



Effects of landscape pattern on water quality at multi-spatial scales in Wuding River Basin, China

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Abstract

Urbanization and agricultural land use have led to water quality deterioration. Studies have been conducted on the relationship between landscape patterns and river water quality; however, the Wuding River Basin (WDRB), which is a complex ecosystem structure, is facing resource problems in river basins. Thus, the multi-scale effects of landscape patterns on river water quality in the WDRB must be quantified. This study explored the spatial and seasonal effects of land use distribution on river water quality. Using the data of 22 samples and land use images from the WDRB for 2022, we quantitatively described the correlation between river water quality and land use at spatial and seasonal scales. Stepwise multiple linear regression (SMLR) and redundancy analyses (RDA) were used to quantitatively screen and compare the relationships between land use structure, landscape patterns, and water quality at different spatial scales. The results showed that the sub-watershed scale is the best spatial scale model that explains the relationship between land use and water quality. With the gradual narrowing of the spatial scale range, cultivated land, grassland, and construction land had strong water quality interpretation abilities. The influence of land use type on water quality parameter variables was more distinct in rainy season than in the dry season. Therefore, in the layout of watershed management, reasonably adjusting the proportion relationship of vegetation and artificial building land in the sub-basin scale and basin scope can realize the effective control of water quality optimization.

Keywords Land use · Landscape pattern · Spatial scale · River water quality · Stepwise multiple linear regression

Introduction

Overexploitation of natural resources and the misuse of land can lead to a shortage of water resources (Li et al. 2018). Land use change objectively records the spatial and temporal dynamic alternation caused by the transformation of the Earth's surface. Land use impacts river ecosystems by altering hydrological cycles, soil erosion, and other ecological

processes. This effect is the integrated response of multiple landscape structures at different scales (Lei et al. 2021; Nash et al. 2009; Xu et al. 2021), including land use structures and landscape patterns (Dou et al. 2022). Understanding the scale effect and influence mechanism of land use and landscape patterns on river water quality can help to optimize the coordinated allocation of landscape patterns and water resources; furthermore, it is vital for land use planning based on water environment protection (You et al. 2023).

With increasing population and economic development, artificial landscapes, such as farmland and land construction, have replaced natural landscapes, such as woodland and grassland. This replacement led to the proportion imbalance of “source” and “sink” landscape types and changes in spatial allocation, thereby deteriorating water quality and negatively impacting the environment (Liu et al. 2022; Wang et al. 2024). Investigations on the relationship between landscape patterns and river water quality has gained attention worldwide, especially in China (Dou, et al. 2022). Landscape patterns show spatial heterogeneity and represent the regular characteristics of the arrangement and distribution

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of spaces with different sizes and properties (Pak et al. 2021; Santy et al. 2020). The landscape pattern index can quantify the landscape composition and spatial configuration and quantitatively analyze the relationship between the landscape index and water quality at the landscape and type levels. Research on landscape pattern indices can facilitate the optimization of the spatial allocation of landscape elements to support watershed water environment management (Wu and Lu 2021).

Since the 1970s, researchers have explored the relationship between different landscape structures and water quality (Ahmad et al. 2021; Rimer et al. 1978). Landscape structure at the sub-watershed scale has a more significant impact on water quality (Julian et al. 2017; Rodrigues et al. 2018). This study showed that the influence of land use landscape structure on water quality was associated with the scale; however, based on the differences in the development trends of different basins and cities around the river, the determination of the optimal spatial scale is affected by the specific study area. The urbanization process and agricultural production in the basin brought about economic development yet exacerbated the problems of eutrophication of the local river reservoirs (Bonansea et al. 2021). Riparian belts play a crucial role in maintaining water quality (Yan et al. 2023), and riparian zones can suitably explain the changing patterns in water quality (Johnson et al. 1997; Xu et al. 2019). However, studies on the relationship between landscape patterns and river water quality at a single scale often failed to explain this relationship (Ji et al. 2015; Ou et al. 2012).

