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Coastal Wetland Restoration Strategies Based on Ecosystem Service Changes: A Case Study of the South Bank of Hangzhou Bay

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Abstract: A unique variety of wetlands known as coastal wetlands that connect terrestrial and marine ecosystems is crucial to reducing and adapting to climate change as well as the advancement of human culture. However, the coastal wetland ecosystem is currently in danger as a result of the increasing intensity of human activity, and wetland restoration and reconstruction have garnered a lot of interest. The differentiated ecological restoration strategies based on ecosystem service change analysis can provide a reference for the effective management and sustainability of coastal wetland ecosystems. The InVEST model and ArcGIS were used to analyze the spatiotemporal changes in ecosystem services before and after the implementation of coastal wetland restoration policies based on remote sensing image data, meteorological and soil data, etc. The ecological restoration pattern of coastal wetlands was divided, and the corresponding ecological restoration strategies were proposed in this study. The following are the results: (1) there are still many wetlands that have been converted to non-wetlands following the implementation of the wetland restoration policy, and the ecosystem services as a whole exhibit a rising and then falling trend, with a rise from 2005 to 2015, a fall in 2015 due to the creation of Hangzhou Bay New District, and a slight improvement to 2020. Among them, the water yield increased continuously, the carbon storage fluctuated, and the habitat quality did not improve significantly. (2) The hot spots of ecosystem services were concentrated in the south and southeast of the study area, with no obvious cold spots. (3) By comprehensively analyzing the changes and spatial patterns of ecosystem services, the coastal wetlands on the south bank of Hangzhou Bay were divided into an ecological conservation zone, a green development zone, and an ecological restoration zone at the township level, and corresponding optimization strategies were proposed. The results can provide a reference for the fine-grained and differentiated management of regional ecosystem services.

Keywords: coastal wetland; ecological restoration; zoning; InVEST

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1. Introduction

Wetland, also referred to as the "kidney of the earth" and "gene pool of species", is the ecosystem on earth with the highest primary productivity because of its numerous roles that include sustaining biodiversity, regulating climate, and conserving water resources [1,2]. Among them, coastal wetlands are a special type of wetland that links terrestrial and marine ecosystems under the joint influence of river freshwater and tidal saltwater. Strong saline and freshwater interactions have shaped them into the most biodiversity-rich ecosystems [3]. As a complex and key zone with strong interaction between multiple circles and zones, coastal wetland ecosystems are regions where geomorphological, geofluid, and biochemical processes interact frequently and play an important role in mitigating and adapting to climate change and serving the development of human society [4,5]. However, due to their relatively harsh water and salt environments, coastal wetland ecosystems tend to have a high degree of vulnerability [6,7]. According to statistics, approximately 50% of salt marshes, 35% of mangroves, and 29% of seagrasses in the global coastal wetlands have been lost or degraded due to environmental stress and human disturbance [8], which has led to a significant reduction in coastal habitats for flora and fauna and a degradation of ecological security [9,10].

China is one of the nations with the most wetland resources, and its overall wetland area ranks fourth globally, behind only Brazil, Russia, and Canada [11]. Despite the diversity and abundance of resources found in China's coastal wetlands, high-intensity human activities such as land reclamation and tourism development have put enormous pressure on these ecosystems. As a result, coastal wetlands have shrunk, habitat loss has occurred, hydrodynamic conditions have been disturbed, and biodiversity has decreased [12]. Studies have shown that about 50% of coastal wetlands have been lost in China in the past 40 years [13,14]. In addition, conservation of coastal wetlands and restoration of degraded wetlands are urgent [15].

Since the 1990s, wetland restoration and reconstruction have been the focus of international ecological research, and the conservation of coastal wetland ecosystems in China has also drawn more attention. In 1992, China formally acceded to the Ramsar Convention with a highly responsible attitude toward society, mankind, and future generations, marking the beginning of an era of wetland conservation in China. The nation subsequently developed several wetland protection policies. To protect and restore coastal wetlands, governments along the coast have heeded the call to adopt wetland ecological restoration policies and carry out coastal wetland ecological restoration projects. However, ecological restoration and urban expansion go hand in hand [16]. Under the influence of urban expansion, especially under the high intensity of human activities in coastal areas, the actual effect of ecological protection of coastal wetlands is not satisfactory [17]. Due to the imbalance between natural resource endowment and social and economic development, ecological problems and restoration needs are often characterized by typical spatial non-stationarity [18]. Given this, how to propose a differentiated coastal wetland restoration strategy plays a key role in improving the benefits of coastal wetland restoration.

This study takes the coastal wetlands on the south bank of Hangzhou Bay as the study area. Based on the InVEST model, remote sensing image data, meteorological data, soil data, and other data, it identifies the spatial pattern of ecosystem services and divides the ecological restoration control areas according to the level of spatio-temporal changes of coastal wetland ecosystem services before and after the implementation of wetland restoration policy (2000–2020). Then, the study puts forward the targeted coastal wetland restoration strategy. The specific research objectives are: (1) to explore the changes of land use types, especially wetland changes, in coastal wetlands on the south bank of Hangzhou Bay before and after the implementation of the coastal wetland restoration policy; (2) to quantify the spatial and temporal changes in ecosystem services and spatial pattern distribution characteristics before and after the implementation of the coastal wetland restoration policy; and (3) to further investigate the ecological restoration zones of coastal wetlands on the south bank of Hangzhou Bay and propose differentiated ecological restoration strategies for different regions. The results of the research can serve as a guide for managing coastal wetland ecosystems in a way that maintains the ecological functions of restored wetlands and promotes the study area's sustainability.

2. Literature Review

Current research on coastal wetland restoration focuses on the following three aspects: (1) the definition of wetland restoration. It is widely recognized that ecological restoration refers to the process of assisting the restoration of degraded, damaged, or destroyed ecosystems [19]. (2) The coastal wetland restoration model. From a methodological perspective, wetland restoration modes can be divided into artificial restoration [20] and natural restoration [21]. This type of research is generally presented in the form of qualitative descriptions and case studies. (3) Assessment of coastal wetland restoration. This kind of research is an important element in the field of wetland restoration, and how to judge the success of ecological restoration has been the focus of scholars. The effectiveness of the ecological restoration of coastal wetlands has also been extensively studied, including the assessment time [22] and evaluation indicators [23–25]. It is impossible to utilize foreign expertise in China due to the dearth of monitoring data for many assessment indicators. Research on the ecological restoration effects of wetlands as a whole can be roughly divided into two categories: (1) assessment of the restoration effects of a particular regional wetland [26,27] and (2) assessment of a particular wetland restoration project [28], both of which are usually realized by constructing an indicator system. In addition, this approach usually only reflects the temporal changes of wetland restoration, which is weak in terms of spatial effects. At the same time, the index system is mainly focused on the structure and functional level of the ecosystem. However, compared with ecosystem structure and function, the services and welfare brought to human beings may be more important [29,30]. From the perspective of human well-being [31,32], on the basis of comprehensive consideration of the change trend and spatial pattern distribution characteristics of ecosystem services, the study on the heterogeneity of ecological restoration demand and regional control are effective measures to promote ecological problems and the premise of differential construction of ecological restoration [33,34]. The InVEST model, which conducts spatial analysis of ecosystem functions in a more refined manner [35,36] and intuitively quantifies multiple ecosystem service levels in the form of maps, can effectively make up for the shortcomings of the current coastal wetland restoration assessment at the spatial and ecosystem service levels.

3. Study Area

The Hangzhou Bay Wetland is a typical coastal wetland in China and is situated in the northeastern part of Zhejiang Province, at the inlet point where the Qiantang River connects to the East China Sea (Figure 1). The wetland on the southern side of Hangzhou Bay was chosen as the study region, and the geographic coordinate center's longitude and latitude are 121.55° E and 30.31° N, respectively. The research area has a total size of 108,874.23 hm^2 and is divided into three sections: the sea, the coastal zone, and the interior region.

