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Study of the Ecosystem Service Value Gradient at the Land–Water Interface Zone of the Xijiang River Mainstem

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Abstract: The ecosystem service value (ESV) gradient-evolution pattern of a river basin's land and water-intertwined zones has a variety of ecosystem service values, such as biodiversity conservation, water conservation, water purification, etc. The study of the ecosystem service value (ESV) gradient-evolution pattern of a river basin's land and water-intertwined zones will provide a scientific basis for the construction and protection of the ecological security pattern of the river basins. In this study, we combined the unit area equivalent factor method and geographically weighted regression (GWR) model to classify and analyze the gradient change pattern of ESV upstream, downstream, and along the river of the Guangdong mainstream section of the Xijiang River in China, and the conclusions are as follows: (1) The corresponding ESV share of each land use type was in the following order: water bodies > broad-leaved forest > artificial wetland > scrub > paddy field > coniferous forest > natural wetland > grassland. The level of each type of ESV does not depend entirely on the size of the area but is determined by the ecosystem service functions it can provide and the level of ESV per unit area; (2) the relationship between land use types along both sides of the river in the Guangdong section of the Xijiang River Basin shows a tendency to shift from water ecosystems to terrestrial ecosystems, and the ESV gradually decreases with the increase in distance from the water. (3) The upstream to the downstream area showed a trend of changing from terrestrial ecosystems to aquatic ecosystems, such as broad-leaved forests, scrublands, water bodies, artificial wetlands, etc., and the mean land ESV showed a general trend of undulating change and decline with the reduction in the distance from the downstream area. (4) Natural factors, such as the topography and geomorphology of the basin and the socio-economic factors of power consumption, influence the spatial distribution characteristics of the ESV in the region; among them, socio-economic factors, such as total power consumption, industrial exhaust gas emissions, industrial wastewater emissions, etc., in the economically developed areas of the Xijiang River Basin are the determinants of the changes in ESV, which are generated by human living and production activities, and these indirectly affect the magnitude of the ESV by influencing the factors of temperature and gas.

Keywords: land–water interface; ecosystem services; GWR model; gradient; land use

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1. Introduction

Land–water interface zones are the junctions between the river and terrestrial ecosystems, and they have been emphasized in ecological and environmental fields in recent years because of their important roles in protecting biodiversity, intercepting and infiltrating ecological flows, such as material and energy flows, and purifying water bodies [1–5]. Overseas research on land–water interface zones has produced more in-depth results, e.g., in the Everglades National Park in Florida, USA, and the Laurentian Great Lakes in

Canada. Natural and socio-economic vulnerability indices have been created via spatial modeling using geographic information systems (GISs). A multidisciplinary approach integrating geological, physical, and socio-economic vulnerability was synthesized to study the integrated vulnerability of the riverine and coastal land–water interface zones under different environmental factors. It was concluded that the spatial variability of the natural environment has a greater impact on ecosystems than temporal fluctuations [6–9]. In China, research on land–water interface zones is focused on Dongting Lake [10], Chaohu Lake [11], Poyang Lake [12], and other important water bodies. The basic characteristics of the landscape pattern changes in the relevant study areas were explored; the landscape changes of different characteristics reflect different land use conditions, and the means and extent of the impact of human activities on the value of ecosystem services were revealed through land use. In the Pearl River Basin, studies on spatial and temporal changes in ecological land use and the evolution and value assessment of landscape patterns have been carried out [13], but there is a lack of research on the value of ecosystem services in the basin's land–water interface zones.

Ecosystem services are the variety of resources and benefits that humans obtain from ecosystems or the direct or indirect contributions of ecosystems to human well-being and benefits [14], which can be categorized into provisioning services, regulating services, supporting services, and cultural services. The amount of goods and services that ecosystems create and provide in the form of economic benefits is called ecosystem service value (ESV). Market values can directly estimate the value of each individual ES using economic laws [15], and scholars have already used this method to study and achieve results in areas such as the San Antonio region of Texas in the USA [16], coastlines [17], and surface freshwaters [18]. Among the non-market values, the method used to evaluate the value equivalent factor per unit area and the INVEST model is the most widely used. INVEST (integrated valuation of ecosystem services and tradeoffs) is a modeling system that was developed by the US Natural Capital Project Team to assess the functional quantity of ecosystem services and their economic value and to support ecosystem management and decision-making, with the ability to simulate changes in the number of ecosystem services under different land cover scenarios and with an intuitive representation of the results of assessments [19]. Many scholars have conducted ESV assessments for important river basins [20,21], forests [22], mangroves [23], coastal areas [24], and agricultural land [25] using the INVEST model method. The method used to evaluate the value equivalent factor per unit area is a dynamic valuation method for ES in China, proposed by Xiegao Di [26], which has been widely used in studies of ecosystem service valuation in spatially heterogeneous ecosystems [27,28]. In this study, the method allows for a more visual comparison of high and low ecosystem service values across gradient zones, which will be calculated based on a modified ESV equivalent scale.

Geographically weighted regression (GWR) models can be used to study the correlation between multiple variables characterized using spatial distribution and the dependent variable by creating local regression equations in each grid, and they are increasingly being used for the spatial analysis of social and environmental data. They allow for "the study of spatial heterogeneity in processes and relationships through a series of local regression models rather than a single global regression model" [29–32]. In view of this, the GWR model was introduced in this study to explore the spatial heterogeneity of the effects of various drivers on the ESV gradient in the study area, enabling the results to shed more scientific light on the possible reasons behind the changes in the ESV gradient in the study area.

The Xijiang River, a major component of the Pearl River system, is the third-largest river in China, the longest river in South China, and the second-largest river in China in terms of navigation volume, flowing successively through five provinces and regions, namely Yunnan, Guizhou, Hunan, Guangxi, and Guangdong. Scholars are concerned about the impact of climate and land use changes on the runoff hydrology of the Xijiang River Basin [33]. At the same time, some scholars also focus on the spatial and temporal changes of the river [34]. In this paper, the land–water interface zone for the upper, middle, and lower reaches of the basin in the Guangdong section of the Xijiang River Basin is divided into the along-river gradient and the upper and lower-reaches gradient, and the gradient analysis of ESV was carried out by using the ecosystem service value valuation methodology based on the area of a unit to explore the gradient change law of ESV in the Guangdong section of the Xijiang River Basin.

Background

As shown in Figure 1, the study area of this paper was the Guangdong section of the Xijiang River Basin. It consists of the Xijiang River Basin Authority area that starts from the provincial boundary of Guangdong Province (vertically) and ends at the Doumen District of Zhuhai City. It has a total length of 342 km, a rainfall catchment of 17,960 km^2, an average annual rainfall of 1577 mm, and an average annual flow rate of 14.96 billion m^3. The study area is rich in water conservancy and hydroelectricity; it has a high shipping capacity and has important resources for the development of agriculture along the coasts and rivers. The cities of Zhaoqing, Foshan, Guangzhou, Jiangmen, Dongguan, Shenzhen, Zhongshan, and Zhuhai, through which the Guangdong section flows, belong to the Pearl River Delta urban agglomeration, which has the largest concentration of population, the strongest innovation capacity, and the strongest comprehensive strength in China, and it is also an important part of the Guangdong–Hong Kong–Macao Greater Bay Area, which has been a significant leader in China's economic development [35]. Relevant studies show that during 1980–2018, due to accelerated urbanization processes, the ecological land on the west bank of the Pearl River Delta has become heavily crowded out, the land use types along the basin are constantly changing, and the functions of their corresponding ecosystems and the ESV per unit area are also changing [13], and this is a typical area where basin ecosystems are changing in a gradient. The buffer zone (i.e., the land–water intersection zone) within 10 km from both sides of the Guangdong section of the Xijiang River Basin was designated as the study area of this paper.

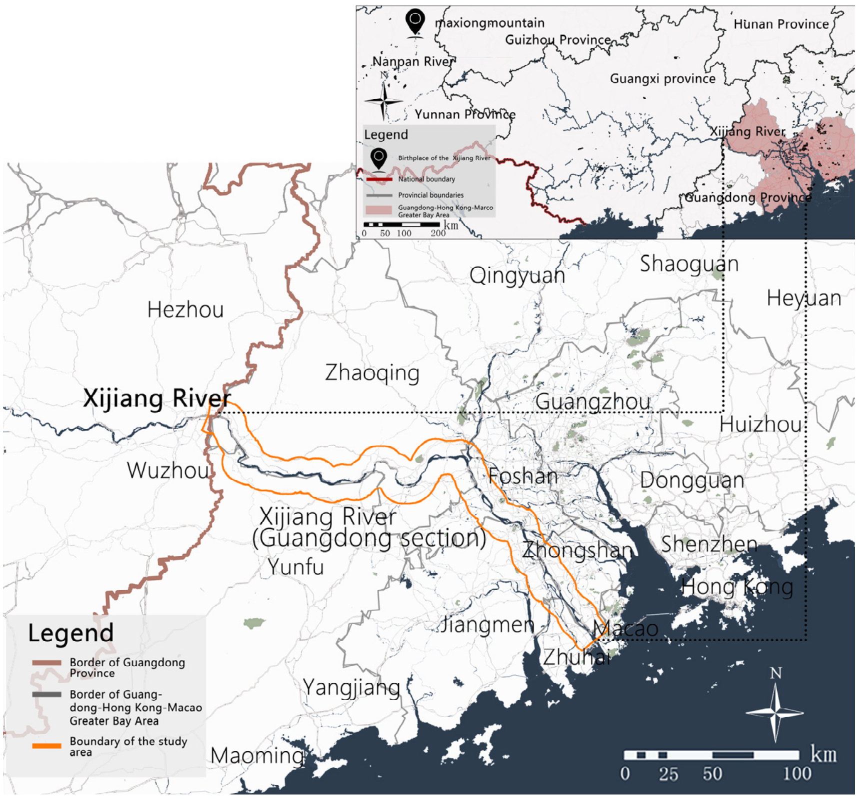

Figure 1. Map showing the location of the water–land ecotone of the Guangdong section of the Xijiang River.

2. Materials and Methods

2.1. Data Sources

The global 30 m fine ground cover product for 2020 (GLC_FCS30-2020), provided by the Cloud Platform for Resource and Environmental Data of the Chinese Academy of Sciences "http://www.resdc.cn/ (accessed on 7 October 2022)", was used. Grain production and grain price data were obtained from the China Statistical Yearbook 2020, Guangdong Statistical Yearbook 2020, and China Statistical Information Network "http://www.tjcn.org/ (accessed on 8 May 2023)" (Table 1). To facilitate the use of the model and to ensure the accuracy of the data, the data were uniformly binned in the study in rasters with 1 km sides.

Table 1. Data sources and accuracy table.