Land use landscape patterns can variably influence water quality (Gao et al. 2024; Maloney et al. 2005; Worrall and Burt 1999). Generally, agricultural production and urban construction lands are major contributors to water pollution, whereas forestland and grassland can inhibit the occurrence of water pollution (De Mello et al. 2018). Water quality could also possibly improve during urbanization, based on land use changes and the urbanization rate (Zhang et al. 2021). The study also shows that there is a substantial relationship between the alternation of the rainy and dry seasons and river water quality, as changes in rainy season precipitation and surface runoff flow can have a significant impact on river flows and pollutant concentrations, and this variation is typically seasonal (Ai et al. 2015; Xiao et al. 2016). Different results were obtained for different river basins. For example, the Hanjiang River Basin has a prominent impact on water quality during the dry season (Li et al. 2013), whereas in the Beiyun River Basin, a strong correlation is present between landscape characteristics and water quality during the rainy season (Shen et al. 2015). Therefore, it is necessary to explore the relationship between basin landscape characteristics and seasonal changes in river water pollutants at a multi-scale level, improve land use planning, and suggest better landscape services (Zhou et al. 2012). Based on this,

we can also predict the possible negative impact of specific types of land use on water quality, so as to take preventive measures to reduce environmental pollution and ecological damage (Deng et al. 2024).

The Wuding River Basin (WDRB) is located in a key area of an ecological restoration project on the Loess Plateau. Cities, industrial parks, villages, farmlands, and other important facilities are distributed along the mainstream and its tributaries. As a typical farming-pastoral staggered region, the WDRB has a complex ecosystem structure and a relatively fragile ecological environment. Moreover, the rapid development of the industrial chain of coal, salt, oil, and gas mining as well as processing is associated with several water resource problems in river basins, particularly water pollution. In recent years, with the improvements in watershed governance, the river water environment has improved; however, the water quality warrants attention.

Therefore, we used stepwise multiple linear regression (SMLR) and redundancy analysis (RDA) to quantify the multi-scale effects of landscape patterns and river water quality changes in the WDRB. This study compares the influence of land use landscape pattern on water quality, enriches the research field of the seasonal characteristics of river water quality in the river basin, promotes the sustainable utilization of water resources in the river basin, and provides the theoretical basis for maintaining the stability of river ecosystem and the health and safety of river water environment. The objectives of this study are to (1) clarify the spatial difference of the land use landscape pattern on the water quality characteristics with the season; (2) explore the response relationship between land use structure and water quality at different spatial scales; and (3) quantify the influence of different types of landscape factors and determine the key landscape indicators affecting water quality.

Materials and methods

Research area overview

The Wuding River (WR), also known as the Hongliu River, is a first-class tributary of the Yellow River, located in the middle reaches of the Yellow River Basin (Fig. 1a), originating from the northern foot of the Baiyu Mountain in Shaanxi Province, flowing to the Inner Mongolia Autonomous Region provinces (regions). The basin area is 29,595 km², mainstream length is 491 km, elevation is 692–1922 m, and the ratio of the whole river is about 1.97‰. The terrain elevation gradually decreases from southwest to northeast. The main tributaries are the Nalin, Hailu Rabbit, Yuxi, Luhe, Dali, and Huaining rivers on the south bank. The annual average temperature in the basin is 7.6–9.9 °C, and the annual average precipitation is between 350 and 430 mm,