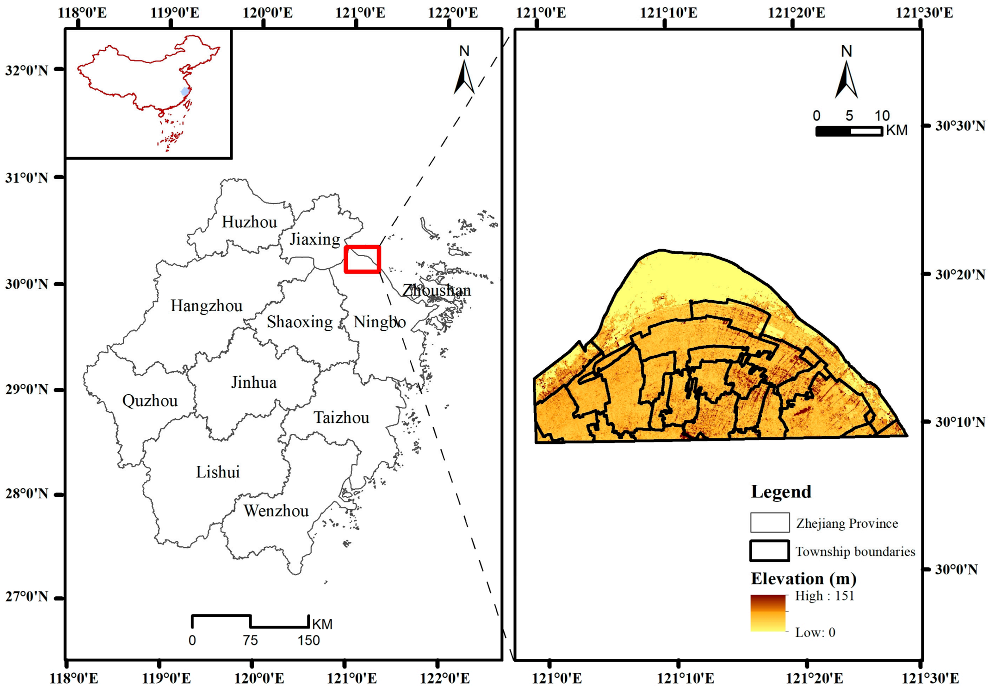

Figure 1. Location of the study area.

Due to the influence of the delta at the mouth of the sea, the area is rich in beach resources with large tide siltation, small tide scouring, and typhoon storm tide period scouring, after the siltation, and finally, it formed a silty beach. In recent years, the government has vigorously promoted the development of Hangzhou Bay and the establishment of Hangzhou Bay New District. With the development of the new district, a large population influx and the intensification of human activities have threatened the wetland resources in the area. At the same time, in 2005, Zhejiang Province officially promulgated the wetland protection policy. Within it, the Hangzhou Bay wetland protection project is divided into two parts: natural wetland and engineering wetland. The natural wetland project is to establish wetland nature reserves, wetland parks, etc., and the engineering wetland project is to achieve the purpose of restoring degraded wetlands through engineering measures.

4. Materials and Methods

4.1. Materials

The land use data of the coastal wetlands on the south bank of Hangzhou Bay for five periods of 2000, 2005, 2010, 2015, and 2020 used in this study were obtained from multi-period remote sensing images based on Google Earth Engine, and the wetland types were classified by visual interpretation based on the Ramsar Convention and the available reference wetland categories in the study area (Table 1). According to the selected training samples and manually marked sample category attributes, the confusion matrix between the training samples and classified products of each year were calculated based on the GEE cloud platform, and the OA accuracy and Kappa coefficient of the corresponding years were calculated, respectively. The test results showed that the overall classification accuracy of land use in the five periods reached more than 80%, and the Kappa coefficient was greater than 0.7, which met the requirements of data accuracy for further research. The DEM data are derived from the latest set of data released by NASA in 2020 (https://earthdata.nasa.gov/esds/competitive-programs/measures/nasadem (accessed on 9 February 2023)). The precipitation, temperature, and other meteorological data were obtained from the Daily Value Dataset of Chinese Terrestrial Climate Data (V3.0), and the data from the meteorological stations around the coastal wetlands on the south bank of Hangzhou Bay were specifically selected for spatial interpolation. Soil data were obtained from the Chinese soil dataset (1:1 million) in the World HWSD soil database (https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed on 9 February 2023)). The data were finally processed to a uniform 30 m resolution using ArcGIS.

Table 1. Wetland type classification system.

Class I	Class II	Description
Natural Wetlands	Shallow Water	Permanently vegetation-free offshore waters with a water level of less than 6 m at low tide.
	Silty Beach	Muddy shoals and various marshy areas on the coast.
	River	The water surface between the shoreline of a naturally formed or artificially excavated river at the normal water level.
	Lake	The water surface is enclosed by the shoreline of the naturally formed standing water area.
Artificial Wetlands	Reservoir/Pond	Artificial lakes, including coastal seashore reservoirs, agricultural ponds, and outflow ponds.
	Paddy	Rice fields that can be planted for one, two, or three seasons or agricultural fields that store water or are wet in winter.
Non-wetlands	Non-wetlands	Buildings for people's daily residence and use, construction projects being developed, or land used for access, etc.

4.2. Methods

4.2.1. Indicator Selection

There are many modules in the InVEST model, and in this study, the most typical ecosystem services of wetlands were selected as assessment indicators through literature combing (Figure 2).

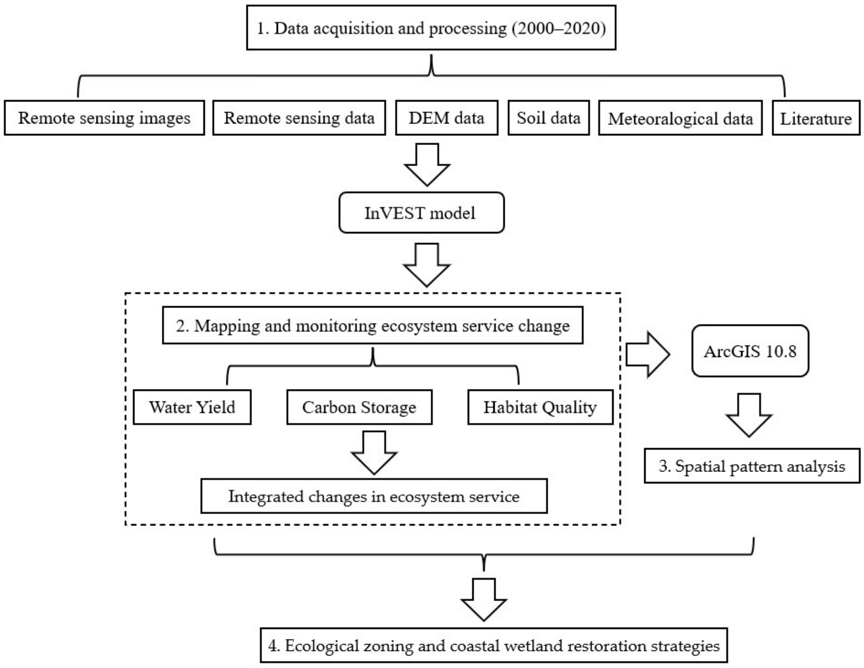

Figure 2. Methodological framework.

(1) Water Yield. Wetlands are closely linked to water security. Water is one of the basic features of wetlands. Among the wetland types listed in the Wetland Convention, rivers, streams, subtidal shallow water areas, estuarine waters, marshes, lakes, ponds, and waters are all important wetland water resources that play an important role in people's lives and national economic development [37]. China is a country with relatively scarce water resources, and the wetland area per capita is 0.6 acres, which is only about one-fifth of the world's wetland area per capita [38]. In China, on the other hand, 96% of the available freshwater is stored in wetlands. Among them, the total water storage in freshwater lakes is 2260×10^8 m^3, which is the main source of drinking water [39]. Therefore, assessing changes in water production services due to coastal wetland restoration plays an important role in ensuring water security.

(2) Carbon storage. Wetlands are about climate change. Wetlands are ecosystem types sensitive to climate change and play an important role in the balance of CO_2 and CH_4. It is estimated that wetlands sequester more than 35% of the total terrestrial ecosystem with less than 6% of the total global land area, providing an important and irreplaceable carbon sequestration service with the highest carbon intensity of all terrestrial ecosystems [40].

(3) Habitat quality. Wetlands are closely related to biosecurity. Wetlands are suitable habitats for many species and are among the most biodiverse ecosystems [41]. Wetlands, which cover 6–8% of the global land area, harbor about 40% of the world's known plant and animal species [42]. Therefore, it is important for wetlands to assess whether coastal wetland restoration has achieved habitat quality enhancement.

4.2.2. Water Yield

The Annual Water Yield module of the InVEST model is a method of estimating the water yield of each grid cell based on a water balance and taking into account climate, topography, soil, and vegetation type. The more water yielded, the greater the water supply. The model parameters were set and tested with reference to the existing literature [43–45], and the specific parameters used in this study are shown in Table 2. The basic principles of the water production module calculation are as follows:

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

where $Y(x)$ is the annual water production of grid cell x, $AET(x)$ is the annual actual evapotranspiration of grid cell x, and $P(x)$ is the annual precipitation of grid cell x.

