land

Article

Comprehensive Ecological Functional Zoning: A Data-Driven Approach for Sustainable Land Use and Environmental Management—A Case Study in Shenzhen, China

Yu Li [1,*], Fenghao Zhang [2], Ruifan Li [2], Hongbing Yu [1,2], Yao Chen [3] and Han Yu [1,4,*]

[1] Guangdong-Hong Kong-Macao Greater Bay Area Environmental Technology Research Center, Shenzhen Research Institute of Nankai University, Shenzhen 518063, China; hongbingyu1130@sina.com
[2] College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China
[3] Shenzhen Lightsun Analysis and Testing Center Co., Ltd., Shenzhen 518029, China
[4] Department of Water Resources Engineering, Lund University, 22100 Lund, Sweden
* Correspondence: liyuhydro@nankai.edu.cn (Y.L.); yhh20212022@gmail.com (H.Y.)

Abstract: A comprehensive approach to ecological functional zoning in the Shenzhen region of China is presented in this study. Through the integration of advanced geospatial analysis tools, multiple data sources, and sophisticated statistical techniques, different ecological functions have been identified and categorized based on a comprehensive set of indicators and spatial analysis techniques. The three-level zoning framework established in this study offers policymakers, urban planners, and environmental managers a nuanced understanding of the region's environmental characteristics, and highlights areas of ecological significance that warrant special attention and protection. It has been demonstrated that the data-driven approach to ecological functional zoning is effective in delineating distinct ecological zones within the study area. This study's findings carry significant implications for future land use planning, conservation efforts, and sustainable development practices in the Shenzhen region. In essence, this study contributes to the broader discourse on ecological planning and environmental management by providing a systematic and data-driven approach to delineating ecological functional zones in urbanizing regions.

Keywords: ecological functional zoning; data-driven approach; sustainable land use; environmental management

Citation: Li, Y.; Zhang, F.; Li, R.; Yu, H.; Chen, Y.; Yu, H. Comprehensive Ecological Functional Zoning: A Data-Driven Approach for Sustainable Land Use and Environmental Management—A Case Study in Shenzhen, China. *Land* **2024**, *13*, 1413. https://doi.org/10.3390/land13091413

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 26 July 2024
Revised: 28 August 2024
Accepted: 30 August 2024
Published: 2 September 2024

1. Introduction

Ecological functional zoning is a vital endeavor that revolves around the regional ecological environment [1,2]. The interconnectedness and mutual constraints of ecological factors within a region give rise to diverse structures, facilitate various ecological processes, deliver a range of services to humanity, and ultimately shape the regional ecological environment [3,4]. The spatial division or integration of ecological functional regions is based on overarching connectivity, spatial continuity, ecological process similarity and dissimilarity, service function characteristics, and the intensity of human activities.

The origins of ecological zoning can be traced back to 1898, when Merriam conducted a comprehensive classification of biological zones and crop zones in the United States, establishing the foundation for a biological-based ecological zoning approach [5]. In recent years, significant progress has been made in applying remote sensing and machine learning techniques to study land–water interfaces and ecological systems [6–8]. Although many studies have employed machine learning algorithms to classify land cover and plant communities in coastal regions, the focus has primarily been on analyzing individual spatial data layers without exploring the interactions and mutual influences among different layers [9,10]. While notable regional-scale ecological zoning efforts have been undertaken [11,12], these initiatives have mainly concentrated on natural ecological factors with limited consideration for the role of humans within ecosystems [13]. Addressing pressing global challenges such as population growth, resource scarcity, and environmental degradation, ecologists have redirected their attention to ecological zoning, recognizing the limitations of past approaches and acknowledging the vital role and impact of human activities on resource development and environmental conservation [14,15].

Chinese researchers have also made significant contributions to the field of ecological zoning [16–19]. Li's work on ecological sensitivity and ecosystem service functions in Hainan Province, as well as Yang's foundational research on national ecology, exemplify efforts to provide a scientific basis for regional economic development policies, sustainable resource management, and ecological preservation [20,21]. Furthermore, Fu [22] proposed a comprehensive framework for national ecological zoning, dividing the country into 3 ecological zones, 13 ecological regions, and 54 ecological areas, considering ecosystem service functions, sensitivity, and human influences. Hong et al. [23] established an ecological vulnerability assessment indicator system comprising nine elements and twelve indicators, focusing on ecological sensitivity, ecological pressure, and self-resilience. It spatially identifies ecologically vulnerable areas within a highly urbanized region. Highly vulnerable areas, primarily located in the western region and intertwined with urban functional zones, suggest the need for establishing an ecological red line and enforcing stringent controls akin to China's existing ecological protection laws. The Chinese government is vigorously advancing its carbon market and began establishing the national carbon market in December 2017 [24]. The efficiency of market information is a crucial measure of market maturity and is essential for participants to devise trading strategies. As one of the pilot cities, Shenzhen's policies play a significant role in its comprehensive ecological functional zoning [25].

However, there is a lack of research on hierarchical methods for coastal ecosystems and the establishment of comprehensive protection systems at the intersection of highly developed areas and urban environments [26–29]. Liu et al.'s study [30] underscores the complexity of economic development's impact on the environment, highlighting differing trends between production and consumption-related pollutants. It suggests that targeted policies addressing both industrial production and consumption patterns are crucial for achieving sustainable development goals in rapidly urbanizing regions like Shenzhen. Ecological security patterns (ESPs) integrate landscape patterns and ecological processes to enhance ecological connectivity, promoting the coordinated development of social systems and ecosystems [31]. Wang et al. [32] chose townships in the Tacheng Basin, Xinjiang, China, as the basic research units, and established an evaluation index system covering ecological protection, agricultural production, and urban development suitability, and they analyzed them using spatial analysis functions and an exclusive matrix method. An assessment system integrating ecological security and economic development was constructed for evaluating these areas, fully considering drivers such as precipitation, temperature, topography, soil, land use, geological disasters, and landscapes that impact the ecosystem [33]. While previous ecological zoning research has primarily focused on large-scale land and watershed spaces, there are a limited number of comprehensive studies on small to medium-scale urban coastal areas, impeding the development of guiding research results used for reference [34,35].

In conclusion, while ecological zoning and mapping have garnered significant attention and research efforts, there is untapped potential for further exploration and development, particularly in addressing the complex ecological challenges at the intersection of urban and highly developed areas. This calls for a concerted effort to advance ecological zoning research and develop comprehensive protection strategies to ensure the sustainable coexistence of human activities and natural ecosystems. The purpose of this study is to propose the theoretical basis and specific zoning techniques for three-level ecological functional zoning at medium and small scales, and to validate and apply this method in the study area.

2. Methodology

This section introduces a comprehensive three-level framework for regional ecological functional zoning, focusing on the scales of watershed, sub-watershed, and river. To further achieve refined management of river basins, a three-level zoning theory is proposed based on the structural characteristics of the ecosystem, building on primary and secondary zoning of the river basin. This theory aims to reflect the spatial differences in the functions of the river basin's ecosystem.

2.1. Zoning Methods

Utilizing a top–down approach, the first and second levels of ecosystem function zoning in watersheds are analyzed using cutting-edge remote sensing and Geographic Information System (GIS) technologies. Large-scale factor distribution maps are spatially overlapped to construct ecological zoning based on various types of aquatic ecosystems. The third-level zoning employs a bottom–up approach at a smaller scale, involving an in-depth analysis of major ecological environmental factors within the study area using GIS techniques and remote sensing. Weight coefficients for indicators are determined in collaboration with expert experience to calculate the zoning values for each level, with the sub-watershed serving as the fundamental unit for zoning. The specific process is detailed in Figure 1. Based on the spatial ecological pattern and evolution characteristics formed under the combined influence of natural geographical features and human activities in Shenzhen City, this paper proposes a three-level framework for ecological functional zoning, corresponding to the spatial scales of watershed, sub-watershed, and river. Different levels of zoning employ different indicators, with subordinate zones constrained by the scope of higher-level zones.

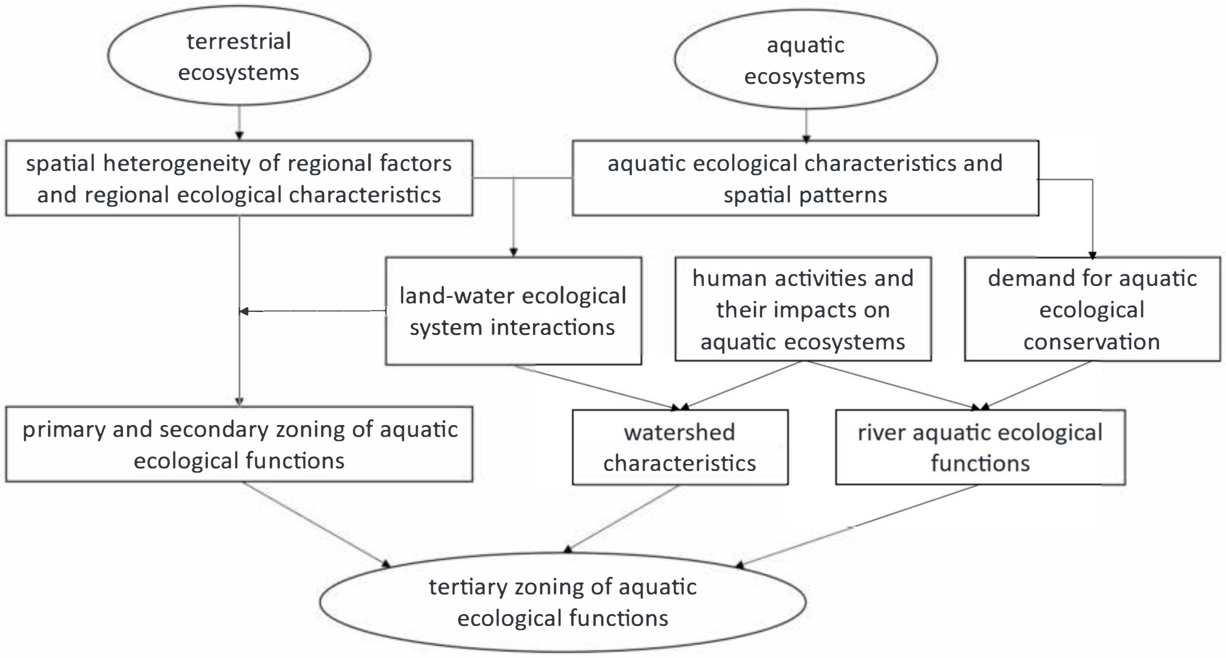

Figure 1. The process flowchart for watershed ecological functional zoning.

