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Evaluating the Influence of Land Use and Landscape Pattern on the Spatial Pattern of Water Quality in the Pearl River Basin

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Abstract: Differences in land use and landscape patterns have become crucial factors affecting regional water quality. In order to investigate the effects of different land use and landscape patterns on water quality, this study used dissolved oxygen (DO), ammonia nitrogen (NH_4^+-N), and potassium permanganate index (COD_{Mn}) from 147 conventional water quality monitoring stations in the Pearl River basin of China from January to December 2021 as representative water quality parameters. The quantitative relationship between land use, landscape pattern, and water quality in the Pearl River basin was investigated using geographic information system technology (GIS) and partial least squares (PLS). The results showed that the overall water quality of the Pearl River basin was relatively positive and mainly threatened by organic pollution. The water quality of the Pearl River basin was affected by the spatial characteristics of land use and landscape pattern, showing a poorer spatial pattern on the eastern and western ends and a better one in the central part of the basin. The developed PLS regression model could better explain the quantitative relationship between water quality, land use, and landscape pattern, concluding that unused urban land has the greatest impact on water quality, with an impact coefficient of more than 0.10. The interspersion juxtaposition index (IJI) for representing landscape patterns had the greatest impact on water quality indicators, with an impact coefficient of −0.15 on DO, 0.13 on NH_4^+-N, and 0.15 on COD_{Mn}, respectively. Meanwhile, land use types such as unused land and water and landscape patterns indicated by the Shannon diversity index (SHDI) and the contagion index (CONTAG) had significant effects on watershed water quality. The results of the study provide a reference value for the optimal adjustment of land use structure and water quality improvement in the basin.

Keywords: water quality; land use; landscape pattern; spatial characteristics; partial least squares

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1. Introduction

A safe water resource is the material basis for sustainable human development [1]. Under the combined influence of climate change and human activities, regional water resource security challenges are becoming increasingly serious [2], with the issue of water quality security having aroused widespread concern [3]. Water quality changes in the basin result from a combination of natural and human factors, including topography, land use type, temperature changes, production activities, etc. [4–6]. Land use change is an important reflection of human activity [7], and it affects regional water quantity and quality by altering the hydrological cycle of watersheds through rainfall, evapotranspiration, runoff, and other processes [8–10]. Alterations in land use patterns and natural landscape patterns due to high-intensity human activities have consequences for the impact on water quality in the catchment area. Studies have shown that agricultural land area is significantly and positively correlated with water quality parameters [11], forested land has a vital role in improving water quality [12], and urban land area is significantly and positively correlated with river water quality [13]. Land use change has now been identified as a major challenge for water resources management and has become one of the core fields and hot issues in global change research [14–16].

In recent years, scholars have used different methods (cluster analysis, correlation analysis, redundancy analysis, SWAT model, geographically weighted regression model, multiple linear regression, etc.) [17–19] to explore the relationship between land use structure and water quality at different scales (catchment, riparian, and reach) [20,21], to qualitatively and quantitatively analyse the main land use types affecting river water quality, and to identify the land use scales and spatial patterns that have an impact on water quality. For example, Xu et al. [22] assessed the impact of land use from the riparian zone to the whole region on river water quality, concluding that land use explained more water quality changes (from 7% to 36%) in the short-distance buffer zone (100, 300, and 500 m) but less (from 2% to 27%) in the long-distance buffer zone (1000 m and the whole region). Wang et al. [23] used redundancy analysis and the partial least squares structural equation model to discuss the relationship between land use change and water quality in the sub-basins around Danjiangkou Reservoir in the dry and wet seasons based on the "source-sink" landscape theory. Wilson [24] quantified the driving effect of land use change on the total suspended solids and total phosphorus concentrations in the Wisconsin River at the Lower Chippewa River Watershed at 10-year intervals through the SWAT model. With the rapid development of computer technology, remote sensing (RS), and geographic information system (GIS) technology, landscape indexes have been introduced to better quantify the relationship between land use and water quality based on the perspective of landscape ecology [25]. Studies have shown that landscape indexes at different scales are closely related to the seasonal water quality of rivers and can better explain the relationship between water quality and land use in a watershed [26,27].

The above studies and examinations interpret the relationship between land use, landscape patterns, and water quality in watersheds. However, previous work focused mainly on the relationship between spatial land use change and water quality at small scales, and there remains uncertainty about the spatial scale at which water quality parameters are most clearly explained. Some studies have shown that the type of land use at the catchment scale has a substantial impact on water quality parameters [28,29], while some research has suggested that land use at the reach or riparian scale better explains changes in water quality [30,31]. Some studies also believe that managing landscape patterns at the riparian zone and sub-basin scales is equally important for water quality protection [32]. There are significant differences in land use and landscape patterns on a large watershed scale, and the study of quantitative relationships between land use and water quality should be a research priority [33]. Exploring the relationship between land use structure, landscape pattern, and water quality in large watershed areas is essential for regional water resource protection, non-point source pollution control, and sustainable use of resources.

The Pearl River basin [34] is the largest watershed in southern China, where there is a great deal of human activity and the economy and society are highly developed. Influenced by natural factors such as soil, topography, climate, precipitation, and human activities, water quality problems in the Pearl River basin are becoming increasingly prominent [35]. Previous studies on water quality in the Pearl River were mostly focused on the relationship between land use and water quality in the small- and medium-scale watersheds [36,37], whereas the large span of the Pearl River basin and widely varied land use differences in different sub-basins have led to considerable diversity in water quality parameters across space. However, relatively few studies exist on the impact of land use and landscape patterns on water quality in the Pearl River basin area. Therefore, this study investigates the quantitative relationship between water quality, land use, and landscape patterns in the Pearl River basin through a combination of GIS and partial least squares (PLS). The objectives of the study are: (1) to reveal the spatial variability of water quality in the Pearl River basin; (2) to identify the spatial characteristics of land use and landscape patterns;

and (3) to quantify the relationship between land use, landscape patterns, and water quality at different spatial and temporal scales in the basin.

