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Spatiotemporal Variation in Water-Related Ecosystem Services during 2000–2020 and Ecological Management Zoning in the Xiangjiang River Basin, China

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Abstract: Exploring the spatiotemporal distribution and interrelationships among water-related ecosystem services (WESs) and conducting ecological management zoning are crucial for regional sustainable development. Taking the Xiangjiang River Basin (XJRB) as an example, this study first quantified three primary WESs, including water conservation, soil retention, and water purification, from 2000 to 2020. Second, the spatiotemporal variation in the interrelationships among WESs were analyzed using global and local bivariate spatial autocorrelation. Third, a water ecological zoning rule was constructed to divide the watershed into three primary and eight secondary water ecological management zones. The results indicate a strong consistency in the changes in the three WESs throughout the period from 2000 to 2020 in the XJRB. Precipitation patterns and urban expansion were the primary factors affecting alterations in the WESs. Spatial heterogeneity and dependence were evident across these ecosystem services. Both trade-offs and synergies were observed among WESs, with synergies playing a dominant role. Positive synergies occurred primarily in woodlands and grasslands, while negative synergies were observed in cultivated land, water areas, and construction land. Three water ecological management zones, including core water ecological management zones, general management zones, and restoration management zones, were delineated at the grid and country scales according to the aggregation properties of the WESs. Ecological management strategies were proposed for different zones. These findings can offer valuable insights for policy makers in land use planning and water ecological management within the XJRB, and can facilitate similar management endeavors in other regions.

Keywords: water-related ecosystem services; InVEST model; ecological management zoning; trade-off and synergy; Xiangjiang River Basin

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1. Introduction

1.1. Importance of Ecosystem Services Related to Water

Water-related ecosystem services (WESs) are the water-related goods and services provided by natural ecosystems via the hydrological cycle, which constitute the ecological environment and foundational resources for human welfare [1–3]. They refer not only to water from river channels, but also to the activities of water in the terrestrial landscape [4]. Increasing amounts of WESs are needed given the continual growth of the population and the development of society [5,6]. However, water's ecological functions have been deteriorating due to land use changes. This exacerbates conflicts between the ecological environment and socioeconomic growth, and threatens the ecosystem's stability and sustainable development [7–9]. Therefore, exploring the spatiotemporal changes and relationships among WESs and implementing appropriate land use governance plays a pivotal role in harmonizing the natural ecosystem and socioeconomic development [10].

Four types of services are provided by the natural ecosystem according to the Millennium Ecosystem Assessment (MA), and these have been further expanded into twenty-four subtypes [11]. Among these services, water conservation (WC), soil retention (SR), and water purification (WP) are the most important WESs, and these can effectively reflect the water service capacity of the ecosystem [12–14]. WC reflects the ability of ecosystems to restore and regulate water [15,16], which is critical for maintaining a stable regional water supply. However, current research often focuses on water yield while neglecting water conservation. Limited research has been conducted on the relationships between water conservation and other ecosystem services. SR primarily indicates the ecosystem's capacity to retain soil and accumulate sediment [17,18], while WP represents the ability of ecosystems in the watershed to intercept, filter, and absorb nutrients such as nitrogen and phosphorus from surface runoff [19]. In particular, land use change is recognized as the primary means by which human activities directly affect natural ecosystems. Different land use practices lead to changes in ecological processes, such as soil moisture, nutrient content, surface runoff, and water conservation, and subsequently result in alterations to the whole region's hydrological cycle. Studies have shown that the transformation of woodland into cultivated and construction areas can increase water yield and soil retention, but diminish the capacity for water conservation and purification. A substantial quantity of unabsorbed nitrogen and phosphorus from agricultural practices enters water bodies through surface runoff [20]. Conversely, afforestation can enhance water conservation, carbon sequestration, and soil retention while also reducing natural runoff, which may lead to or exacerbate water scarcity in arid areas [21–25].

Studies have quantified the typical ecosystem services and analyzed the spatiotemporal distribution and evolutionary patterns in combination with the locations of hot and cold spots [26–28]. On this basis, the interrelationships among different services are examined using the Spearman coefficient [29], Pearson coefficient [22,26], Moran's index [30,31], etc. Further analyses are conducted on alterations in the supply and demand of ecosystem services and the factors influencing them [32–34]. Ecosystem services do not exist independently and exhibit either positive or negative effects on each other [35,36]. Synergy implies that one service changes together with another in the same direction, while trade-off indicates that the enhancement of one service is mirrored by a reduction in another. Trade-offs and synergies among ecosystem services exhibit considerable spatial heterogeneity and dependence in different ecological environments [37,38]. Understanding these mechanisms and influencing factors among ecosystem services, as well as utilizing the relationships for regional ecological management, remains a crucial focus in current research.

Ecological management zoning is a fundamental and important step for decision makers seeking to implement effective land use management. To date, scholars have explored various methods by which to divide management zones at different scales [39–41]. Service bundles have been proposed based on statistical clustering methods [42], and the K-Means method has been utilized for regional divisions [43,44]. Additionally, some studies have performed zoning using Maximum Entropy Model (MaxEnt 3.4.1) [45–47], which was combined with economic and environmental values to identify priority areas. The method is reliable and comprehensive, and can effectively identify the priority areas. However, there are still some shortcomings. The existing methods take into account the aggregation characteristics among ecological services, but cannot flexibly reflect the priorities of ecosystem services. Meanwhile, priority protection mainly focuses on areas with good ecological services [48], while other regions with moderate and poor ecological services are overlooked. Protecting priority areas alone cannot achieve harmonized development in the entire region [20,32]. Therefore, it is imperative to optimize management strategies to ensure the consistent enhancement of services across the entire region.

Research on WESs in China mainly concentrates on arid and semi-arid areas in the north [49–51]. Conversely, there are relatively few studies examining the interrelationships among WESs in the humid southern regions. The Xiangjiang River Basin (XJRB) constitutes a significant component of the Yangtze River Basin in South China (Figure 1) [52]. The basin is characterized by good hydrothermal conditions and a widespread distribution of cultivated land in central and downstream areas, with relatively flat terrain. It is a typical agricultural region in southern China, and an important rice-producing region of Hunan Province. Despite the abundant rainfall in the basin, irrigation water consumption makes up 70% of the overall water usage [53], leading to significant water pollution [54]. Moreover, the area displays uneven spatial and temporal rainfall patterns, as well as distinct seasonal variations, which contribute to persistent issues in the water environment and water ecology. Scholars have conducted research on WESs in the XJRB [12,53], but there are still gaps in terms of the methods and strategies for watershed ecological management.