Data Name	Data Description	Data Format/Accuracy	Data Source
Administrative boundary	Official government planning boundary	Shp	National Catalogue Service For Geographic Information "https://www.webmap.cn/main.do?method=index (accessed on 7 October 2022)"
Land use	Land use	Raster/30 m	Resource and Environment Science and Data Center, Chinese Academy of Sciences "www.resdc.cn (accessed on 7 October 2022)"
Temperature	Average annual surface temperature	Raster/1 km	
Humidity	Average annual surface humidity	Raster/1 km	
GDP per unit area	Average GDP per square kilometer	Raster/1 km	
Rainfall	Annual rainfall	Raster/1 km	
Evapotranspiration	Annual evapotranspiration	Raster/1 km	
Night light	Artificial night light	Raster/1 km	Geospatial data cloud platform "http://www.gscloud.cn/ (accessed on 24 January 2023)"
Elevation	Data of average elevation	Raster/30 m	
Vegetation cover index (NDVI)	Average annual NDVI	Raster/500 m	
Population density	Average population per square kilometer	Raster/1 km	Open Spatial Demographic Data and Research "https://hub.worldpop.org/ (accessed on 8 May 2023)"
Food production and food price data	Grain economic data of Guangdong Province	Excel	China Statistical Yearbook 2020, Guangdong Statistical Yearbook 2020, and China Statistical Information Network "http://www.tjcn.org/ (accessed on 8 May 2023)"
Industrial proportion	Proportion of primary, secondary, and tertiary industries	Excel	
Total electricity consumption	Total electricity consumption	Excel	
Industrial emissions	Industrial emissions	Excel	
Industrial wastewater discharge	Discharge of industrial wastewater	Excel	
Electricity and energy consumption of industrial enterprises above scale for the whole year	Discharge of industrial wastewater Annual power energy consumption of industrial enterprises above scale	Excel	

2.2. Research Methodology

2.2.1. Site Classification

After referring to the Global 30 m Fine Surface Cover Product 2020 [36] and combining it with data taken from field research and the literature, the land use types in the study area were finally classified into nine categories: grassland, scrub, built-up land, broad-leaved forests, artificial wetlands, natural wetlands, paddy fields, water bodies, and coniferous forests, where water bodies correspond to water body ecosystems, paddy fields correspond to paddy ecosystems, artificial wetlands correspond to artificial wetland ecosystems, etc. The ESV of constructed land is extremely low; therefore, it was not included in the calculation of this study.

2.2.2. Gradient Division at the Spatial Level

Gradient Division along the River

The corridors formed by the land–water interface zones are an integral part of the water body landscape and can better reflect the disturbances to the water bodies. The corridor formed by the land–water interface zone is an integral part of the water bodies landscape, which can better reflect the disturbances suffered by the water bodies. In order to show the gradient variation of the ESV transverse profiles in the aquatic–land interface zone, after considering the ecological spatial characteristics and the scope of the study area, the gradient along the river was divided into four distances, namely, 500 m, 1000 m, 1500 m, and 2000 m, as the unit of gradient division according to the geographic characteristics of the Xijiang River Basin. After a comprehensive comparison, the smaller the spacing, the more favorable this is for the expression of spatial differentiation, but the less amount of data contained in the gradient. The larger the spacing, the more unfavorable this is for the expression of spatial differentiation, but the more data contained in the gradient, the greater the analysis that can be completed. When combined with the purpose of this study, which needs to achieve a certain accuracy of spatial differentiation as well as a sufficient amount of data, 1000 m was finally chosen as the increment of the gradient. The along-river gradients are uniformly named in the text: along-river gradient 1, along-river gradient 2, and so on, dividing the study area (starting from the centerline of the Xijiang River mainstem) into 10 gradient classes to determine the ESV gradient.

Upstream and Downstream Gradient Division

In order to investigate the ESV gradient upstream and downstream of the study area, a buffer zone of 10 km on both sides of the mainstem of the Guangdong section of the Xijiang River was divided into 10 zones based on the centerline of the mainstem of the river, taking into account the ecological and spatial characteristics of the study area. The specific division operation was as follows: the centerline of the mainstem of the Guangdong section of the Xijiang River Basin (approximately 342 km) was divided into 10 equal parts, and a dividing line was made perpendicular to the centerline of the river at the point of segmentation, and the buffer zones in the range of 10 km on each side from the centerline of the river (to a total of 20 km) were cut vertically perpendicular to the centerline of the river so that we obtained 20 km land–water intersection zones in the Guangdong section of the Xijiang River mainstem in 10 equal parts, corresponding to the ten gradients, respectively. These were named the first level of the river section, the second level of the river section, the third level of the river section, and so on; each gradient basically represents the area from the upper reaches to the lower reaches of the geospatial characteristics and different types of land-use modes, and at the same time, it is also convenient for analyzing comparisons with the gradient along the river. Each gradient was calculated and analyzed as a separate ESV research unit (Figures 2 and 3).

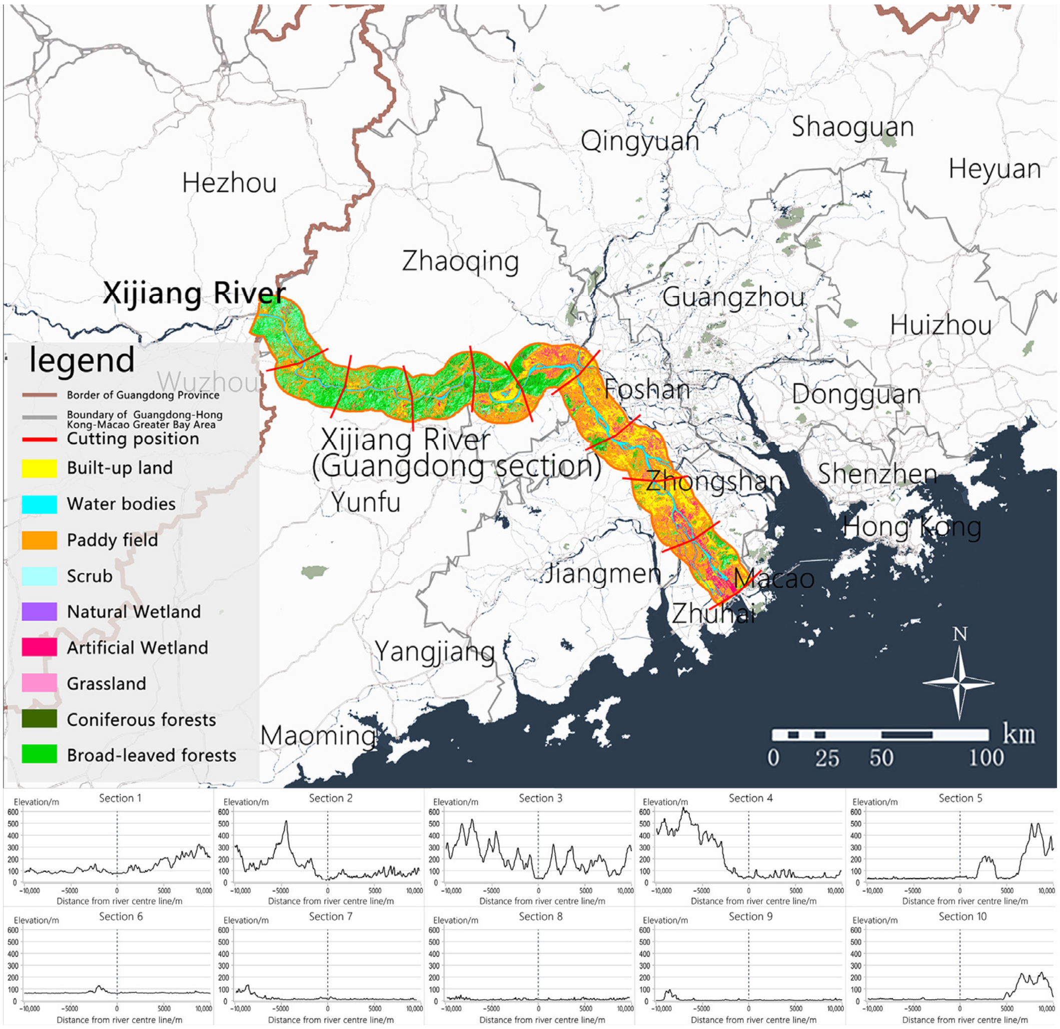

Figure 2. Land use type map of a 1–10 km stretch along the river of a land and water interface zone of the Guangdong section of the Xijiang River Basin, as well as the profiles of the study subarea lines.

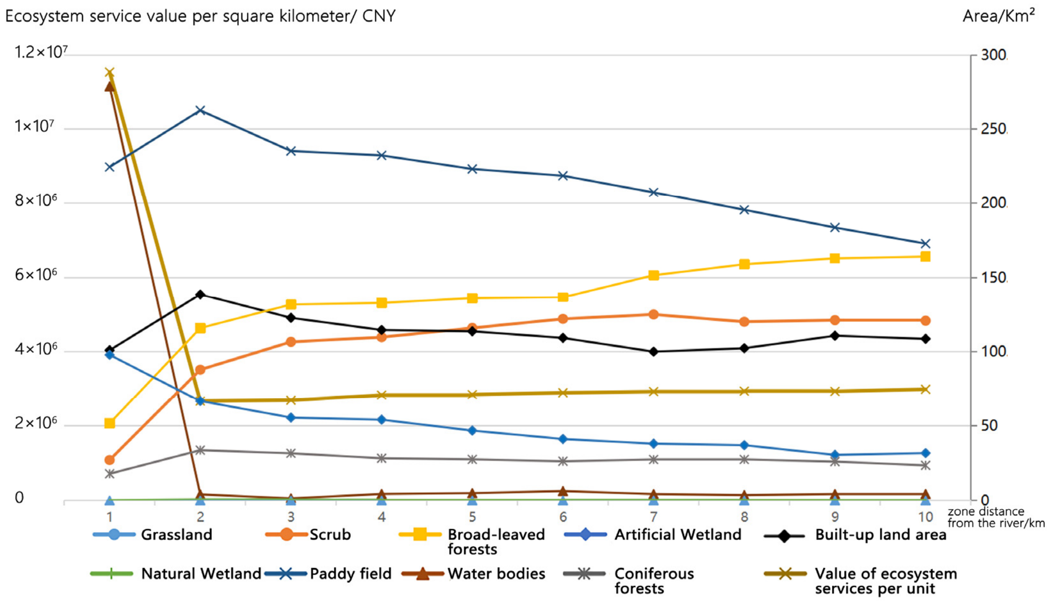

Figure 3. The change trends of ecosystem service value per square kilometer and area of land use types with lateral gradient.

2.2.3. Method for ESV Evaluation in the Unit Area

Costanza et al. calculate the ESV based on estimating individuals' "willingness to pay" for ecosystem services and constructing regional price and supply curves between "residual" or "net rent" markets". Xie Gao Di combined this with the actual situation in China to carry out a comprehensive assessment of a national-scale ESV and its dynamic changes [37]. The indirect costs and conversion to monetary units were examined using methods presented in the literature, weighted calculations, proportionality, and expert experiences [26].

The calculation method used references the evaluation method of the ESV employed by Xie Gao Di et al. and the ESV equivalent table per unit area of China's terrestrial ecosystems formulated by them [26]. The specific formula is shown in Equation (1):

$$ESV_i = \sum_{j=1}^{m} A_{ij} \times VC_j \tag{1}$$

where ESV_i is the ESV (CNY) of j ecosystem type in area i; A_{ij} is the land use area of j ecosystem type in area i (hm^2), and VC_j is the ESV per unit area of j ecosystem type. Since the economic value of the food production capacity per unit area of farmland without human labor is one-seventh of that with human labor [38], in order to make the calculation more real and reliable, we made the following amendments to VC_j, excluding farmland.

$$E = Q \times \frac{1}{7}F \tag{2}$$

$$VC_j = E \times V_j \tag{3}$$

where Q is the average grain yield in Guangdong Province in 2020, which was 590,400,000 kg/km^2; F is the average purchase price of rice in Guangdong Province in 2020, which was 2.66 CNY/kg; E is the value of unit equivalent (CNY/km^2), and V_j is the equivalent value of the corresponding land use type.