2. Materials and Methods

2.1. Study Area

The Pearl River basin (21°31~26°49′ N, 102°14′~115°53′ E) is the third-largest watershed in China and the largest in South China [38]. The terrain of the basin shows a trend of high in the northwest and low in the southeast (Figure 1), spanning the Yunnan-Guizhou Plateau, the hills of Guangdong and Guangxi, and the Pearl River Delta plain from west to east, with a total catchment area of about 453,700 km^2.The basin is located in the tropical and subtropical climate zone, with an average annual temperature of 14–22 °C and an average annual rainfall of 1200–2200 mm. Vegetation coverage is high, and the vegetation community structure is diverse [39]. The Pearl River basin is a highly developed region with a crucial position in the social-economic development of China. Among them, the Guangdong-Hong Kong-Macao Greater Bay Area is the most economically dynamic economic zone in the Asia-Pacific region, known as the southern gate of China [40]. However, affected by economic and social development, spatial and temporal variability of water resources, and land use, the environmental problems caused by the water ecology in the Pearl River basin are becoming more and more severe.

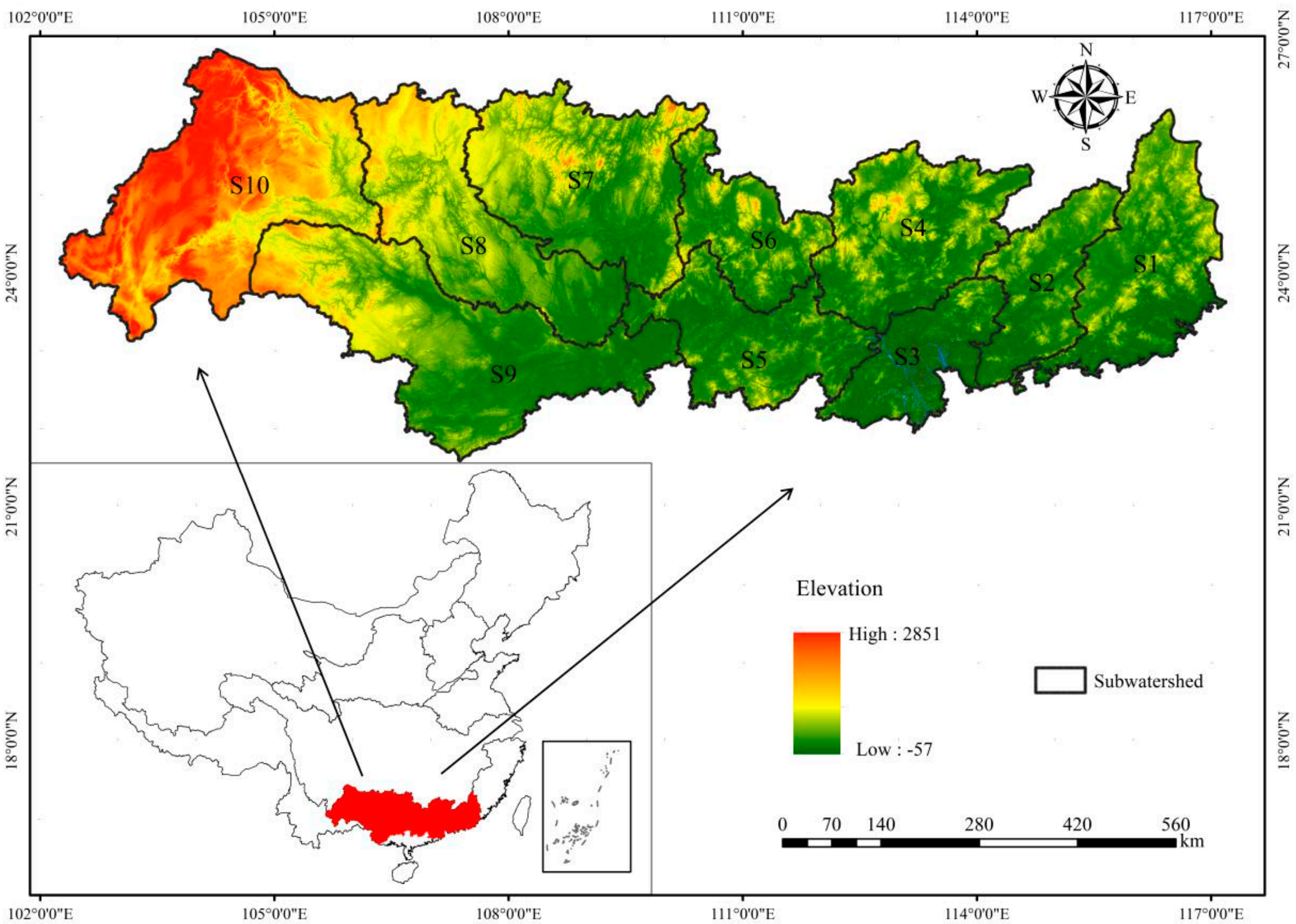

Figure 1. Location and subbasin division of the Pearl River basin (S1: Hanjiang basin, S2: Dongjiang basin, S3: Pearl River Delta, S4: Beijiang basin, S5: Xijiang trunk, S6: Guihe River basin, S7: Liujiang River basin, S8: Hongshui River basin, S9: Nanbeipanjiang River basin, S10: Yujiang basin).

2.2. Water Sampling

Research shows that the index parameters of dissolved oxygen (DO), ammonia nitrogen (NH_4^+-N), and potassium permanganate index (COD_{Mn}) can explain the regional water quality [41]. Therefore, this study chose DO, NH_4^+-N, and COD_{Mn} as the representative water quality parameters. Monitoring data from 165 monitoring stations in the study area were collected from the China National Environmental Monitoring Centre (http://www.cnemc.cn/, accessed on 1 September 2022), and stations with outliers or repairs were excluded. The monthly monitoring data of DO, NH_4^+-N, and COD_{Mn} from 147 representative monitoring stations in the study area from January to December 2021 were screened out for research.