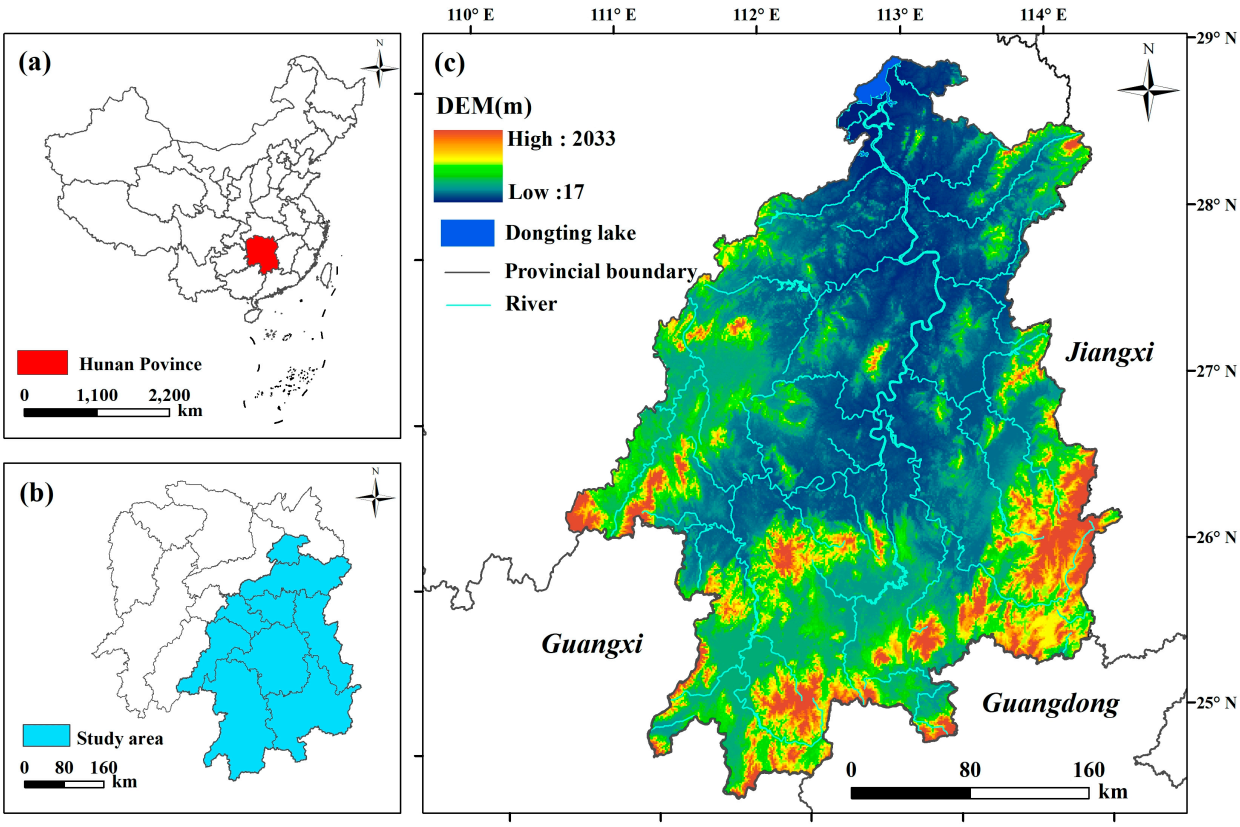

Figure 1. Location map of the XJRB. (**a**) Hunan province in China. (**b**) XJRB in Hunan. (**c**) Topography and river system of the XJRB. The provincial boundary shows other provinces adjacent to the XJRB.

1.2. Aim of the Article

This study explores the spatiotemporal distribution and interconnections among WESs and constructs a zoning rule for water ecological management based on aggregation characteristics. The goals of this study include the following: (1) quantifying and mapping the WESs and their spatiotemporal distribution; (2) examining the trade-offs and synergies between WESs and their evolution in response to land use changes; and (3) constructing a water ecological management zoning rule according to the relationships between the WESs and proposing corresponding strategies for different zones. This study offers a scientific basis for land use management, and thus plays a critical role in safeguarding the well-being and sustainable advancement of the watershed ecosystem.

2. Materials and Methods

2.1. Study Area

The XJRB is situated within the subtropical monsoon region of China (24°31′–29°52′ N, 110°30′–114°15′ E). It is an important economic zone and a densely populated region within the Yangtze River Basin. The study area covers only the basin in Hunan province, encompassing 9 cities and 67 counties, including Yongzhou, Chenzhou, Hengyang, Shaoyang, Loudi, Zhuzhou, Xiangtan, Changsha, and Yueyang City. The basic unit is the country's administrative region. The yearly average temperature is 17.4 °C, with the annual total precipitation ranging from 1200 to 1700 mm. Precipitation primarily occurs during the spring and summer seasons [55]. The terrain is complex and diverse, and is mainly covered by mountains and hilly forests in the southern, eastern, and western areas, whereas the central and northern areas exhibit relatively flatter topography. Due to rapid economic growth and accelerated urbanization, especially regarding the rapid expansion of the Chang-Zhu-Tan urban agglomeration in the downstream area, the demand for WESs in the watershed continues to increase [56]. The growing demand for these services and the deteriorating ecological environment have put great pressure on the watershed ecosystem. Accordingly, effective ecological management measures are of great importance in advancing watershed ecosystem services.

2.2. Data Sources

The basic data include the land use data, meteorological observation data, digital elevation model (DEM) data, soil data, and administrative boundaries (Table 1). The land use data have been categorized into woodland, cultivated land, grassland, construction land, water, and bare land, with a resolution of 1 km, from 2000 to 2020. The data were generated from Landsat TM, ETM+, and OLI images by manual visual interpretation. The comprehensive accuracies of the classification reached 94.3% [57,58]. Meteorological data were derived from 53 stations with daily precipitation, temperature, relative humidity, and pressure in the basin. After removing null and outliers, the data were interpolated via the ANUSPLIN method for yearly precipitation. Soil data include the type and texture of the soil, organic carbon content, particle size ratio, and other attributes. DEM data were downloaded from the geospatial data cloud website, and the resolution was 90 m. The boundaries include rivers and roads of the countries and districts in relevant sections of the XJRB. All of the data were transformed into the CGCS2000_GK_CM_111E and resampled to 1 km × 1 km using ArcGIS 10.8. Figure 2 shows the framework of the study.

Table 1. The specific data sources utilized in this study.

Data	Type	Resolution	Data Source
Land Use Data [59]	Raster	1 km × 1 km	Resources and Environmental Science and Data Center, Chinese Academy of Sciences, http://www.resdc.cn (accessed on 8 May 2022)
Meteorological Data [60]	point	Daily	China Meteorological Data Network, http://data.cma.cn (accessed on 10 May 2022)
Soil Data [61,62]	Raster	1 km × 1 km	Chinese Soil Data Set (v1.1) of the Harmonized World Soil Database (HWSD), http://westdc.westgis.ac.cn (accessed on 9 May 2022)
Digital Elevation Model [63]	Raster	90 m × 90 m	Geospatial Data Cloud, https://www.gscloud.cn (accessed on 8 May 2022)
Boundaries [19]	Vector	-	National Earth System Science Data Center, http://www.geodata.cn (accessed on 8 May 2022)

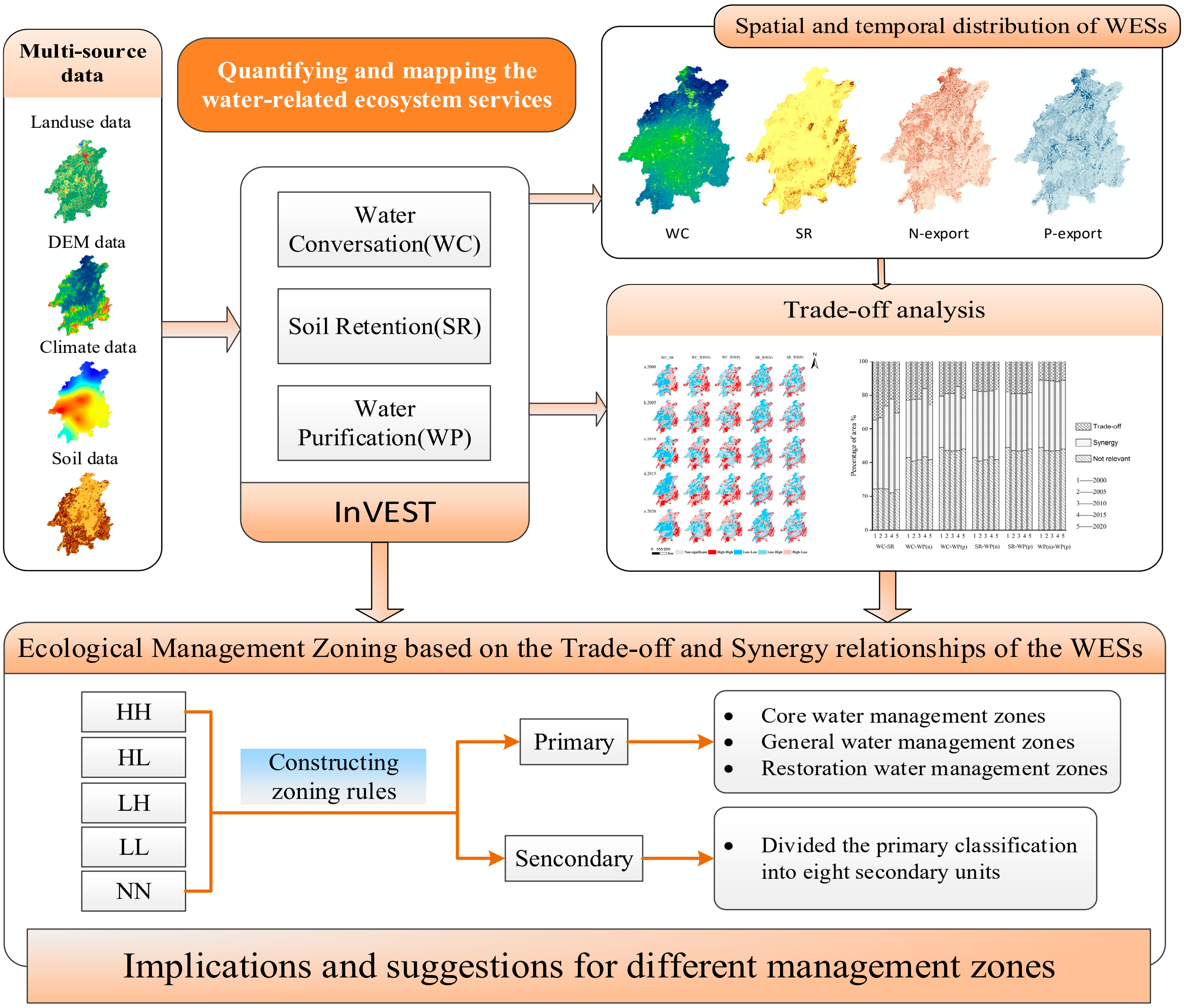

Figure 2. The framework for water ecological management zoning in this study. WC = water conservation; SR = soil retention; WP = water purification.