Table 2. Biophysical table.

LULC	Kc	Root_Depth (mm)	Vegetation
Shallow Water	1.2	200	0
Silty Beach	0.5	4500	1
River	1	1000	0
Lake	1	1	0
Reservoir/Pond	1	1000	0
Paddy	1.2	2000	1
Non-wetlands	0.3	200	0

4.2.3. Carbon Storage

Carbon storage in ecosystems mainly includes four basic carbon pools: aboveground biomass, belowground biomass, soil carbon, and dead organic carbon. The carbon storage module in the InVEST model calculates the total carbon storage in the study area based on the average carbon density of aboveground, belowground, soil, and dead organic matter for different land use types. Its calculation formula is as follows:

$$C_{total} = (C_{i-above} + C_{i-below} + C_{i-soil} + C_{i-dead}) \times S_i \quad (2)$$

where $C_{i-above}$ is the aboveground biomass carbon density of land use type i (t·hm^{-2}); $C_{i-below}$ is the belowground biomass carbon density of land use type i (t·hm^{-2}); C_{i-soil} is the soil carbon density of land use type i (t·hm^{-2});C_{i-dead} is the dead organic matter carbon density of land use type i (t·hm^{-2}); C_{total} is the total carbon stock of land use type (t); and S_i is the area of land use type (hm^2).

As mentioned above, the carbon stock of an ecosystem consists of four carbon pools with different land use and land cover types (LULC) in terms of carbon density and area. The carbon density of LULC can be obtained by field sampling. However, field surveys are time-consuming and relatively difficult, while it has been shown that the carbon density of the same LULC in the same climate zone is similar [46,47]. Therefore, the carbon density data of each land use type required for this study referred to the existing studies in the neighboring areas. Through an extensive literature review [44,48,49], the carbon density data for this study were finalized as follows (Table 3):

Table 3. Carbon density of different wetland types.

LULC	$C_{i\text{-}above}$ (t/ha)	$C_{i\text{-}below}$ (t/ha)	$C_{i\text{-}soil}$ (t/ha)	$C_{i\text{-}dead}$ (t/ha)
Shallow Water	0.00	0.00	0.00	0.00
Silty Beach	1.00	1.00	0.99	0.00
River	0.00	0.00	53.70	0.00
Lake	0.00	0.00	144.13	0.00
Reservoir/Pond	0.00	0.00	88.14	0.00
Paddy	5.42	1.96	146.2	1.00
Non-wetlands	0.00	0.00	0.00	0.00

4.2.4. Habitat Quality

Habitat quality services were assessed through the Habitat Quality module of the InVEST model. This module conducts evaluations based on land use types and biodiversity threat factors and thus assesses habitat quality. The model simulates the assessment of the spatial distribution of habitat quality based on the habitat suitability of each ecosystem type for plants and animals and the threat intensity of human disturbance factors. The model parameters were set with reference to the user manual and the existing literature [50–52], as shown in Tables 4 and 5. The module is calculated on the following principle:

$$Q_{xj} = H_j\left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right] \quad (3)$$

where Q_{xj} is the habitat quality of raster x in land use type j; H_j is the habitat suitability of different land use types; D_{xj} is the habitat degradation level of raster x in land use type j; k is the half-saturation constant, generally half of the maximum value (obtained by running the module once); and z is the normalization constant, generally taking the value of 2.5.

Table 4. Threat factor parameters of coastal wetlands in the south bank of Hangzhou Bay.

Threat	Max_Dist (km)	Weight	Decay
Paddy	1	0.7	Linear
Non-wetlands	3	1	Exponential

Table 5. Sensitivity of LULC to each threat.

LULC	Habitat	Threat	
		Paddy	Non-Wetlands
Shallow Water	1	0.2	0.2
Silty Beach	0.8	0.4	0.2
River	0.9	0.7	0.9
Lake	1	0.7	0.7
Reservoir/Pond	0.9	0.6	0.7
Paddy	0.7	0	0.5
Non-wetlands	0	0	0

4.2.5. Hotspot Analysis

To investigate the spatial clustering distribution characteristics of various ecosystem services in coastal wetlands on the south bank of Hangzhou Bay, this study used hot spot analysis to identify whether there are statistically significant high-value areas (hot spots) and low-value areas (cold spots) in the spatial distribution of water production, carbon storage, and habitat quality [52]. The spatial aggregation characteristics of each ecosystem service were analyzed at the township scale by using the Getis-Ord Gi index calculated with the spatial statistics tool of ArcGIS 10.8.

5. Results

5.1. LULC Change

A comparison of the area of land use types on the south bank of Hangzhou Bay in the years before and after the implementation of the wetland restoration policy (Table 6) reveals that the natural wetlands, artificial wetlands, and non-wetlands changed drastically during the 20 years (Figure 3). Before the wetland restoration policy was implemented (2000), the area of wetlands on the south bank of Hangzhou Bay was larger than that of non-wetlands, and the area of natural wetlands was larger than that of artificial wetlands. Among the specific wetland types, the area of shallow water is the largest, and the area of paddies is the second. From 2000 to 2005, the area of natural wetlands declined by 24.09%

and the area of artificial wetlands rose, with the largest increase in the area of paddies. The land use transfer matrix from 2000 to 2005 (Table 7) shows that all types of wetlands were heavily converted into non-wetlands. Because the study area is on the south bank of the inlet delta, with strong tides, a wide and gentle coastline, and a unique topography that makes the study area a hydrodynamic isolation zone where sediment tends to accumulate, there is a clear trend of shallow marine waters being converted to other types of wetlands, such as reservoir ponds on the one hand and silty beaches on the other [53]. The area is fertile and nutrient-rich for fish and shrimp farming and food cultivation, which further promotes the artificial reclamation of natural wetlands, consistent with the conversion of 1927.35 ha of silty beach area to paddy fields as shown in the transfer matrix.

Table 6. Change in the area of LULC before and after the implementation of the wetland restoration policy.

LULC	2000 (before) (ha)	2005 (Implementation Started) (ha)	2020 (after) (ha)
Shallow Water	25,152.89	22,298.77	3710.61
Silty Beach	8943.39	4494.51	3703.64
River	1670.58	544.05	1113.03
Lake	247.32	1.53	1281.78
Total Natural Wetlands	36,014.18	27,338.86	9813.06
Reservoir/Pond	2687.94	7567.47	11,040.93
Paddy	27,091.18	33,789.55	19,024.20
Total Artificial Wetlands	29,779.12	41,357.02	30,065.13
Non-wetlands	43080.99	40,178.29	68,996.03
Total non-wetlands	43,080.99	40,178.29	68,996.03
Total Wetlands	65,793.30	68,695.88	39,878.19