2.3. Spatial Data

The study on the relationship between land use and water quality does not consider the difference in land use by month and season and draws on the land use data of 2020, which is similar to the sampling date. The Globe Land 30 data was derived from the China National Fundamental Geographic Information Centre (http://www.globallandcover.com/, accessed on 1 September 2022). The data is developed by using the classification of the image as a 30 m multispectral image, including TM5, ETM+, and OLI multispectral images from Landsat, HJ-1, and GF-1 multispectral images of the China Environmental Disaster Mitigation Satellite. The land use types (i.e., agricultural land, forestland, grassland, water, urban land, and unused land) in the Pearl River basin (Table 1) were determined according to the national standard land use classification (GB/T21010−2017) [42]. The DEM data was derived from the SRTMDEMUTM 90-metre resolution digital elevation model of the Geospatial Data Cloud (http://www.gscloud.cn/, accessed on 1 September 2022). The Pearl River basin is divided into ten sub-basins (S1–S10) according to DEM and water distribution conditions. Using ArcGIS10.3 software, land use data for each sub-basin was extracted.

Table 1. Selected land use types and landscape pattern indexes.

Variables		Description
Land use	Agriculture	Agricultural land in the watershed
	Forest	Forestry land in the watershed
	Grassland	Grassland in the watershed
	Water	Water area in the watershed
	Urban	Urban construction land in the watershed
	Unused	Undeveloped land in the watershed
Landscape	NP	Degree of landscape fragmentation
	PD	Degree of landscape fragmentation
	LSI	Degree of landscape fragmentation
	CONTAG	Degree of landscape aggregation
	LPI	Dominance of the landscape
	IJI	Degree of landscape separation
	SHDI	Heterogeneity of the landscape

From the landscape indexes [43] characterising landscape fragmentation, aggregation, dominance, and diversity, seven indexes with high generality were selected as shown in Table 1, including number of patches (NP), patch density (PD), landscape shape index (LSI), contagion index (CONTAG), largest patch index (LPI), interspersion juxtaposition index (IJI), and Shannon diversity index (SHDI).

2.4. Analytical Methods

2.4.1. Spatial Autocorrelation Analysis

Local Moran's I index [44] was used to identify the spatial distribution pattern of each water quality index, with values ranging from −1 to 1. The calculation is as follows:

$$\begin{cases} I = \dfrac{N}{\sum\limits_{i=1}^{N}\sum\limits_{j=1}^{N} w_{ij}} \dfrac{\sum\limits_{i=1}^{N}\sum\limits_{j=1}^{N} w_{ij}(x_i-\overline{x})(x_j-\overline{x})}{\sum\limits_{j=1}^{N}(x_i-\overline{x})^2} \\ I_i = \dfrac{N}{\sum\limits_{j=1}^{N} w_{ij}} \dfrac{\sum\limits_{j=1}^{N} w_{ij}(x_i-\overline{x})(x_j-\overline{x})}{\sum\limits_{j=1}^{N}(x_i-\overline{x})^2} \end{cases} \tag{1}$$

where x_i and x_j are the water quality parameters of the i and j monitoring points, respectively. $\overline{x}$ is the mean value of index; N is monitoring points; w_{ij} is the spatial weight between the water quality parameters of monitoring points i and j. The Moran's I index was tested for significance, and the significance level was p = 0.05.

2.4.2. Partial Least Squares

The partial least squares (PLS) integrated the advantages of principal component analysis, canonical correlation analysis, and multiple linear regression [45]. In this study, PLS was used to establish a model to analyse the relationship between watershed water quality parameters and land use types and to find the land use factors with important explanatory significance to water quality, which were expressed as follows:

$$\mathrm{c}(\alpha) = A_i + \sum_{i=1}^{n}(P_i \times \beta_i) \tag{2}$$

where c is the concentration of the water quality parameter (mg/L), α is the water quality parameter, including DO, $NH_4{}^+$-N, COD_{Mn}, A_i is the influence constant term of ith influence factors on water quality parameters. P_i is the standardised value of the ith influence factor, and β_i is the influence coefficient of the ith influence factor on water quality parameters.

Variable importance in the projection (VIP) is a critical discriminant of PLS [46]. According to the magnitude of the VIP value, it is possible to determine which of the different independent variables with multicollinearity are the most explanatory for the dependent variable. For the jth independent variable x_j, which is used to explain the dependent variable y_k, the VIP value is calculated as follows:

$$VIP_j = \left\{ p\sum_{n=1}^{m}\sum_{k} R^2(y_k, t_n)\omega_{nj}^2 \Big/ \sum_{n=1}^{m}\sum_{k} R(y_k, t_n) \right\}^{1/2} \tag{3}$$

where p represents the number of independent variables, m represents the number of components extracted from the independent variable, k represents the kth dependent variable, t_n represents the n component of the independent variable, $R^2(y_k,t_n)$ represents the square of the correlation coefficient between y_k and t_n, and $w^2{}_{ij}$ represents the contribution weight of independent variable x_j to the construction of the tn component. It is generally believed that the independent variables with VIP > 1 have significant explanatory significance for the dependent variable, and the larger the VIP value, the more significant the explanatory significance.

2.5. Statistical Analysis

The land use data of each sub-basin were extracted to analyse the current land use status and landscape pattern characteristics, and then the water quality characteristics of each sub-basin were analysed based on the water quality data, and the relationship between the land use, landscape pattern, and water quality of the whole basin was established through the PLS model. The kurtosis and skewness methods were used to check whether the water quality data satisfied the normal distribution before analysis. Spatial autocorrelation analysis of water quality for the local Moran's I index was performed using the spatial statistical tools of ArcGIS10.3 software. The landscape index was extracted from the raster map by ArcGIS10.3 and calculated by Fragstats4.0 software at the landscape level. The PLS calculation process was completed using SIMCA14.1 software, with the average concentration of water quality parameters in each sub-basin as the response variable of the model and the land use type and landscape indexes as the analysis variable impact, which was input into the model after standardization. Some images were completed using Origin2021b software and ArcGIS10.3 software.