2.3. Ecosystem Services Quantification

2.3.1. Water Conservation

Under the InVEST model, water conservation is employed to numerically assess the water-holding capabilities of various ecosystems, considering factors such as evapotranspiration and runoff from distinct land cover types [64,65]. Built upon the Budyko curve, this approach calculates water yield as the difference between annual precipitation and actual evapotranspiration. By considering diverse surface runoff characteristics, it derives the water conservation capacity via the subtraction of surface runoff from the calculated water yield. The equation is outlined below [66,67]:

$$Y(x) = \left\{1 - \frac{AET(x)}{P(x)}\right\} \times P(x) \tag{1}$$

where $Y(x)$ is the yearly water yield, $AET\ (x)$ is the yearly actual evapotranspiration, and $P\ (x)$ is the yearly precipitation of pixel x.

In this formula, the evapotranspiration of vegetation $\frac{AET(x)}{P(x)}$ is determined by the hypothesis formula introduced by Fu [68] and Zhang [69].

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \frac{PET(x)}{P(x)}^{\omega}\right]^{\frac{1}{\omega}} \tag{2}$$

where $PET(x)$ denotes the potential evapotranspiration of pixel x, and ω is a non-physical parameter that represents inherent climate and soil attributes.

$$PET(x) = Kc(lx) \times ET_0(x) \tag{3}$$

where $Kc(lx)$ is the coefficient for vegetation evapotranspiration. $ET_0(x)$ indicates the reference evapotranspiration, which was calculated using the Pennman–Montieth formula [70].

$$ET_0 = \frac{0.408\Delta(R_n - G) + \frac{900}{T+237}U_2(e_s - e_a)}{\Delta + (1 + 0.34U_2)} \tag{4}$$

where R_n represents net radiation, T represents the daily average temperature, e_s is the saturated water vapor pressure, e_a is the actual water vapor pressure, Δ is the slope of the saturated water vapor pressure curve, G stands for the soil heat flux, and U_2 represents the wind speed at a height of 2 m.

$$WC(x) = Y(x) - Runoff(x) \tag{5}$$

$$Runoff(x) = P(x) \times C_j \tag{6}$$

$WC(x)$ is the yearly water conservation, $Runoff(x)$ stands for the surface runoff, $P(x)$ represents the yearly precipitation of pixel x, and C_j represents the surface runoff coefficient for various land use categories [71]. The runoff coefficient was obtained with reference to the guidelines for red line delineation in relation to ecological protection in China and other literature [67,72,73].

2.3.2. Soil Retention

Soil retention was assessed through the Sediment Delivery Ratio (SDR) module. The model is based on the universal soil loss equation and takes the sediment interception of different land types into consideration [74]. The vegetation cover factor C and soil conservation practice factor P were determined with reference to relevant studies, along with the specific local conditions of XJRB [12]. The formula [75] is outlined as:

$$RKLS_x = R_x \times K_x \times LS_x \tag{7}$$

$$USLE_x = R_x \times K_x \times LS_x \times C_x \times P_x \tag{8}$$

$$SR_x = RKLS_x - USLE_x \tag{9}$$

where SR_x indicates the soil conservation capacity, and $RKLS_x$ and $USLE_x$ are the quantities of potential and actual soil erosion, respectively; R, K, and LS are the factors of rainfall erosion, soil erosion, and the slope length gradient, respectively [76]; and C and P are the factors of vegetation cover and soil retention practice, respectively [77].

2.3.3. Water Purification

The Nutrient Delivery Ratio module was employed to quantify the water purification capacity, which signifies the capability of the watershed to intercept and remove water pollutants. It can illustrate the source and transport process of nutrients in the basin by calculating the nutrient export in each grid cell and summarizing the nutrient output and retention in each basin. The output of the module is the quantity of exported nitrogen (N) and phosphorus (P), which is inversely proportional to the water purification effect. A larger output implies a weaker water purification capacity. The main algorithm is outlined below [64,78]:

$$X_{expi} = load_{surf,i} \times NDR_{surf,i} + load_{sub,i} \times NDR_{sub,i} \tag{10}$$

$$X_{exptot} = \sum X_{expi} \tag{11}$$

where X_{exptot} represents the cumulative export of nutrients from the watershed; X_{expi} signifies the nutrient outflow from grid i; $load_{surf}$ and $load_{sub}$ are the nutrient load on the surface and underground; and NDR_{surf} and NDR_{sub} are the nutrient transfer rates on the surface and underground, respectively.

2.3.4. Bivariate Spatial Autocorrelation

Bivariate spatial autocorrelation extends the concept of univariate spatial autocorrelation under spatial statistical methods [79]. It includes both global and local bivariate spatial autocorrelation. The former assesses the correlation coefficients between services, and the results can be divided into positive values ($I > 0$, synergy), negative values ($I < 0$, tradeoff), and non-correlation ($I = 0$). The latter reveals the spatial agglomeration characteristics between adjacent elements, and the results can be categorized into five types: high–high type (HH), high–low type (HL), low–high type (LH), low–low type (LL), and non–correlation (NN).

In order to measure the relationships between the WESs in the XJRB, we transformed the calculation data of each service into 1 km × 1 km vector data using ArcGIS10.8, and then calculated the global and local spatial autocorrelation using GeoDa (Version 1.14.0). Synergies were identified in the HH and LL cluster areas, and trade-offs were found in the HL and LH cluster areas. The computation of the Moran's I is outlined below [34,80]:

$$I_G = \frac{n\sum_{i=1}^{n}\sum_{j\neq 1}^{n} w_{ij}\, z_i^l\, z_j^m}{(n-1)\sum_{i=1}^{n}\sum_{j\neq 1}^{n} w_{i,j}} \tag{12}$$

$$I_L = z_i^l \cdot \sum_{j=1}^{n} w_{ij} \cdot z_j^m \tag{13}$$

$$z_i^l = \frac{X_l^i - \overline{X}_l}{\sigma_l} z_j^m = \frac{X_m^j - \overline{X}_m}{\sigma_m} \tag{14}$$

where I_G and I_L represent the global and local bivariate Moran's I, respectively. The range of Moran's I is $[-1, 1]$. n signifies the total number of geographic elements, and w_{ij} is the spatial weight between neighboring elements. $\overline{X}_l$, $\overline{X}_m$, σ_l, and σ_m are the average value and standard deviation of ecosystem services l and m, respectively. X_l^i and X_m^j are the computation results of ecosystem services l and m in spatial units i and j, respectively.

3. Results

3.1. Alterations in Land Use and Land Cover

The XJRB is situated in the mountainous area of southern China, where woodland and cultivated land predominate as the primary land use categories (Figure 3). By 2020, woodland covered 61.67%, cultivated land accounted for 29.97%, and other land accounted for 8.36%. Notably, the land utilization types within the watershed underwent noticeable transformations between 2000 and 2020, particularly in the middle and lower reaches. The extent of construction land showed the most remarkable increase, from 1597 km^2 in 2000 to 3709 km^2 in 2020, with an average annual increase of 105.6 km^2. Conversely, cultivated land exhibited a consistently declining pattern, amounting to a cumulative reduction of 1132 km^2 over the past two decades. Woodland and grassland gradually decreased, with particularly significant changes between 2015 and 2020, and with most regions converted into cultivated land, grassland, and construction land. In contrast, the extents of water and bare land changed only slightly over the same period.