Most of the wetlands on both sides of the Xijiang River were farmland, fish ponds, shrimp ponds, and other pits and reservoirs used for agricultural production and still had the basic characteristics of wetlands because their surface features were characterized by large bodies of water [39]. In this study, this part of the site was divided separately from the water system as an artificial wetland, distinguishing it from the other natural wetlands that had not been artificially transformed. The equivalence factor was corrected with the shadow engineering method, with reference to a related study conducted by Li Lin [32]. The conversion of the equivalent factor of artificial wetlands in this study is achieved through the ratio of artificial wetlands to natural wetlands, and the results are shown in Table 2 below.

Table 2. Ecosystem service value per unit area before and after the modification of the constructed wetland ecosystem was used as the scale.

		Before Amendment	After Amendment	
Ecosystem Services Classification	**Classification**	**Wetlands**	**Wetlands**	
	Secondary Classification	**Natural Wetlands**	**Natural Wetlands**	**Artificial Wetlands**
Supply service/CNY 10^4	Food production	0.51	0.51	0.3
	Raw material production	0.5	0.5	0.3
	Water supply	2.59	2.59	1.7
Regulating services/CNY 10^4	Gas regulation	1.9	1.9	1.2
	Climate regulation	3.6	3.6	2.4
	Purification of the environment	3.6	3.6	2.4
	Hydrology	24.23	24.23	15.8
Support services/CNY 10^4	Soil conservation	2.31	2.31	1.5
	Maintaining nutrient cycles	0.18	0.18	0.1
	Biodiversity	7.87	7.87	5.1
Cultural service/CNY 10^4	Aesthetics landscape	4.73	4.73	3.1

Since the study area was divided into equal parts along the river perpendicular to the centerline of the river, in order to eliminate the effect of the area difference between the gradients along the river in the cut, the land-averaged ESV for each type of land cover in the study area was obtained by dividing the ESV for each type of land cover in each study area by the total area of the corresponding study area, which was used as the main object of the comparative analysis.

The calculation method of the land-averaged GDP was applied to calculate the land-averaged ESV of the different types of ecosystems in the study area, as shown in Equation (4):

$$ESV_{ijz} = \frac{ESV_{ij}}{A_i} \tag{4}$$

where ESV_{ijz} is the land-averaged ESV of ecosystem type j for study area i (CNY/km^2), and A_i is the land use area of study area i (km^2).

2.2.4. ESV Driver Model Construction

In order to ensure the scientific validity of the study, the geographically weighted regression (GWR) model was invoked to assess the effect of the drivers on the ESV in the study area at the spatial level, which was modeled as follows:

$$y_i = \beta_0(U_i, V_i) + \sum_{k=1}^{n} \beta_k(U_i, V_i) x_k(U_i, V_i) + \varepsilon_i \tag{5}$$

$$\beta_k(U_i, V_i) = \left[X^T W(U_i, V_i) X\right]^{-1} X^T W(U_i, V_i) y \tag{6}$$

where β_0 (U_i, V_i) is the geographically weighted regression intercept of the spatial position of (U_i, V_i), β_k (U_i, V_i) is the weighted regression coefficient of the independent variable (driver) of the kth at the (U_i, V_i) spatial location, x_k (U_i, V_i) is the value of the kth independent variable (driver) at the (U_i, V_i) spatial location, and ε_i is the algorithmic residuals. X^T is the transpose of the independent variables (drivers), and W (U_i, V_i) is the distance weight matrix.

The GWR model applies the weighted least squares (WLSs) method to estimate the parameters of each observation, and the Gaussian function is generally used to construct the weighting function when weighting. The basic idea of a Gaussian function is to represent the relationship between the weights and distance by selecting a continuous, monotonically decreasing function. The specific formula is as follows:

$$W_{ij} = esp\left[-\left(d_{ij}/h\right)^2\right] \tag{7}$$

where h is the bandwidth of the AIC criterion, and the larger the bandwidth, the slower the weights decay with increasing distance, and conversely, the faster the weights decay. d_{ij} is the direct spatial distance between sample point i and sample point j.

A total of 21 factors relating to natural systems and socio-economic elements were selected as the ecosystem service driving the variables of the Guangdong section of the Xijiang River Basin; the ecosystem of the Guangdong section of the Xijiang River Basin in 2020 in the nearest state was selected as the object of analysis to evaluate and analyze the driving factors; and, finally, the simulation results were spatially visualized in ArcGIS10.7 software to analyze the effects of the driving factors on the ESV in the study area.

3. Results

3.1. Overall Analysis

3.1.1. Characteristics of Land Use Types

Multiply the land use area occupied by each ecosystem type in the study area with the corresponding unit area equivalent factor to obtain the ESV in the study area and compare the percentage of ESV for each ecosystem type.

The area and ESV data of each land use type in the study area are shown in Table 3. The total area of the Xijiang River Basin's land–water interface zone in 2020 was 6771.83 km^2, and the area share of each land use type in the study area was in the descending order of magnitude: paddy field > broad-leaved forest > constructed land > scrub > artificial wetland > water system > coniferous forest > natural wetland > grassland.

Table 3. Summary of the land use area and corresponding ecosystem service value in the Guangdong section of the Xijiang River.

Type of Land Use	Area/km^2	The Proportion of the Area/%	Ecological Services Value/CNY 10^4	The Proportion of ESV/%
Grassland	0.24	0.00	61.68	0.00
Scrub	1056.47	15.60	360,747.12	13.72
Built-up land	1121.44	16.56	0.00	0.00
Broad-leaved forest	1342.16	19.82	691,059.56	26.28
Artificial wetlands	500.71	7.39	381,829.72	14.52
Natural wetlands	5.75	0.08	6705.38	0.25
Paddy fields	2156.18	31.84	188,176.53	7.16
Water bodies	317.66	4.69	894,546.93	34.02
Coniferous forests	271.22	4.01	106,669.80	4.06
Total	6771.83	100	2,629,796.72	100

3.1.2. The ESV in the Study Area

According to Table 3, the total ESV of the land–water interface zone in the study area was CNY 2,629,796.72 million, and the proportion of the ESV of the different land types was in the order of water bodies ecosystems > broad-leaved forest ecosystems > artificial wetland ecosystems > scrub ecosystems > paddy field ecosystems > coniferous forest ecosystems > natural wetland ecosystems > grassland ecosystems. The service values of water bodies, broad-leaved forests, artificial wetlands, and scrub ecosystems are obviously higher than that of other ecosystems, among which the ESV of water bodies reached CNY 8,945,469,300, accounting for 34.02%, while the service values of grassland and natural wetland ecosystems are relatively low.

3.1.3. Value of the Four Major Ecosystem Services

As shown in Table 4, the values of the four major categories of ES are, in descending order: value of regulating services > value of supporting services > value of cultural services > value of provisioning services. Among them, the total value of regulating services in the study area is the highest, and the total value of provisioning services is the lowest. In the results relating to regulating services, the water bodies ecosystem provides the highest amount of value, more than one-third of the total amount; in the results relating to the provisioning services, the water bodies ecosystem provides the most value, which is already more than half of the total amount; in the results relating to the supporting services, the broad-leaved forest ecosystem provides the highest amount of value, occupying nearly half of the total amount, and in the results relating to the cultural services, the value of the artificial wetland ecosystem is the most prominent, occupying about one-third of the total amount. In terms of cultural services, the value of artificial wetland ecosystems is the most prominent, accounting for approximately one-third of the total.

3.2. The Lateral Gradient Analysis

The ESV gradient was calculated across 10 zones of distance from the river, as shown in Table 5.

Table 4. Total table of four service values of the water–land ecotone in the Guangdong section of Xijiang River.

Type of Ecosystem	Provisioning Services		Regulating Services		Support Services		Cultural Services	
	Value/CNY 10^4	Proportion/%	Value/CNY 10^4	Proportion/%	Value/CNY 10^4	Proportion/%	Value/CNY 10^4	Proportion/%
Grassland ecosystems	3.9	0.0039	39.8	0.002	14.9	0.0039	3	0.0028
Scrub ecosystems	19,909.8	19.9293	243,421.3	11.9546	81,061.4	20.9925	16,354.5	15.3531
Broad-leaved forest ecosystems	38,843.9	38.8818	461,910.8	22.6848	158,386.6	41.0174	31,918.2	29.9639
Artificial wetland ecosystems	25,837.1	25.8623	244,890.9	12.0268	75,264.6	19.4913	34,823.9	32.6917
Natural wetland ecosystems	464.0	0.4644	4296.2	0.211	1335.4	0.3458	609.7	0.5724
Paddy field ecosystems	−57,081.8	−57.1376	221,071.1	10.857	19,833.5	5.1363	4353.7	4.0871
Water bodies ecosystems	65,779.7	65.844	789,997.8	38.7973	25,299.9	6.5519	13,469.5	12.6448
Coniferous forest ecosystems	6145.8	6.1519	70,585.8	3.4665	24,948.4	6.4609	4989.7	4.6842
Total	99,902.4	100	2,036,213.7	100	386,144.7	100	106,522.2	100

Table 5. The revised lateral gradient table of the ecosystem service value in the water–land ecotone of the Guangdong section of the Xijiang River. Unit: CNY 10^4.

	ESV of 1 km Distance/CNY 10^4	ESV of 2 km Distance/CNY 10^4	ESV of 3 km Distance/CNY 10^4	ESV of 4 km Distance/CNY 10^4	ESV of 5 km Distance/CNY 10^4	ESV of 6 km Distance/CNY 10^4	ESV of 7 km Distance/CNY 10^4	ESV of 8 km Distance/CNY 10^4	ESV of 9 km Distance/CNY 10^4	ESV of 10 km Gradient/CNY 10^4
Grassland ecosystems	4.7	4.4	6.0	6.1	7.2	7.0	9.4	5.1	6.3	5.5
Scrub ecosystems	9302.4	30,038.9	36,404.8	37,468.3	39,581.2	41,659.7	42,675.3	40,999.8	41,372.1	41,244.5
Broad-leaved forest ecosystems	26,667.4	59,654.1	67,788.0	68,334.9	69,998.7	70,345.7	78,040.7	81,837.1	83,906.7	84,486.3
Artificial wetland ecosystems	74,673.7	50,943.2	42,435.5	41,363.9	35,790.8	31,485.4	29,107.8	28,338.7	23,388.1	24,302.7
Natural wetland ecosystems	420.6	1064.0	874.0	645.1	664.1	742.0	712.0	570.7	471.8	541.0
Paddy field ecosystems	19,600.0	22,907.1	20,531.7	20,277.6	19,483.3	19,087.8	18,107.5	17,071.3	16,027.7	15,082.5
Water bodies ecosystems	785,207.2	11,877.8	4244.6	12,714.1	14,251.4	18,109.9	12,483.0	10,530.8	12,507.4	12,620.7
Coniferous forest ecosystems	7092.9	13,304.8	12,479.6	11,171.7	10,884.8	10,392.1	10,857.1	10,874.8	10,298.6	9313.6
Total	922,968.9	189,794.1	184,764.2	191,981.8	190,661.5	191,829.7	191,992.8	190,228.3	187,978.7	187,596.8

3.2.1. Trends in the Value of Ecosystem Services at the Lateral ESV Gradient

According to Figure 3, it can be seen that the ESV per unit area of the Xijiang River interface zone shows a cliff-like decreasing trend with a distance from the river of between 1 and 2 km, and then this tends to stabilize. This is due to the fact that the ESV per unit area provided by water bodies and wetlands is the highest among all ecosystem types, and the vast majority of the 1–2 km closest to the neutral line of the river belongs to the river and the wetlands on both sides of the river, and the percentage of the area where the land use is comprised of water bodies, and natural wetlands are absolutely dominant in comparison with the other gradients; ultimately, the ESV within the range of the gradient is significantly higher than the other gradients, and it levels off with the increase in other ecosystems such as grasslands, scrubland, and woodlands; woodlands and other ecosystems increased, and the ESV value decreased significantly and then leveled off. In the 0–10 km gradient along the river, the area and service value of broad-leaved forest ecosystems increased significantly with the gradient, whereas the ESV of the paddy field and artificial wetland ecosystems decreased gradually with the gradient.