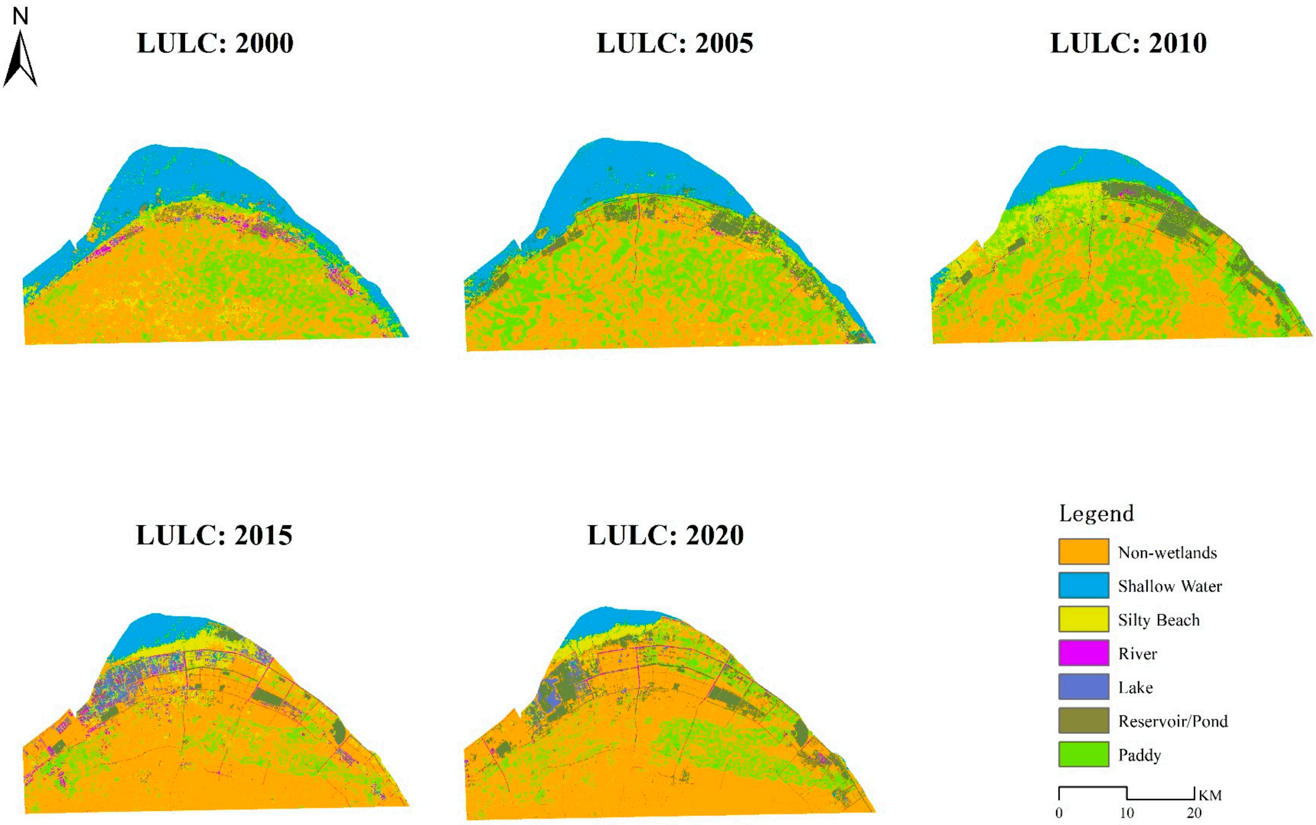

Figure 3. Changes in land use types in the south bank of Hangzhou Bay from 2000 to 2020.

Table 7. Land use transfer matrix for the south bank of Hangzhou Bay from 2000 to 2005.

2000 \ 2005	Shallow Water	Silty Beach	River	Lake	Reservoir/Pond	Paddy	Non-Wetlands	Total
Shallow Water	18.31%	1.65%	0.06%	0.00%	1.71%	0.78%	0.60%	23.11%
Mudflat	1.21%	0.67%	0.08%	0.00%	1.53%	1.77%	2.95%	8.21%
River	0.03%	0.20%	0.07%	0.00%	0.73%	0.15%	0.35%	1.53%
Lake	0.00%	0.02%	0.01%	0.00%	0.14%	0.02%	0.04%	0.23%
Reservoir/Pond	0.32%	0.20%	0.09%	0.00%	1.12%	0.33%	0.41%	2.47%
Paddy	0.32%	0.66%	0.09%	0.00%	0.89%	13.20%	9.72%	24.88%
Non-wetlands	0.30%	0.73%	0.10%	0.00%	0.83%	14.79%	22.83%	39.57%
Total	20.48%	4.13%	0.50%	0.00%	6.95%	31.04%	36.90%	100.00%

After the official implementation of the wetland restoration policy (after 2005), various types of land have changed to varying degrees. The area of non-wetlands increased by 28817.74 ha and the encroachment on the wetlands remained dramatic. The area of non-wetlands increased dramatically from 2010 to 2015, from 38,984.97 ha in 2010 to 66,719.04 ha, an increase of 71.14%. From 2000 to 2020, the total area of wetlands on the south bank of Hangzhou Bay decreased, of which natural wetlands decreased by 17,525.8 ha or 64.11% and artificial wetlands decreased by 11,291.89 ha or 27.30%, related to the policy of returning farmland and ponds to wetlands. The land use transfer matrix for 2005 to 2020 (Table 8) shows a substantial shift to non-wetlands for both natural and artificial wetlands. The most obvious shift between wetlands and each other is in shallow waters. There are three directions of transfer from shallow marine waters: first, silty beaches, mainly due to the accumulation of silt caused by tidal flushing in the delta; second, reservoirs/ponds, associated with fish and shrimp aquaculture; and third, paddies, associated with the growth of basic food needs associated with population growth. The second is the transformation of silty beaches into reservoirs/ponds, which is caused by the same reasons as the transformation of shallow waters into reservoirs/ponds.

Table 8. Land use transfer matrix for the south bank of Hangzhou Bay from 2005 to 2020.

2005 \ 2020	Shallow Water	Silty Beach	River	Lake	Reservoir/Pond	Paddy	Non-Wetlands	Total
Shallow Water	3.27%	2.94%	0.38%	0.79%	4.03%	2.63%	6.44%	20.48%
Mudflat	0.06%	0.06%	0.11%	0.07%	0.98%	0.46%	2.38%	4.13%
River	0.00%	0.00%	0.05%	0.01%	0.17%	0.05%	0.21%	0.50%
Lake	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Reservoir/Pond	0.02%	0.11%	0.29%	0.15%	2.45%	0.79%	3.13%	6.95%
Paddy	0.02%	0.14%	0.09%	0.06%	1.07%	9.97%	19.69%	31.04%
Non-wetlands	0.03%	0.16%	0.09%	0.10%	1.43%	3.58%	31.51%	36.90%
Total	3.41%	3707.64	1.02%	1.18%	10.14%	17.43%	63.37%	100.00%

5.2. Change in Water Yield

The water yield results revealed an upward trend for the coastal wetland on the south bank of Hangzhou Bay from 2000 to 2020 in terms of both yearly water output and water yield depth (Figure 4). The average water yield depth was 567.46 mm, followed by values of 710.08 mm, 1116.10 mm, and 1168.27 mm. The volume of water production was 6.18×10^8 m^3, 6.18×10^8 m^3, 7.73×10^8 m^3, 12.16×10^8 m^3, and 12.73×10^8 m^3, respectively. In terms of time series, the water yield depth and water yield showed a significant downward trend before the wetland restoration. After the wetland restoration, the average values of water yield depth and water yield showed an increasing trend, with an increase of 101.62%. From the overall spatial area, the water yield of coastal wetlands on the south bank of Hangzhou Bay shows a trend of low in the north and high in the south, increasing gradually from the sea to the coastal zone to the inland, with a slightly higher level at the silty beaches. Before wetland restoration (2000–2005), the high-value area of water yield shrank significantly, and in 2005, the medium-value area was dominant, with few high-value areas; meanwhile, the maximum water yield depth decreased from 1157.49 mm to 1059.09 mm from 2000 to 2005. After wetland restoration, the high-value area of water yield grew and expanded mainly from the coastal zone to the south of the study area, and the low-value area was concentrated around the shallow water areas, which also shrank as the areas of shallow water decreased. In terms of land use types (Table 9), both wetland and non-wetland water yielding capacity before wetland restoration showed a decreasing trend. After wetland restoration, the average water yield depth of natural wetlands kept rising overall, and the rise was obvious by 2020; artificial wetlands showed a fluctuating rise, and the improvement in 2020 compared with 2005 was also significant. From 2000 to 2020, the average water yield depths of different land use types on coastal wetlands in the south bank of Hangzhou Bay were, in descending order, silty beaches, non-wetlands, paddies, rivers, lakes, reservoirs/ponds, and shallow waters, and the average water yield depths per unit area of each land use type were 1106.08 mm, 965.58 mm, 857,78 mm, 296.13 mm, 289.64 mm, 289.57 mm, and 177.15 mm, respectively. Water production capacity is generally inversely proportional to evapotranspiration [54]. Non-wetlands have a larger water output because the existence of many artificially made surfaces increases the impervious area and changes the water balance, which leads to less precipitation infiltration and more flood flows [55].