2.2. Sub-Watershed Unit Division Techniques

The determination of the study area's scope and boundary involves generating the watershed boundary through the application of a digital elevation model (DEM) and adjusting the sub-regions based on the water system map. The resolution of the DEM utilized for sub-watershed division is intricately determined based on data availability and the scale of the three-level zoning, typically employing a 90 m resolution elevation dataset.

2.3. Construction of Indicator System for Three-Level Zoning

The selection of indicators for three-level zoning primarily revolves around considering the influential factors of watershed characteristics on the structure of water ecosystems, aiming to differentiate the characteristics of diverse regional habitats and functional disparities. Not only do the natural conditions of rivers play a pivotal role, but the surrounding landscape and human activities are also significant factors impacting river ecosystems at the catchment scale. Therefore, the selection of candidate indicators for three-level zoning should encapsulate the influence of both natural and human activities on the structure of water ecosystems.

2.4. Techniques for Identification of Main Functions

Based on the established zoning and classification system for rivers in Shenzhen, Zhang et al. [36] focused on the ecological flow of the Shenzhen River. This research underscores the importance of tailored ecological flow assessments based on river characteristics and geographical zones, contributing to more effective and sustainable river management strategies.

The framework proposes a three-level hydro-ecological functional zoning system corresponding to three spatial scales: basin, sub-basin, and river. This aims to achieve finer-scale watershed management. Based on primary and secondary divisions within the watershed, the theory proposes a three-level zoning approach grounded in the structural characteristics of aquatic ecosystems. This framework aims to reflect spatial variations in the functional capabilities of watershed aquatic ecosystems.

The indicators for each level of zoning reflect specific features influenced by regional backgrounds at the ecosystem type level for the primary zone, and spatial differentiation rules for natural environmental factors such as topography, climate, and hydrology affecting regional ecosystem differences at the watershed scale. The indicators for the secondary zone reflect spatial differentiation rules for natural environmental factors such as topography and vegetation affecting regional ecosystem differences at the sub-watershed scale. The indicators for the tertiary zone characterize the river type and functional differences influenced by land use and river structures at the watershed scale. Tölgyesi et al. [37] used single statistical tests to compare vegetation units based on relative ecological indicator values with different approaches and weighting methods. The weights of the evaluation indicators are determined through an extensive literature review and expert judgment [38,39].

In summary, this study presents a robust framework for regional ecological functional zoning, incorporating state-of-the-art technologies, expert insights, and comprehensive indicator systems to effectively manage ecosystem functions within watersheds.

3. Case Study

3.1. Overview of the Study Area and Data

Shenzhen, a prominent city comprising nine administrative districts and one new district, occupies a land area of 1997.47 square kilometers. Situated in the south-central coastal region of Guangdong Province, China (as shown in Figure 2). Shenzhen's rapid development faces significant challenges due to its scarcity of resources and energy as one of China's initial cities committed to low-carbon development [40]. The city's economic, social, and ecological demands are substantial, necessitating an urgent exploration of pathways toward green, low-carbon, and efficient development. Shenzhen's urban development is intertwined with a complex ecological pattern shaped by both natural evolution and recent human interventions [41]. The integration of land and sea forms a sophisticated system, wherein the destruction of terrestrial and marine ecosystems, regional cross-media pollution, and interactions between natural and anthropogenic factors pose severe environmental stressors, hindering sustainable development. Long-standing segmented management of terrestrial and marine ecological environments exacerbates this challenge. The city's development is intricately linked to material and energy exchanges between its urban and marine components, reflecting a coupled and mutually influential integrated ecological system. Effective environmental strategies must therefore adopt a holistic approach, coordinating land–sea management to address ecological challenges and provide robust theoretical and technological support for Shenzhen's sustainable development as a special economic zone.

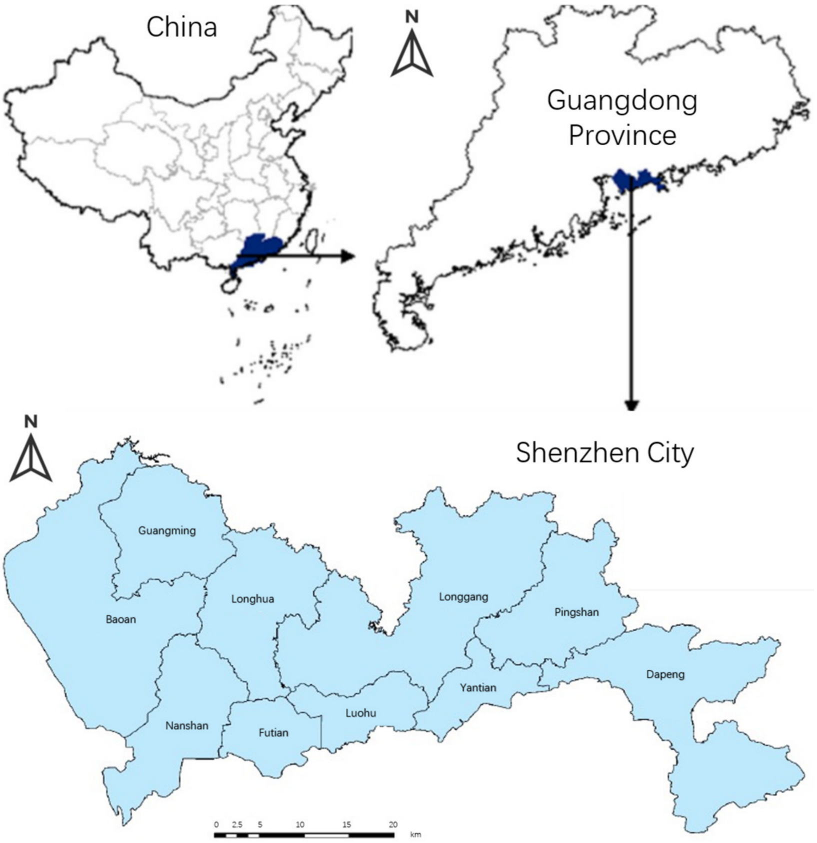

Figure 2. The boundary of Shenzhen City and its location in Guangdong Province, China.

The land use data for Shenzhen in 2020, including the classification data based on GlobelLand30, are sourced from various entities. Socio-economic data, such as population and GDP, are provided by the Resource and Environmental Science and Data Center. Climate and environmental data, including soil type, annual average temperature, and annual average precipitation, are also sourced from the Resource and Environmental Science and Data Center. Elevation and slope data come from the Geographic Spatial Data Cloud, while the distances to water bodies (rivers) and lakes are obtained from the National Geographic Information Resource Catalog Service System. All data are projected using the WGS_1984_UTM_Zone_51N coordinate system.

High-resolution geospatial data, including the 1:250,000 digital elevation model (DEM) and 1:250,000 water system map of the Shenzhen region, were utilized in this study, in conjunction with advanced geospatial analysis tools such as the Arc Hydro Tools module in ArcGIS 10.8. Predefined sub-division criteria for sub-regions were adhered to, leading to the successful delineation and extraction of small watershed units within the urban expanse of Shenzhen. A total of 148 defined sub-region units across the entirety of the study area were yielded by analysis, as illustrated in Figure 3.