3.2.2. Trends in Lateral Changes in the Value of the Four Major Ecosystem Services

As can be seen from Figures 4 and 5, for provisioning service, the ESV of the water bodies within the 1 km gradient is absolutely dominant in the total value of the provisioning services of all ecosystem types. The roles of other ecosystem types are gradually emphasized as the gradient along the river increases. The ecosystem provisioning service value of artificial wetland ecosystems was the highest in the 2–5 km gradient. The ecosystem provisioning service value of broad-leaved forests was the highest in the 6–10 km gradient along the river. The total value of the provisioning services of water bodies, artificial wetlands, and broadleaf forest ecosystems dominates in the process of an increasing gradient, reflecting the trend of the three provisioning service components, namely, water supply, food production, and raw material production, which are appropriately laid out according to the distance from the river and the geographic characteristics of the specific production needs.

In regulating services, water bodies, broad-leaved forests, and artificial wetland ecosystems have the highest ESV. Rivers are important media for water cycling, and vegetation and wetlands have a prominent role in regulating near-surface temperature and humidity. In the 1 km zone, the regulating service value of water bodies was absolutely dominant, and after the 2 km zone, the role of other ecosystem types gradually increased; among them, broad-leaved forest ecosystems had a greater increase in regulating service value and evolved into the ecosystem type with the most significant service value.

In terms of support services, within the 1 km gradient, artificial wetlands and water bodies provide the highest value of support services. As the gradient along the river increases, the service value of other ecosystems also increases; among them, broad-leaved forests have the most obvious increment, surpassing artificial wetlands at the 3 km gradient along the river, evolving into the ecosystem type with the most significant value of support services.

As for cultural services, the value of the cultural services of artificial wetland ecosystems accounted for nearly half of the value, dominating the total value of the cultural services of all ecosystem types. However, as the gradient increased, the value showed a gradual decrease. At the 1 km gradient along the river, aquatic ecosystems provide the greatest value of cultural services, followed by artificial wetland ecosystems. At the 2 km gradient along the river, the cultural value provided by water bodies shrinks more, while the cultural value provided by artificial wetlands accounts for more than half of the value. As the gradient along the river increases, the proportion of broad-leaved forests, scrub, coniferous forests, and other ecosystems gradually increases, among which broad-leaved forest ecosystems had the most obvious increment, surpassing man-made wetlands at the 9 km gradient along the river to become the ecosystem with the highest value of cultural services in the study area.

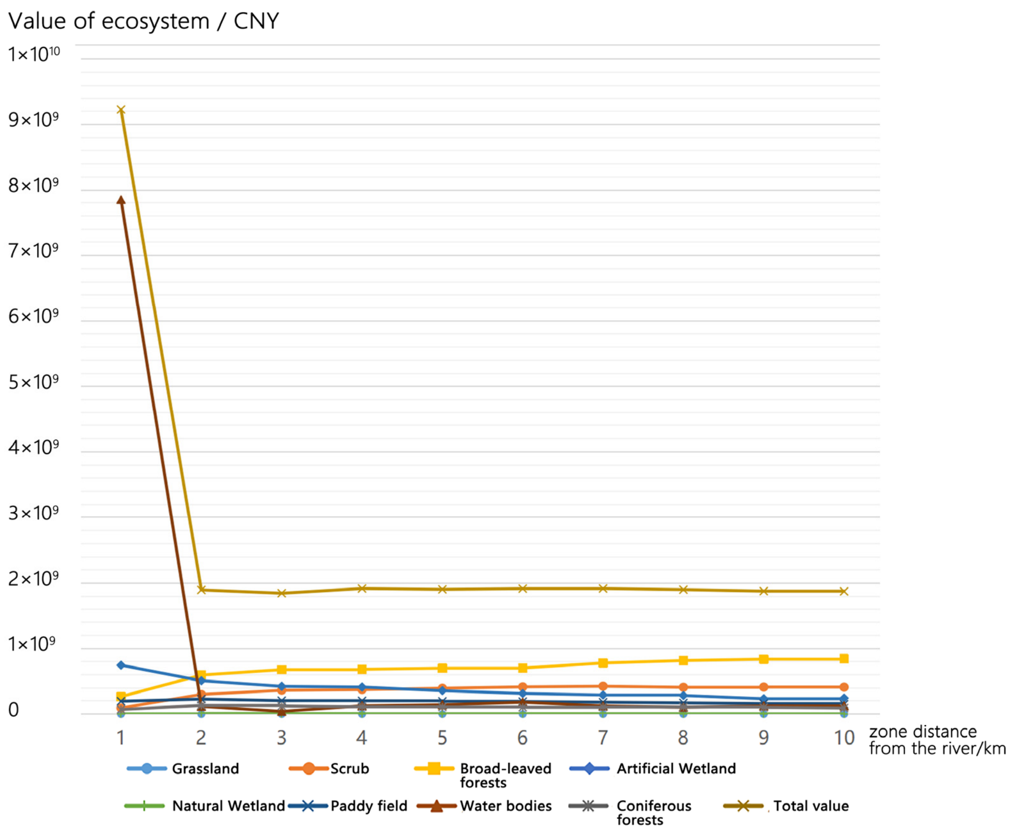

Figure 4. Variation trend of each ecosystem and total service value with the lateral gradient.

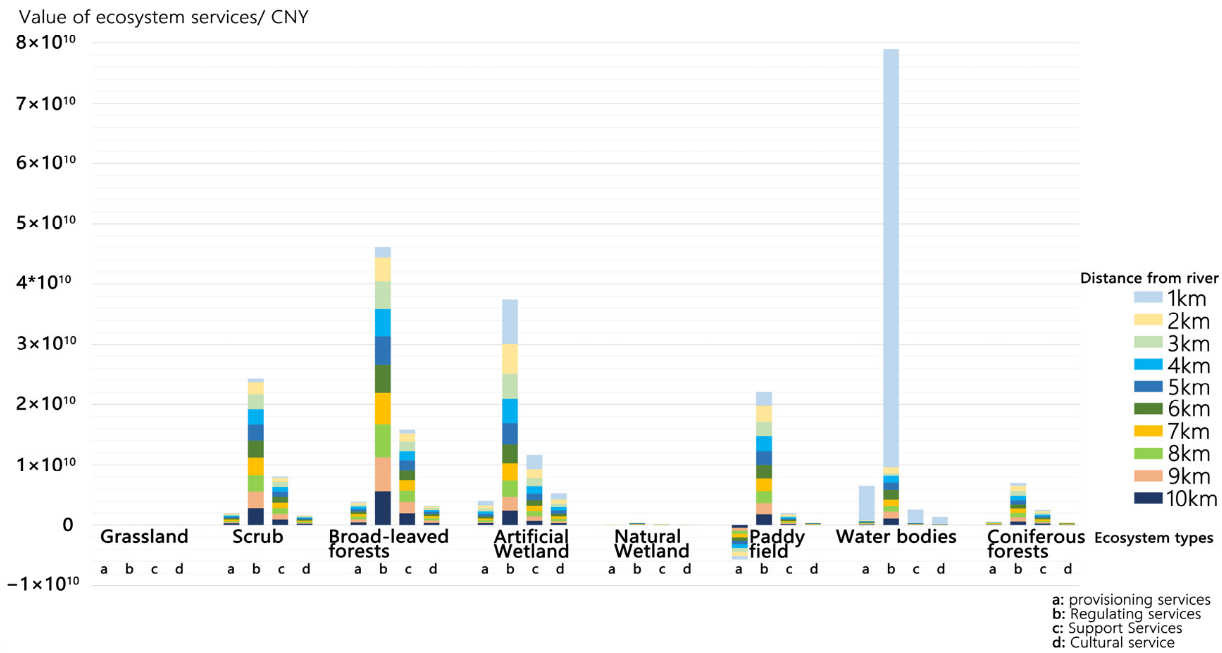

Figure 5. Distribution of service value at the different lateral gradient levels in eight ecosystems.

The total value of the cultural services of the water bodies, artificial wetlands, and broad-leaved forest ecosystems are ordered in terms of dominance, reflecting the regularity of human beings setting up different utilization paths, such as landscape tours, wetland parks, and forest parks, according to the geographic features within different distances from the river.

The terrestrial broadleaf forest ecosystem, which is about 6–10 km away from the water, dominates both the regulatory services and provisioning services within the corresponding gradient, reflecting the outstanding contribution of this ecosystem to the terrestrial functions of ecosystem services, such as the purification of the environment, climate regulation, soil preservation, maintenance of nutrient cycling, and biodiversity on land.

3.3. Upstream and Downstream Gradient Analysis

Trends in the Value of Ecosystem Upstream and Downstream Gradient Levels

Using the equivalent table of ESV per unit area before and after the correction, the upstream and downstream gradient of the mean ESV for land in the land–water interface zone of the Guangdong section of the Xijiang River Basin was calculated, as shown in Table 6. It can be seen that the total mean ESV for the land of the land–water interface zone of the Xijiang River is relatively stable in the 1–4 levels of the river section and then shows a fluctuating downward trend, and this phenomenon is consistent with the geographic and economic situation in reality: geographically, the fourth level of the river section is in the boundary area between the hilly area of northern Guangdong and the plain of the Pearl River Delta; economically, the fourth level of the river section is at the junction of the economically underdeveloped and more evenly distributed northern Guangdong region and the economically developed but uneven Guangdong–Hong Kong–Macao Greater Bay Area. Different human activities and development intensities are the main influences that cause the curve to fluctuate downward after the fourth level of the river section. The trend in the mean value for land in terms of broad-leaved forests and scrubs is relatively the same as the trend for the mean ESV of the land of the land–water interface zone, which indicates that at levels 1–4 of the river section, the ecosystems of broad-leaved forests and scrublands had a greater influence on the total mean ESV for the land of the Xijiang River water–surface interface zone. For gradients 1–5, the average value of water bodies was low and stabilized, and from gradient 5 onwards, the increment was more obvious with the increase in the gradient. For gradients 9–10, the trend in the change in the value of water bodies was consistent with the trend in the total land mean ESV of the Xijiang River mean ESV for land, which indicates that in the area of the Xijiang River estuary, the value of water bodies ecosystems had a greater contribution to the total mean ESV of the land of the Xijiang River (mean ESV for land) (Figure 6).