3. Results

3.1. Water Quality Characteristics and Spatial Pattern

Reading the water quality monitoring results, the overall water quality in the Pearl River basin was relatively good, with the water quality parameters basically meeting the surface water class III standard (GB3838−2002) [47]. The average concentration of DO was (7.75 + 1.38) mg/L, and the average concentration of NH_4^+-N was (0.17 + 0.23) mg/L, among which the COD_{Mn} concentration was higher, and the average concentration was (2.43 + 1.94) mg/L. The COD_{Mn} concentration in some monitoring sites reached the class IV water standard, indicating that the water in the Pearl River basin was probably polluted by organic matter. As shown in Figure 2, the changes in water quality parameters in each sub-basin of the Pearl River basin showed notable spatial differences. The DO (Figure 2b) showed a relatively high concentration in the central part of the basin (S4–S8) and lower concentrations in the upper Xijiang River (S9 and S10), the largest tributary, and the downstream estuary (S1, S2, and S3). Meanwhile, the NH_4^+-N (Figure 2c) and COD_{Mn} (Figure 2d) were spatially characterised by low concentrations in the central part (S4–S8) and higher concentrations in the upper Xijiang River (S9, S10) and the downstream estuary (S1, S2, and S3).

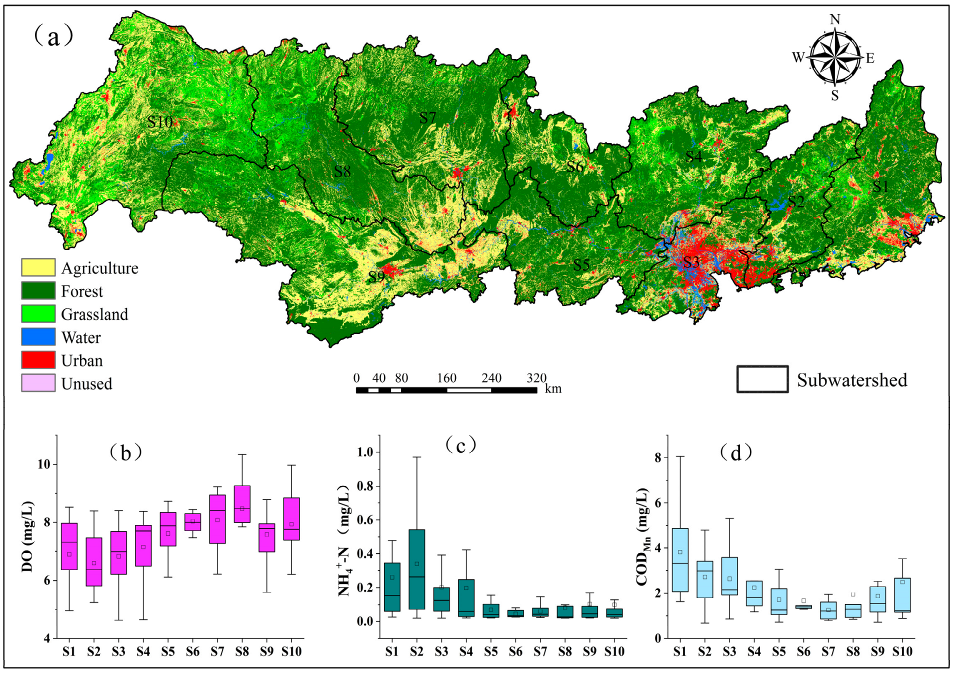

Figure 2. The spatial pattern of land use (**a**) and water quality (**b**–**d**) in the Pearl River basin.

The Global Moran's I index of DO, NH_4^+-N, and COD_{Mn} in the Pearl River basin was 0.27 (Z_value = 5.59, $p < 0.01$), 0.09 (Z_value = 2.06, $p < 0.01$), and 0.24 (Z_value = 4.86, $p < 0.01$), respectively. The three water quality parameters showed a certain spatial autocorrelation among all sections of the basin. The local spatial autocorrelation diagnosis results of water quality parameters at each section are shown in Figure 3. Consistent with the above analysis, DO concentrations showed low aggregation values in S1, S2, and S3, NH^{4+}-N concentrations showed high aggregation values in S1, S2, and S3, and COD_{Mn} concentrations showed high aggregation values in S10 and the downstream estuary S1, S2, and S3.