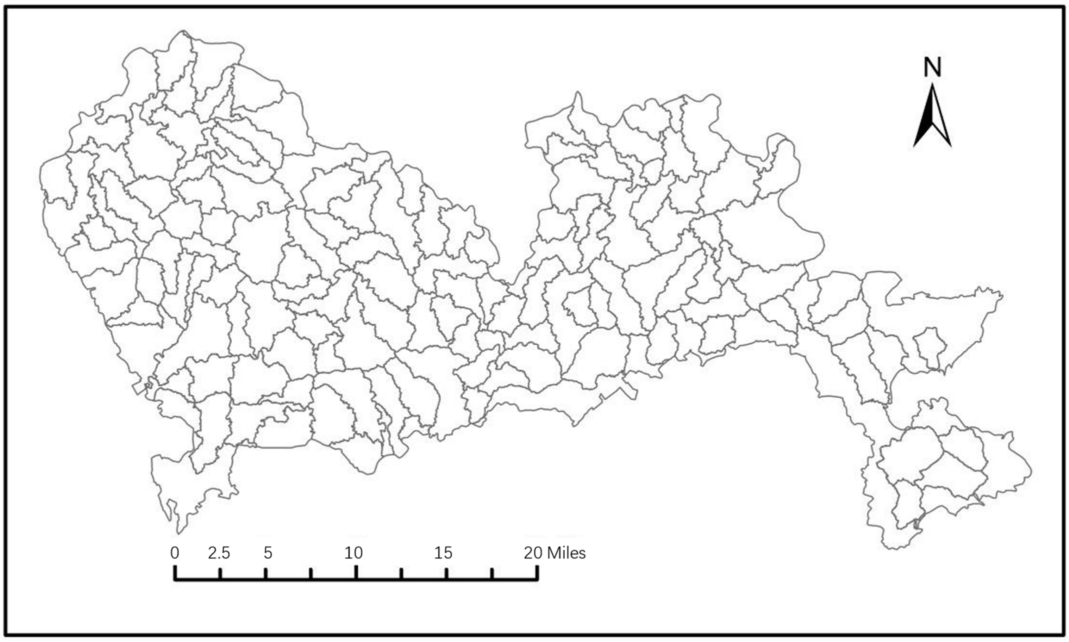

Figure 3. The sub-regional unit map of Shenzhen City.

This detailed geospatial analysis not only provides valuable insights into the unique topographical characteristics of Shenzhen, but also lays a solid foundation for further research in urban planning, environmental management, and sustainable development initiatives within the region.

3.2. Identification of Candidate Indicators

The establishment of a three-level ecological function sub-division index necessitates the incorporation of watershed characteristic indicators, along with the assessment of human activities' influence on aquatic ecosystems. Considering the distinctive features of the Shenzhen region and considering the ecological relevance, typology, and accessibility of sub-division indicators, a meticulous selection of candidate indicators and their corresponding ecological significance was undertaken and is comprehensively presented in Table 1.

Table 1. Statistical values of alternative indicators of zoning.

	Index	Unit	Minimum	Maximum	Range	Mean	Standard Deviation	Coefficient of Variation (%)
F1	Forest Area Ratio	%	0.00	100.00	100.00	36.00	34.50	95.92
F2	GDP Per Unit Area	10^4 CNY/km^2	0.00	29,550.30	29,550.30	362.67	1343.41	370.42
F3	Drainage Density	km^{-1}	0.00	6.60	6.60	0.46	0.44	96.64
F4	Farmland Area Ratio	%	0.00	100.00	100.00	37.00	31.50	85.13
F5	Urban Area Ratio	%	0.00	95.00	95.00	3.00	6.12	204.20
F6	Watershed Slope	Degree	0.00	17.56	17.56	4.00	3.61	90.14
F7	Watershed Slope Direction	-	0.00	286.24	286.24	170.43	21.31	12.50
F8	Water Area Ratio	%	0.00	100.00	100.00	3.00	8.90	296.67
F9	Volume of Water	mm	0.00	13,667.88	13,667.88	5419.74	1085.70	20.03
F10	Population Density	p/km^2	0.00	10,841.00	10,841.00	116.91	446.76	382.13
F11	Grassland Area Ratio	%	0.00	100.00	100.00	11.00	15.90	144.30

The indicators used in three-level zoning play a crucial role in assessing how watershed characteristics shape aquatic ecosystems, delineating diverse habitat features and functional distinctions among different geographical regions. These indicators encompass not only the inherent natural conditions of rivers, but also the broader landscape context [42]. Moreover, human activities, particularly alterations in local land use patterns, exert profound impacts on riverine ecology at the watershed scale. Thus, when selecting alternative indicators for tertiary zoning, it is essential to consider these anthropogenic influences alongside natural factors [43,44]. Methods employed for indicator selection include rigorous sensitivity analyses to gauge data variability, spatial autocorrelation analyses to understand the spatial patterns of the environmental factors, and statistical approaches such as the Principal Component Analysis and correlation analyses to identify key influencing factors.

The data sources and acquisition methods for these candidate indicators encompassed a range of thematic maps, such as digital elevation models, water system maps, administrative boundary maps, and land use maps specific to the Shenzhen region provided by the Resource and Environmental Science and Data Center, China. The spatial resolution of the geographic information is 90 m. Each thematic map was integral to the calculation of the sub-division index.

Drawing upon the 2020 vector data map of land use in Shenzhen offered by the Resource and Environmental Science and Data Center, China, this study focused on the extraction of six distinct land use categories, namely farmland, forest land, grassland, water area, urban area, and unused layers. An overlay analysis was conducted to derive dBase-type data for each layer within the small watershed unit, facilitating subsequent calculations of the proportion of land use types within each specific small watershed unit using the following Formula (1):

$$P_I(\%) = \frac{\sum A_i}{\sum A_T} \tag{1}$$

where P_I is the area proportion of each land type, A_i is the area of each land type in each small watershed unit, and A_T is the area of the delineated small watershed.

3.2.1. Sensitivity Analysis of Indicators

The usability of data in a sub-division analysis is contingent upon its sensitivity. Hence, the candidate indicators for the Shenzhen sub-division underwent an initial sensitivity analysis using SPSS 20.0 software to assess their suitability. The coefficient of variation for each indicator is detailed in Table 1. Notably, indicators such as population density, GDP per unit area, urban area ratio, and grassland area ratio exhibited coefficients of variation exceeding 100%, signifying substantial variability capable of capturing spatial environmental nuances and thus enhancing the efficacy of the sub-division analysis. Conversely, the watershed slope and water volume demonstrated coefficients of variation at 12.50% and 20.03%, respectively, indicating minimal variability and homogeneous characteristics across the watershed.

Consequently, guided by the sensitivity analysis outcomes, the watershed slope direction and water volume were excluded from further consideration. The ensuing selection of indicators for an in-depth analysis comprised population density, GDP per unit area, water area ratio, urban area ratio, grassland area ratio, drainage density, forest area ratio, watershed slope, and farmland area ratio.

3.2.2. Factor Analysis

In this study, a factor analysis was conducted to identify the primary factors that define the water environment in Shenzhen and to select indicators with the most significant contribution to the sub-division results. The varimax rotation method [45] was employed to ensure the independence of factors, and the determination of the number of common factors extracted was based on the criterion that the eigenvalue should surpass 1.0 [46]. Table 2 presents the characteristic values of the candidate indicators at various sub-division levels, indicating the extraction of four common factors.

Table 2. Eigenvalues of factor analysis of alternative indicators.

Principal Component	Initial Eigenvalue			Selection Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Sum	Variance %	Accumulate %	Sum	Variance %	Accumulate %	Sum	Variance %	Accumulate %
1	2.890	32.110	32.110	2.890	32.110	32.110	2.461	27.341	27.341
2	1.717	19.076	51.186	1.717	19.076	51.186	2.063	22.924	50.265
3	1.372	15.241	66.426	1.372	15.241	66.426	1.411	15.680	65.945
4	1.095	12.171	78.597	1.095	12.171	78.597	1.139	12.652	78.597

Refer to Table 3 for the composition matrix post-factor rotation utilizing the maximum variance orthogonal method. In the current study, factor loadings greater than 0.75 were deemed significant [47] and this classification was adopted by Singh et al. [48] and Qian et al. [49]. Indicators exhibiting factor loading values surpassing 0.75 were selected, encompassing forest area ratio, farmland area ratio, watershed slope, population density, urban area ratio, water area ratio, drainage density, and GDP per unit area, for further scrutiny.

Table 3. Alternative index factor analysis rotation component matrix.

	Principal Component 1	Principal Component 2	Principal Component 3	Principal Component 4
Zscore (F1)	0.932	−0.218	−0.118	−0.142
Zscore (F2)	−0.013	−0.086	−0.064	0.977
Zscore (F3)	−0.082	0.030	0.821	0.062
Zscore (F4)	0.854	0.061	−0.174	−0.361
Zscore (F5)	−0.222	0.841	−0.058	−0.091
Zscore (F6)	0.884	−0.107	−0.172	−0.097
Zscore (F8)	−0.031	0.047	0.765	−0.105
Zscore (F10)	−0.057	0.885	−0.062	−0.036
Zscore (F11)	−0.013	0.727	0.252	0.001

3.2.3. Aquatic Biological Correlations Analysis

The correlation between environmental indicators and aquatic biological attributes was examined to elucidate the principal environmental factors influencing the spatial distribution of aquatic ecosystems, and to ascertain the environmental indicators exhibiting strong correlations with the spatial distribution of aquatic organisms. Leveraging aquatic biological survey data spanning from 2015 to 2020 in the Shenzhen region, ArcGIS software was adeptly employed to extract the sub-division index data for each sampling point's small watershed, composing an environmental data matrix comprising candidate sub-division indicators.

Initially, a detrended correspondence analysis (DCA) [50] was conducted on the algae indicators, revealing an eigenvalue of 2.208 < 4, thereby indicating the appropriateness of a redundancy analysis (RDA) [51] for probing the relationship between the algae plant community and sub-division indicators. Through a Mantel Carlo test analysis in RDA, all sub-division indicators exhibited noteworthy correlations with the first sorting axis (AX1) ($F = 30.321$ and $p = 0.002$) and all sorting axes ($F = 2.971$ and $p = 0.004$).