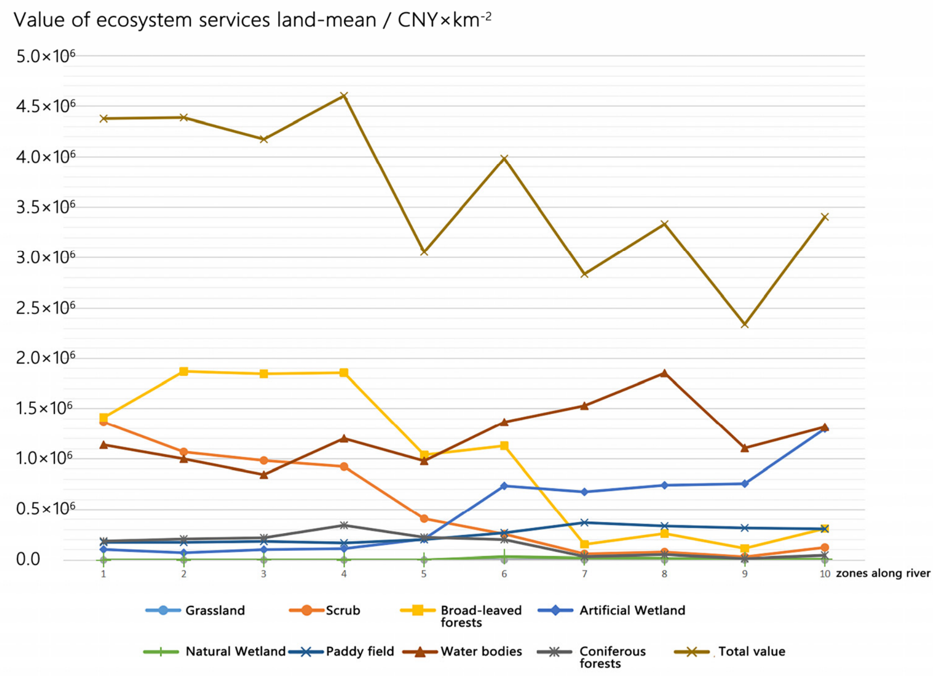

Figure 6. Variation in the trends for the mean ESV of land with the upstream and downstream gradient.

Table 6. The revised upstream and downstream gradient table for the average ecosystem service value in the land and water interface zone of the Guangdong section of the Xijiang River.

Type of Land Use	Land Mean Ecosystem Service Value/CNY $\times$ km^{-2}									
	Zones along River 1	Zones along River 2	Zones along River 3	Zones along River 4	Zones along River 5	Zones along River 6	Zones along River 7	Zones along River 8	Zones along River 9	Zones along River 10
Grassland	160.43	141.27	109.34	136.28	77.70	125.11	43.11	19.94	15.25	45.99
Scrub	1,365,599.32	1,069,295.79	984,299.26	925,022.31	407,431.00	254,341.65	58,517.80	76,776.86	29,088.37	122,059.18
Construction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Broad-leaved forest	1,412,518.28	1,869,851.60	1,845,724.86	1,856,288.68	1,039,748.70	1,129,807.40	152,100.26	259,970.98	112,668.96	308,159.35
Artificial wetlands	102,035.29	69,176.82	100,354.47	110,040.58	204,911.86	734,815.89	675,373.66	741,547.84	756,599.16	1,298,946.04
Natural wetlands	0.00	48.19	322.16	187.44	1591.64	32,075.69	19,596.50	15,711.19	8592.92	8355.62
Paddy fields	172,730.24	172,614.99	181,867.54	166,310.84	199,730.23	266,662.39	367,637.98	334,179.32	314,590.49	305,155.07
Water bodies	1,139,794.73	1,000,860.16	845,184.08	1,202,578.94	980,128.48	1,366,028.30	1,530,015.71	1,852,949.26	1,107,438.60	1,317,514.74
Coniferous forests	184,426.05	205,281.43	217,340.74	341,134.29	222,510.46	199,621.26	33,151.70	52,562.70	13,345.84	45,738.33
Total	4,377,264.34	4,387,270.27	4,175,202.44	4,601,699.36	3,056,130.08	3,983,477.70	2,836,436.72	3,333,718.08	2,342,339.59	3,405,974.33

As can be seen from Figure 7, the value of the provisioning services of broad-leaved forests within levels 1–4 of the river section dominated all ecosystem types, but from the sixth level of the river section onwards, the value of the ecosystem provisioning services of broad-leaved forests showed a clear downward trend until it reached a lower level. The value of the ecosystem provisioning services of water bodies always occupied an important position at all upstream and downstream gradients, and the value of the ecosystem provisioning services of water bodies gradually increased from the fifth level of the river section onwards, eventually occupying an absolutely dominant position. The ecosystem provisioning services value of artificial wetlands increased continuously from the fifth level of the river section and reached a peak at the ninth level of the river section.

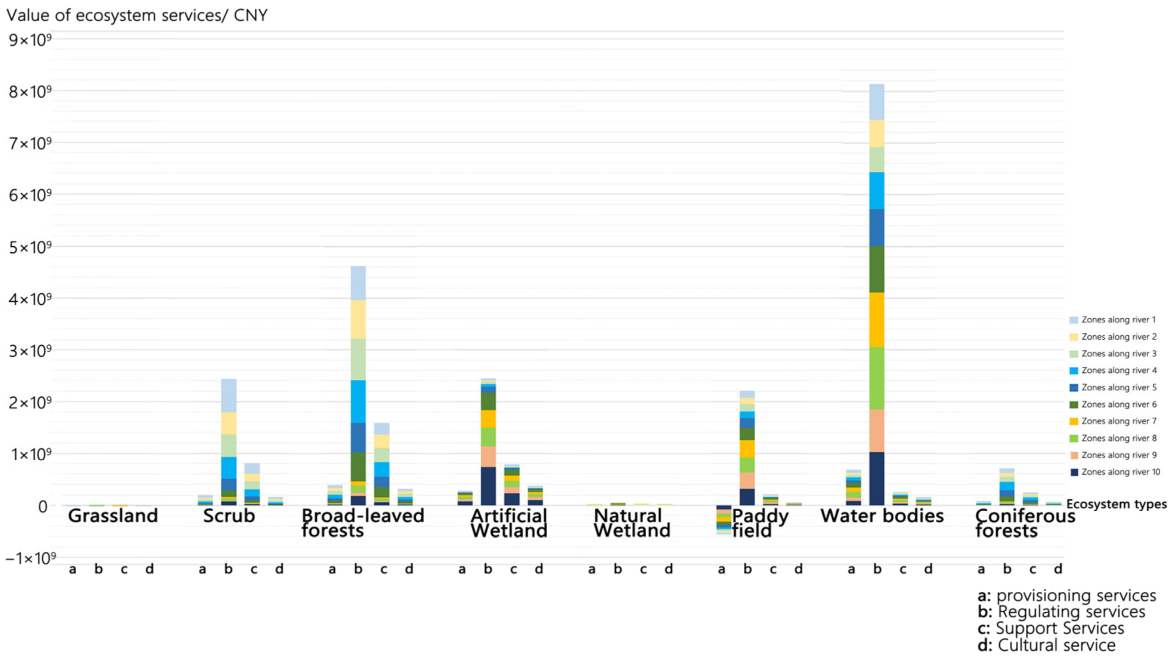

Figure 7. Ecosystem service values provided by different ecosystems in 10 zones along the river.

As for the regulating services, the ecosystem regulating value of waters had the highest proportion, and within levels 4–10 of the river section, the ecosystem regulating service value of water bodies dominates. Meanwhile, broad-leaved forests, scrub, paddy fields, and artificial wetlands all had high shares; the ecosystem provisioning service value of broad-leaved forests plays a prominent role at the 1–6 level of the river section but falls to a lower level from the seventh level of the river section. The ecosystem regulating service value of scrubland is at a high level in levels 1–4 of the river section but gradually drops to a low level from the fifth level of the river section; the ecosystem regulating service value of artificial wetlands increases significantly from tertile 5 and reaches the highest value in tertile 10.

In terms of support services, the amount of ecosystem support service value provided by broad-leaved forests was the highest within levels 1–6 of the river section, followed by scrub, but fell to a lower level from the seventh level of the river section onwards. As the upstream and downstream gradient increases, the proportion of the service value of other ecosystems increases, with artificial wetlands showing the most obvious increment, becoming the ecosystem type with the most significant value of support services from the sixth level of the river section onwards.

In terms of cultural services, artificial wetlands dominated the total value of the cultural services of all ecosystem types and increased with increasing upstream and downstream gradients, contributing significantly to the value of cultural services in the study area. In levels 1–6 of the river section, the ecosystem cultural service values of broad-leaved forests and scrub were more important. The value of the ecosystem cultural services of broad-leaved forests shrinks significantly after the seventh level of the river section.

3.4. Analysis of ESV Drivers

According to the relevant research results [38–40] and a combination of the actual situation of the study area, a total of 21 factors of the natural system and socio-economic elements were preliminarily selected as the alternative driving variables of ES in the study area, and the ecosystem of the study area was chosen as the object of analysis in 2020 to evaluate and analyze its driving factors.

An ordinary least squares (OLSs) test was conducted on the screened driving factors, and it was found that when all factors were included in the model, although the overall goodness of fit satisfied the pass condition, only some of them passed the model's probabilistic test, most of the variables showed strong spatial covariance, and the autocorrelation of the spatial residuals exceeded 0.45, which resulted in a weaker explanatory power of the model. In order to ensure the scientific validity and authenticity of the results, the model's driving factors were further screened in ranked combinations with a goodness-of-fit greater than 0.5, a *p*-value bordering 0.05, and a redundancy test of less than 7.5 as the screening conditions. A total of 17 factors (Table 7), among which the fitting effect is significant, were selected as variables and were tested again, and their basic data characteristics were found through raw data tables. The probability or robust probability test was well characterized, the redundancy test was passed, and the model was well characterized.

The simulation results were spatially visualized in ArcGIS10.7 software to obtain the results of the GWR model fitting in the Guangdong section of the Xijiang River Basin (Figure 8), along with the spatial distribution of the regression coefficients of the service function drivers for the ecosystem (Figure 9). In the simulation results of the goodness-of-fit (R^2), the average goodness-of-fit in the study area was higher than 0.67, and the model's efficiency was credible; in the simulation results of the fitted t-value, the t-value of the model in most of the study area was within the range of -2.58~2.58, and the model's structure was credible. The highest goodness-of-fit was found at the junction of Guangdong and Guangxi and the estuary, where the geomorphology and vegetation types were relatively homogeneous, while the lowest goodness-of-fit was found in the transition area between the northern Guangdong hills and the Pearl River Delta plain, where the geomorphology and vegetation types were more complex.