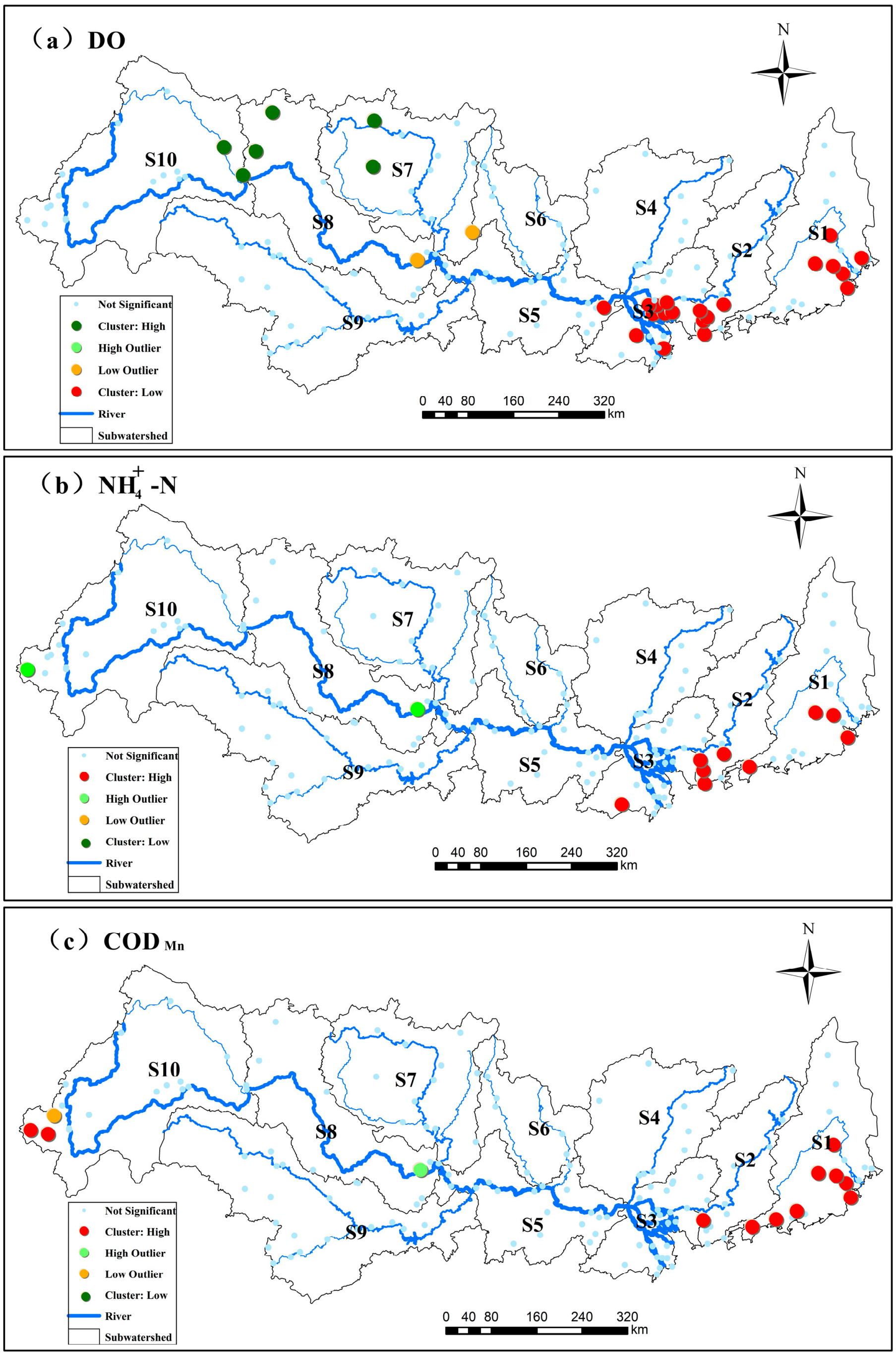

Figure 3. Local spatial autocorrelation diagnosis results of water quality (**a**) DO, (**b**) NH_4^+-N, and (**c**) COD_{Mn}.

3.2. Spatial Pattern of Land Use and Landscape

The land use structure in the Pearl River basin is shown in Figure 4. Forestland (58.42%) and agricultural land (25.31%) were the primary land use types in the Pearl River basin, followed by grassland (9.91%) and urban land (4.20%). These four types of land use were also basically dominant within each sub-basin. The spatial distribution of land use in the watershed is shown in Figure 2a. Overall, the upper eastern and western parts of the Pearl River basin were dominated by agricultural land and grassland, while the central reaches were dominated by agricultural land and forestland, with some urban land scattered. The water system near the downstream estuary was well developed, and the area of water bodies has increased. This region was highly developed socio-economically, and the land for construction had gradually increased and became the main land use type.

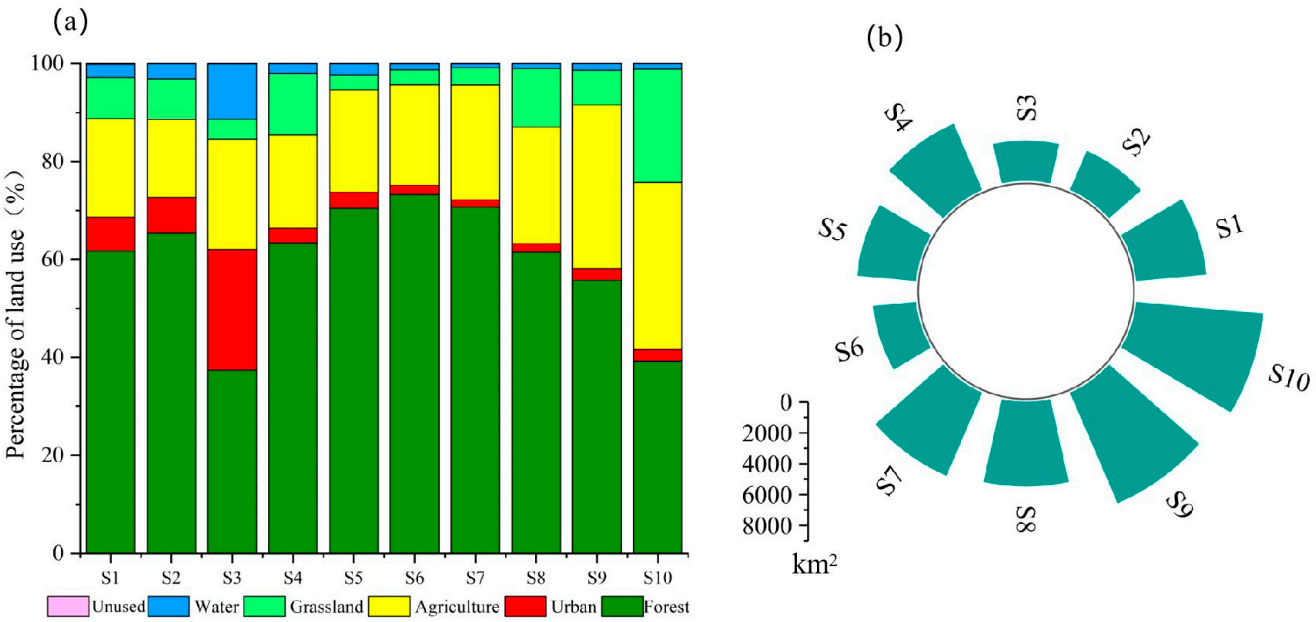

Figure 4. Land use characteristics (**a**) and area of each sub-watershed (**b**).

The landscape indexes of NP, PD, LSI, CONTAG, LPI, IJI, and SHDI in the study area also showed obvious spatial heterogeneity (Table 2). The landscape fragmentation indexes of NP, PD, and LSI were the largest in S10, indicating a high degree of landscape fragmentation and a more even distribution of patch types such as forest land, agricultural land, grassland, and urban land within the area. The landscape aggregation index CONTAG was higher in S5, S6, and S7, exceeding 60%, indicating that a certain dominant landscape patch type forms good connectivity with low landscape fragmentation. The landscape separation index IJI was the largest at S3, with a value of 78.15%. The higher landscape dominance index LPI indicates less human disturbance, with LPI being the largest at S6 and S7 and the smallest at S3 and S10. The higher the landscape diversity index SHDI, the greater the landscape diversity and the increased landscape heterogeneity, and the SHDI was the largest in S3 and S10. In summary, the spatial landscape pattern of the Pearl River basin showed a relatively concentrated and less fragmented landscape type in the central part and a more fragmented and more diverse landscape at the eastern and western ends, which are disturbed by human activities.

Table 2. Spatial distribution characteristics of landscape patterns in the Pearl River basin.