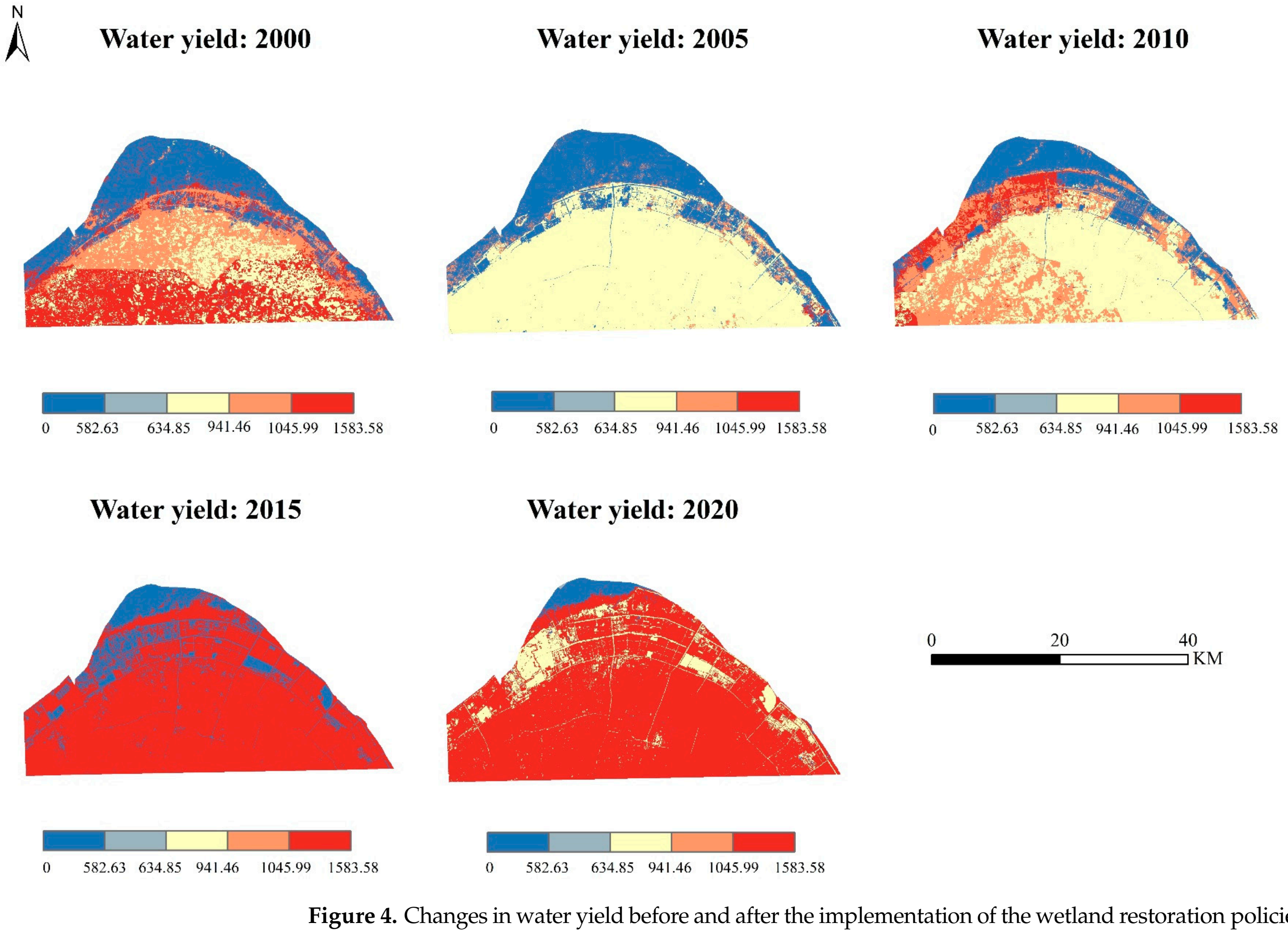

Figure 4. Changes in water yield before and after the implementation of the wetland restoration policies.

Table 9. Water yield of different LULC. (Unit: mm).

LULC	2000	2005	2010	2015	2020
Shallow Water	313.25	0	0	0.02	572.40
Silty Beach	1077.70	991.90	1146.67	1479.29	1390.55
River	495.98	15.95	0	249.56	715.50
Lake	490.41	1.83	0	222.70	734.15
Reservoir/Pond	487.45	10.62	0	230.64	716.71
Paddy	890.73	725.55	852.78	1208.97	1138.86
Non-wetlands	1053.81	856.92	949.41	1362.87	1296.57

5.3. Change in Carbon Storage

The research results are described from both a temporal and a spatial perspective (Figure 5). In terms of the temporal changes in carbon storage, the carbon storage of the study area in 2000, 2005, 2010, 2015, and 2020 was 4.58×10^6 t, 5.93×10^6 t, 7.23×10^6 t, 3.40×10^6 t, and 4.17×10^6 t, respectively. Carbon storage showed an increasing trend before wetland restoration. After wetland restoration, the carbon storage on the south bank of Hangzhou Bay fluctuated and changed, with a significant decrease from 2010 to 2015 and a slight improvement in 2020.

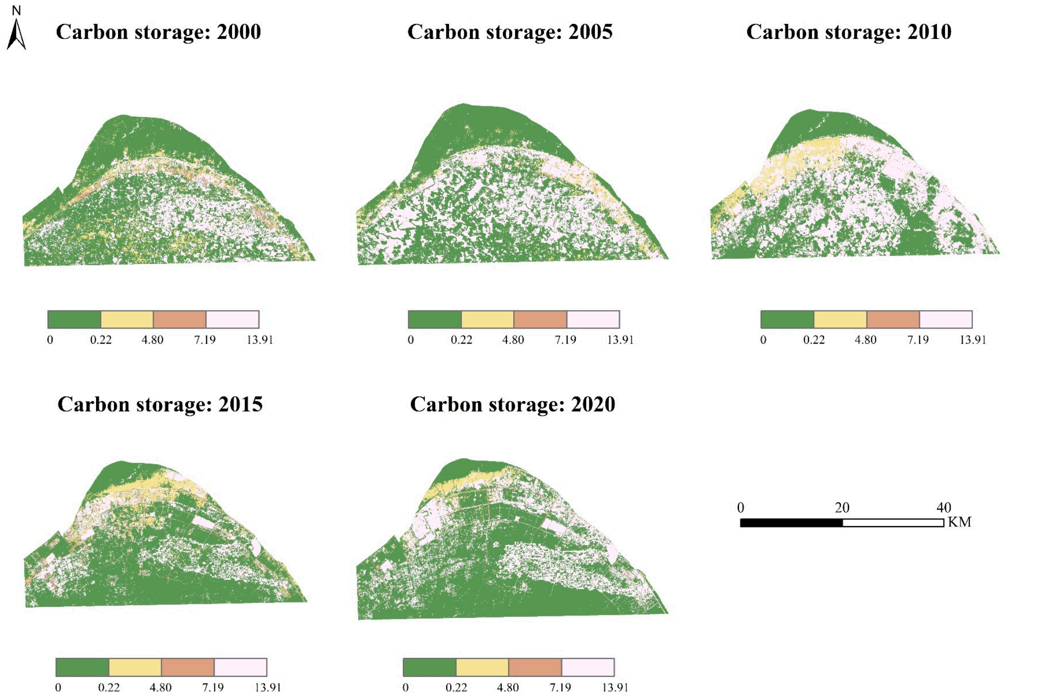

Figure 5. Changes in carbon storage before and after the implementation of the wetland restoration policies.

Before and after the wetland restoration policy's implementation, there was not much of a shift in the spatial distribution pattern of carbon storage on the south coast of Hangzhou Bay. Carbon storage increases gradually according to the pattern of the watershed–coastal zone and the inland area, and the high-value areas are scattered in the inland area. Carbon storage decreased in the central and southern parts of the study area after 2010, combined with land use type transformation, indicating that many paddies were converted to non-wetlands during this period. According to the carbon density data, paddies have a strong carbon storage capacity, while the non-wetland carbon storage capacity is weak. A large number of paddy fields were converted to non-wetlands, so the carbon storage capacity decreased sharply. Low-value areas are mainly located in shallow waters and non-wetland areas. As the areas of shallow waters decrease and the areas of non-wetlands increase, the areas of low-value regions also change simultaneously, specifically showing a decrease in low-value regions in the north and an increase in low-value regions in the central and south areas.

5.4. Change in Habitat Quality

The habitat quality results of the study area were obtained by InVEST model analysis, and the data (0–1) indicated the habitat quality from poor to good. The habitat quality was classified into five classes using the ArcGIS natural breakpoint method, as shown in Figure 6. The results showed that, in terms of time scale, the mean values of the habitat quality index in the study area in 2000, 2005, 2010, 2015, and 2020 were 0.459, 0.465, 0.442, 0.248, and 0.207, respectively. The overall habitat quality of the study region started to decline once the wetland restoration policy was put in place (2005–2020).