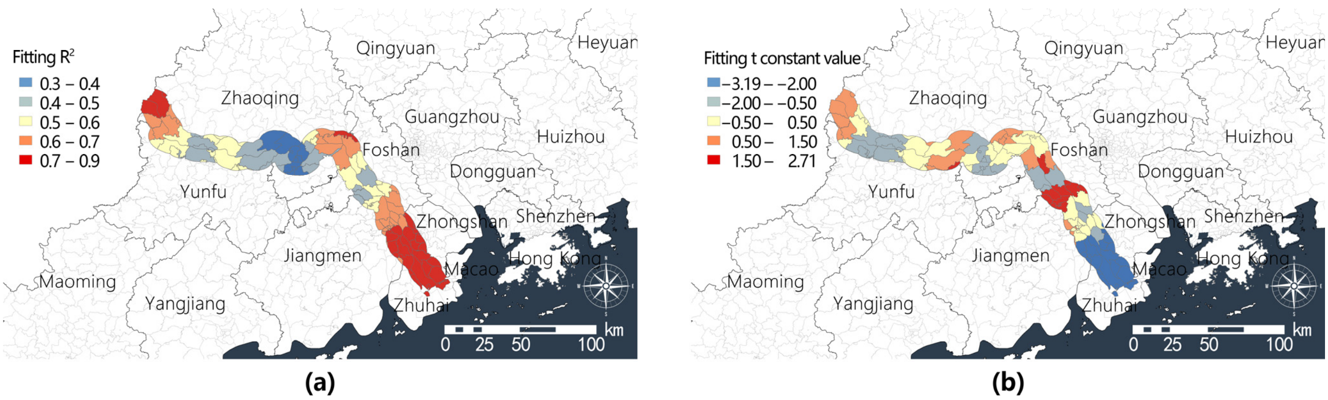

Figure 8. Fitting results of the geographically weighted regression (GWR) model: (**a**) goodness-of-fit (R^2); (**b**) fit constant t results.

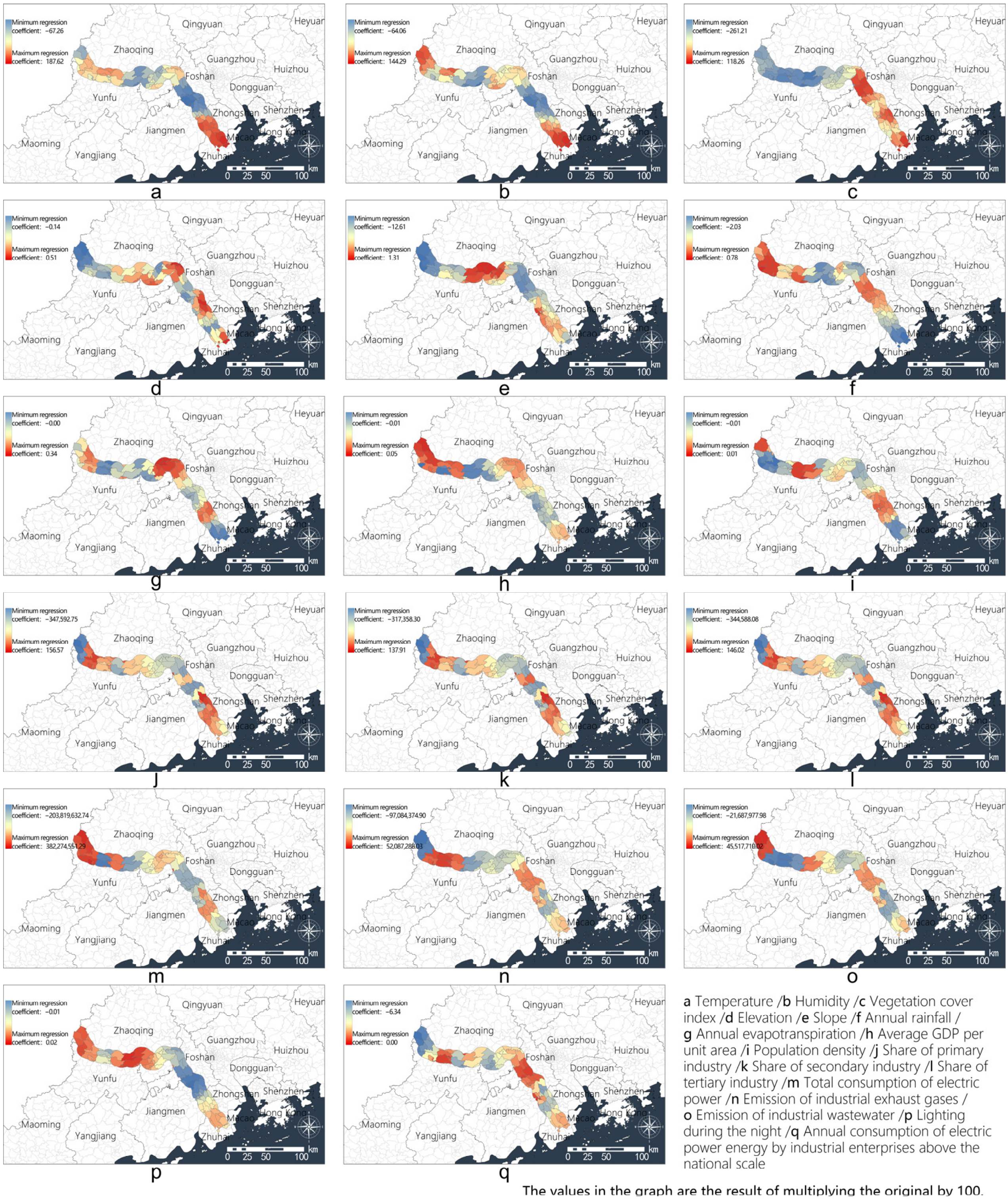

Figure 9. Spatial distribution of regression coefficients between each driving factor and ecosystem service in the Guangdong section of the Xijiang River.

Table 7. Statistical analysis of the driving factors.

	Driving Factor	Average Value	Standard Deviation	Maximum Value	Minimum Value
Natural environmental factors	Temperature/°C	23.14	0.77	24.10	18.90
	Humidity/%rh	78.62	1.27	82.80	75.70
	NDVI	0.71	0.19	1.00	0.00
	Elevation/m	213.59	218.56	973.00	0.00
	Slope/%	12.34	6.01	66.45	0.00
	Annual rainfall/mm	1737.83	86.36	2004.25	1564.5
	Annual evapotranspiration/kg·m^{-2}	1082.19	145.78	1411.75	544.25
Socio-economic factors	GDP per unit area/CNY·km^{-2}	8645.12	5954.76	153,465.00	501.00
	Population density/population·km^{-2}	1115.68	1306.44	122,797.00	1.50
	Proportion of primary industry/%	14.41	11.49	37.9	0.03
	Proportion of secondary industry/%	43.61	11.88	75.60	22.70
	Proportion of tertiary industry/%	40.78	11.24	70.80	21.54
	Total electricity consumption/10^8 KW·h	271.16	193.74	710.30	78.56
	Industrial emissions/10^4 t	2481.89	753.73	3691.97	1057.7
	Discharge of industrial wastewater/10^8·t	6185.73	3354.09	11,455.08	1581.97
	Night light/nWcm^{-2}sr^{-1}	24.86	18.41	59.52	0.01
	Annual power energy consumption of industrial enterprises above designated size/10^4 KW·h	303,192.90	329,690.49	1,079,429	29,301

3.4.1. General Characteristics of the Influence of Each Driving Factor on the ESV in the Study Area

From the analysis, the temperature, humidity, rainfall, proportion of primary industry, proportion of secondary industry, and proportion of tertiary industry showed obvious regional and small patchy driving characteristics on ES in the study area. Vegetation cover, slope, total electricity consumption, industrial exhaust emissions, and industrial wastewater emissions in terms of ES in the study area showed obvious patchy driving characteristics.

3.4.2. Gradient Characteristics of the Effect of Each Driver on the ESV in the Study Area

The combination of fitting factors selected for the study included 17 driving factors. Since the regression coefficients for some of the factors are too small, the regression coefficients for all the factors were multiplied by 100 to increase the sensitivity of the parameter and to better reflect the differences between the situations. Among these, the four driving factors, GDP, population density, nighttime lighting, and evapotranspiration, were fitted to the ESV in the study area with an effect of less than 0.5, which is a very weak influence. Meanwhile, the lowest regression coefficient of the elevation factor was −0.14, the highest regression coefficient was 0.51, and the spatial difference of factor influence was not obvious. The lowest regression coefficient of the factor of electricity energy consumption of industrial enterprises that was above scale for the whole year was −6.34, and the highest regression coefficient was 0. The spatial difference of the factor influence was not obvious. In order to ensure the scientific nature of the analysis, a regression coefficient of ±1.00 was selected, and the spatial difference for the impact of the driving factor for gradient analysis, in which the temperature, humidity, industrial exhaust emissions, and industrial wastewater emissions factor had a greater relative impact, is shown in Table 8.

Table 8. Gradient characteristics of the influence of each driving factor on the ESV in the study area.

<table>
<tr><th></th><th>Zones along River 1</th><th>Zones along River 2</th><th>Zones along River 3</th><th>Zones along River 4</th><th>Zones along River 5</th><th>Zones along River 6</th><th>Zones along River 7</th><th>Zones along River 8</th><th>Zones along River 9</th><th>Zones along River 10</th></tr>
<tr><td>Temperature</td><td colspan="3">The topography of the region is predominantly mountainous, with high elevations, low average temperatures, low impacts from human activities, reduced human interference with ecology, and vegetation types dominated by broad-leaved evergreen forests, presenting positively driven characteristics.</td><td colspan="2">The topography of the region is predominantly mountainous and hilly, with a decrease in elevation, an increase in average temperature, an increase in the impact of human activities, a high degree of development, a decrease in the percentage of broad-leaved forests and a decrease in the functioning of the woodland, which is characterized by a negative drive.</td><td>The region is positively driven by the impact of the construction of forest parks, which has increased the value of cultural services and support services.</td><td colspan="2">The topography of the region is predominantly hilly with low elevations, and a high rate of urbanization in Foshan has resulted in a high level of ecological disturbance by humans and an increase in mean temperature, showing strong negative driving characteristics.</td><td colspan="2">The region is close to the mouth of the sea, the terrain is dominated by plains, the atmosphere is affected by the cycle between land and water and ocean currents, the temperature is lowered, the climate is warmer and suitable for crop cultivation and growth, the proportion of paddy fields and artificial wetlands increases, and the value of provisioning services and the value of cultural services improves, presenting a stronger positively driven characteristic [39,40].</td></tr>
<tr><td>Humidity</td><td colspan="3">The vegetation in the region is dominated by broad-leaved forests with high humidity, which has a more significant moderating effect and shows positive driving characteristics.</td><td>The vegetation in the region is dominated by coniferous forests, but the regional temperatures are higher than the optimal growth temperatures for coniferous forests, showing weak negative driving characteristics.</td><td colspan="2">The area is positively driven by the construction of forest parks, which have increased humidity.</td><td colspan="2">The region has a humid climate, increased human activities, and increased occupation of artificial wetlands, construction land, and paddy fields, crowding out the space of scrub and broad-leaved forest ecosystems, showing negative driving characteristics.</td><td colspan="2">In regions with similar temperatures, water availability is a major determinant of the level of species diversity in different regions, and plant diversity is maximized in wetter climates, while wetter soils provide conditions for increased plant productivity [40,41]. Showing a clear positive driving effect.</td></tr>
</table>