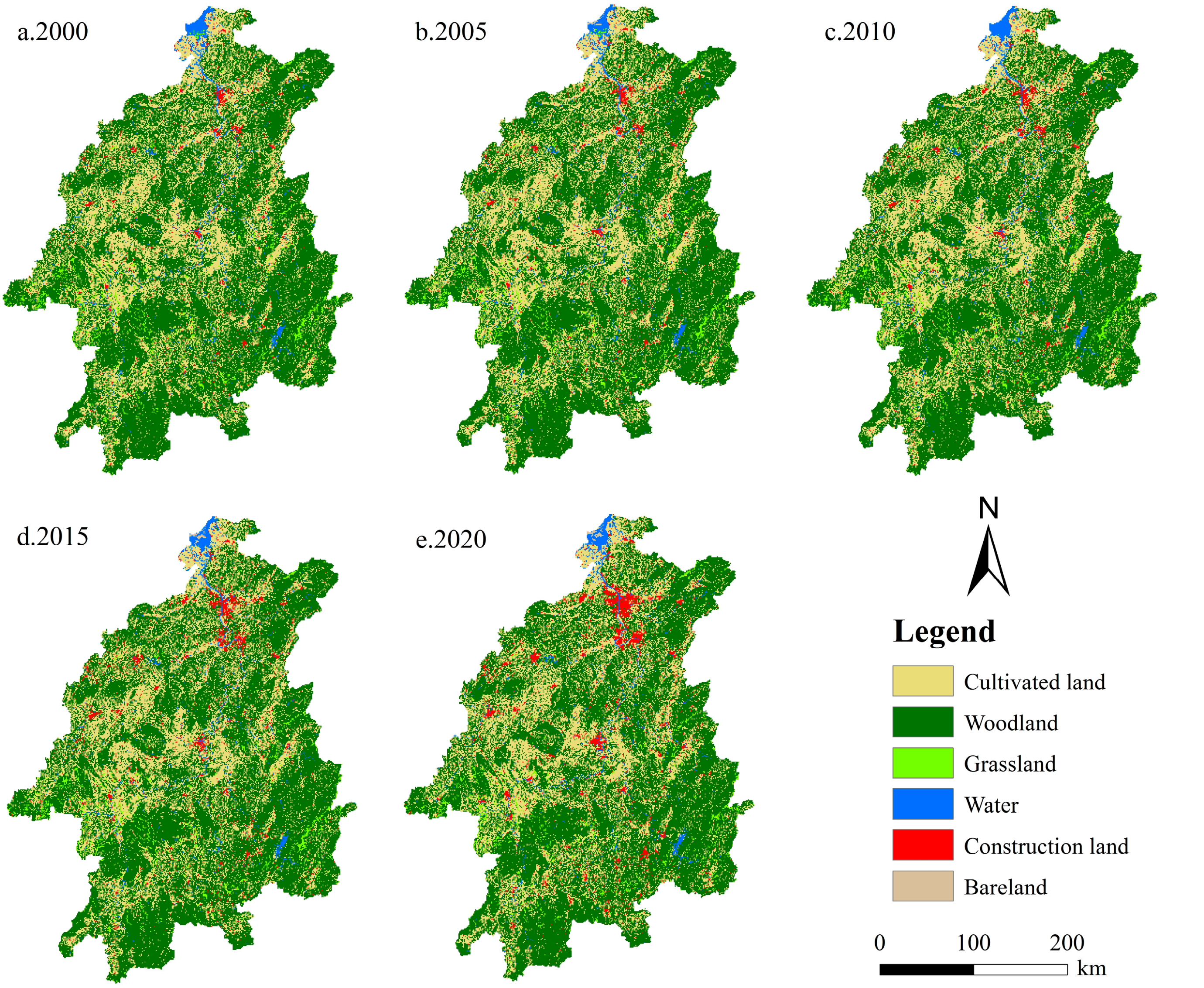

Figure 3. The spatiotemporal distribution of land use from 2000 to 2020 in the XJRB.

The Sankey diagram above illustrates the transitions in land use between two time periods (Figure 4). The left side of the diagram depicts land use types in the initial year, while the right side represents land use types in the final year. It is evident here that the land use alterations primarily involved cultivated land, woodland, and construction land. The main changes over the entire period concerned the mutual transformations between cultivated land and woodland. Moreover, the primary sources of increased construction land were cultivated land and woodland, with cultivated land contributing to a larger portion of this transformation. Between 2000 and 2005, urban development proceeded at a steady pace. However, starting from 2005, there was a quick spread of construction land, with a particularly notable increase in 2015–2020.

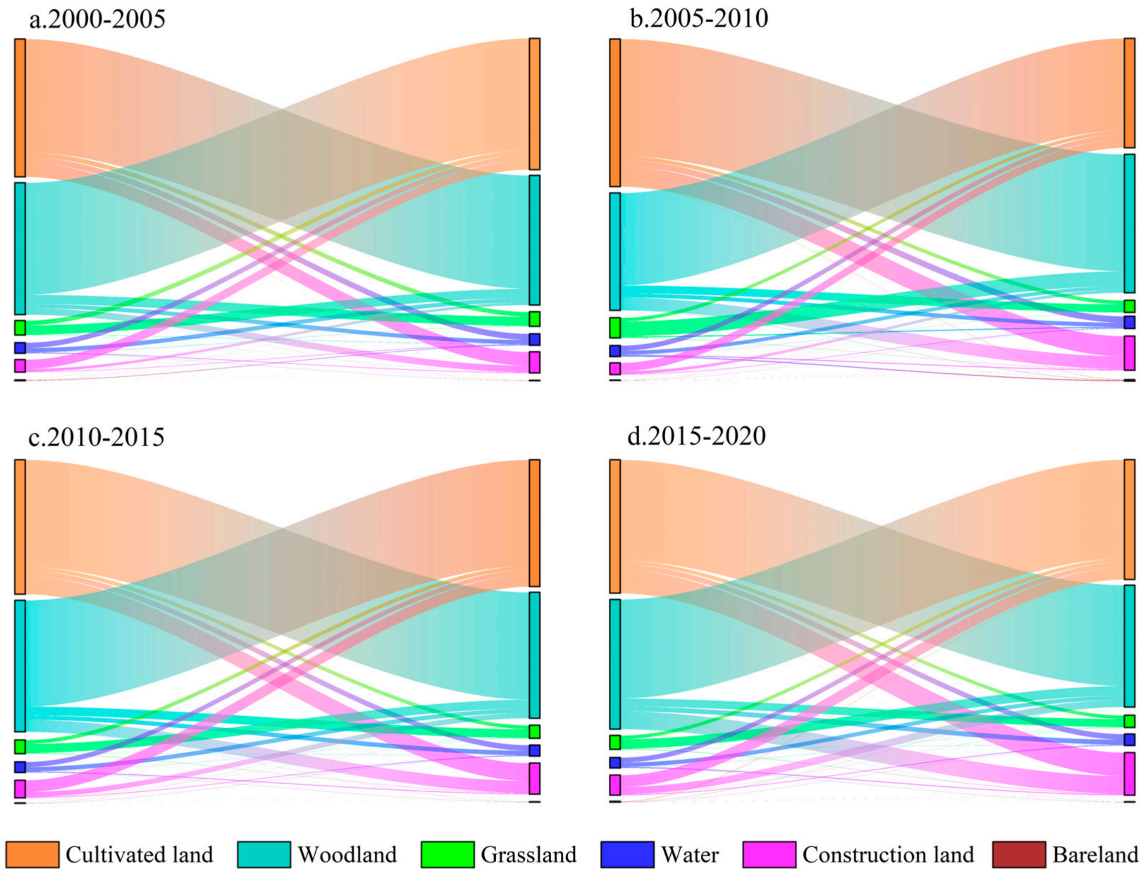

Figure 4. Sankey charts illustrating land use transitions in 2000–2020.

3.2. Spatiotemporal Changes of WESs

Alterations in land use practices will inevitably influence the provision of ecological services. Figure 5 shows the spatiotemporal patterns and changing trends of ecosystem services. The WC services exhibited obvious spatiotemporal variation characteristics in 2000–2020. Here, we can see a fluctuating trend, initially decreasing, then increasing, and then decreasing again, with the lowest value of 707.25 mm in 2005 and the highest value of 990.42 mm in 2015. The WC gradually increased in terms of spatial distribution from the central to the southern and northern areas of the watershed. Regions with high values were primarily identified as woodland and grassland in the southern and eastern areas, which was consistent with the regions of high precipitation and steep terrain. In contrast, regions with low values were situated in the central area of the watershed, characterized by a relatively flat terrain.

Soil retention services showed consistent fluctuation with water conservation from 2000 to 2020. In 2015, soil retention services were significantly increased under the influence of heavy rainfall, and the total amount of soil retention reached 34×10^8 t/y. However, from 2015 to 2020, a sharp decline of 37.0% in SR occurred due to the decrease in woodland and precipitation. The services exhibited distinct spatial differentiation, ranging from 0 to 3.85×10^5 t/km^2 over the entire period. There was a gradual decrease in SR from the southeast to the northwest. Regions with steep terrain, such as woodland and mountains in the upper streams, were associated with high values. In these areas, the topography was undulating, with abundant precipitation resulting in high levels of potential erosion. Nevertheless, the dense vegetation coverage on the slopes of the valley enhanced the soil retention capacity, ultimately leading to remarkably high soil retention services. Low values were found in relatively flat cultivated land and construction areas because of the extensive management there.