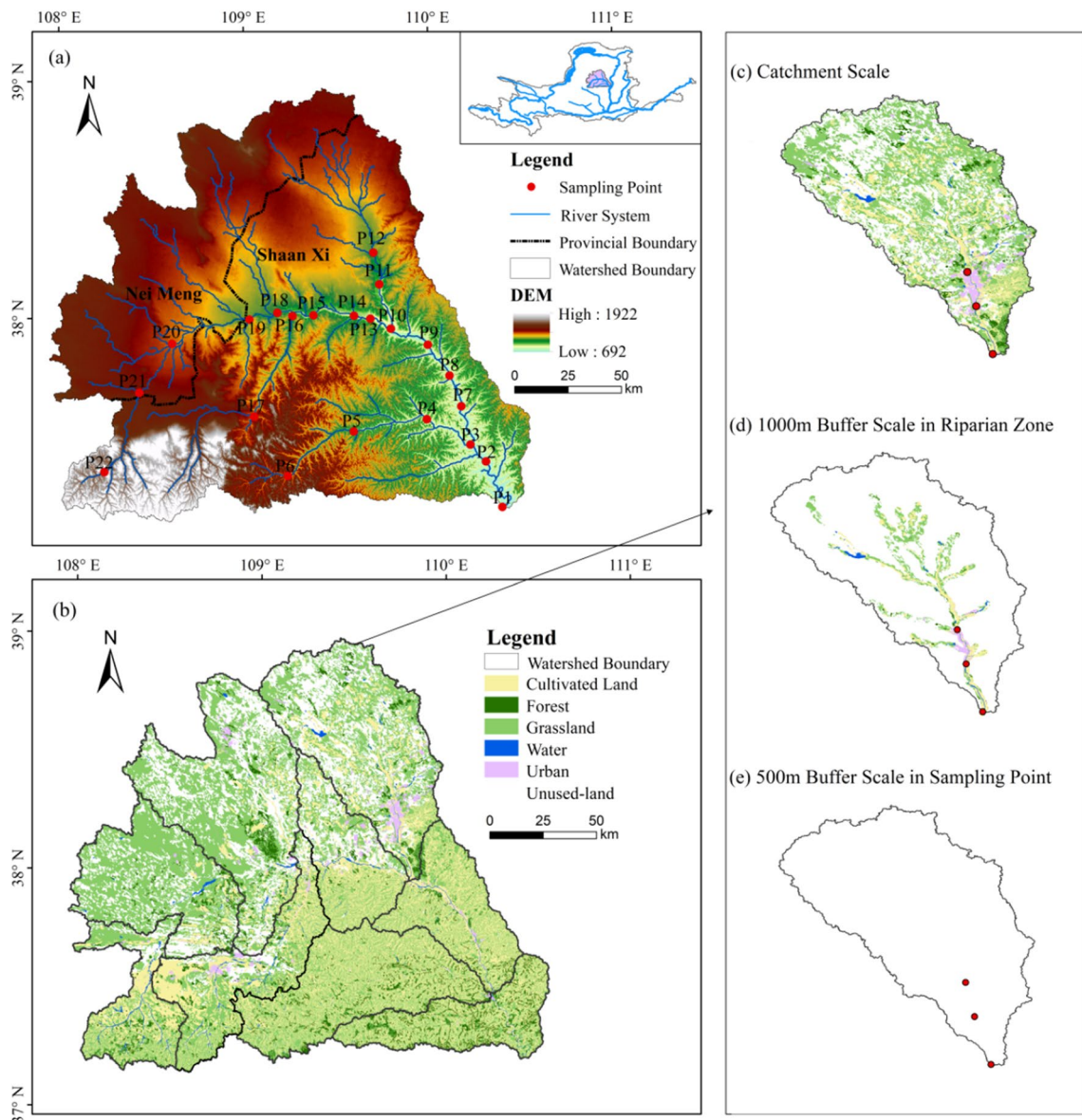


Fig. 1 Overview of the study area. (a) DEM and Location Diagram; (b) Land Use Distribution; (c) Catchment Scale Diagram; (d) Schematic Diagram of 1000 m Buffer Zone in Riparian Zone; (e) Schematic Diagram of 500 m Buffer Zone in Sampling Point

increasing from northwest to southeast. The topology of the basin is complex, with fragile ecology in the desert hinterland, loess hills, and other landforms. The basin is located in the boundary zone between semi-humid and semi-arid areas, which have a temperate continental monsoon climate with rain and heat. The basin is dominated by grassland, cultivated land, and unused land, accounting for 43.9%, 27.6%, and 20.5% of the whole basin, respectively.