Table 8. *Cont.*

	Zones along River 1	Zones along River 2	Zones along River 3	Zones along River 4	Zones along River 5	Zones along River 6	Zones along River 7	Zones along River 8	Zones along River 9	Zones along River 10
Vegetation cover index	Since the promotion of ESV by increasing NDVI is not a simple linear relationship, and there is a downward parabolic constraint on its promotion function, the promotion effect on both ESV and soil and water conservation services shows a characteristic of increasing and then decreasing with the increase in vegetation cover [42]. The region is mountainous with an average NDVI of 0.89, and when the NDVI exceeds 0.8, the plant cover continues to increase, and the promotion of ESV decreases. The various capacities of vegetation to contain water and soil retention reached the maximum growth threshold and then showed a decreasing trend.					The topography of the region is dominated by hills and plains, the population density increases, the vegetation cover decreases, similar to the threshold of the constraint line, and the regulating and supporting services of vegetation increase, showing obvious positive driving characteristics.				
Elevation	The terrain of the region is predominantly mountainous and sloping, prone to problems such as landslides and soil erosion, and unfavorable to human activities, with low value of provisioning services and cultural services, showing negative driving characteristics.			The terrain of the region is dominated by mountains and hills, with large slopes, increased impacts of human activities, a large degree of development, and a reduction in the function of forest land, but the construction of forest parks has a certain degree of ecological protection, showing weak negative drive characteristics.			The topography of the region is predominantly hilly with small slopes, and the impacts of human activities are further increased, with a consequent further reduction in woodland function, showing negative driving characteristics.		The topography of the region is dominated by plains with small slopes, high impacts of human activities, high degree of development, land use types dominated by paddy fields, artificial wetlands, and construction land, and crops are planted in large quantities, and the value of provisioning services and cultural services have been increased, which shows a weak negative driving characteristic.	
Quantity of rainfall	The study area belongs to the subtropical monsoon climate zone, with abundant precipitation, which is conducive to the growth of vegetation and has a positive effect on the formation and evolution of the ecological environment, showing positive driving characteristics.			The topography of the region is dominated by hills, with reduced precipitation, and the area share of broad-leaved forests decreases, showing a weak negative correlation driving characteristics, but influenced by the construction of forest parks, part of the region shows weak positive driving characteristics.			The region's gentle topography, frequent atmospheric circulation between land and sea, and increased rainfall are ecologically friendlier and exhibit positive driving characteristics.		The topography of the region is dominated by plains and is located at the mouth of the sea, which is highly influenced by ocean currents and ocean currents, and natural disasters such as flooding occur, causing damage to the ecosystem and presenting a weakly negatively driven character.	

Table 8. *Cont.*

	Zones along River 1	Zones along River 2	Zones along River 3	Zones along River 4	Zones along River 5	Zones along River 6	Zones along River 7	Zones along River 8	Zones along River 9	Zones along River 10
Share of primary industry	The primary industry in Fengkai County, to which the study area belongs, accounts for 37.9% of the total, with relatively backward production methods and high environmental burdens, showing negatively correlated driving characteristics.	The primary sector accounts for about 25% of the total but is limited by the mountainous terrain, with less human intervention and a small environmental burden, showing positively correlated driving characteristics.	The primary industry accounts for a relatively high proportion of the total, the intensity of human development is greater, and the impact on the environment is greater, showing strong negative correlation characteristics.	The primary industry accounts for a lower proportion of the population, the terrain is predominantly mountainous, and human activities are less destructive to the environment, showing a positive correlation with the driving characteristics.	The gradual flattening of the terrain and the increased development and utilization of agricultural land have led to the emergence of agricultural surface pollution, increasing the environmental burden and presenting a negatively correlated driving characteristic.		The share of the primary sector falls below 3%, which reduces the environmental impact and characterizes the positive correlation drive.	The proportion of primary industry has rebounded to about 8%, and with the construction of agriculture as one of the advantages of economic development, man-made interference has increased, increasing the burden on the environment and showing a strong negative correlation characteristics.	The primary sector's share fell to below 3%, reducing the environmental burden and showing positively correlated driving characteristics.	

Table 8. *Cont.*

	Zones along River 1	Zones along River 2	Zones along River 3	Zones along River 4	Zones along River 5	Zones along River 6	Zones along River 7	Zones along River 8	Zones along River 9	Zones along River 10
Share of secondary industry	The industries in Fenkai County are dominated by traditional manufacturing industries such as non-ferrous metal smelting and rolling processing industries, which have obvious negative impacts on the environment and, therefore, show strong negative correlation driving characteristics.	The region's secondary sector accounts for less than 30% of the total, reducing the pressure on the ecosystem and showing positive correlation driving characteristics.	The region's secondary industry has increased its share to between 35 and 50% and is dominated by traditional industries, increasing environmental pressure and showing strong negative correlation-driving characteristics.	Industry accounts for a high proportion of the total but is characterized by a weak negative correlation drive as it follows the concept of green and circular development to mitigate environmental pressure.	The secondary industry has developed strongly, accounting for about 40–70% of the total, forming clusters of automobile parts, hardware, chemicals, new building materials, etc. The environmental pressure is high, showing a strong negative correlation driving characteristic.		Sanshui District secondary industry accounted for about 70% industry to be transformed and upgraded, showing a strong negative correlation characteristics; Nanhai and Gaoming Districts emerging industries are developing well, easing the pressure on the environment, showing a positive correlation driving characteristics.	The region's secondary industry is in a period of transformation and upgrading, and its effect on environmental pressure mitigation has not yet been prominent, showing a negative correlation and driving characteristics.	The secondary industry in the region accounts for about 50–70%, but the economic benefits brought by development are promptly fed back into the investment in ecological environmental protection and management, instead promoting the improvement of the local ecological environment, showing a positive correlation driving characteristics.	

Table 8. *Cont.*

	Zones along River 1	Zones along River 2	Zones along River 3	Zones along River 4	Zones along River 5	Zones along River 6	Zones along River 7	Zones along River 8	Zones along River 9	Zones along River 10
Share of tertiary sector	Fengkai County's tertiary industry accounts for 29.7% of the total, with a backward industrial structure and a large environmental burden, showing a strong negative correlation driving characteristics.	The tertiary sector, which accounts for about 40–50% of the total, is less damaging to the ecosystem and shows a strong positive correlation driving characteristic.	Bordering the fourth level of the river section, which exhibits negative correlation driving characteristics, contributes less to ESV because its terrain is predominantly mountainous and less developed for cultural services.	The tertiary industry in the region accounts for about 35.1%, and its share is increasing year by year. The industrial structure is in the process of transformation and upgrading, which is conducive to reducing the burden on the environment, showing a weak negative correlation driving characteristics.	Dinghu District in Zhaoqing City is affected by the construction of the park. Tertiary industry accounted for about 50%, but the tertiary industry in Gaoyao District accounted for only 28.6%, and the industrial structure is more backward, so the overall negative correlation drives the characteristics.		Bordering with the eighth level of the river section shows positive correlation driving characteristics, although the proportion of tertiary industry in Gaoming District is only 21.54%, but the emerging entrepreneurship is well constructed, and the tertiary industry is in an accelerated stage of establishment; meanwhile, the tertiary industry in Nanhai District accounts for 43.55% of the total, which is less burdensome to the environment.	The proportion of tertiary industry in this area is about 60–70%. Although the proportion is high, the development of tertiary industry is more inclined to cultural and entertainment services, construction services, and other service industries that encroach on the ecological land.	The tertiary industry in the region accounts for about 45–70% of the total, and the overall industrial structure is good and less damaging to the ecosystem, showing a positive correlation driving characteristics.	

Table 8. *Cont.*

	Zones along River 1	Zones along River 2	Zones along River 3	Zones along River 4	Zones along River 5	Zones along River 6	Zones along River 7	Zones along River 8	Zones along River 9	Zones along River 10
Total electricity consumption	The region is characterized by less total electrical consumption, less economic activity, and a lower burden of environmental pressures, showing a strong positive correlation drive.		The region borders the second level of the river section, where total electrical consumption increases, and the population concentrates there, causing more environmental disturbances and showing negatively correlated driving characteristics while bordering the fourth level of the river section, where total electrical consumption decreases and economic activity decreases, reducing environmental pressures and showing positively correlated driving characteristics.	Industrial development in the region has a higher electrical demand and more economic activity, which, to some extent, increases the environmental pressure, showing a negative correlation with driving characteristics.	The total amount of electrical consumption in the region has increased, and it is a plain area that is suitable for human activities and increased economic activities. In addition, the region has good landscape resources and a high degree of development of ecosystem cultural services, such as the construction of the National Forest Park in Dinghu District, thus showing an overall positive correlation driving characteristics.			The total electrical consumption in the region is the highest in the upstream and downstream gradient, indicating that the region has a higher demand for electrical in all sectors, more frequent economic activities, and, therefore, a heavy burden on the environment, showing a negative correlation driving characteristics.	The region has a high total electrical consumption but a good industrial structure and a more balanced demand, which facilitates the mitigation of environmental pressures and shows a positive correlation driving characteristics.	The region is characterized by a negative correlation driven by an increase in total electrical consumption, an increase in economic activity, and an increase in anthropogenic interventions.

Table 8. *Cont.*

	Zones along River 1	Zones along River 2	Zones along River 3	Zones along River 4	Zones along River 5	Zones along River 6	Zones along River 7	Zones along River 8	Zones along River 9	Zones along River 10
Industrial emissions	The proportion of industry in the area is small; the traditional regional industries rely on energy and resources to a high degree, and the exhaust emissions are relatively small but are subject to the level of science and technology and management; there is the behavior of direct and stealthy exhaust emissions. It shows weak negative correlation driving characteristics.			The proportion of industry in this region has increased, mainly in the traditional manufacturing industry. Negative factors such as industrial sulfur dioxide and soot emissions in urban areas have brought huge purification pressure to the ecological environment, showing a negative correlation with driving characteristics.			In this region, Foshan City has a deep industrial development foundation and a good economic development trend. At the same time, it attaches great importance to industrial pollution remediation work and has achieved great results in waste gas treatment, reducing environmental pressure. However, industrial emissions still have an ecological impact, showing a negative correlation drive characteristic.		In parts of Jiangmen City and Zhongshan City in the region, industry accounts for a relatively high proportion of industrial emissions, such as sulfur dioxide and other industrial emissions, which aggravates the burden on the environment, showing a negative correlation driving characteristics.	The proportion of industry in this region is reduced, the pollution source is reduced, and the environmental burden is reduced. However, industrial emissions still have an early ecological impact, showing negative correlation driving characteristics.

Table 8. *Cont.*

	Zones along River 1	**Zones along River 2**	**Zones along River 3**	**Zones along River 4**	**Zones along River 5**	**Zones along River 6**	**Zones along River 7**	**Zones along River 8**	**Zones along River 9**	**Zones along River 10**
Industrial wastewater discharge	The proportion of industry in this area is small, and the industry is mainly based on the processing of building materials with low wastewater discharge. However, constrained by the level of science and technology and management level, the degree of wastewater treatment is low, and there is direct and smuggled discharge into the river. Weak support regulating services jeopardizes the environment, presenting weak negative driving characteristics.			The industrial structure of Deqing County of Zhaoqing city and Yun'an District of Yunfu City is upgraded. Wastewater discharges increase, showing negative driving characteristics.	In this region, Duanzhou District and Gaoyao District of Zhaoqing City are dominated by the high-tech and manufacturing industries. In Dinghu District, Sihui city, the traditional manufacturing industry accounts for a relatively large portion, all showing negative driving characteristics.		Foshan City pollution remediation work is good, and through Forest City construction, the environmental pressure is small, mostly showing weak negative driving characteristics. Among them, Sanshui and Shunde districts are intensive in secondary industries, and industrial wastewater has a certain impact on the environment, showing patchy negative driving characteristics.		In this area, the industrial proportion of Xinhui District in Jiangmen City is large, and the industrial wastewater has a great impact on the environment. In Zhongshan city, the proportion of traditional industries near inland areas is large, while the proportion of industries near Zhuhai and Macao is gradually decreasing, the proportion of service industries is increasing, and the discharge of industrial wastewater is reduced. In addition, the city is close to the estuary, which is influenced by ocean currents and accelerates the water cycle, showing positive and negative driving characteristics of regionalization.	