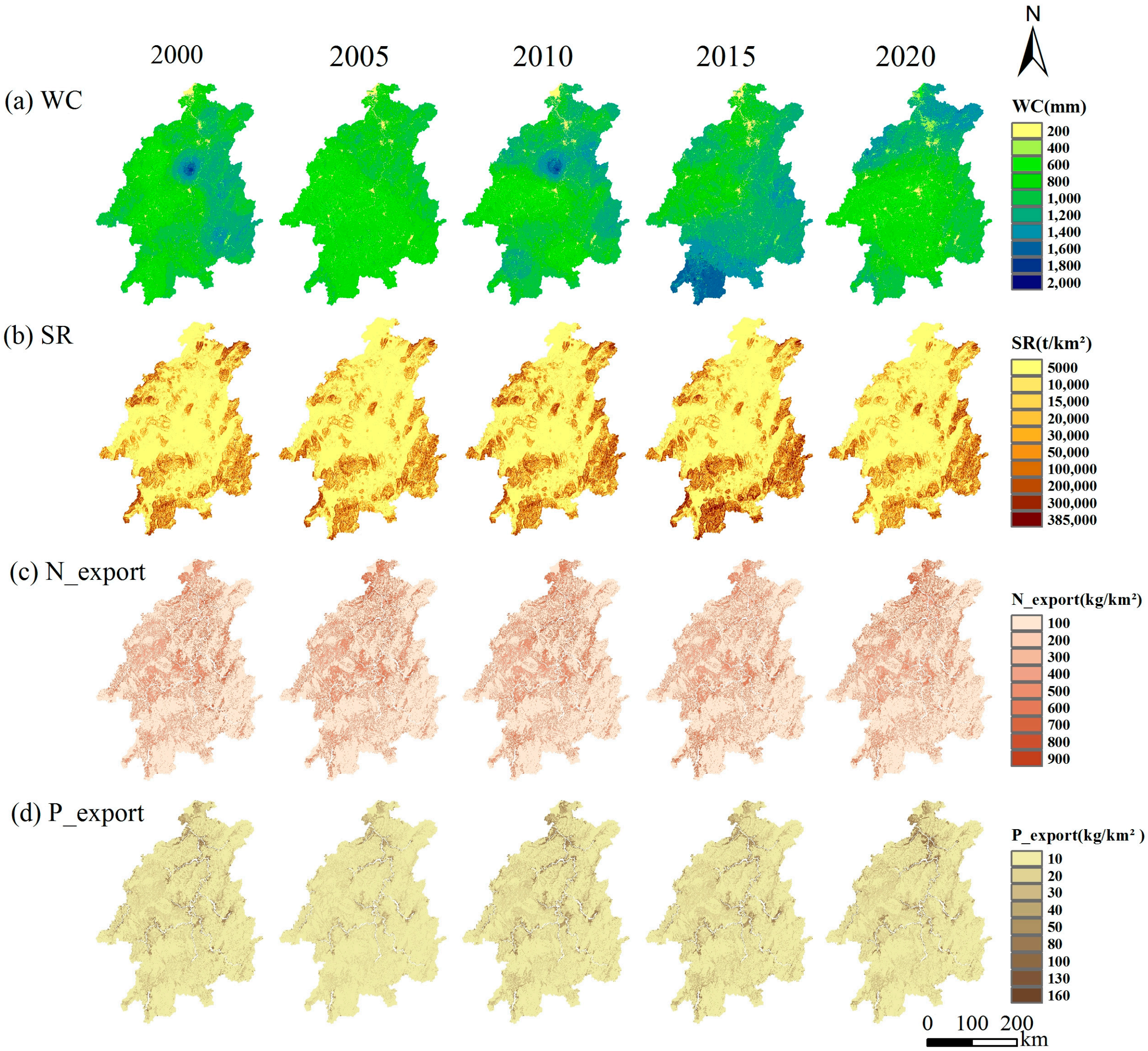

Figure 5. Spatial patterns and changing trends of WESs during 2000–2020 in the XJRB. WC = water conservation; SR = soil retention; N_export = the amount of nitrogen exported; P_export = the amount of phosphorus exported.

Water purification services remained relatively stable from 2000 to 2020. The change in N export was less than 2%, while P export showed an increase of 5.29%. The quantities of N and P export were between 0 and 850 kg/km^2 and 0 and 150 kg/km^2, respectively. The high-export regions for N were situated in the central and northern areas, primarily covered by cultivated land. Conversely, regions of lower value were positioned in the eastern and southern regions, predominantly covered by woodland. Notably, urban construction land and cultivated land were high-value areas for P export, whereas woodlands in the upstream area demonstrated the effective interception of both N and P nutrients.

3.3. Trades-Offs and Synergies of WESs

Under the dual influence of external environment factors and internal processes, ecosystem services often exhibit trade-offs or synergistic relationships with one another. Based on the calculation of WESs in the XJRB, we constructed a 1 km × 1 km fishing net using ArcGIS, and then linked the WESs' results. Given that greater amounts of N and

P export correspond to a decrease in water purification capacity, the reverse value of N and P export was employed to represent the water purification service. Subsequently, we conducted global and local bivariate spatial autocorrelation analyses to examine the interrelationships between WESs and to identify spatial clustering characteristics.

3.3.1. Temporal Variations of Trades-Offs and Synergies

Table 2 shows the bivariate spatial autocorrelation coefficients of WESs in the XJRB. The results indicate that, from 2000 to 2020, WESs in the XJRB showed a synergistic relationship throughout the watershed (Moran's $I > 0$, and $p < 0.01$), with an index of less than 0.35, which is consistent with previous findings [12,52]. Specifically, the synergies between WC and SR gradually increased from 2000 to 2015, reaching the highest value in 2015 (Moran's $I = 0.3237$). However, this synergy between the two services was significantly weakened from 2015 to 2020. The synergy between WC and WP (N, P) exhibited a fluctuating pattern—initially declining, followed by an increase, and finally another decline. The lowest degree of synergy was observed in 2010, followed by the strongest synergistic relationship in 2015, and a weaker synergy in 2020. Notably, the SR and the capacity for N and P purification demonstrated a high degree of consistency. The synergistic relationship between SR and WP also showed a fluctuating trend, but it contrasted with the synergy between WC and SR. This trend initially exhibited an increase, followed by a decrease, and then a subsequent increase, with the highest level of synergistic intensity being seen in 2020. The growth of urbanization and the intensive management of cultivated land have contributed to the improvement of regional soil erosion and nutrient discharge, thus strengthening the positive synergy between SR and WP.

Table 2. Bivariate spatial autocorrelation coefficients of WESs in the XJRB.

Year	WC–SR	WC–WP (N)	WC–WP (P)	SR–WP (N)	SR–WP (P)
2000	0.0655	0.0904	0.12	0.1679	0.1437
2005	0.1046	0.0817	0.115	0.1748	0.1498
2010	0.1799	0.0621	0.1094	0.1693	0.1485
2015	0.3237	0.1303	0.1687	0.1593	0.1426
2020	0.072	0.0141	0.0835	0.1805	0.1574

Note: Moran's $I > 0$, and $p < 0.01$.

There were both trade-off and synergistic relationships over the years in the XJRB, with synergies accounting for the largest proportion (Figure 6). The synergies between WC and SR gradually increased from 2000 to 2015, and the proportion of synergies reached 55.74% in 2015, while trade-offs represented only 22.27%. However, in 2020, synergies decreased by 45.37%, and trade-offs increased to 30.73%. The non-significant areas in relation to WC and WP (N) accounted for about 42% of the basin from 2000 to 2020, while their synergies rose from 34.01% in 2000 to 40.54% in 2015 and then declined to 32.36% in 2020, which is consistent with the trends observed in Moran's index. Similarly, the non-significant areas regarding WC and WP (P) were slightly larger than those for N, averaging about 48%. The areas of non-significance between WP (N, P) and SR were consistent with those between WC and WP (N, P), but the ratios between trade-offs and synergies exhibited notable variations. The synergies between SR and WP (N) in 2000, 2005, 2010, 2015, and 2020 were 39.87%, 41.29%, 40.58%, 39.13%, and 41.50%, respectively. On the other hand, the trade-offs remained consistently lower in the same years. The proportion of synergy between SR and WP (P) was relatively low compared to the proportion between SR and WP (N), and slightly changed over the two decades studied.