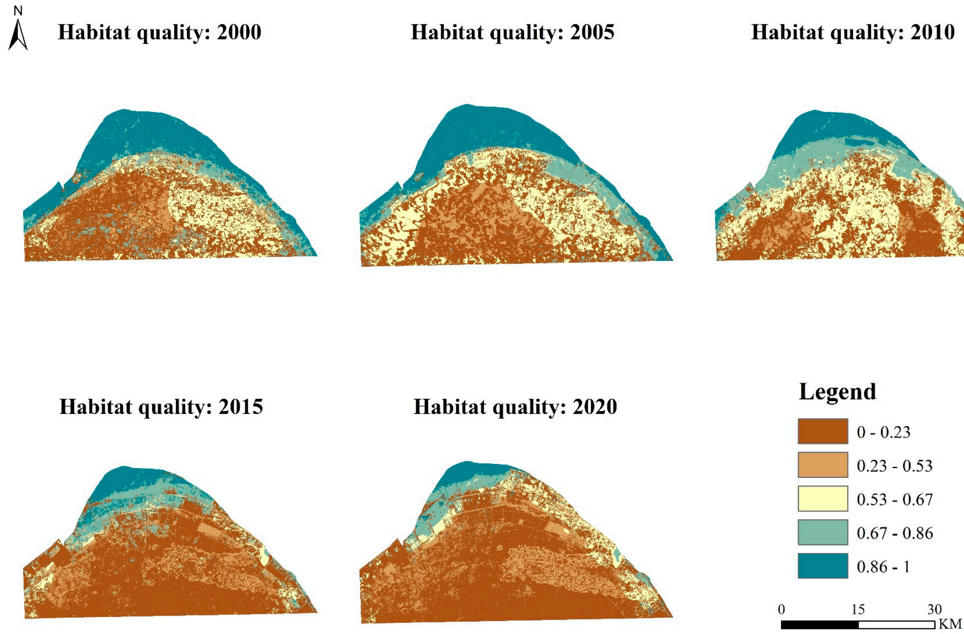

Figure 6. Changes in habitat quality before and after the implementation of the wetland restoration policies.

On a spatial scale, the spatial distribution of habitat quality in Hangzhou Bay is relatively uniform, decreasing from the sea to the inland. The habitat quality is highest in shallow waters and poor in terrestrial areas. The habitat quality of the shallow waters is the highest due to its low anthropogenic impact. However, under the combined effect of natural factors (e.g., silt accumulation) and human factors (e.g., reclamation), the sea area decreases and the coastline changes, followed by the change of the sea area to land, which leads to a rapid decline in habitat quality. As a result, the areas of high value have been significantly reduced. In inland areas, the area of low value is also increasing due to the conversion of artificial wetlands to non-wetlands.

5.5. Comprehensive Analysis of Changes in Ecosystem Service

The integrated changes in ecosystem service functions were determined by normalizing each ecosystem service function and superimposing equal weights (Figure 7) [56]. On the time scale, the mean values of the integrated ecosystem service index in the study area from 2000 to 2020 were 0.45, 0.46, 0.49, 0.39, and 0.40, respectively, with similar trends to those of individual ecosystem services. The integrated ecosystem services showed an increasing trend after the implementation of the wetland restoration policy in 2005 but decreased during the establishment phase of Hangzhou Bay New District and eased in 2020. On a scale, the study area is generally dominated by low-value areas, mainly concentrated in the sea and non-wetlands in the south of the study area. From 2000 to 2010, the area of high-value areas and medium-value areas increased with silt accumulation and farmland reclamation, and the area of low-value areas decreased accordingly. From 2010 to 2015, the area of low value increased, mainly concentrated in the expansion of construction land in the south of the study area, and the area of medium value increased with the expansion of silt beaches. From 2010 to 2015, the low-value area increased, mainly concentrated in the expansion of construction land in the south of the study area; the medium-value area increased with the expansion of silty beaches; and the high-value area decreased, concentrated in Xinpu Town, Fuhai Town, Guanhaiwei Town, Shengshan Town, and Chongshou Town.

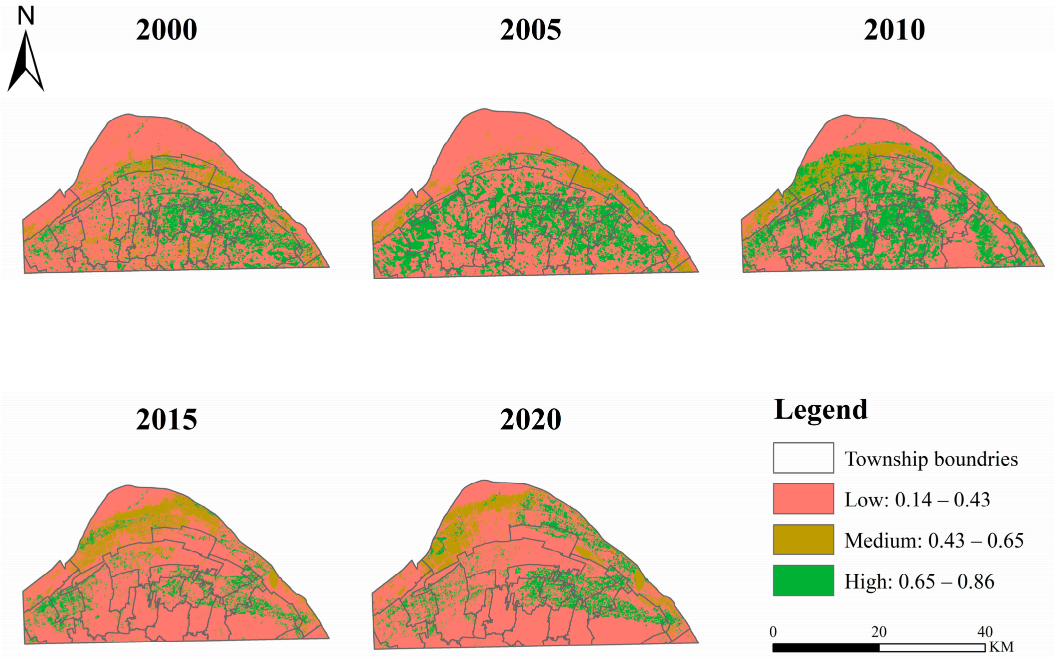

Figure 7. Integrated changes in ecosystem service before and after the implementation of the wetland restoration policies.

5.6. Hotspot Analysis

Based on the results of single ecosystem services and integrated ecosystem services of coastal wetlands on the south bank of Hangzhou Bay, the ArcGIS 10.8 spatial statistics tool was used to calculate the distribution areas of cold hotspots for each ecosystem service separately in order to measure the spatial pattern characteristics.

From Figure 8, it can be seen that the non-significance of water yield is dominant in the south bank of Hangzhou Bay from 2000 to 2020; there are few hotspot areas, mainly in Linshan Town and Simen Town in the southwest of the study area. The cold spot areas are in the municipal silty beaches. In the years with high water yields or large increases, the non-significant area increased greatly, while the significant area shrank in an extreme manner, and only a few cold spots were in the sea area. In 2015 and 2020, there were no hot spots in the study area. The distribution boundary between cold and hot spots of carbon storage is not obvious. On the whole, the change in the range of hot spots is consistent with the trend of carbon storage, and the areas with high carbon storage are the hot spot areas. Since the five periods, the range of hot spot areas has changed, but most of them are concentrated in Fuhai Town, Shengshan Town, Kandun Street, Xinpu Town, Guanhaiwei Town, and other places. From 2000 to 2020, the distribution boundaries of cold hot spots were clear, and the significant areas of cold hot spots decreased while the non-significant areas increased. The hot spot area is located on city beach land, which is a shallow water area and a high-value area of habitat quality. The cold spot area is located in the south and southwest of the study area, but with the expansion of construction land, the cold spot area decreases, and by 2020, there will be no cold spot area in the study area.