ID	NP	PD (N/ha^{-1})	LSI	CONTAG (%)	LPI (%)	IJI (%)	SHDI
S1	118,524	2.58	196.39	51.94	55.57	61.37	1.12
S2	65,387	2.38	138.45	54.24	59.32	61.81	1.08
S3	66,011	2.53	148.76	41.37	13.61	78.15	1.43
S4	134,367	2.88	208.17	53.64	22.25	54.53	1.05
S5	73,347	1.91	146.67	61.57	40.11	51.76	0.88
S6	34,938	1.25	91.34	66.97	67.72	52.72	0.79
S7	99,561	1.70	164.17	64.74	65.75	44.34	0.81
S8	135,682	2.47	231.12	54.52	49.97	48.92	1.01
S9	174,289	2.23	236.34	56.10	31.77	51.00	1.03
S10	295,238	3.53	375.06	44.84	14.88	48.37	1.22

3.3. Relationship between Land Use and Landscape Patterns and Water Quality

The established partial least squares model of water quality indicators of the watershed with land use types and landscape indexes (model results are shown in Table 3), in general, the PLS model results were better to indicate the land use types and landscape indexes that have significant explanatory significance on water quality. The influence coefficients of different land use types and landscape indexes on water quality indicators are shown in Figure 5, indicating that land use types such as urban land and unused land and landscape patterns such as IJI, SHDI, and CONTAG have significant influence on water quality indicators ($|\beta_i| > 0.1$). Among them, the land use types of unused land and urban land both have a negative effect on DO, with influence coefficients of -0.13 and 0.11, respectively, while both have positive effects on COD_{Mn} and $NH_4{}^+$-N. The landscape index IJI had the greatest effect on water quality index, played a negative effect on DO with an influence coefficient of -0.15, and had a positive effect on COD_{Mn} and $NH_4{}^+$-N with influence coefficients of 0.15 and 0.13, respectively. DO also showed a significant positive correlation with forest land and CONTAG and a significant negative correlation with SHDI. COD_{Mn} and $NH_4{}^+$-N also showed a significant positive correlation with SHDI and a significant negative correlation with agricultural land, forest land, and CONTAG. It showed that different land types and landscape indexes also had significant differences in correlation with water quality indicators.

Table 3. PLS models for different land use types, landscape indexes, and water quality indicators.

Var	Expression *
DO	$c(DO) = 12.089 + \sum_{i=1}^{n} (P_i \times b_i)$
$NH_4{}^+$-N	$c(NH_4{}^+ - N) = 1.487 + \sum_{i=1}^{n} (P_i \times b_i)$
COD_{Mn}	$c(COD_{Mn}) = 3.101 + \sum_{i=1}^{n} (P_i \times b_i)$

* R^2X(cum) = 0.76; R^2Y(cum) = 0.83; Q2(cum) = 0.72 and P_i are the land use type and landscape index, respectively.

The predicted values obtained from the PLS model fit well with the observed values [R^2 = 0.71 for DO (Figure 6a), R^2 = 0.76 for $NH_4{}^+$-N (Figure 6b), and R^2 = 0.82 for COD_{Mn} (Figure 6c)], and most of the points were homogeneously distributed around the y = x curve, indicating that land use type changes and landscape indexes were instrumental to the water quality. Figure 7 shows the VIP values of land use types and landscape indexes affecting water quality. The order of the comprehensive impact on water quality was IJI > unused land > SHDI > CONTAG > urban land > water > PD > agricultural land > forestland > LPI > NP > grassland > LSI, where the VIP values of unused land, urban land, water, IJI, SHDI, and CONTAG were greater than 1, which play an important role in the change of water quality in the watershed.