The RDA analysis outcomes concerning the algae plant community and environmental factors are delineated in Table 4. Drawing insights from the factor analysis results, four common factors were discerned. The foremost eigenvalue surfaced on the first sorting axis (AX1), which emerges as the predominant factor dictating the distribution of algae plant communities. AX1 mirrors the extent of the environmental factors' impact on the distribution of algae plant communities, with a correlation coefficient of 0.720 between AX1 and the environmental factors, signifying a robust correlation. The Shenzhen sub-division candidate indicators and algae plant community RDA dual-axis plot are portrayed in Figure 4. The arrows symbolize the candidate sub-division indicators, with the length of the line segment denoting the degree of correlation between the indicator and the biological community, the angle between the arrow connection and the sorting axis representing the level of correlation with the water environment, and the quadrant in which the arrow is positioned indicating a positive or negative correlation with the water environment.

Table 4. RDA analysis results of algae community and environmental factors.

Axis	Eigenvalue	Correlation Coefficient	Cumulative Percentage of Variance	
			Species	Species-Environment
AX1	0.464	0.720	46.438	96.109
AX2	0.008	0.483	47.323	97.920
AX3	0.006	0.547	47.935	99.243
AX4	0.004	0.292	48.321	100.000

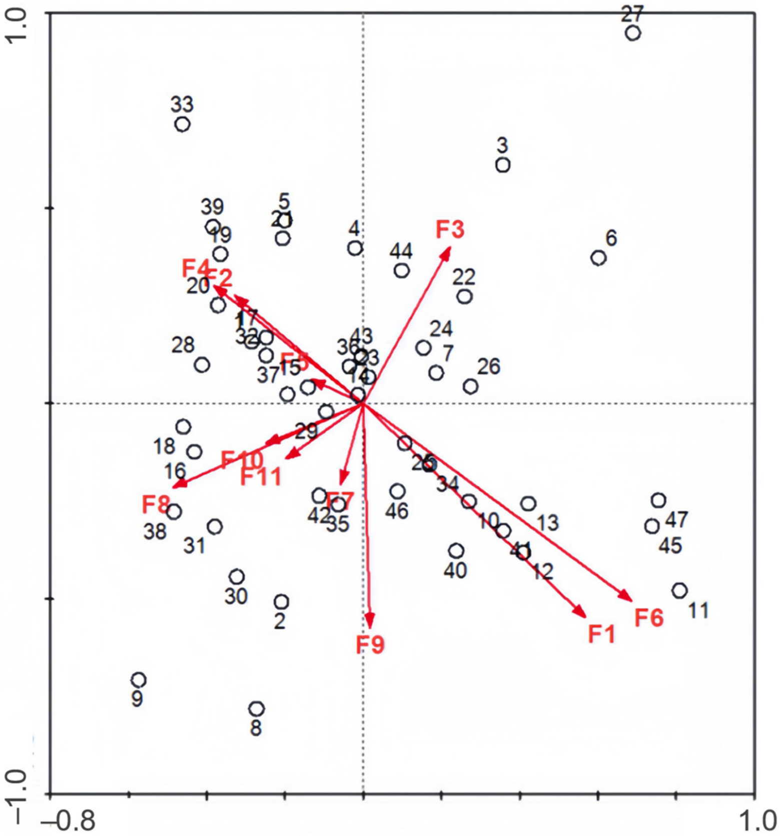

Figure 4. Alternative indicators of tertiary zoning and RDA analysis results of algae community.

Based on the findings presented in Figure 4, it is evident that watershed slope (F6) exhibited a positive correlation with AX1, demonstrating the highest correlation coefficient of 0.495. Similarly, forest area ratio (F1) demonstrated a positive correlation with AX1, boasting a correlation coefficient of 0.4098. In contrast, water area ratio (F8), farmland area ratio (F4), and GDP per unit area (F2) were found to be negatively correlated with AX1, with corresponding correlation coefficients of −0.350, −0.276, and −0.236, respectively. Although population density (F10), urban area ratio (F5), and drainage density (F3) did not exhibit significant correlations with AX1, the retention of the urban area ratio was deemed essential to signify the impact of human activities on aquatic ecosystems.

3.2.4. Correlation Analysis

To assess the independence of information among the selected parameters, a correlation analysis was conducted on the ecological correlation-selected indicators, employing the correlation coefficient to quantify the relative strength of the relationship between the quantitative variables. When the absolute value of the correlation coefficient $|R| < 0.5$, it suggests a substantial degree of information overlap between the two indicators, thereby necessitating the removal of environmental factors with diminished information content to uphold the independence of the sub-division indicators [52].

The outcomes of the indicator correlation analysis are detailed in Table 5. Notably, the correlation coefficients between forest area ratio and watershed slope, as well as farmland area ratio, were determined to be 0.422 and 0.444, respectively. Furthermore, the correlation coefficient between watershed slope and farmland area ratio stood at 0.399, bearing a significant level of 0.000, signifying a substantial correlation. Additionally, the correlation coefficient between urban area ratio and watershed slope was determined to be −0.254, also demonstrating a significant correlation. Despite the significant correlation trends observed in the candidate indicators for the three-level sub-division, their correlation coefficients all fell below 0.5, indicating a limited degree of information overlap between the candidate indicators, thereby warranting their retention.

Table 5. Correlation analysis matrix of three-level alternative indicators.

		F1	F2	F4	F5	F6	F8
F1	Pearson correlation	1					
	Significance (bilateral)						
F2	Pearson correlation	−0.129 **	1				
	Significance (bilateral)	0.000					
F4	Pearson correlation	−0.444 **	−0.290 **	1			
	Significance (bilateral)	0.000	0.000				
F5	Pearson correlation	−0.303 **	−0.143 **	0.242 **	1		
	Significance (bilateral)	0.000	0.000	0.000			
F6	Pearson correlation	0.422 **	−0.043 **	−0.399 **	−0.254 **	1	
	Significance (bilateral)	0.000	0.000	0.000	0.000		
F8	Pearson correlation	−0.117 **	−0.078 **	−0.050 **	0.068 **	−0.141 **	1
	Significance (bilateral)	0.000	0.000	0.000	0.000	0.000	

** Significant correlation at 0.01 level (bilateral).

In summary, following a correlation analysis, six indicators—forest area ratio, urban area ratio, GDP per unit area, water area ratio, watershed slope, and farmland area ratio—were identified as the three-level sub-division indicators for ecological function in Shenzhen.

3.3. Shenzhen City Ecological Function Three-Level Zoning

3.3.1. Zoning Index Spatialization

The spatialization of various indicators was conducted to illustrate the spatial distribution and variation of Shenzhen City's ecological function three-level zoning indicators, as depicted in Figure 5. Variations in the six zoning indicators were observed.

The forest area ratio in Shenzhen City ranges from 0 to 100%, with a total forest area of approximately 64,323.61 hectares and an average forest area ratio of 32%. This encompasses various types of forest land such as tree forests, bamboo forests, shrub lands, and other forest lands. The distribution shows larger forest areas in high-altitude mountainous regions and smaller forest areas in low-altitude plain areas. Specifically, tree forests cover 62,682.69 hectares, accounting for 97%; bamboo forests cover 42.86 hectares, accounting for 0.07%; shrub lands cover 747.21 hectares, accounting for 1.16%; and other forest lands cover 850.85 hectares, accounting for 1%. Forest lands are predominantly concentrated in the Dapeng, Longgang, and Pingshan districts, constituting 63% of the city's forest land.

The agricultural land area ratio in Shenzhen City ranges from 0 to 50%, with a cultivated land area of approximately 2844.74 hectares and an average agricultural land area ratio of 2%. This includes paddy fields, irrigated lands, and dry lands. Cultivated lands are mainly clustered in the Guangming, Bao'an, and Pingshan districts, representing 66% of the city's cultivated land.