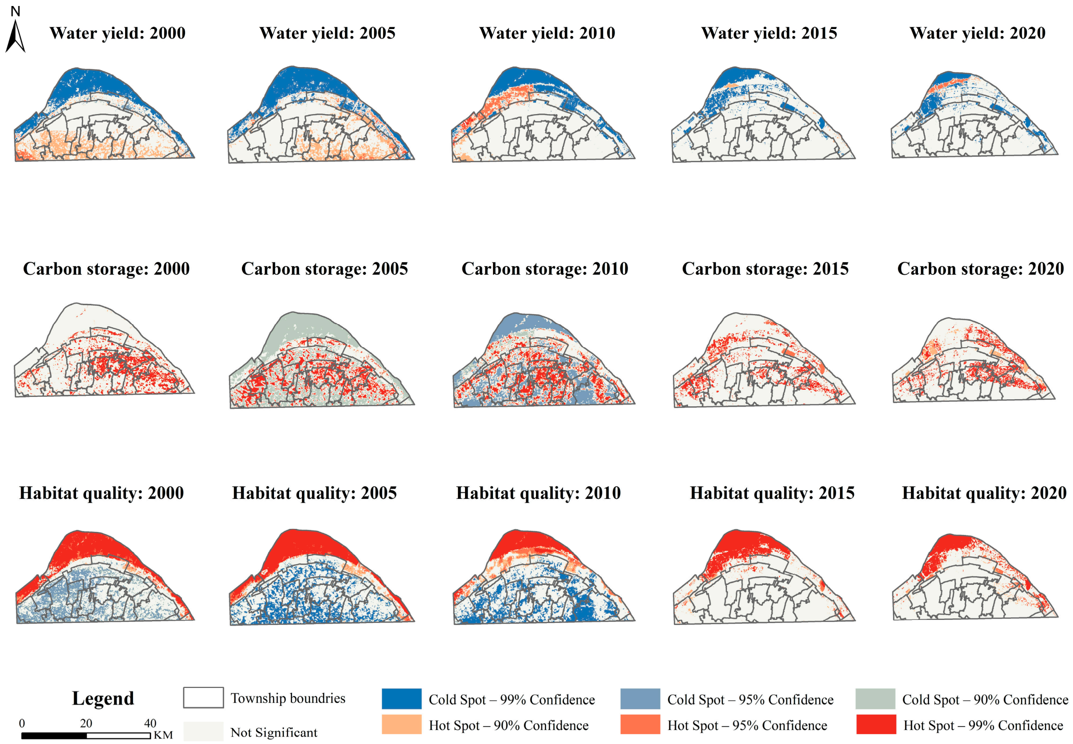

Figure 8. Spatial distribution of hotspots for single ecosystem services.

Based on the spatial analysis of hotspots of the integrated ecosystem services, the spatial combination pattern of high cluster values of ecosystem services can be identified, so that the differentiated ecosystem service management tools can be spatially positioned at the township level. From Figure 9, it can be seen that the spatial changes of hotspot areas from 2000 to 2020 are not obvious, mainly in the eastern and southeastern parts of the study, and Xiaocao'e Town in the west is also a hotspot area. There are no obvious cold spot areas, and the ecosystem services in the five periods are mainly significant. Combined with the spatial change analysis of integrated ecosystem services, it was found that the hotspot area is usually the high-value area of the integrated ecosystem.

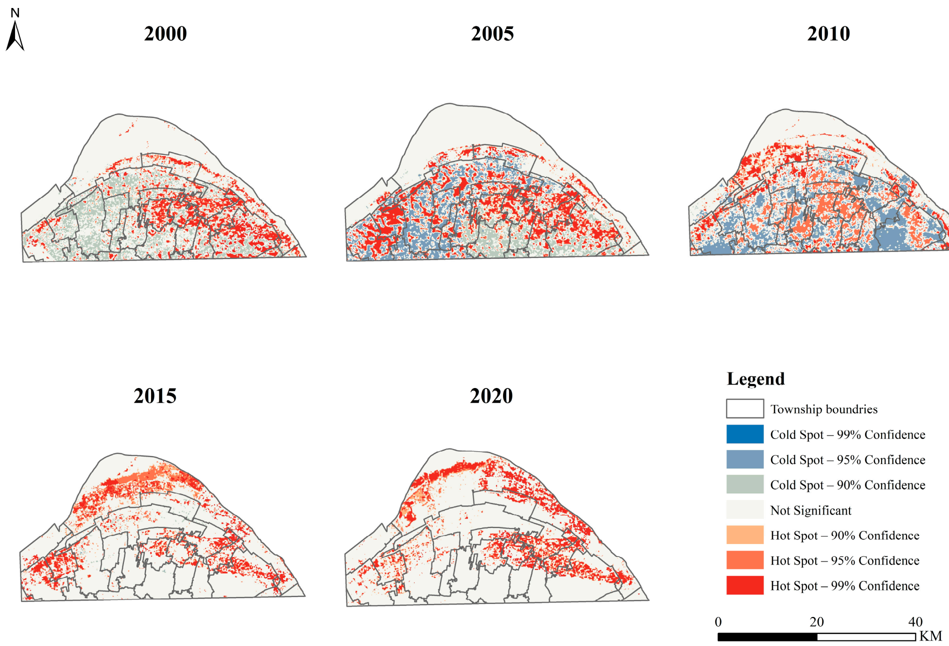

Figure 9. Spatial distribution of hotspots for integrated ecosystem services.

5.7. Coastal Wetland Ecological Restoration Zoning

Based on the spatial changes and the distribution of hotspots of integrated ecosystem services, the coastal wetland on the south bank of Hangzhou Bay was divided into three ecological zones at the township scale, namely, an ecological conservation area, an ecological restoration area and a green development area (Figure 10). Specifically, the high-value integrated ecosystem services area and hotspot area are taken as ecological conservation areas. The main area of integrated ecosystem service, whose LULC type is a wetland, is ecological restoration areas. In addition, the low-value area of integrated ecosystem service whose LULC type is non-wetland is the green development area. The results of zoning are blurred at the township level with administrative boundaries.

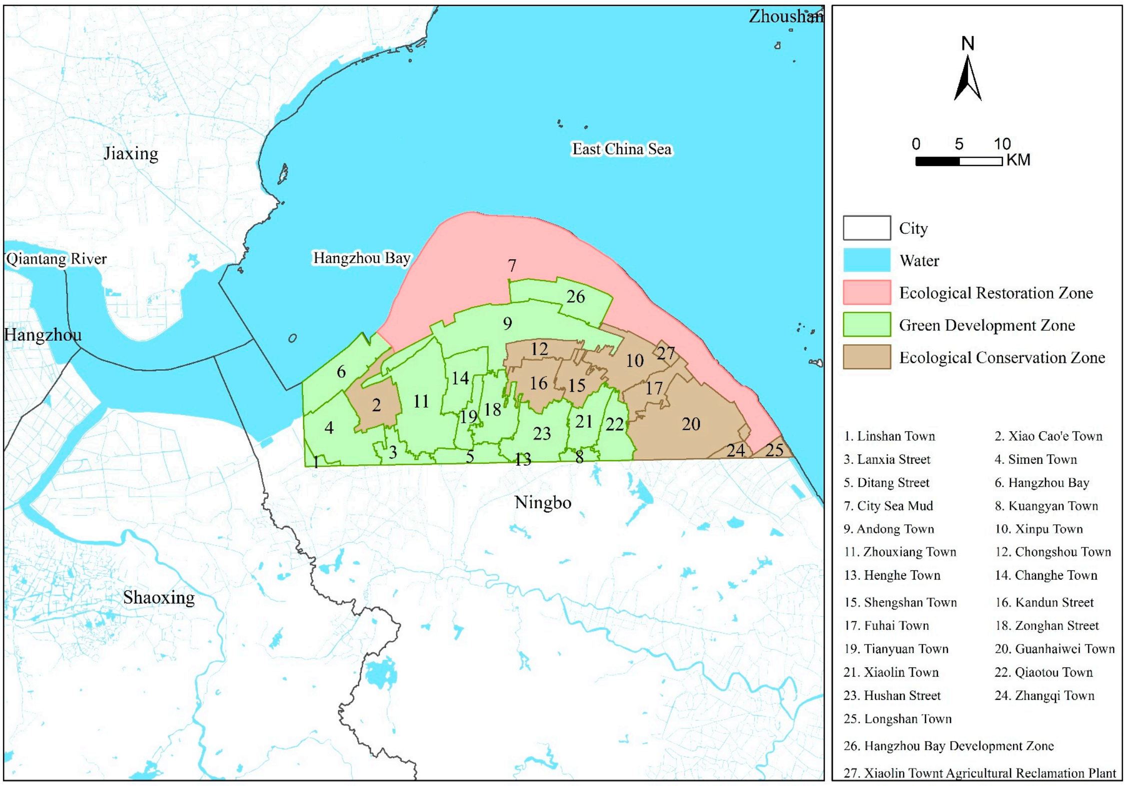

Figure 10. Ecological restoration zoning at the town scale on the south bank of Hangzhou Bay.

The ecological conservation area is concentrated in the eastern part of the study area, including Xiao Cao'e Town, Xinpu Town, Chongshou Town, Xiaolin Town, Shengshan Town, Kandun Street, Fuhai Town, Guanhaiwei Town, Zhangqi Town, and Longshan Town. The area is dominated by paddies, with low pressure on ecological degradation and a well-integrated state of ecosystem services. It is the ecological core area of coastal wetlands on the south bank of Hangzhou Bay, which is extremely important for ecological stability. The area should focus on natural restoration, adopt ecological space circle control, prohibit construction and development in the surrounding area, and reduce the interference of human factors with the ecological environment. At the same time, under the premise of ensuring food security, we can take the measure of "returning the paddies to wetlands" to achieve the purpose of natural wetland restoration.