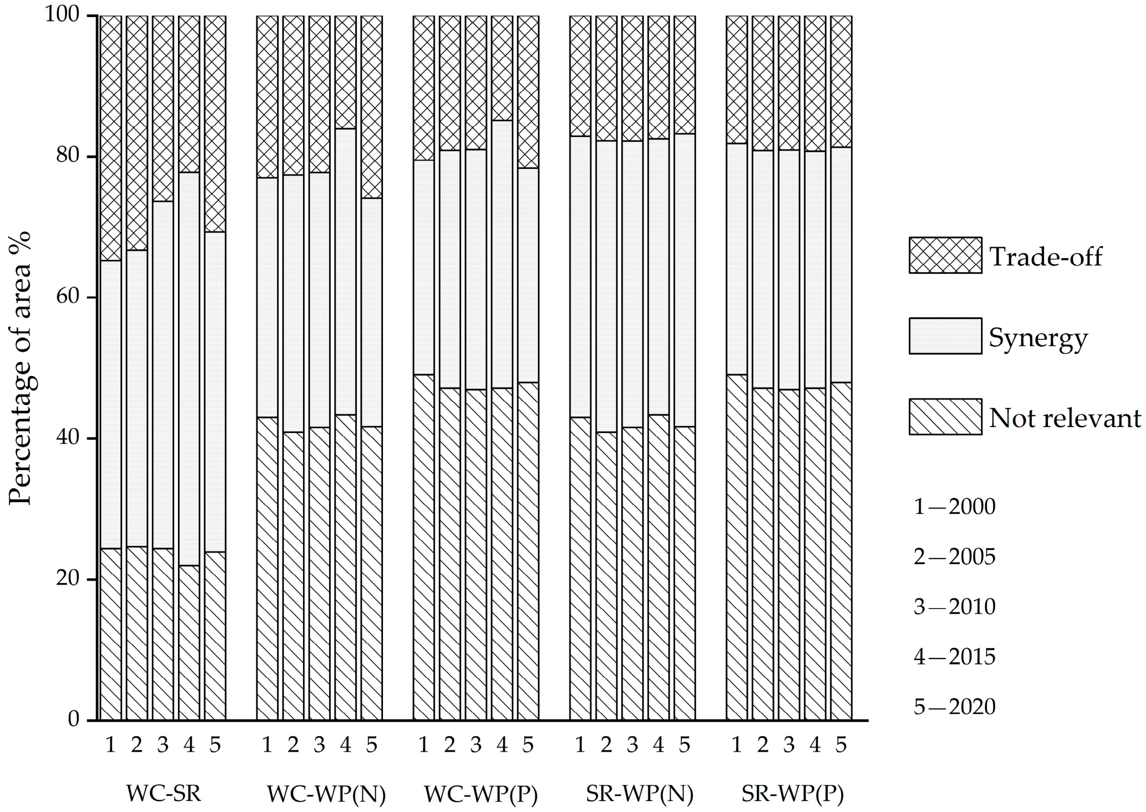

Figure 6. Proportion of trade-offs and synergies during 2000–2020: 1 = 2000; 2 = 2005; 3 = 2010; 4 = 2015; and 5 = 2020. The relationships among WESs include trade-offs, synergies, and those deemed not relevant. WC-SR represents the relationships between WC and SR. Others abbreviations follow the same rule.

3.3.2. Spatial Distribution of Trades-Offs and Synergies

Figure 7 illustrates the spatial allocations of interrelationships among the WESs during 2000–2020. Synergies among the WESs were found mostly in the southern and southeastern regions of the XJRB, which were characterized by extensive woodland distribution, as well as in the central and downstream areas, which were covered with cultivated land. Positive synergies among the WESs manifested in the upper reaches, where extensive grassland and woodland thrived due to the abundant vegetation cover and sufficient precipitation. Negative synergies were mainly located in relatively flat areas, construction land, water areas, and cultivated land due to the extensive use of fertilizers and poor management. Trade-offs were primarily located in regions with more pronounced land use changes, including the cultivated land and woodland in low hilly areas.

In 2020, the synergy/trade-off ratio between SR and WP (N) in the cultivated land reached 10.32. The services related to construction land were dominated by LL clustering because of the large degree of surface runoff and high nutrient export. The synergistic/trade-off ratios between SR and WP (N) and SR and WP (P) in 2020 were 9.05 and 19.45, respectively. Bare land predominantly occupied the northern region of the watershed, and the WC and SR services here were low due to the sparse vegetation coverage. The export of nutrients was also low because this area was less affected by human activities. Therefore, WC and SR showed significant synergies in terms of LL aggregation, while WC and WP, as well as SR and WP, showed pronounced trade-offs. Consistent stability was observed in the synergistic/trade-off ratios between WP, WC, and SR in bare land in 2015, ranging from 0.21 to 0.25. Additionally, the ratio between WC and SR was found to be 18.8.

Figure 7. Bivariate local spatial autocorrelation of pairs of WESs in XJRB in 2000–2020. High–High represents positive synergy relationships, Low–Low represents negative synergies, and Low–High and High–Low indicate trade-off relationships.

3.4. Ecological Management Zoning Based on the Clustering Characteristics

In the XJRB, the WESs have primarily been characterized by synergistic relationships throughout the last two decades, and the spatial clustering features have not changed significantly ($I < 0.35$). Considering the high Pearson coefficient between N and P export ($R^2 > 0.9$), we have selected the spatial aggregation characteristics between water conservation, soil retention, and water purification (N) in 2020 to construct zoning rules at the grid and country scales. Considering the importance of the WESs, the priorities of ecosystem services were ordered as follows: water conservation was ranked first, with soil retention coming next, and water purification third. The region was divided into three primary zones (core water management zones, general water management zones, and restoration water management zones) and eight secondary zones.

3.4.1. Constructing Zoning Rules

According to the characteristics of spatial clustering, each element can be divided into the HH, HL, LH, LL, or NN type. The core water management zones mainly consisted of HH clusters and were supplemented by insignificant distribution regions, which we then divided into core, key, and sub-key management units. The core management units were all characterized by HH clusters, indicating that the natural ecosystems of the elements and their surroundings were excellent. The key management units and sub-key management units were worse than the core management units, and were mainly characterized by HH clusters and non-significant correlation areas. General management zones were aggregated by HL or LH supplemented with NN clusters; this means that the high-value area of one service may be surrounded by a low-value area of another service. These were further divided into two sub-management units: priority management units and general management units. Priority management units were next to the sub-key management units and better than general units, while other areas with less significant aggregation characteristics and sporadic distributions were classified into general management areas. The LL or LH clusters were divided into restoration water management zones, which were then divided into three types of sub-restoration management unit. The natural ecosystems in these units were poor and fragile. Finally, we merged neighboring regions according to the combination rules (Table 3).

Table 3. Zoning rules based on bivariate local spatial autocorrelation types of WESs in 2020.

Zoning Types	Management Units (MU)	Bivariate Local Spatial Autocorrelation Types		
		WC–SR	WC–WP	SR–WP
Core water management zones	Core_MU	HH	HH	HH/LH
	Key_MU	HH	NN	NN
	Sub-key_MU	NN	HH	HH/LH
General water management zones	Priority_MU	NN	LH	HH/LH
	General_MU	ELSE	ELSE	ELSE
Restoration water management zones	Sub-key restoration_MU	LH	LH	HH
	Key restoration_MU	LL/LH	LH	LH
	Core restoration_MU	LL/HL	LL/HL	LL

3.4.2. Water Ecological Management Zones

Water ecological management zones were constructed based on the combination rules (Figure 8). The core water ecological management zones had good natural environments and excellent service functions, acting as natural barriers in water ecological protection. The areas of the core management units were 11,865 km^2, accounting for 56.8% of this zone (Figure 9). They were mostly found in the southern and southeastern areas of the XJRB, encompassing the central and southern regions of Yongzhou, Zhuzhou, and Chenzhou City. The primary land use categories within this unit were woodland and grassland. Key management units and sub-key management units accounted for 43.2% of this zone. Their spatial pattern closely resembled that of the core units. The area of the general management zones was 48,986 km^2, accounting for 48.49% of the total watershed. Among these, the priority management units only accounted for 10.38%. These were located in the transitional zones of woodland and cultivated land, and were mostly concentrated around the core management zones, including the low mountains and hilly areas of Hengyang, Yangzhou, and Chenzhou. The general management units were widely distributed, accounting for 89.62% of this zone. They were generally located in low, hilly areas and cultivated land, with no obvious spatial clustering characteristics. The restoration water ecological zone encompassed 31,155 km^2, accounting for 30.8% of the basin. It exhibited extensive distribution across cultivated land, water, and construction land in the western, central, and northern regions of the watershed. The areas of core restoration management units, key restoration units, and sub-key units were 23,047 km^2, 4236 km^2, and 3872 km^2, respectively.