4. Discussion

The overall ESV of the study area was CNY 26,297.967 million, and the area share of each land use type in the study area was in the following order: paddy field > broad-leaved forest > built-up land > scrub > artificial wetland > water system > coniferous forest > natural wetland > grassland, and the corresponding ESV share of each land use type was in the following order: water bodies > broad-leaved forest > artificial wetland > scrub > paddy field > coniferous forest > natural wetland > grassland. Among the various types of ESVs in the study area, the ESV of water bodies accounted for the highest proportion, with a total amount of CNY 894.5469 million, accounting for 34.02%, and its provisioning service value was the most prominent, accounting for 65.844% of the value of all ecosystem provisioning services, followed by the regulating service value, with a proportion of 38.80%. Next, broad-leaved forest ecosystems accounted for 20–40% of the overall ESV. However, the ecosystems of paddy fields, which accounted for the largest area of land use types in the study area, all accounted for less than 11% of the ESV of all types and supplied CNY −570.818 million, accounting for −57.14% of all ecosystem supply service values. The provisioning service value of the paddy field ecosystem was negative because the paddy field ecosystems in the study area were dominated by rice cultivation, which consumes a large amount of water resources during the growth process, and its water conservation function is weak and shows a negative growth trend; if the paddy field areas were transformed into other types of ecosystems, the provisioning service value would increase [28–31,43].

The artificial wetlands in the Guangdong section of the Xijiang River mainstem are a relatively unique type of wetland. It is mainly used for the aquaculture of fish and shrimp and other aquatic products, with a regular layout, presenting low species richness compared with natural wetlands, reflecting the influence of factors such as market demand and the government's subjective willingness to make decisions on the landscape ecosystems. In the course of this study, based on the different wetland utilization patterns in the study area, the ESV equivalent factor of artificial wetlands in the Guangdong section of the Xijiang River mainstem was corrected using the shadow engineering method, which distinguished the ESV of artificial wetlands from that of natural land and was conducive to the explanation of the differences in the service value of the same area of artificial and natural wetland site types. However, the correction method is rough and needs to be further subdivided by the local aquatic products' aquaculture price data and the impacts of farmland and aquaculture on the artificial wetland ecosystems to explore a more realistic artificial wetland ESV equivalent factor.

Within the 1 km gradient along the river, as an important interface between water and land, which is the most frequent and intense area of material exchange and energy flow in the land–water interface zone, the value of the water bodies is ES-dominated, contributing to about 80% of the provisioning services and 85% of the regulating services. Then, as the distance from water increases, the ecosystems of the water bodies gradually transition to ordinary terrestrial ecosystems. Instead, the service value of artificial wetlands and broad-leaved forest ecosystems gradually dominate, with the artificial wetland ecosystems having the highest service value in the 2–5 km gradient along the river and broad-leaved forest ecosystems having the highest service value in 6–10 km gradient along the river. Waters and wetlands play a positive role in flood control, water purification, and soil conservation and are an irreplaceable part of regional socio-economic development. The study of the spatial change drivers of the ecosystem service values of water bodies, broad-leaved forests, artificial wetlands, and scrublands will provide a scientific basis for revealing the relationship between the geographic characteristics of the riverine and terrestrial intertwined zones, the spatial distribution of land use types, and the ecosystem service values, as well as the impacts of human activities on the value of ecosystem services [44].

Within levels 1–4 of the river section, because of the large distribution of mountainous areas and favorable climate, broad-leaved forest ecosystems have the highest per capita service value and perform ecosystem service functions such as water conservation; the terrestrial ecosystem service values decrease as the distance from the lower reaches of the

Xijiang River shrinks and gradually transitions to aquatic ecosystems; after the fifth level of the river section, with the increase in human activities and the need for land-use type construction and economic development, the mean land service value of broad-leaved forest and scrub ecosystems gradually declines, and the mean land service value of water bodies and artificial wetland ecosystems gradually dominates; within levels 5–6 of the river section, there is a staggering point between the mean land service values of water bodies and broad-leaved forest ecosystems due to the plains areas exceeding the mountainous areas, the expansion of the water bodies area, and the increase in water use for urban construction, and the mean land service value of the water bodies ecosystems then exceeds that of the broad-leaved forests; within levels 7–10 of the river section, the mean land service value of the artificial wetland ecosystems is second only to that of water bodies, providing mainly provisioning and cultural services; within the eighth level of the river section, the mean land service value of water body ecosystems is at its peak, providing about 124% of the value of the provisioning services and 59% of the value of the regulating services. The GWR model fitting results of the Guangdong section of the Xijiang River Basin obtained from the study show that the driving relationship between each driving factor and the ecosystem service function in the study area is not a simple linear relationship. When referring to relevant research [45], the constraint lines between vegetation coverage, water production, and soil conservation services are all in the form of an open downward parabola. That is, after vegetation coverage reaches a certain threshold, there is a constraint effect on the value of ecosystem services, which is consistent with vegetation coverage. The driving relationship happens between the degree factors and ecosystem service functions in the study area. Its specific analysis needs to be further deepened in subsequent research.

Among the driving spatial characteristics, temperature, humidity, rainfall, the share of the primary industry, the share of the secondary industry, and the share of the tertiary industry have obvious regional and small patchy driving characteristics for the ES in the study area. Vegetation cover, slope, total consumption of electric power, the emissions of industrial exhaust gases, and the emissions of industrial wastewater in the study area showed obvious region characteristics, and the spatial differences in the impact of elevation and annual consumption of electric power energy by industrial enterprises above the national scale were not obvious. Among the driving intensity characteristics, humidity, rainfall, and the share of the three major industries showed small-scale, patchy, and intense heterogeneity; GDP, population density, lighting during the night, and evapotranspiration were too low in intensity, and the rest of the factors were shown to be blocking the driving characteristics. The differences in topography, geomorphology, and socio-economic development of the Guangdong section of the Xijiang River Basin determine the above spatial differentiation phenomenon.

Based on various types of data through the equivalent factor method and the geographically weighted regression (GWR) model to explain the trend in the changes of the lateral, upstream, and downstream gradients of various types of ESVs in the study area, the changes in the ESVs are the result of the joint action of a variety of factors; for example, while humidity and temperature directly affect the ESV, together they indirectly affect the level of ESV through vegetation cover. The waste gas and water produced by industry, the weight of each industry, and the local level of technology also indirectly affect the ESV through their influence on vegetation cover and temperature. It is difficult to comprehensively understand the influencing factors by only discussing the contribution and the positive and negative correlations. At present, the study of the gradients of the ESV in the study area is still in the primary stage, and there may be an incomplete problem in the argumentative data related to the relationship between various types of influencing factors and the change in the ESV in the gradient range, so we expect to introduce more research methods to explore the process of the change in the ESV and the influencing mechanism from different perspectives through in-depth qualitative analyses and to continue to improve and optimize the results in the future studies.

Based on the results of the study, we propose the following recommendations for the development of each region: (i) For the Yunfu–Foshan section of the Xijiang River Basin, it is necessary to continuously enhance the kinetic energy of development, accelerate industrial transformation and upgrading, and improve the capacity of scientific and technological innovation; actively promote the green development of the population, and strengthen the implementation of the green mode of production that is resource-intensive and frugal and low-carbon and environmentally friendly; save and intensively use resources such as land, water and energy, and promote the recycling of resources so as to alleviate the damage to urban natural systems caused by the expansion of urban built-up land, and to improve the quality of urbanization in an all-round way. (ii) For the Foshan City–Zhuhai City stream section of the Xijiang River Basin, scientific and appropriate paddy land reclamation should be carried out on the basis of safeguarding the basic ecological communities so as to strengthen the protection of natural ecology; moderate the expansion of the spatial extent of broadleaf forest ecosystems under the premise of guaranteeing ecological security so as to repair the species diversity and community complexity of the region's ecology and make up for the region's tendency to be weaker in terms of regulating, supporting, and cultural services; make full use of the influence of the humid environment, give full play to its advantages, and reasonably develop and utilize artificial wetland to further enhance the value of the ecosystem services of the artificial wetland as well as the ESV function.

5. Conclusions

Based on the results of the study, the following conclusions are made:

(1) The level of each type of ESV does not depend entirely on the size of the area but is determined by the ecosystem service functions it can provide and the level of ESV per unit area. Water bodies and wetland ecosystems provide the highest land-averaged ESVs of all ecosystem types and mainly provide provisioning and regulating services, further confirming the ecological importance of water bodies for hydrological regulation and climate regulation [46–48];

(2) The relationship between land use types on both sides of the Guangdong section of the Xijiang River Basin shows a trend from water ecosystems to terrestrial ecosystems, and the ESV decreases gradually with the increase in distance from the water. The trend in the ecosystem service value of the Xijiang River's interface zone varying with the distance from the water bodies corroborates, to some extent, the superiority of the interface zone over the land in terms of ecological functions and values. It indicates that ecological protection measures within 1 km of the river should be increased at the water bodies scale, attention should be paid to the protection of forest land within 6–10 km, and artificial wetlands should be gradually replaced by natural wetlands to enhance the value of water bodies ecosystem services [49,50];

(3) In relation to the Guangdong section of the Xijiang River Basin, the land-averaged ESV shows an overall undulating trend and decreases with decreasing distance from downstream areas. On the upstream and downstream gradient, because of the geographic environmental differences and urbanization development, the land use system at the upstream and downstream gradient in different regions changed subsequently, and the ecosystem structure gradually tended to develop into diversified forms, with broad-leaved forests as the main form. The land-averaged ESV showed a fluctuating and decreasing trend, and the landscape pattern showed an intensification of fragmentation, an increase in richness, and a trend of landscape diversification. Once again, this proves that different land use types and landscape spatial configurations will lead to landscape spatial heterogeneity, which, through landscape function conduction, will, to a certain extent, trigger spatial differences in ESVs, ultimately leading to spatial differences in ESVs, which shows that the higher the degree of landscape fragmentation and the higher the dispersion of landscape types, the lower the law of an ESV [51].

(4) By constructing a geographically weighted regression model to analyze the spatial differentiation characteristics and intrinsic causes of the impacts of natural systems and socio-economic factors on the value of land ecological services (ESV), it is known that the dominant drivers of ecosystem services in the waterway intersection zone of the Guangdong section of the Xijiang River mainstem are the total amount of electric power consumption, industrial exhaust gas emissions, and industrial wastewater emissions, which suggests that the socio-economic factors have a greater impact on the ESV in the economically developed areas. These factors are generated by human living and production activities, which indirectly affect the size of ESV by influencing factors such as temperature and gas. In the context of global warming, natural factors, such as temperature, humidity, and rainfall, in the basin and socio-economic factors, such as the share of industries in each county and city, affect the spatial distribution characteristics of ESV in the region, while topographic and geomorphological factors, such as slope and vegetation cover, and socio-economic factors, such as energy consumption, electricity, and the emission of industrial waste gases and wastewater, are the determinants of changes in the generation of the ESV. It shows that the enhancement of ESV in water bodies requires both the fulfillment of ecosystem services based on geographic characteristics and the adjustment of human approaches to land use and production and living to cope with a range of natural and anthropogenic issues, such as global economic recession, global warming, and sudden public health events [46,52–55].

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