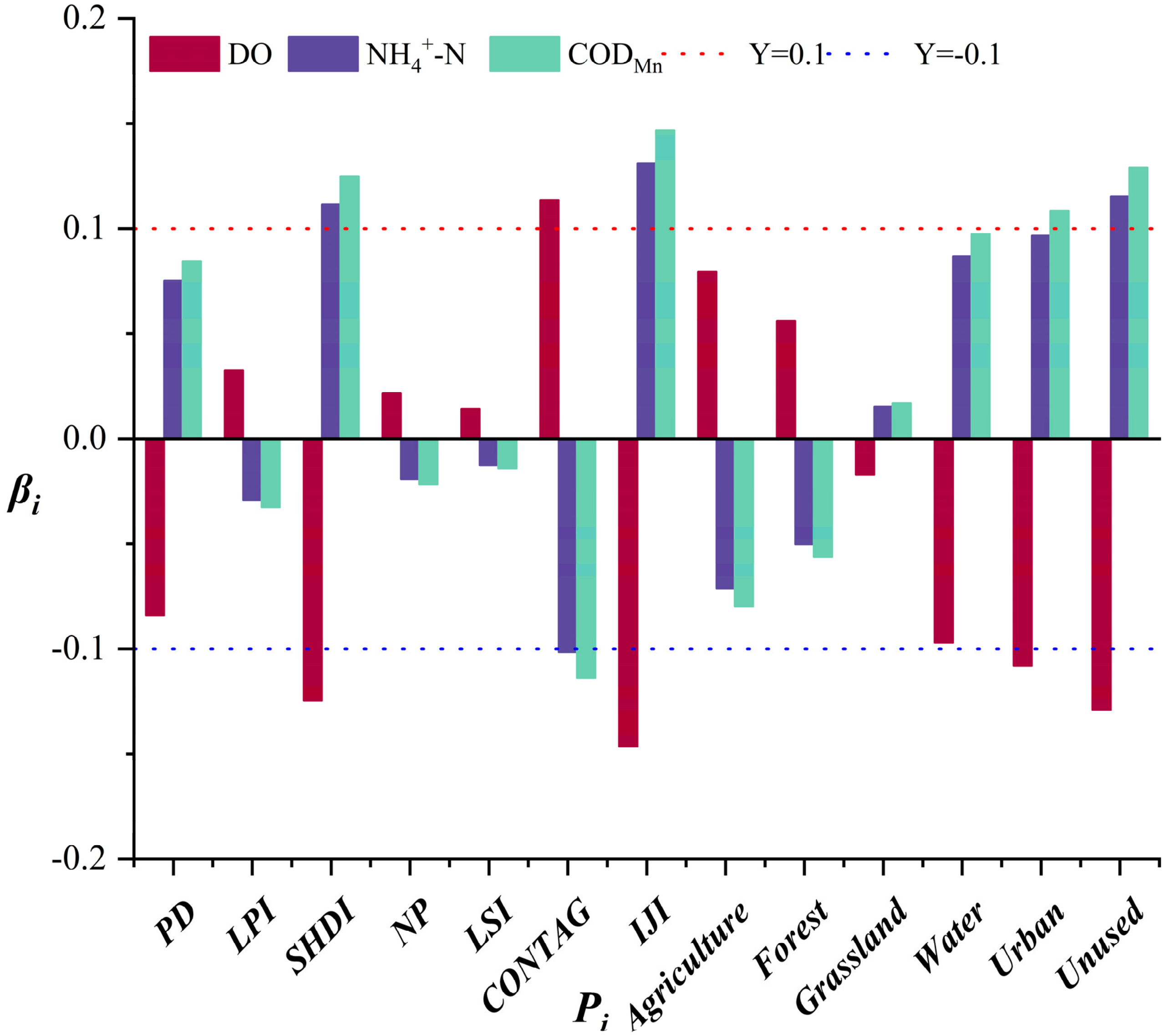

Figure 5. The influence coefficients of different land use types and landscape indexes on water quality indicators.

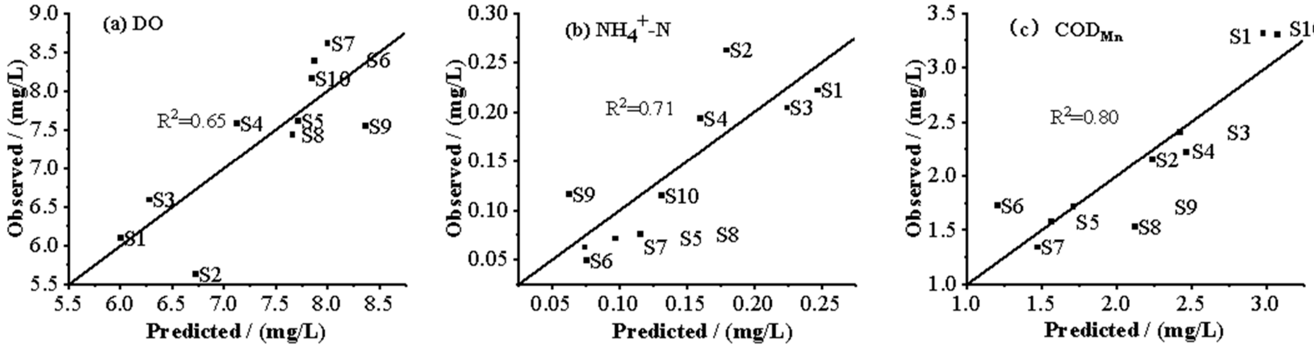

Figure 6. Effect of fitting the predicted and observed values of water quality parameters in PLS (**a**) DO, (**b**) NH_4^+-N, and (**c**) COD_{Mn}.

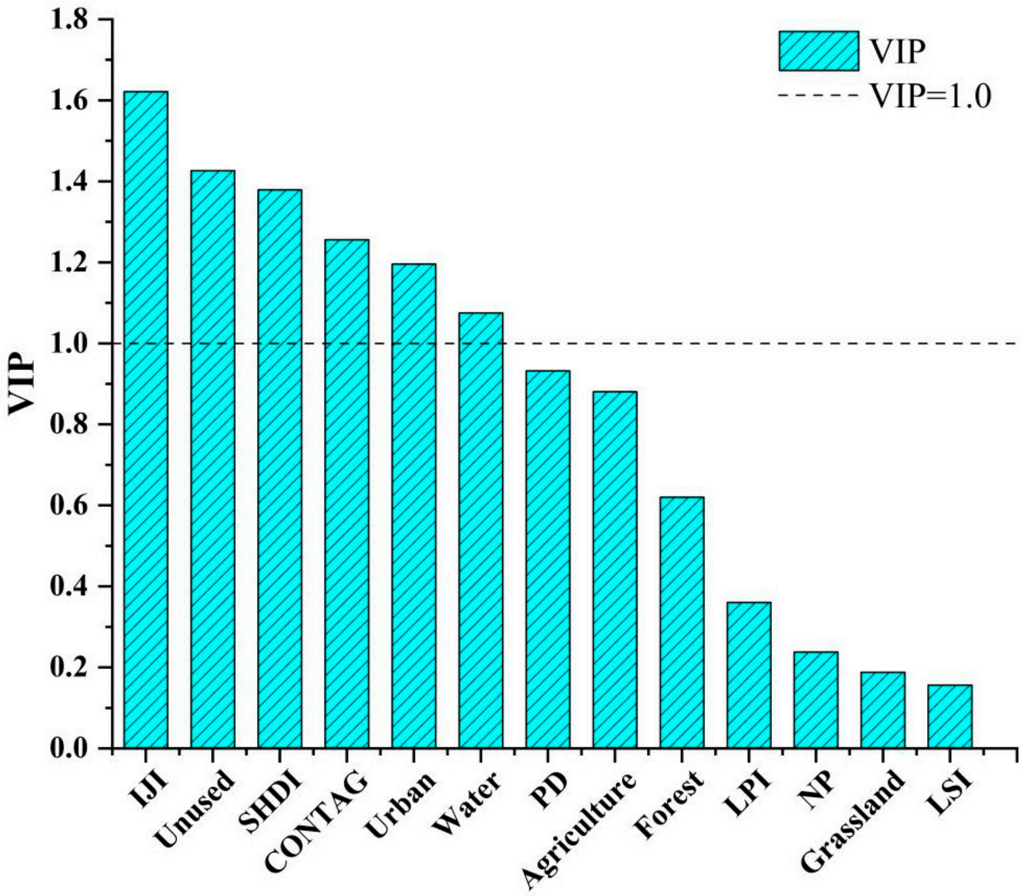

Figure 7. The VIP values of land use types and landscape indexes affect water quality.