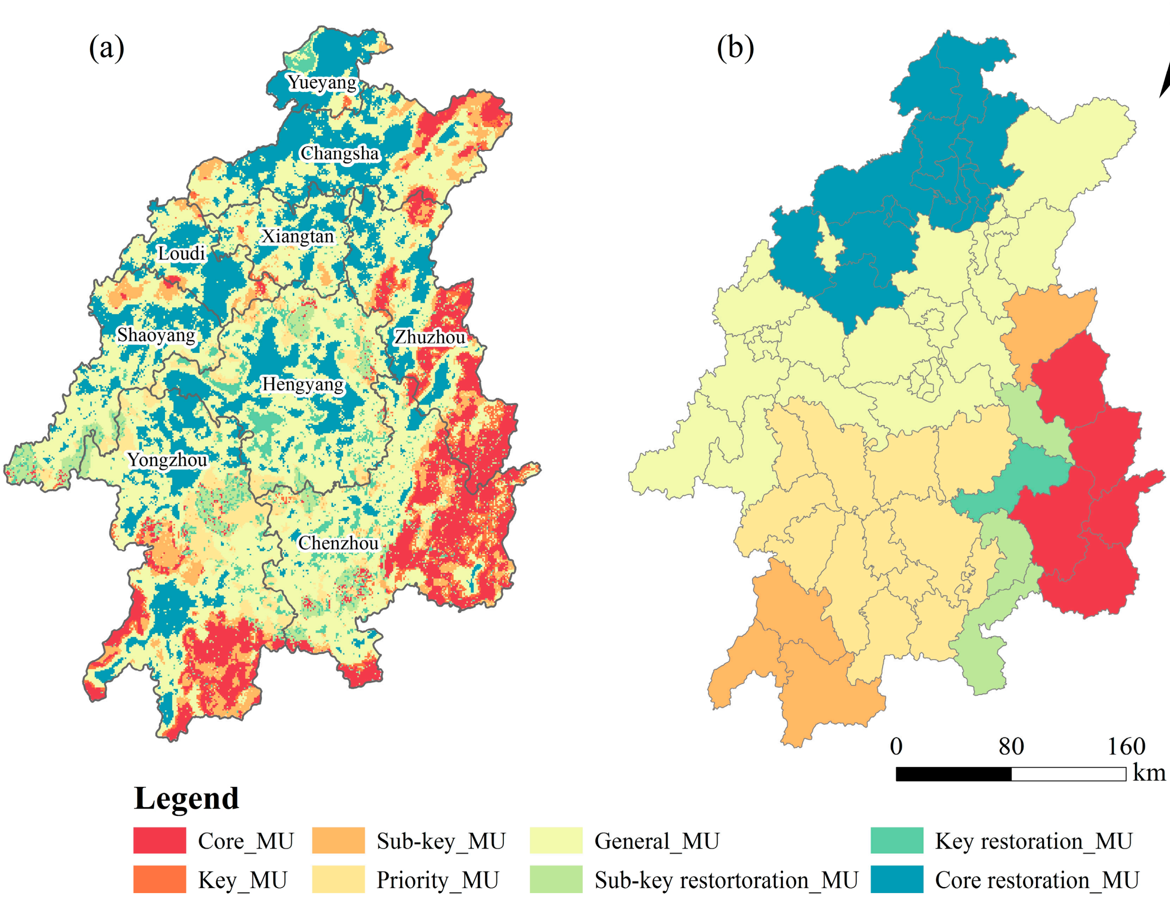

Figure 8. Water ecological management zoning for XJRB. (**a**) Water management zones at the grid scale. (**b**) Water management zones at the country scale.

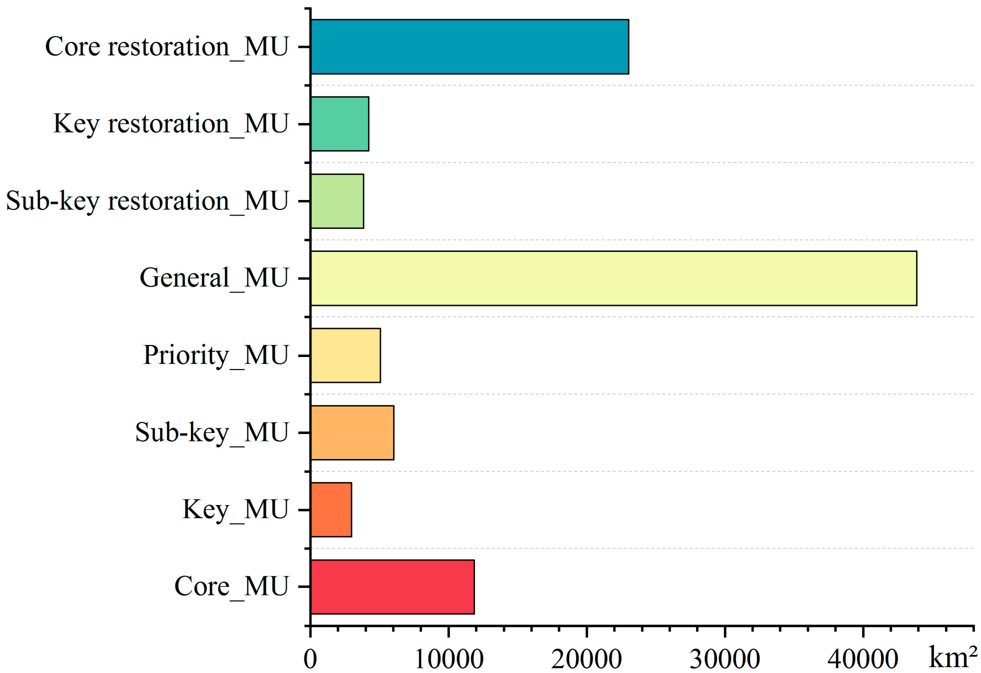

Figure 9. Areas of ecological management zones at the grid scale. MU = management unit—the secondary zones of water ecological management.

The zoning results at the country scale exhibited contiguous characteristics and maintained good consistency with the findings at the grid level (Table 4). The core water management zones covered nine counties. Among these, five counties (i.e., Chaling, Yanling, Rucheng, Guidong, and Zixing) were divided into core management units, and four (i.e., Jiangyong, Jianghua, Dao, and You) were divided into sub-key management units. No counties were divided into key management units. These counties were all situated in the southwestern and eastern regions of the watershed, and were characterized by excellent ecological conditions and minimal human disturbance. Greater emphasis should be placed on ecological preservation to ensure the sustainable delivery of ecosystem services in this area. There were 40 counties divided into general water management zones, accounting for 57.14% of the total. The priority management units covered 13 counties, mainly located in Yongzhou and Chenzhou (e.g., Lanshan, Xintian, Shuangpai, Qiyang, Jiahe, Guiyang, etc.). The ecological conditions in these areas were less favorable than those in the core management zones, but superior to those in other regions. The general management units were represented by 27 counties, the largest number of any of the partition units. They were widely dispersed throughout the central part of the basin, including most counties within Hengyang, Shaoyang, and Xiangtan Cities (e.g., Shaoyang, Shaodong, Xinshao, Hengyang, Hengnan, Hengshan, Qidong, Xiangtan, Liling, etc.). These are important grain-producing areas within the watershed. The focus in these counties was on attaining a harmonious equilibrium between ecological preservation and economic advancement. The restoration management zones covered 21 counties, among which 17 were divided into core restoration units, 3 (Suxian, Yizhang, Anren country) were divided into sub-key restoration units, and only 1 (Yongxing) in Chenzhou was divided into key restoration units. All of the core restoration units were distributed in the downstream area of the watershed, and were greatly influenced by human behaviors. The primary reason for the limited provision of WESs in this unit is the substantial conversion of ecological land into construction land, resulting in decreased water conservation, increased soil erosion, and heightened nutrient discharge.

Table 4. Water ecological management zoning at the county scale.

Zoning Types	Management Units (MU)	County
Core water management zones	Core_MU	Chaling, Yanling, Rucheng, Guidong, and Zixing
	Key_MU	
	Sub-key_MU	You, Dao, Jiangyong, and Jianghua Yao autonomous county
General water management zones	Priority_MU	Beihu and Lengshuitan districts; Leiyang, Changning, Guiyang, Jiahe, Linwu, Lingling, Qiyang, Shuangpai, Ningyuan, Lanshan, and Xintian
	General_MU	Liuyang, Liling, Xiangtan, Hengyang, Hengnan, Hengshan, Hengdong, Qidong, Xinshao, Shaoyang, Xinning, Shaodong, Lengshuijiang and Dongan country; Hetang, Lusong, Tianyuan, Lukou, Zhuhui, Zhengxiang, Nanyue, Shuangqing, Daxiang, Beita, and Louxing Districts.
Restoration water management zones	Sub-key restoration_MU	Suxian, Yizhang, and Anren
	Key restoration_MU	Yongxing
	Core restoration_MU	Changsha, Ningxiang, Xiangxiang, Shaoshan, Xiangyin, Miluo, Lianyuan and Shuangfeng; Tianxin, Furong, Yuelu, Kaifu, Yuhua, Wangcheng, Shifeng, Yuhu, and Yuetang Districts.