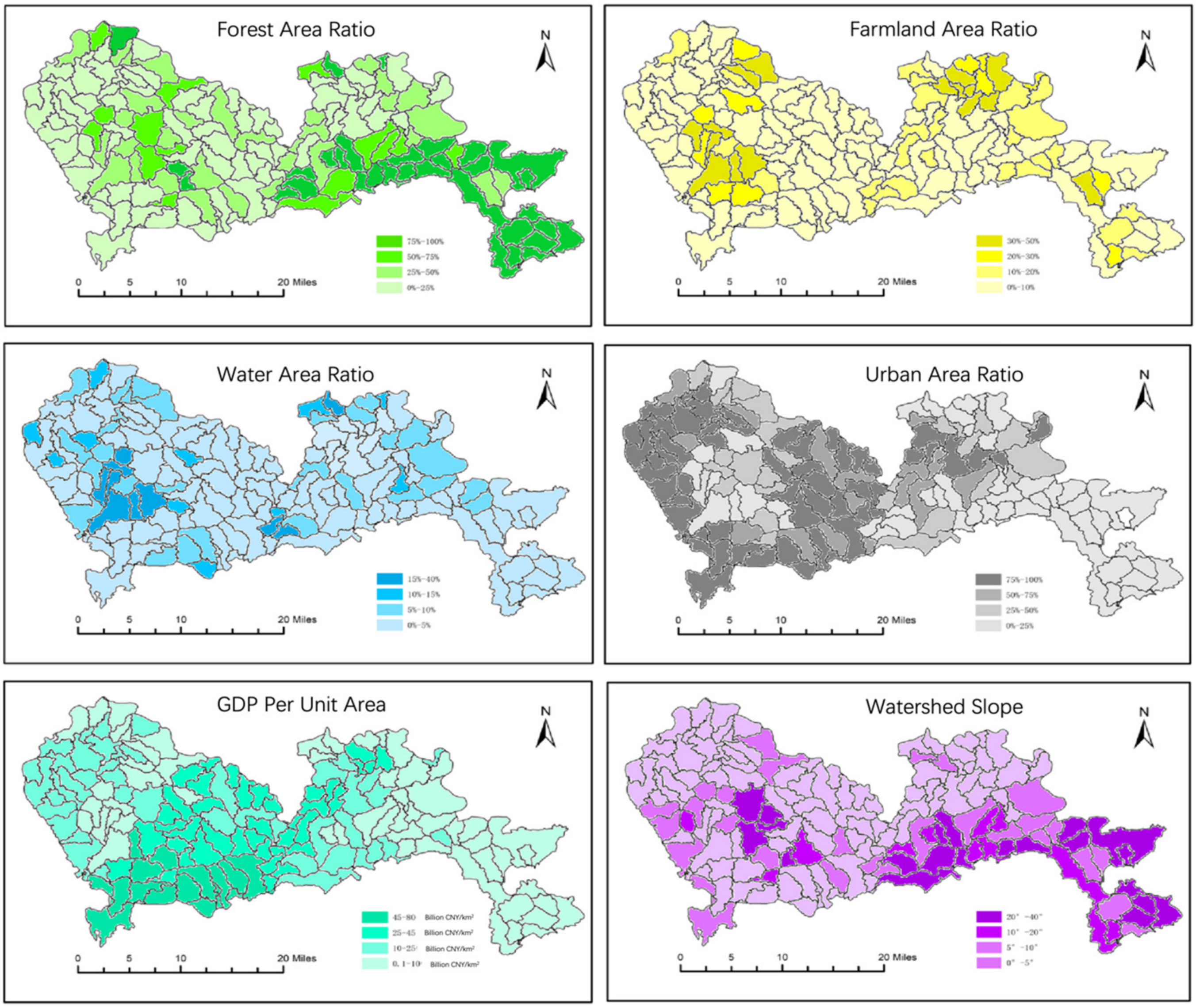

Figure 5. Map of Shenzhen City's ecological function three-level zoning indicators.

The water area ratio in Shenzhen City ranges from 0 to 35%, with water bodies and water facilities covering approximately 9392.55 hectares and an average water area ratio of 5%. This includes river water surfaces, lake water surfaces, reservoir water surfaces, pond water surfaces, channels, and water engineering construction lands. Water bodies and water facilities are prominently present in the Bao'an, Longgang, and Dapeng districts, comprising 58% of the city's water area.

The urban area ratio in Shenzhen City spans from 0 to 100%, with urban, rural village, and industrial lands covering approximately 92,416.05 hectares, with an average of 46%. This category includes various types of urban lands, rural residential areas, mining and industrial construction areas, scenic spots, and special land uses.

The GDP per unit area in Shenzhen City ranges from 0.1 to 7.2 × 10^5 CNY/km^2, with an average value of 1.62 × 10^5 CNY/km^2. The distribution closely aligns with the urban area ratio distribution in Shenzhen City.

The regional slope in Shenzhen City ranges from 0 to 39.56 degrees, with an average of 5 degrees. Steeper slopes are predominantly found in Dapeng New District, Yantian District, and the junction of the Nanshan and Bao'an Nanshan districts.

3.3.2. Indicator Weight

This study employs the entropy weight method [53] to determine the weight of each indicator. This method objectively evaluates the importance of indicator factors based on the information provided by the observation values of each indicator. The calculation steps are detailed as follows [53]:

Construct an $i \times j$ matrix with the indicator data as column vectors.

Calculate the characteristic weight (P_{ij}) of the j-th indicator for the i-th measurement value using Formula (2).

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{2}$$

Compute the entropy of each indicator (e_j) based on the characteristic weight using Formula (3).

$$e_j = -\frac{1}{ln\ n}\sum_{i=1}^{n} P_{ij} ln\ P_{ij} \tag{3}$$

Determine the weight of each indicator (w_j) according to Formula (4).

$$w_j = (1 - e_{ij})/\sum_{j=1}^{n}(1 - e_{ij}) \tag{4}$$

The results of the ecological indicators' weights in Shenzhen City are presented in Table 6.

Table 6. Weight of zoning indicators.

Index	**Weight**
Forest area ratio	0.170
farmland area ratio	0.140
Water area ratio	0.246
Urban area ratio	0.256
GDP per unit area	0.068
Watershed slope	0.120

3.3.3. Comprehensive Indicators Analysis

Following the determination of the weight factors for each indicator, a weighted sum calculation is applied to each zoning indicator within the range of each zoning unit. This process yields the comprehensive value for each small watershed in Shenzhen City. The spatial distribution map illustrating Shenzhen City's ecological function comprehensive values is depicted in Figure 6.

In this study, the K-means algorithm is employed to conduct a spatial clustering analysis within each secondary zone based on the comprehensive value of water ecological function. Subsequently, zoning boundaries are established through expert analysis and adherence to the principle of sub-zone integrity, leading to the delineation of tertiary zoning results.

Shenzhen City is partitioned into 24 ecological function three-level areas as shown in Figure 7. These divisions exhibit significant variations in ecosystem characteristics and background conditions, primarily manifesting through distinctive zoning indicators. The differentiation in ecological function zoning across Shenzhen underscores the diverse ecological landscapes and environmental attributes present within the region.

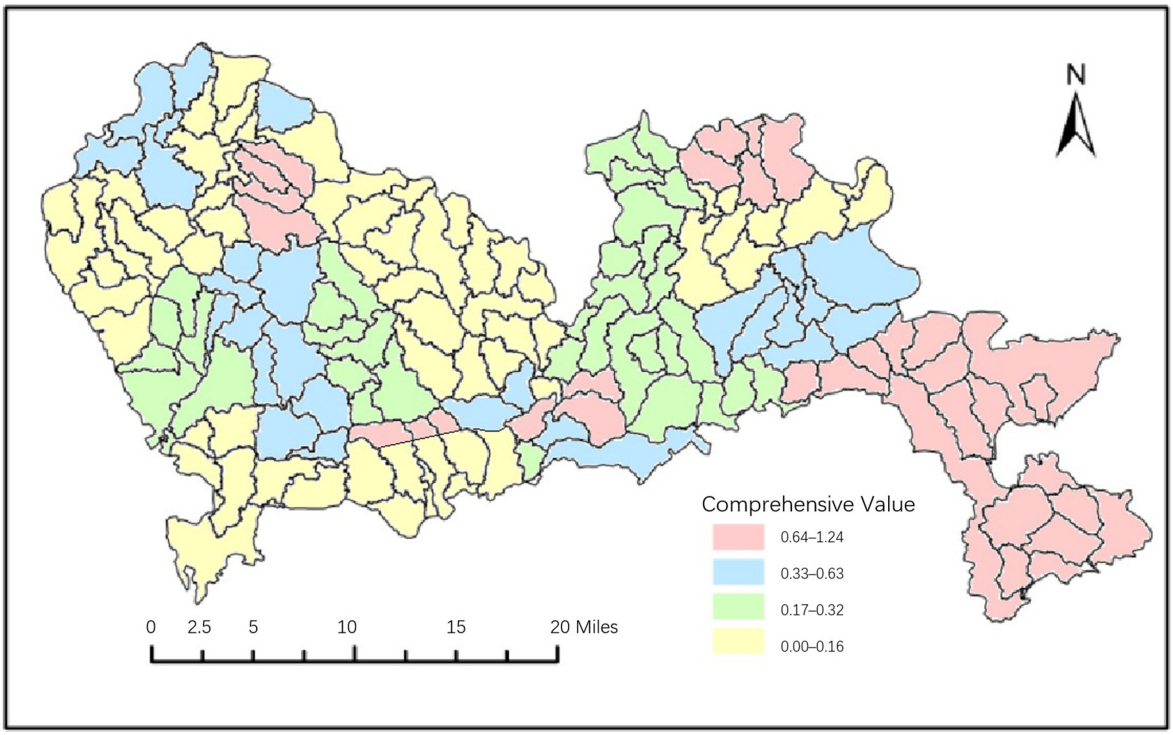

Figure 6. Comprehensive value of ecological function in Shenzhen.