4. Discussion

4.1. Effect of Land Use on Water Quality

Water qualities are affected by land use types and their spatial patterns, and pollutant loads vary by land use type at different scales [48]. The migration of pollutants and surface runoff on various land use types are influenced by various natural and man-made factors [49]. Numerous studies have shown that human-driven land use practices can have multiple impacts on watershed ecology and diversity through a variety of complex pathways [50–52]. This study shows that water quality parameters in the Pearl River basin are significantly related to urban land, unused land, and forestland (Figure 5). The results of the spatial analysis are as follows: PLS showed that the urban land in the Pearl River basin was negatively correlated with DO and positively correlated with COD_{Mn} and NH_4^+-N. Forestland was positively correlated with DO but negatively correlated with COD_{Mn} and NH_4^+-N. Unused land was negatively correlated with DO and positively correlated with COD_{Mn} and $NH4^+$-N. These results are consistent with the research by Wang et al. [53] on the interaction between land use types and water quality in a typical watershed of the Huaihe River Basin in China over a 7-year period, which found that the impact of forest/grassland land use on water quality was positive, while the impact of agricultural/developed land use on water quality was negative. These results indicate that urban land, unused land, and forestland are the main land use types affecting the water quality in the Pearl River basin.

From the perspective of the spatial distribution of water quality, the east and west ends of the Pearl River basin are greatly disturbed by human activities and occupy a large proportion of urban land, especially near the Pearl River Delta, which is densely populated and highly urbanized. As a result, the region has poor water quality (Figure 3). Regier et al. [54] found that with the increase in urban land area, pollutants from impervious surfaces directly enter the water body with rainfall runoff, increasing the concentration of water pollutants and declining water quality. Generally speaking, the larger the urban land area, the higher the concentration of water pollutants in adjacent rivers [55]. However, forestland accounts for a larger proportion in the centre of the Pearl River basin, and the water quality is somewhat better. This is because forestland is the "sink" landscape of water pollutants, which inhibits the output of water pollutants in the basin, can degrade pollutants, and has a positive effect on river water pollution [56]. According to the type of land use, the water bodies can dilute and degrade pollutants, so watershed area and water quality generally show a negative correlation [57]. Unused land receives less disturbance from human activities and less pollution from the water body, which benefits water quality and safety [58]. However, agricultural land is greatly disturbed by human activities and is the "source" of potential pollutants in water, which has a negative effect on river water quality [59].

4.2. Effects of Landscape Patterns on Water Quality

The changes in the composition and configuration of the landscape pattern may affect the processes of pollutant occurrence, transport, and transformation in the watershed, thereby altering the number of pollutants entering the river and significantly impacting watershed water quality [60]. Studies have shown that changes in landscape patterns appreciably affect water quality, and the landscape pattern index can well explain the pollutant load in water [61,62]. In this study, water quality parameters were significantly correlated with some landscape patterns (Table 2). IJI was negatively correlated with DO and positively correlated with COD_{Mn} and $NH4^{+}$-N. CONTAG was positively correlated with DO but negatively correlated with COD_{Mn} and $NH_4{}^{+}$-N. SHDI was positively correlated with COD_{Mn} and $NH4^{+}$-N and negatively correlated with DO. This is consistent with the research of He et al. [63] in the hinterland of the Lixia River in China. The spatial differences in landscape indexes were also consistent with water quality. Landscape fragmentation indexes NP, PD, and LSI were greatest in the S10 watershed, where patch types such as forestland, agricultural land, grassland, and urban land were more uniformly distributed. The CONTAG and LPI were higher in the S5, S6, and S7 regions of the centre reaches of the Xijiang River, where the water quality was better and forestland and agricultural land dominated. IJI and SHDI were the largest in S3, with more human activity, a large urban land area, and poor water quality.

Studies have shown that the more fragmented the landscape, the more heterogeneous it becomes and the higher the risk of water quality disruption in the watershed [64–66]. Changes in landscape patterns can also reflect the characteristics of potential anthropogenic disturbances [67]. Zhang et al. [68] thought that the strong influence of anthropogenic disturbance increases landscape fragmentation, and land use types such as agricultural land and urban land destroy the spatial distribution characteristics of the original natural landscape, making the patches develop in the direction of fragmentation and irregularity and reducing the landscape dominance [69]. The landscape fragmentation indexes of NP, PD, and LSI in S10 show higher values because of the more uniform distribution of patch types such as forestland, agricultural land, grassland, and urban land, and correspondingly, the water quality in the area was, to a certain extent, inferior. The S3 has the largest proportion of urban land area. As a result, the region has the largest IJI and SHDI and the worst water quality index, indicating that due to the increase in intensity of human activity, the watershed landscape types are more diverse, landscape fragmentation has increased, and water quality is threatened by increased [70]. However, the larger the values of LPI and CONTAG, the more aggregated the landscape patches and the lower the fragmentation, so the less water quality is affected [71]. Overall, the landscape index can reflect the socio-economic status of the study area to some degree, thus revealing the role of human factors in landscape patterns and reflecting the impact of land use and landscape patterns on water quality.

5. Conclusions

This study investigated the quantitative relationship between different land uses, landscape patterns, and water quality in the Pearl River basin using spatial autocorrelation and the PLS model. The results showed that the Pearl River basin is mainly threatened by organic pollution, and the water quality of the basin showed a spatial pattern of poorer in the eastern and western ends and better in the central part. According to the spatial pattern of water quality, the land use types in the Pearl River basin were mainly forestland, agricultural land, and grassland in the eastern and western upper reaches, while urban land and water in the downstream estuary were dominant; the landscape pattern showed the spatial characteristics of aggregation and low fragmentation of landscape types in the central part, high fragmentation, and large landscape diversity in the eastern and western ends. The quantitative PLS model showed that unused land and urban land had the greatest impact on the water quality, and the coefficient of impact on the water quality index was over 0.10. The IJI had the greatest impact on the water quality index, and the coefficient of impact on DO was −0.15, and the coefficients of impact on NH_4^+-N and COD_{Mn} were 0.13 and 0.15, respectively. According to the research results, local management planning can take measures such as preventing the spread and agglomeration of cultivated land and urban land, optimising the allocation of forest and grassland, and strengthening the control of pollution sources to achieve effective management of water quality in the Pearl River.

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