4. Discussion

4.1. Assessment of WESs and Variation in Trade-Off and Synergy

Three water-related ecosystem services were assessed from 2000 to 2020 in our study. Existing studies have often focused on the WESs of water yield, water purification, soil retention, and food production [81–83]. There are few studies focusing on the relationships between WC and other WESs. In our study, we considered water conservation as a crucial indicator when assessing regional hydrological regulation. It serves as a valuable metric for illustrating the natural ecosystem's ability to store and regulate water, and is significantly influenced by precipitation patterns and underlying surface conditions [15,84]. For instance, construction land exhibits a higher water yield compared to woodland due to the increased evapotranspiration from vegetation. Nonetheless, the degree of water conservation is relatively low under the same conditions due to the high surface runoff observed in construction land [85]. Therefore, WC, SR, and WP were selected as indicators of the water ecosystem services for our study.

The WESs in the XJRB could be divided into three stages during the study period. In the first, from 2000 to 2005, they decreased. At this stage, the rapid development of China's social economy placed significant pressure on the ecological environment, and the reduction in rainfall further contributed to a declining pattern regarding WESs. Then, the WESs gradually increased during 2005–2015, as is consistent with the findings of existing research [12,53]. The increased precipitation, the execution of the Grain for Green program, and the development of high-quality farmland were the main driving forces in this period [86,87]. However, from 2015 to 2020, the accelerated urbanization in China triggered the transformation of woodland and cultivated land into construction areas, consequently causing a swift decline in water ecosystem services [88]. Therefore, controlling the rapid expansion of urbanization and reducing the occupation of ecological land by construction land will improve the protection of the water ecological environment.

The trade-off and synergistic relationships were also investigated among the three WESs using both global and local bivariate spatial autocorrelations. The findings reveal that the interrelationships among WESs in the XJRB were all synergistic, as is consistent with the findings of existing studies [3,20,30]. However, the degrees of synergy varied during these years. The synergies between WC and SR and between WC and WP increased quickly from 2000 to 2015 due to the rapid growth of the population and urbanization, while the synergies between SR and WP were weakened during the same period. This is because rapid urbanization increases the quantity of water-impermeable surface, which enhances soil retention and water yield capacity [84,85]. However, it also contributes to an increase in nutrient discharge, thus weakening water the purification capacity [13]. Additionally, climate change also plays an important role in this process, especially via the direct effects of precipitation changes on the WESs [89,90]. From 2000 to 2015, there was a gradual increase in precipitation, which led to a significant improvement in WC and SR. Meanwhile, WP underwent a slight enhancement under the combined influences of climate change and human activity. Between 2015 and 2020, with rising temperatures and reduced precipitation [91], all three ecosystem services showed significant declining trends, and the trade-offs and synergies among these services also underwent significant shifts. As temperatures continue to rise and extreme weather events become more frequent in the future [92], the interactions among water-related ecosystem services will endure even greater impacts. For example, the rise in temperature may accelerate the evaporation of water resources and negatively affect SR and WC. The increasing frequency of extreme precipitation events may improve soil retention and water yield, but may also lead to flooding and nutrient erosion, subsequently affecting the water purification process [93]. Therefore, we should more closely examine the impacts of human activities and climate change on ecosystem services in order to better understand the dynamics and evolutions of these relationships.

4.2. Implications of Zoning Management

Water-related ecosystem services have significant impacts on both the natural environment and socioeconomic development. Core management zones represent the most important areas for WESs in the watershed. In these zones, it is critical to consider the protection of the environment as a primary goal. Specialized protection practices, such as redlines for ecological conservation and Grain for Green programs, should be implemented [94]. Social activities that damage the landscape, vegetation, topography, and landform should be strictly prohibited. On the other hand, development restrictions may affect the living standards and environments of native residents. Therefore, ecological compensation measures and tourism development activities can be pursued to improve the livelihood of local people [19,95]. Local governments need to increase financial support in order to achieve ecological civilization construction.

General water ecological management zones are predominantly located in the center of the watershed, and serve as the main areas for agricultural production. Emphasis should be placed on integrated agricultural production development and environmental protection in the administration of these areas. In general management zones, some regions with high service functions have been found to be surrounded by low-value services (e.g., HL clusters). In addition to maintaining the stability of high service functions, it is important to prevent assimilation by the surrounding areas, as this may lead to the deterioration of their original water ecological functions [96]. In transition regions between woodland and farmland, avoiding the conversion of woodland to cultivated land and promoting the growth of sparse woodland can benefit regional water ecological functions. In addition, establishing buffer zones along rivers can reduce soil erosion and nutrient emissions from agricultural activities.

Restoration water management zones were mostly found in the downstream regions, encompassing agricultural and construction areas, which were heavily affected by human activities [97]. The extensive management of cultivated land, along with the disposal of domestic and industrial wastewater, has exacerbated the difficulty of water environment protection in these areas [98]. Therefore, it is imperative for decision-makers to develop effective water ecological restoration polices that will enhance the provision of WESs. For agricultural areas, the consumption of fertilizers and pesticides can be reduced to limit the export of N and P. Optimizing agricultural planting structure and implementing intensive management practices are essential ways to harmonize food production and the agricultural ecological surroundings. Given its effects in terms of enhancing water conservation and soil retention, it is essential to consider converting steeply sloping cultivated land into woodland and grassland ecosystems. In the case of construction land, controlling rapid population growth and improving the treatment efficiency of industrial and domestic wastewater can effectively improve water ecological services. Additionally, reducing the agglomeration of construction land, improving the urban greening rate, and establishing urban ecological corridors are also important in mitigating the negative effects of urbanization on the environment.

4.3. Limitations and Prospects

Although the results of water ecological management zoning may offer beneficial information for water ecological governance in the XJRB, several drawbacks remain in the present research. Firstly, only three WESs and their relationships were quantified in this study. In future research, it will be important to incorporate other water-related services, such as food production and flood regulation, in order to comprehensively assess water ecosystem dynamics. Moreover, the accuracy of the results may be impacted by the constraints of the InVEST model. More accurate parameters and biophysical coefficients are needed in future studies. Secondly, this study did not consider the factors influencing WESs and their relationships, which limits our ability to fully understand the mechanisms behind WES changes. Therefore, it is imperative to explore the interplay between climate and human activities with regard to their effects on trade-offs in future research. Thirdly, ecological management zoning was based solely on the aggregation characteristics of WES supply, without considering the demand for these services. Integrating ecological service demand into management zoning is essential to achieve a more holistic and effective water ecosystem management strategy.

5. Conclusions

This study assessed three critical WESs in the XJRB during the period of 2000–2020 using the InVEST model. We examined the spatiotemporal variations and trade-offs among these WESs, and subsequently divided the watershed into three management zones and eight secondary zones by constructing a zoning rule. The conclusions are as follows:

(1) The three WESs showed fluctuating patterns throughout the study's duration, as they first decreased (from 2000 to 2005), then increased (from 2005 to 2015), and subsequently rapidly declined (after 2015). Among these WESs, WC and SR showed significant changes, with the most significant changes reaching 40.0% and 44.1% in 2015, respectively. WP services exhibited minor fluctuations throughout this period.

(2) The WESs exhibited significant spatial heterogeneity and dependence. The interrelationships of the WESs in the XJRB indicated both trade-offs and synergies, but synergistic relationships were the most prevalent. The woodland and grassland mainly presented positive synergy, while the cultivated land, water areas, and construction land mainly displayed negative synergy.

(3) In addition, the watershed was divided into core water ecological management zones, general water ecological management zones, and restoration water ecological management zones, with reference to the clustering attributes of the WESs. The core water ecological management zones were predominantly distributed in the southern and eastern parts of the watershed. The restoration of water ecological management zones was primarily clustered in the middle and lower reaches. General water ecological protection areas were mostly clustered in the transitional areas between cultivated land and woodland.

(4) Different management policies have been proposed for the three management zones. The protection of the natural ecosystem should be given top priority in the core management zones. Local governments should increase their financial support to negate the contradiction between environment protection and the improvement of residents' living standards. General management zones need to achieve a balance in the relationships between agricultural production and environmental protection, and to reduce soil erosion and nutrient output related to agricultural activities. More attention needs to be paid to the restoration management zones. Controlling the rapid growth of the population, improving the efficiency of industrial and domestic sewage treatment, and encouraging ecological construction are effective means by which to alleviate the pressure on the ecological environment in the region.

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Abbreviations

List of abbreviations used in the article (in alphabetical order).

CGCS2000	China Geodetic Coordinate System 2000
DEM	Digital Elevation Model
HH	High–High
HL	High–Low
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
LH	Low–High
LL	Low–Low
MA	Millennium Ecosystem Assessment
MU	Management Units
NN	Non-correlation
SR	Soil Retention
WC	Water Conservation
WESs	Water-related Ecosystem Services
WP	Water Purification
XJRB	Xiangjiang River Basin

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