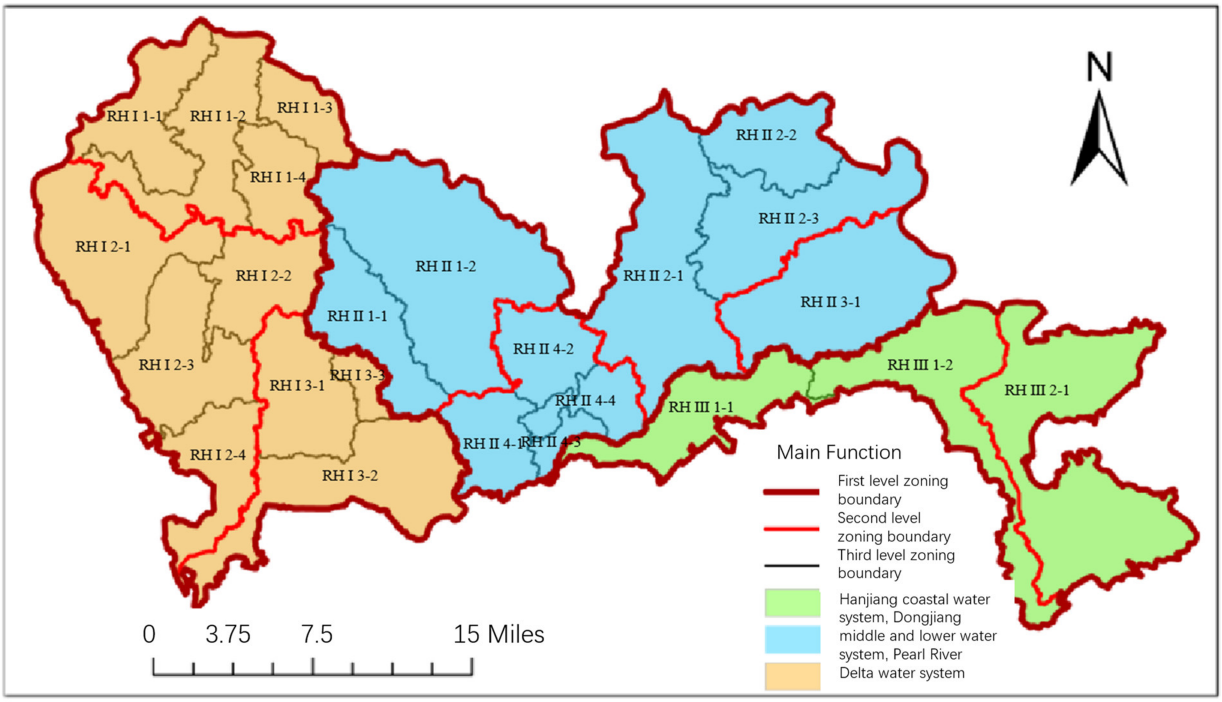

Figure 7. The three-level zoning map of Shenzhen City.

In terms of spatial distribution, the primary functional differences among the three ecological functional zones in Shenzhen are significant. The upper reaches of the watershed are mostly characterized by ecological maintenance and water conservation functions, with Dapeng New District predominantly being an ecological maintenance area. The urban support areas are mainly concentrated in the upper reaches of the watershed, such as Futian District, Luohu District, and Nanshan District. The agricultural production areas are mainly located in the flat areas with sufficient water sources and lower slopes, primarily in the northeast corner of Longgang District and Nanshan District.

According to the three-level zoning, policymakers can develop plans more specifically. For example, RHI1-1 focuses on the upstream basin of the Maozhou River in the Pearl River Delta, emphasizing the conservation of high-functioning habitats, including protecting forest ecosystems and biodiversity by strictly prohibiting deforestation for cultivation, enhancing river protection awareness, implementing reasonable conservation measures, establishing a strict development approval system, and preventing soil erosion. RHI2-3 focuses on the hilly river types within the midstream basin of the Pearl River Delta's Zhujiang Estuary, emphasizing high-function water source protection areas. It aims to improve water body environments by avoiding human activities that disturb them, minimizing large-scale hydraulic construction, enhancing river protection awareness, implementing reasonable conservation measures, establishing a strict development approval system, preventing soil erosion, and suggesting water quality management goals in line with Class III water quality standards. RHII1-2 focuses on the urban support function area of the urban river types in the Guanlan River basin of the Dongjiang River system, emphasizing high-pressure functional restoration. It involves restructuring industries to include investments in high-tech and non-polluting projects, improving regional environments, and promoting ecological urban development. This includes implementing reasonable conservation measures and establishing a strict development approval system.

4. Discussion

Several studies indicate that changes in urban coastal ecosystems are closely related to land–sea utilization, coverage types, terrestrial inputs, management, and development practices. Terrestrial ecosystems significantly impact nearshore ecological systems and their evolution. The substantial material and energy flows driven by human activities on land contribute to uncertainties in the evolution of coastal ecosystems, leading to environmental degradation. Hong et al. [54] indicated consistent ecological corridor sensitivity grades in Shenzhen, with high sensitivity in the north and low values in the south, dominated by moderately sensitive corridors. A land-use control program is designed considering current management practices and future land demands, outlining withdrawal, reservation, occupation, and avoidance policies. Peng et al. [55] explored the dynamics of urban ecological land in Shenzhen City, driven by rapid urbanization and its associated socio-economic development and ecological protection conflicts. Using multivariate logistic regression, the research quantified the factors influencing these changes and maps the transition probabilities of ecological land. Factors such as slope, proximity to construction land, and the rate of growth in construction land were identified as crucial determinants influencing changes in urban ecological land.

The three-level ecological functional zoning framework developed in this study provides a robust foundation for policymakers, urban planners, and environmental managers to make informed decisions regarding land use, conservation efforts, and sustainable development in the Shenzhen region. By identifying and categorizing different ecological functions based on a comprehensive set of indicators and spatial analysis techniques, this zoning approach offers a nuanced understanding of the region's environmental characteristics and highlights areas of ecological significance that warrant special attention and protection.

Yi et al. [56] utilized a comparative evaluation approach to analyze changes in positive and negative ecological elements within Shenzhen's coastal zone. These elements were classified based on land uses derived from multiple remote sensing sources and a land-use degree index. The findings indicate that human activities have exerted stronger impacts on the west coast compared to the east coast of Shenzhen. It observed a gradual increase in environmental protection awareness of the government since 2000; however, this did not correspond to an improvement in ecosystem health. The research findings of this paper are consistent with that. Additionally, there has been a significant increase in research on ecosystem multifunctionality, which refers to the capacity of ecosystems to provide multiple functions and/or services simultaneously throughout the world [57]. This study enhances ecological planning and environmental management by offering a systematic, data-driven method for defining ecological functional zones in urbanizing areas. Compared to previous studies [58,59], the three-level zoning proposed in this paper provides more refined management of the study area, extending to the scales of watershed, sub-watershed, and river. Furthermore, this paper supports the conclusion that urban land use is crucial for zoning plans to foster sustainable urban development [27].

Furthermore, the application of the K-means algorithm for a spatial clustering analysis proved to be an effective method for delineating distinct ecological zones within the study area. This approach not only allows for the identification of areas with similar ecological functions, but also helps in recognizing spatial patterns and relationships among different environmental variables. Such insights are crucial for prioritizing conservation efforts, implementing targeted land management strategies, and promoting sustainable development practices that are in harmony with the natural environment.

Ecological zoning holds significant value for other regions worldwide. It provides insights into effective urban environmental management practices, sustainable development strategies, and approaches to balancing economic growth with ecological preservation. Shenzhen's experience can offer valuable lessons on integrating green spaces, conserving natural habitats, managing urban expansion, and promoting environmental sustainability amidst rapid urbanization. These lessons can be adapted and applied in various global contexts facing similar challenges of urban development and environmental conservation [60,61].

It is important to note that the results of this study are contingent upon the availability and accuracy of the input data, as well as the assumptions and criteria used in the ecological zoning process. Future research could benefit from incorporating more detailed field surveys, remote sensing data, and stakeholder consultations to validate and refine the zoning framework presented here. Additionally, the continuous monitoring and evaluation of the ecological conditions in the Shenzhen region will be essential to assess the effectiveness of the zoning scheme over time, and to adapt it to changing environmental dynamics and human activities. The shortcomings of ecological zoning methods include complexity in integrating diverse marine and terrestrial ecosystem data and difficulty in addressing spatial and temporal dynamics of both marine and terrestrial environments simultaneously [62–64]. There is a limited availability of comprehensive datasets covering both marine and terrestrial ecosystems. Future research will also include exploring how ecological zoning impacts carbon emission markets, since ecological zoning and carbon emission markets are interconnected in several ways.

Overall, this research contributes to the broader discourse on ecological planning and environmental management by offering a systematic and data-driven approach to delineating ecological functional zones in urbanizing regions. By integrating spatial analysis techniques, ecological indicators, and stakeholder engagement, this study lays the groundwork for promoting sustainable development practices that safeguard ecological integrity and enhance the quality of life for current and future generations in Shenzhen.

5. Conclusions

Rapid global economic development has brought significant challenges in the form of overexploitation and the depletion of ecological resources, as well as environmental degradation. As a result, research focus has shifted towards watershed-based ecological management, with a particular emphasis on ecological zoning. To address the evolving needs of ecological environment management and protection, ecological zoning has become a primary approach for regional ecological environment management in the future.

