 2010 (**a**), 2015 (**b**), and 2019 (**c**), and the average from 2010 to 2019 (**d**).

Table 1. The 10,000 CNY GDP water resources ecological footprint (hm²/10,000 CNY).

Cities \ Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Changsha	0.138	0.111	0.098	0.089	0.081	0.073	0.065	0.059	0.064	0.051	0.082
Zhuzhou	0.309	0.233	0.211	0.196	0.177	0.157	0.146	0.142	0.138	0.121	0.183
Xiangtan	0.347	0.286	0.255	0.227	0.202	0.193	0.175	0.159	0.160	0.153	0.216
Hengyang	0.388	0.311	0.276	0.259	0.234	0.207	0.187	0.180	0.186	0.160	0.239
Shaoyang	0.615	0.480	0.428	0.396	0.358	0.321	0.293	0.268	0.250	0.203	0.361
Yueyang	0.315	0.277	0.238	0.219	0.200	0.205	0.194	0.194	0.179	0.159	0.218
Changde	0.409	0.240	0.298	0.267	0.246	0.230	0.212	0.200	0.200	0.181	0.258
Zhangjiajie	0.360	0.292	0.260	0.239	0.212	0.189	0.170	0.158	0.142	0.138	0.216
Yiyang	0.455	0.416	0.353	0.323	0.283	0.252	0.246	0.232	0.225	0.217	0.300
Chenzhou	0.363	0.294	0.263	0.242	0.217	0.200	0.180	0.173	0.160	0.159	0.225

Yongzhou	0.554	0.435	0.386	0.354	0.320	0.294	0.264	0.247	0.230	0.206	0.329
Huaihua	0.432	0.345	0.297	0.266	0.251	0.228	0.206	0.203	0.190	0.178	0.260
Loudi	0.430	0.311	0.279	0.251	0.234	0.200	0.179	0.177	0.163	0.155	0.238
Xiangxi	0.458	0.441	0.391	0.362	0.332	0.304	0.292	0.269	0.252	0.215	0.332
Hunan Province	0.329	0.268	0.236	0.215	0.196	0.179	0.164	0.155	0.148	0.136	0.203

4. Discussion

4.1. The Relationship between Water Resources and Precipitation

Precipitation and potential ET represent the water supply and water demand in a catchment, respectively [46,47]. Their temporal variability is the dominant driver of the temporal dynamics of catchment water storage [48]. The spatial pattern of average annual precipitation (Figure 3a) corresponds well with other studies [49,50]. These areas with a high ET are located in mountains with high perennial vegetation coverage; the maximum vegetation coverage exceeds 90%, resulting in significant transpiration [51]. Hunan Province comprises the main component (up to 82.7%) of the Dongting Lake Basin (see map in [52]), and can be regarded as a catchment. The temporal dynamics of all three types of water resources and precipitation are shown in Figure 9a. The dynamics of all water resources were in good agreement with those of precipitation. There was a marked positive correlation between water resources and precipitation (Figure 9b). Regarding the correlation between annual precipitation, and total water resources, surface water resources, and groundwater resources, R^2 values were 0.80, 0.80, and 0.69, respectively. This indicates that precipitation could explain 80% and 69% of the surface (total) water resources and groundwater resources in Hunan Province, respectively. This is probably due to the dominant topographic area comprising mountainous and hilly terrain, and because precipitation is mostly concentrated on the surface to form runoff in Hunan Province. Other studies [53,54] also argued that with population growth and expansion of irrigated agriculture, water resources management to a great extent depends on changes in precipitation, especially in arid areas.