The distribution of land use was consistent with the topography and landform zoning of the basin. WDRB is an ecologically fragile area. Although it is rich in mineral resources and scenic hydropower resources, soil erosion is relatively serious, which seriously restricts the sustainability

of local ecological, economic, and social development (Wang et al. 2023c; Zhao et al. 2023). In recent years, China has continuously increased its investment in soil erosion control, and with the continuous implementation of soil and water conservation measures such as soil and water conservation ecological projects and dam projects such as silt dams on the Loess Plateau, soil erosion control has entered a stable development stage, and the quality of the ecological environment in the Wuding River Basin has continued to improve, which has become a typical example of soil erosion control in China. As a typical water and soil conservation management basin on the Loess Plateau, human activities within the WDRB are complex, and water resource

allocation and water environment management in the river basin have become an increasing concern.

Data sources

A total of 22 sampling points were collected in 2022 on the basis of traffic and flood, considering the river living water location, wastewater discharge position, river hydrology and riverbed conditions, tributary inflow and hydraulic construction, river vegetation and water erosion, and other factors affecting water quality uniformity (Fig. 1a). Data were collected during the dry (April) and rainy seasons (September), and 10 representative water quality indicators were tested at each sampling point, namely hydrogen potential (pH), dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia nitrogen ($\text{NH}_3\text{-N}$), chemical oxygen demand (COD and COD_{Mn}), total nitrogen (TN), total phosphorus (TP), fluoride (F^-), and sulfide (S^{2-}). At each sampling point, water samples were collected from depths of 0–20 cm using an upright water surface. Three replicate water samples were collected at each sampling point. Plastic equipment was used to remove floating or submerged branches and dead leaves, and the sites were immediately evenly mixed. After 30 min, the water sample was loaded into a polyethylene bottle as a comprehensive sample for monitoring (Zheng et al. 2023).

The WDRB land use data we used in this study downloaded the Landsat7ETM remote sensing data of the study area in 2020 from the Geospatial Data Cloud (<https://www.gscloud.cn/>), and interpreted the land use grid data using ENVI with a resolution of $30\text{ m} \times 30\text{ m}$ (Fig. 1b). Grasslands were distributed throughout the basin, and cultivated land was majorly present in the south of the watershed. Unused land is mostly found in the northern region, which belongs to the sandstorm area, with a lower population distribution and relatively weak economic development. The river system distribution in the basin was uneven, and the river network was dense in the Loess hilly area. In the northwestern sandstorm area, fewer rivers with shorter lengths were observed.

Research method

The entire watershed was divided into nine sub-basins based on ArcSWAT 10.2 (USDA) hydrological analysis software, land use structure was analyzed, and the corresponding landscape index was calculated. Evaluations were performed using the SMLR analysis and RDA. According to land use characteristics and water quality cluster analysis, the response relationship between land use, corresponding landscape index, and river water quality can be obtained. The findings could aid in providing reasonable suggestions on the connection between water pollution control in river basins and the development of surrounding cities. The study process is illustrated in Fig. 2 (Yan, et al. 2023).

Watershed division and landscape index calculation

The scale of the correlation between river water quality and land use should be reasonably selected according to the topography and landforms in the study area, mainly involving the watershed, sub-basin, and buffer zone (Lei, et al. 2021). Considering the topography, river confluence, and other factors combined with the field investigations, we divided the WDRB into nine sub-basins according to the water system distribution and considered the corresponding section sampling point at the exit of each sub-basin as the control point. Dividing the watershed into three spatial ranges of different degrees has obvious comparative significance for discussing the influence of different land use landscape patterns on water quality. Therefore, in the three spatial ranges of sub-basin, 1000 m riparian buffer zone and 500 m sampling point buffer zone are proposed. Select the diagram of wd 4 (Fig. 1c–e).

According to the divided sub-basin (Fig. 3), the land use structure of the 1000-m buffer zone was similar to that of the entire basin, whereas that of the 500-m buffer zone of the sub-basin differed. Construction land accounted for 93.5% of wd-P2; only cultivated land and water in wd-P4 accounted for 70.5% and 29.5%, respectively, and grassland area of wd-P7 was 99.8%.