This paper establishes a three-level zoning theoretical framework for river basin aquatic ecology and conducts a practical case study in Shenzhen, a representative coastal city. This study includes the completion of a three-level zoning of terrestrial and shoreline aquatic ecological functions in Shenzhen, as well as an assessment of shoreline development suitability, leading to the following key conclusions:

1. Definition and framework of watershed ecological function zoning: The concept and system of ecological zoning are elucidated. This method not only reflects the impact of natural factors on ecological systems, but also quantitatively incorporates the influence of human activities within a certain range. It considers the dual function of aquatic ecosystems in self-sustaining and providing water resources for human needs. Considering the spatial scales of different watershed levels, the hierarchical structural characteristics of aquatic ecosystems, and other factors, a comprehensive framework for the three-level zoning of watershed aquatic ecological functions is proposed. Specific zoning methods for different levels within the system are suggested, ultimately establishing a complete technical roadmap and research methodology for the three-level zoning of watershed aquatic ecology.
2. Theoretical basis and technical methods for three-level zoning of river basin aquatic ecological functions: Based on the integrity of aquatic ecosystems, a structural characteristic index is proposed as the three-level zoning indicator for watershed aquatic ecological functions. This index can distinguish habitat characteristics and functional differences in different regions, thus enabling more effective management. In pursuit of finer river basin management, a three-level zoning theory based on the structural characteristics of aquatic ecosystems is presented, complementing the existing two-level zoning. This expanded framework better captures the spatial variability of aquatic ecosystem functions within river basins. Additionally, corresponding zoning objectives and unique principles are introduced. Guided by the three-level zoning theory, this paper proposes a method for dividing zoning units (sub-basin units), covering the division, indicator system construction, zoning technology, technical pathways, and main function identification.
3. Completion of three-level zoning for terrestrial aquatic ecological functions in Shenzhen: In line with ecological zoning goals, 148 small basin units were identified. Through factor and correlation analyses, six key three-level zoning indicators for aquatic ecosystems were established, with weights determined by the entropy weight method. A spatial cluster analysis was used to integrate these results, resulting in 24 zones with distinct aquatic ecological functions. Standards for ecological function assessment, indicator weights, and evaluation principles were defined, with zoning results validated through a spatial functional analysis, finalizing the three-level zoning plan for Shenzhen.

Through this comprehensive investigation, this study not only contributes to the theoretical understanding of watershed aquatic ecological function zoning, but also provides valuable insights and a solid methodology for its practical implementation, as demonstrated in the detailed case study in Shenzhen.

Author Contributions: Conceptualization, Y.L. and H.Y. (Han Yu); methodology, H.Y. (Han Yu); software, F.Z.; validation, F.Z. and R.L.; investigation, F.Z. and R.L.; resources, H.Y. (Hongbing Yu); writing—original draft preparation, Y.L.; writing—review and editing, H.Y. (Han Yu); supervision, Y.C.; funding acquisition, H.Y. (Han Yu). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shenzhen Science and Technology Program, grant number No. KCXFZ20211020172542001.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to the data management regulations of the Shenzhen Research Institute of Nankai University.

Conflicts of Interest: Author Yao Chen was employed by the company Shenzhen Lightsun Analysis and Testing Center Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Fang, Q.; Zhang, L.; Hong, H.; Zhang, L.; Bristow, F. Ecological function zoning for environmental planning at different levels. *Environ. Dev. Sustain.* **2008**, *10*, 41–49. [CrossRef]
2. Xu, F.; Shao, Y.; Xu, B.; Li, H.; Xie, X.; Xu, Y.; Pu, L. Evaluation and zoning of cultivated land quality based on a space–function–environment. *Land* **2023**, *12*, 174. [CrossRef]
3. Talukdar, G.; Bhattacharjya, R.K.; Sarma, A.K. Understanding the effect of long term and short term hydrological components on landscape ecosystem. *Ecol. Inform.* **2023**, *77*, 102267. [CrossRef]
4. Deng, Y.; Ming, L.; Hai, Y.; Chen, H.; Jize, D.; Luo, J.; Yan, X.; Zhang, X.; Yao, S.; Hou, M. Has the Establishment of National Key Ecological Function Zones Improved Eco-Environmental Quality?—Evidence from a Quasi-Natural Experiment in 130 Counties in Sichuan Province, China. *Land* **2024**, *13*, 677. [CrossRef]
5. Merriam, C.H. *Life Zones and Crop Zones of the United States (No. 10)*; US Government Printing Office: Washington, DC, USA, 1898; pp. 7–8.
6. Dong, J.; Metternicht, G.; Hostert, P.; Fensholt, R.; Chowdhury, R.R. Remote sensing and geospatial technologies in support of a normative land system science: Status and prospects. *Curr. Opin. Environ. Sustain.* **2019**, *38*, 44–52. [CrossRef]
7. Liu, C.; Li, W.; Zhu, G.; Zhou, H.; Yan, H.; Xue, P. Land use/land cover changes and their driving factors in the Northeastern Tibetan Plateau based on Geographical Detectors and Google Earth Engine: A case study in Gannan Prefecture. *Remote Sens.* **2020**, *12*, 3139. [CrossRef]
8. Aryal, B.; Escarzaga, S.M.; Vargas Zesati, S.A.; Velez-Reyes, M.; Fuentes, O.; Tweedie, C. Semi-automated semantic segmentation of arctic shorelines using very high-resolution airborne imagery, spectral indices and weakly supervised machine learning approaches. *Remote Sens.* **2021**, *13*, 4572. [CrossRef]
9. Abdi, A.M. Land cover and land use classification performance of machine learning algorithms in a boreal landscape using Sentinel-2 data. *GIScience Remote Sens.* **2020**, *57*, 1–20. [CrossRef]
10. Martínez Prentice, R.; Villoslada Peciña, M.; Ward, R.D.; Bergamo, T.F.; Joyce, C.B.; Sepp, K. Machine learning classification and accuracy assessment from high-resolution images of coastal wetlands. *Remote Sens.* **2021**, *13*, 3669. [CrossRef]
11. Herridge, D.F.; Win, M.M.; Nwe, K.M.M.; Kyu, K.L.; Win, S.S.; Shwe, T.; Min, Y.Y.; Denton, M.D.; Cornish, P.S. The cropping systems of the Central Dry Zone of Myanmar: Productivity constraints and possible solutions. *Agric. Syst.* **2019**, *169*, 31–40. [CrossRef]
12. Wickware, G.M. Classification for Stratification, Mapping, and Data Display for Range Inventories: Comment and Discussion. In *Developing Strategies For Rangeland Management*; CRC Press: Boca Raton, FL, USA, 2021; pp. 631–646.
13. Dufour, S.; Rodríguez-González, P.M.; Laslier, M. Tracing the scientific trajectory of riparian vegetation studies: Main topics, approaches and needs in a globally changing world. *Sci. Total Environ.* **2019**, *653*, 1168–1185. [CrossRef] [PubMed]
14. Zheng, Z.; Wu, Z.; Chen, Y.; Yang, Z.; Marinello, F. Exploration of eco-environment and urbanization changes in coastal zones: A case study in China over the past 20 years. *Ecol. Indic.* **2020**, *119*, 106847. [CrossRef]
15. Li, Z.T.; Li, M.; Xia, B.C. Spatio-temporal dynamics of ecological security pattern of the Pearl River Delta urban agglomeration based on LUCC simulation. *Ecol. Indic.* **2020**, *114*, 106319. [CrossRef]
16. Gao, J.; Zou, C.; Zhang, K.; Xu, M.; Wang, Y. The establishment of Chinese ecological conservation redline and insights into improving international protected areas. *J. Environ. Manag.* **2020**, *264*, 110505. [CrossRef]
17. Li, X.; Yu, X.; Wu, K.; Feng, Z.; Liu, Y.; Li, X. Land-use zoning management to protecting the Regional Key Ecosystem Services: A case study in the city belt along the Chaobai River, China. *Sci. Total Environ.* **2021**, *762*, 143167. [CrossRef]
18. Zong, S.; Hu, Y.; Zhang, Y.; Wang, W. Identification of land use conflicts in China's coastal zones: From the perspective of ecological security. *Ocean Coast. Manag.* **2021**, *213*, 105841. [CrossRef]
19. Jin, X.; Wei, L.; Wang, Y.; Lu, Y. Construction of ecological security pattern based on the importance of ecosystem service functions and ecological sensitivity assessment: A case study in Fengxian County of Jiangsu Province, China. *Environ. Dev. Sustain.* **2021**, *23*, 563–590. [CrossRef]
20. Li, R.; Zheng, H.; Polasky, S.; Hawthorne, P.L.; O'Connor, P.; Wang, L.; Li, R.; Xiao, Y.; Wu, T.; Ouyang, Z. Ecosystem restoration on Hainan Island: Can we optimize for enhancing regulating services and poverty alleviation? *Environ. Res. Lett.* **2020**, *15*, 084039. [CrossRef]
21. Yang, L.; Li, X.; Yang, Q.; Zhang, L.; Zhang, S.; Wu, S.; Zhou, C. Extracting knowledge from legacy maps to delineate eco-geographical regions. *Int. J. Geogr. Inf. Sci.* **2021**, *35*, 250–272. [CrossRef]
22. Fu, B. Several key points in territorial ecological restoration. *Bull. Chin. Acad. Sci.* **2021**, *36*, 64–69.
23. Hong, W.; Jiang, R.; Yang, C.; Zhang, F.; Su, M.; Liao, Q. Establishing an ecological vulnerability assessment indicator system for spatial recognition and management of ecologically vulnerable areas in highly urbanized regions: A case study of Shenzhen, China. *Ecol. Indic.* **2016**, *69*, 540–547. [CrossRef]
24. Liu, J.; Jiang, T.; Ye, Z. Information efficiency research of China's carbon markets. *Financ. Res. Lett.* **2021**, *38*, 101444. [CrossRef]
25. Yu, X.; Wan, K.; Du, Q. Can carbon market policies achieve a "point-to-surface" effect?—Quasi-experimental evidence from China. *Energy Policy* **2023**, *183*, 113803. [CrossRef]