The ecological restoration area is distributed in the northern coastal zone of the study area, including the whole area of the municipal tideland. The habitat quality in this area is higher, but the water yield and carbon storage are low, and the integrated ecosystem service is at its lowest value in the study area. Due to policies such as the reclamation of the sea and the establishment of Hangzhou Bay New District, the coastal zone has been expanding towards the sea. The silt beaches are reclaimed from the inland direction and continuously silted to the sea direction. When the rate of reclamation is higher than the rate of silt accumulation, the silt beach is over-reclaimed, and the ecosystem function of the area shows a trend of continuous degradation [57], so there is an urgent need to carry out ecological restoration. For the region, on the one hand, it is necessary to prevent the continuous disorderly expansion of construction land, and on the other hand, it is necessary to carry out artificially assisted restoration through hydrological restoration, base restoration, and other technical means, such as terrain modification, ecological water replenishment, and river desilting. At the same time, attention should be paid to the habitat suitability of the region. On the one hand, the damage caused by invasive species such as Spartina alterniflora to native species was closely monitored. On the other hand, the biodiversity of wetlands can be improved by limiting fishing, establishing protected areas, breeding, and releasing.

The green development area is located in the central and western locations of the study area, including other townships in the study area. This area is mainly construction land, with a large population and a relatively developed economy. At the same time, it also faces common problems such as the sharp contradiction between humans and land and the deterioration of the ecological environment. On the one hand, it is necessary to strictly control the damage of infrastructure to the ecological environment in this region, limit its outward expansion, determine ecological assessment and feasibility analysis strategies, and improve the regional ecological benefits and environmental carrying capacity. On the other hand, on the basis of protecting the basic ecological landscape, we should uphold the concept of "low impact" development and construction, use appropriate land to safeguard the economy, promote the intensive and economical use of land, and ensure the realization of regional green development.

6. Discussion

6.1. Influencing Factors of Ecosystem Service Changes in Coastal Wetlands

Through the analysis of the change in coastal wetland ecosystem services combined with the change in land use structure on the south bank of Hangzhou Bay, it was found that the restoration of coastal wetlands is influenced by both natural and anthropogenic factors.

Regarding natural factors, the main factor is silt accumulation due to tidal flushing. Located on the southern shore of a semi-enclosed estuary, the study area is characterized by strong tides and a wide, gentle coastline. The concentration of suspended sediment in the tidal water of Hangzhou Bay is high, and the suspended sediment consists mainly of surface runoff and suspended particles from the Yangtze River. The south bank is a hydrodynamic isolation zone prone to sediment accumulation, so the day-to-day accumulation of sediment leads to the degradation of the shallow waters, transforming them into silty beaches and providing a natural basis for further artificial reclamation. The anthropogenic factor is mainly the expansion of construction land and the population growth brought by urbanization. From the change in land use type area, it can be clearly seen that Hangzhou Bay New District, which was approved by the government in 2010, has caused a large number of wetlands to transform into non-wetlands, which has reduced ecosystem services [53]. Economic development has attracted a large number of migrants. As the population increases, so does the demand for land for housing and transportation infrastructure. Human beings are constantly adjusting land use types and structures to create the space needed for human activities, so the pressure for adequate spatial resource needs is shifting to wetlands [58].

6.2. Policy Implications

After entering the 21st century, Hangzhou Bay has made great achievements in social and economic development. As a newcomer after the Guangdong–Hong Kong–Macao Greater Bay Area, the rise of Hangzhou Bay Area radiates the world-class core group of the Yangtze River Delta [59]. However, under the influence of high-intensity human activities, the Hangzhou Bay coastal wetland ecosystem is also facing unprecedented risks and challenges [60].

In the past two decades, the development intensity of the south bank of Hangzhou Bay has been increasing, so it is particularly important to further strengthen wetland protection and clarify the focus of wetland protection policies. This study shows that the ecological environment of the study area has not significantly improved since the implementation of the wetland restoration policy, but some ecosystem services have declined due to reclamation. The ecological improvement effect brought about by the wetland protection policy cannot compensate for the damage caused by economic development. Therefore, according to the research results and previous research experience, the following policies and measures are proposed to promote the effectiveness of wetland conservation policies in general.

(1) The construction activity in wetlands needs to be tightly controlled [61]. Through the analysis of the changes in coastal wetland ecosystem services on the south bank of Hangzhou Bay, it was found that the transformation from wetlands to non-wetlands is the main reason for the decrease in ecological benefits. Therefore, it is necessary to improve the land use efficiency of construction land and avoid the further occupation of wetlands by combining the planning policy of the Yangtze River Delta with the integrated development of urban agglomerations. (2) Wetlands' ecological conservation and rehabilitation should be strengthened. To gradually restore the coastal wetlands destroyed by reclamation, we must strictly adhere to the red line of ecological protection of the Hangzhou Bay coastal wetland, strengthen reconstruction and restoration efforts, and adhere to natural restoration as the primary and artificial restoration as a supplement. At the same time, attention should be paid to the survival and habitability of plants and animals to improve the level of biodiversity in degraded and restored wetlands. (3) Establishing a long-term monitoring and management system for coastal wetlands on the south bank of Hangzhou Bay, investigating them block by block, setting up a dynamic monitoring system, quickly recognizing the dynamic changes of nearshore wetlands and natural coastlines, and taking action to prevent sediment buildup in shallow waters are all necessary.

6.3. Research Limitations

(1) Due to the limitations of the remote sensing image resolution and the field survey conditions, the wetland classification system in this study did not include wetland vegetation cover types and did not analyze the ecosystem services generated by typical vegetation in Hangzhou Bay coastal wetlands, such as reed, seeds, Scirpus mariqueter, Spartina alterniflora, mangrove, and Tamarix. However, the expansion of Spartina alterniflora as an invasive alien species leads to the growth and reproduction of native species being hindered or even dying, resulting in the loss of food and habitats for many animals, which was not considered deeply in this study.

(2) The assessment of coastal wetland ecosystem service functions on the south bank of Hangzhou Bay covers food production, cultural recreation, climate regulation, etc. Only the most typical water yield, carbon storage, and habitat quality of wetlands were selected as indicators in this study, and the results obtained are not comprehensive enough. Other types of ecosystem service changes brought about by wetland restoration can be further explored in the future.

7. Conclusions

This study starts with the spatial-temporal changes of ecosystem services, combines it with remote sensing image data, meteorological data, soil data, and other data, calculates the water yield, carbon storage, and habitat quality of coastal wetland in the south bank of Hangzhou Bay before and after the implementation of the wetland restoration policy (2000–2020) by relying on the InVEST model, and analyzes the spatio-temporal trends and spatial pattern distribution characteristics. To provide scientific guidance for the ecological protection and restoration of coastal wetlands, the ecological restoration pattern of coastal wetlands on the south bank of Hangzhou Bay is divided according to the analysis.

The results show that: (1) before and after the implementation of the wetland restoration policy, the area of natural and artificial wetlands is decreasing, and the area of non-wetlands is increasing. The most obvious transformation of wetlands into each other is the transformation of shallow waters into silty beaches. (2) In general, integrated ecosystem services increased initially before declining, showing a minor improvement in 2020 compared to 2015, with urban growth being the primary factor in the reduction. In particular, water production is increasing, and carbon storage fluctuates, showing a steep fall from 2010 to 2015 and a return in 2020. The state of the habitat has not improved. (3) From the perspective of spatial distribution patterns, the spatial change in ecosystem service hotspots is not obvious from 2000 to 2020. The hotspots are mainly concentrated in the east and southeast, and Xiaocao'e Town in the west is also a hotspot area. The ecosystem services are mainly insignificant. (4) Based on the changing trend of ecosystem services and the distribution pattern of spatial cold and hot spots, the coastal wetlands on the south bank of Hangzhou Bay were divided into three ecological zones: an ecological conservation zone, an ecological restoration zone, and a green development zone. From the perspective of wetland management, differentiated management and control measures of coastal wetlands in the south bank of Hangzhou Bay are suggested based on the zoning results in order to promote the coordinated development of coastal wetland ecosystems and social economies in the south bank of Hangzhou Bay and to achieve a "win–win" situation.

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