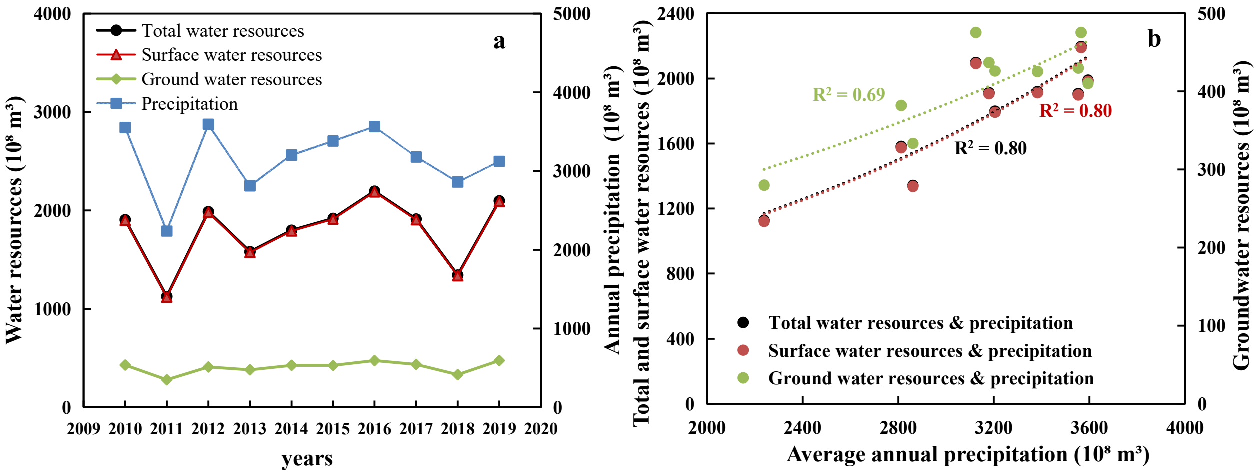

Figure 9. Temporal dynamics of water resources and precipitation from 2010 to 2019 (**a**) and the relationship between average annual precipitation (in units of 10^8 m³/year converted from mm/year from multiple areas of Hunan Province), and annual total water resources (in black), surface water resources (in red), and groundwater resources (in green) (**b**).

However, some cities, such as Changsha and Zhuzhou, had relatively high precipitation (Figure 3a) and few water resources (Figure 2b). In contrast, Huaihua had relatively low precipitation (Figure 3a) and abundant water resources (Figure 2b). A potential reason is the differences in water resource consumption, such as water use for human activities. For example, Changsha and Zhuzhou with large populations and high economic development levels had a large EF_w, while Huaihua showed the opposite. Previous studies [55–57] investigated the relationship between urbanization, economic growth, and water use change for water resources management. The logarithm of total water use had a significant negative correlation with the logarithm of gross domestic product in Hunan Province [55], corresponding well with the results in this study.

4.2. Advantages and Limitations of This Study

This study evaluated the sustainable utilization of water resources in terms of supply and demand sides based on climate variability and human activities in Hunan Province, south China. Previous research focused on water resource footprint and/or water resource carrying capacity in water resource utilization at different scales [58–60], natural disasters (e.g., floods, droughts) [61] or were based on climate changes [62], but few studies considered both explicitly. Furthermore, many studies paid more attention to water resources research in arid and semi-arid regions [62,63]. However, a review [64] of sustainable water resources in China highlighted that frequent drought and water contamination caused by climate changes and economic development in some areas in south China, threatens the sustainability of water resources. Thus, it is worthwhile to explore the sustainable utilization of water resources based on both climate changes and socio-economic development explicitly in south China.

This study focused on the amount of water resources based on both climate changes and socio-economic development. Water quality is also the key to water resource management [17,65]. The most serious environmental and economic impacts were observed in Hunan Province across Chinese mainland due to chromium, cadmium, and arsenic emissions [66]. Heavy metal wastewater is the outstanding water pollution problem in Hunan Province in recent decades [66–69]. Thus, Future work in water resources should focus on both water quantity and quality in this area.

The results indicate that average annual precipitation is higher than ET in Hunan Province, and annual ET showed an increasing trend in most cities (Figure 4b), in agreement with the results using MOD16 data in China on a national scale [70–72] and a coupled ET and gross primary product model (PML-V2) at a global scale [73]. However, the ET trend has shown inconsistent results at a regional scale in China, e.g., an increasing trend in Henan Province [74] and a decreasing trend in Shangxi Province [75]. Due to the challenges in estimating ET at a large scale, previous studies have employed different remote sensing products or approaches, possibly resulting in uncertainty of ET estimation [76]. It should be noted that only MOD16A data were used in this study, an alternative range of ET products and methods should be adopted to explore the spatial-temporal ET in future studies.

5. Conclusions

The sustainable utilization of water resources in terms of supply and demand was evaluated in Hunan Province from 2010 to 2019 based on climate change (i.e., precipitation and actual ET) and human activities (i.e., EF_w). The results indicate that: (1) on the supply side, overall water resources show an increasing tendency in Hunan Province. While the spatial patterns of water resources are highly heterogeneous, with high values in the east and south, and low values in the west and north of Hunan Province. This is mainly due to the spatial distribution of precipitation, which contributes up to 80% of the amount of total water resources, followed by human activities such as economic development and population numbers; (2) on the demand side, actual ET was high in mountains probably due to high vegetation coverage. EF_w, mainly based on water consumption by human activities, was high in the relatively developed prefecture-level cities such as Changsha, Xiangtan, and Yueyang. The mean percentage of agricultural EF_w remained dominant at approximately 60% but showed a steady decreasing trend during the period of 2010–2019. That of eco-environmental EF_w was increasing; and (3) in general, the sustainable utilization of water resources in Hunan Province is rational. The water resource utilization pressure was slightly higher in relatively developed cities. The decreasing W_{GDP} indicates that economic development is efficient in Hunan Province but does not involve high water consumption levels. The potential for water resource development and utilization is large in eastern and southern Hunan Province. This study evaluates the sustainable utilization of water resources based on both climate changes and socio-economic development explicitly. Moreover, these findings are beneficial for regulating resource allocation from the macro level, and for narrowing the differences among prefecture-level cities. It also provides useful information for the formulation of policies, such as the cross-regional mobilization of water resources.

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