26. Lin, J.; Li, X. Large-scale ecological red line planning in urban agglomerations using a semi-automatic intelligent zoning method. *Sustain. Cities Soc.* **2019**, *46*, 101410. [CrossRef]
27. Domingo, D.; Palka, G.; Hersperger, A.M. Effect of zoning plans on urban land-use change: A multi-scenario simulation for supporting sustainable urban growth. *Sustain. Cities Soc.* **2021**, *69*, 102833. [CrossRef]
28. Xu, Z.; Peng, J.; Dong, J.; Liu, Y.; Liu, Q.; Lyu, D.; Qiao, R.; Zhang, Z. Spatial correlation between the changes of ecosystem service supply and demand: An ecological zoning approach. *Landsc. Urban Plan.* **2022**, *217*, 104258. [CrossRef]
29. Zhou, Y.; Wu, T.; Wang, Y. Urban expansion simulation and development-oriented zoning of rapidly urbanising areas: A case study of Hangzhou. *Sci. Total Environ.* **2022**, *807*, 150813. [CrossRef]
30. Liu, X.; Heilig, G.K.; Chen, J.; Heino, M. Interactions between economic growth and environmental quality in Shenzhen, China's first special economic zone. *Ecol. Econ.* **2007**, *62*, 559–570. [CrossRef]
31. Liu, X.; Su, Y.; Li, Z.; Zhang, S. Constructing ecological security patterns based on ecosystem services trade-offs and ecological sensitivity: A case study of Shenzhen metropolitan area, China. *Ecol. Indic.* **2023**, *154*, 110626. [CrossRef]
32. Wang, G.; Yang, D.; Xia, F.; Zhong, R.; Xiong, C. Three types of spatial function zoning in key ecological function areas based on ecological and economic coordinated development: A case study of Tacheng Basin, China. *Chin. Geogr. Sci.* **2019**, *29*, 689–699. [CrossRef]
33. Sun, M.; Yang, R.; Li, X.; Zhang, L.; Liu, Q. Designing a path for the sustainable development of key ecological function zones: A case study of southwest China. *Glob. Ecol. Conserv.* **2021**, *31*, e01840. [CrossRef]
34. Ning, J.; Liu, J.; Kuang, W.; Xu, X.; Zhang, S.; Yan, C.; Li, R.; Wu, S.; Hu, Y.; Du, G.; et al. Spatiotemporal patterns and characteristics of land-use change in China during 2010–2015. *J. Geogr. Sci.* **2018**, *28*, 547–562. [CrossRef]
35. Wang, W.; Jiao, L.; Jia, Q.; Liu, J.; Mao, W.; Xu, Z.; Li, W. Land use optimization modelling with ecological priority perspective for large-scale spatial planning. *Sustain. Cities Soc.* **2021**, *65*, 102575. [CrossRef]
36. Zhang, L.; Liu, J.; Wan, D.; Yao, H.; Zheng, J.; Jiang, Y. Analysis and calculation of ecological flow in Shenzhen River based on zoning and classification. In *Advances in Civil Engineering and Environmental Engineering*; CRC Press: Boca Raton, FL, USA, 2023; Volume 2, pp. 494–503.
37. Tölgyesi, C.; Bátori, Z.; Erdős, L. Using statistical tests on relative ecological indicator values to compare vegetation units–Different approaches and weighting methods. *Ecol. Indic.* **2014**, *36*, 441–446. [CrossRef]
38. Chi, G.; Yu, S.; Zhou, Y. A novel credit evaluation model based on the maximum discrimination of evaluation results. *Emerg. Mark. Financ. Trade* **2020**, *56*, 2543–2562. [CrossRef]
39. Li, Y.; Wang, X.K.; Zhang, H.Y.; Wang, J.Q.; Li, L. An integrated regional water quality assessment method considering interrelationships among monitoring indicators. *Environ. Monit. Assess.* **2021**, *193*, 1–20. [CrossRef]
40. Xian, C.; Gong, C.; Lu, F.; Wu, H.; Ouyang, Z. The evaluation of greenhouse gas emissions from sewage treatment with urbanization: Understanding the opportunities and challenges for climate change mitigation in China's low-carbon pilot city, Shenzhen. *Sci. Total Environ.* **2023**, *855*, 158629. [CrossRef] [PubMed]
41. Bin, Y.; Jingjing, J.; Lixin, M.; Peng, Y. Sustainable energy options for a low carbon demonstration city project in Shenzhen, China. *J. Renew. Sustain. Energy* **2015**, *7*, 023122. [CrossRef]
42. Czúcz, B.; Keith, H.; Maes, J.; Driver, A.; Jackson, B.; Nicholson, E.; Kiss, M.; Obst, C. Selection criteria for ecosystem condition indicators. *Ecol. Indic.* **2021**, *133*, 108376. [CrossRef]
43. Talke, S.A.; Jay, D.A. Changing tides: The role of natural and anthropogenic factors. *Annu. Rev. Mar. Sci.* **2020**, *12*, 121–151. [CrossRef]
44. Akhtar, N.; Syakir Ishak, M.I.; Bhawani, S.A.; Umar, K. Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water* **2021**, *13*, 2660. [CrossRef]
45. Kaiser, H.F. The varimax criterion for analytic rotation in factor analysis. *Psychometrika* **1958**, *23*, 187–200. [CrossRef]
46. Braeken, J.; Van Assen, M.A. An empirical Kaiser criterion. *Psychol. Methods* **2017**, *22*, 450. [CrossRef]
47. Liu, C.W.; Lin, K.H.; Kuo, Y.M. Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. *Sci. Total Environ.* **2003**, *313*, 77–89. [CrossRef]
48. Singh, K.P.; Malik, A.; Singh, V.K.; Mohan, D.; Sinha, S. Chemometric analysis of groundwater quality data of alluvial aquifer of Gangetic plain, North India. *Anal. Chim. Acta* **2005**, *550*, 82–91. [CrossRef]
49. Qian, Y.; Migliaccio, K.W.; Wan, Y.; Li, Y. Surface water quality evaluation using multivariate methods and a new water quality index in the Indian River Lagoon, Florida. *Water Resour. Res.* **2007**, *43*, 7–8. [CrossRef]
50. Hill, M.O.; Gauch, H.G., Jr. Detrended correspondence analysis: An improved ordination technique. *Vegetatio* **1980**, *42*, 47–58. [CrossRef]
51. Ter Braak, C.J.; Prentice, I.C. A theory of gradient analysis. In *Advances in Ecological Research*; Academic Press: Cambridge, MA, USA, 1988; Volume 18, pp. 271–317.
52. Asuero, A.G.; Sayago, A.; González, A.G. The correlation coefficient: An overview. *Crit. Rev. Anal. Chem.* **2006**, *36*, 41–59. [CrossRef]
53. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
54. Hong, W.; Guo, R.; Su, M.; Tang, H.; Chen, L.; Hu, W. Sensitivity evaluation and land-use control of urban ecological corridors: A case study of Shenzhen, China. *Land Use Policy* **2017**, *62*, 316–325. [CrossRef]

55. Peng, J.; Zhao, M.; Guo, X.; Pan, Y.; Liu, Y. Spatial-temporal dynamics and associated driving forces of urban ecological land: A case study in Shenzhen City, China. *Habitat Int.* **2017**, *60*, 81–90. [CrossRef]
56. Yi, L.; Chen, J.; Jin, Z.; Quan, Y.; Han, P.; Guan, S.; Jiang, X. Impacts of human activities on coastal ecological environment during the rapid urbanization process in Shenzhen, China. *Ocean Coast. Manag.* **2018**, *154*, 121–132. [CrossRef]
57. Garland, G.; Banerjee, S.; Edlinger, A.; Miranda Oliveira, E.; Herzog, C.; Wittwer, R.; Philippot, L.; Maestre, F.T.; van Der Heijden, M.G. A closer look at the functions behind ecosystem multifunctionality: A review. *J. Ecol.* **2021**, *109*, 600–613. [CrossRef]
58. Carlucci, M.B.; Brancalion, P.H.; Rodrigues, R.R.; Loyola, R.; Cianciaruso, M.V. Functional traits and ecosystem services in ecological restoration. *Restor. Ecol.* **2020**, *28*, 1372–1383. [CrossRef]
59. Jalkanen, J.; Toivonen, T.; Moilanen, A. Identification of ecological networks for land-use planning with spatial conservation prioritization. *Landsc. Ecol.* **2020**, *35*, 353–371. [CrossRef]
60. Bibri, S.E.; Krogstie, J.; Kärrholm, M. Compact city planning and development: Emerging practices and strategies for achieving the goals of sustainability. *Dev. Built Environ.* **2020**, *4*, 100021. [CrossRef]
61. Almenar, J.B.; Elliot, T.; Rugani, B.; Philippe, B.; Gutierrez, T.N.; Sonnemann, G.; Geneletti, D. Nexus between nature-based solutions, ecosystem services and urban challenges. *Land Use Policy* **2021**, *100*, 104898. [CrossRef]
62. Soininen, J.; Bartels, P.I.A.; Heino, J.; Luoto, M.; Hillebrand, H. Toward more integrated ecosystem research in aquatic and terrestrial environments. *BioScience* **2015**, *65*, 174–182. [CrossRef]
63. d'Alcalà, M.R. Similarities, differences and mechanisms of climate impact on terrestrial vs. marine ecosystems. *Nat. Conserv.* **2019**, *34*, 505–523. [CrossRef]
64. Prampolini, M.; Savini, A.; Foglini, F.; Soldati, M. Seven good reasons for integrating terrestrial and marine spatial datasets in changing environments. *Water* **2020**, *12*, 2221. [CrossRef]