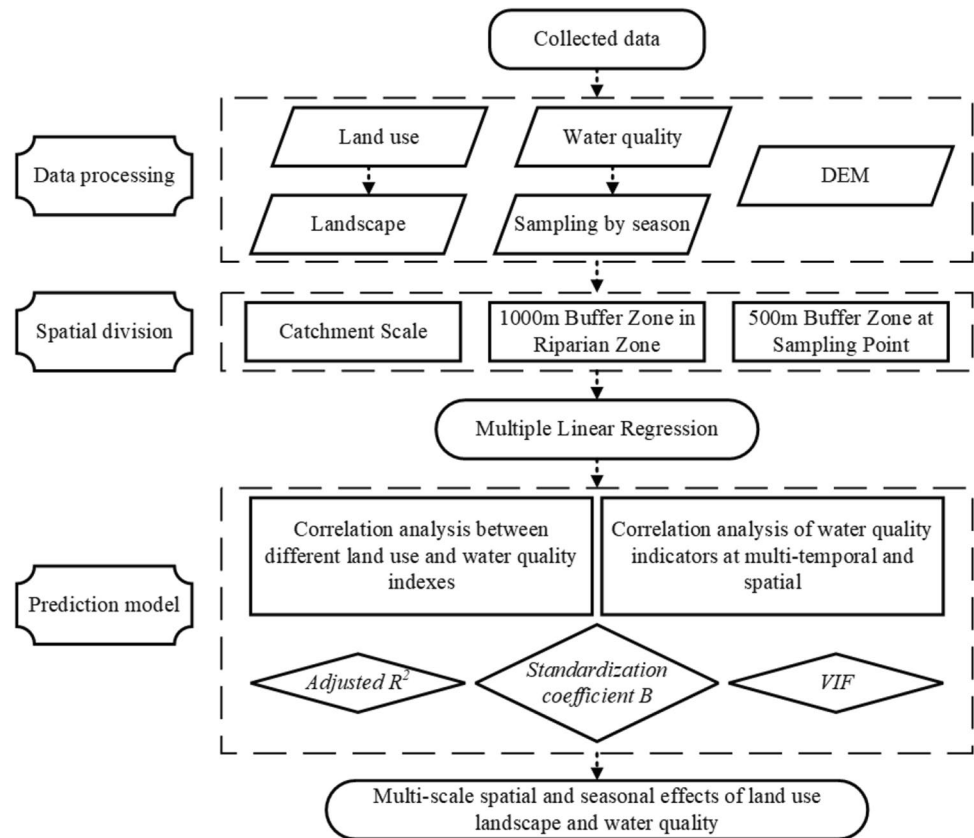
The landscape index refers to a simple quantitative index that can highly concentrate landscape pattern information, reflecting the characteristics of some aspects of its structural composition and spatial configuration (Cheng et al. 2023; Xu et al. 2023). Six landscape indices were selected (Table 1), of which four belong to the type scale (largest patch index (LPI), landscape shape index (LSI), patch density (PD), and proportion of like adjacency (PLADJ)) and two to the landscape scale (Shannon's diversity index (SHDI) and contagion index (CONTAG)) (Xu et al. 2022; Zhang et al. 2020). The landscape index of each land use type at different scales was obtained by calculating the land use distribution structure data using the Fragstats 4.2 (USA, Oregon State University).

Statistical analysis

Based on the measured and remote sensing data, SPSS 25 and Canoco 5 software were used to conduct reasonable visual data processing; discuss the correlation between different spatial scales, land use structures, and river water quality; and explore the influence of different seasonal landscape pattern indices and land use structures on river water quality (Xu et al. 2020).

The application of the SMLR model uses SPSS 25 software to process the data of the landscape indices of water quality in different seasons and different land types, screen out the water quality indices with significant correlation at

Fig. 2 Framework of the study



different spatial scales, maintain the corresponding reasonable landscape index, analyze the current situation, and provide reasons for the association (Ngabire et al. 2022).

As a classical multi-factor correlation analysis method, RDA can not only represent the contribution rate of a single individual environmental change factor to watershed water quality but also reflect the influence of multiple environmental variables on all water quality indicators (Zhang et al. 2022). RDA analysis based on the correlation matrix was used owing to the different dimensions of the water quality indices.

Results and analysis

Landscape index analysis at different spatial scales

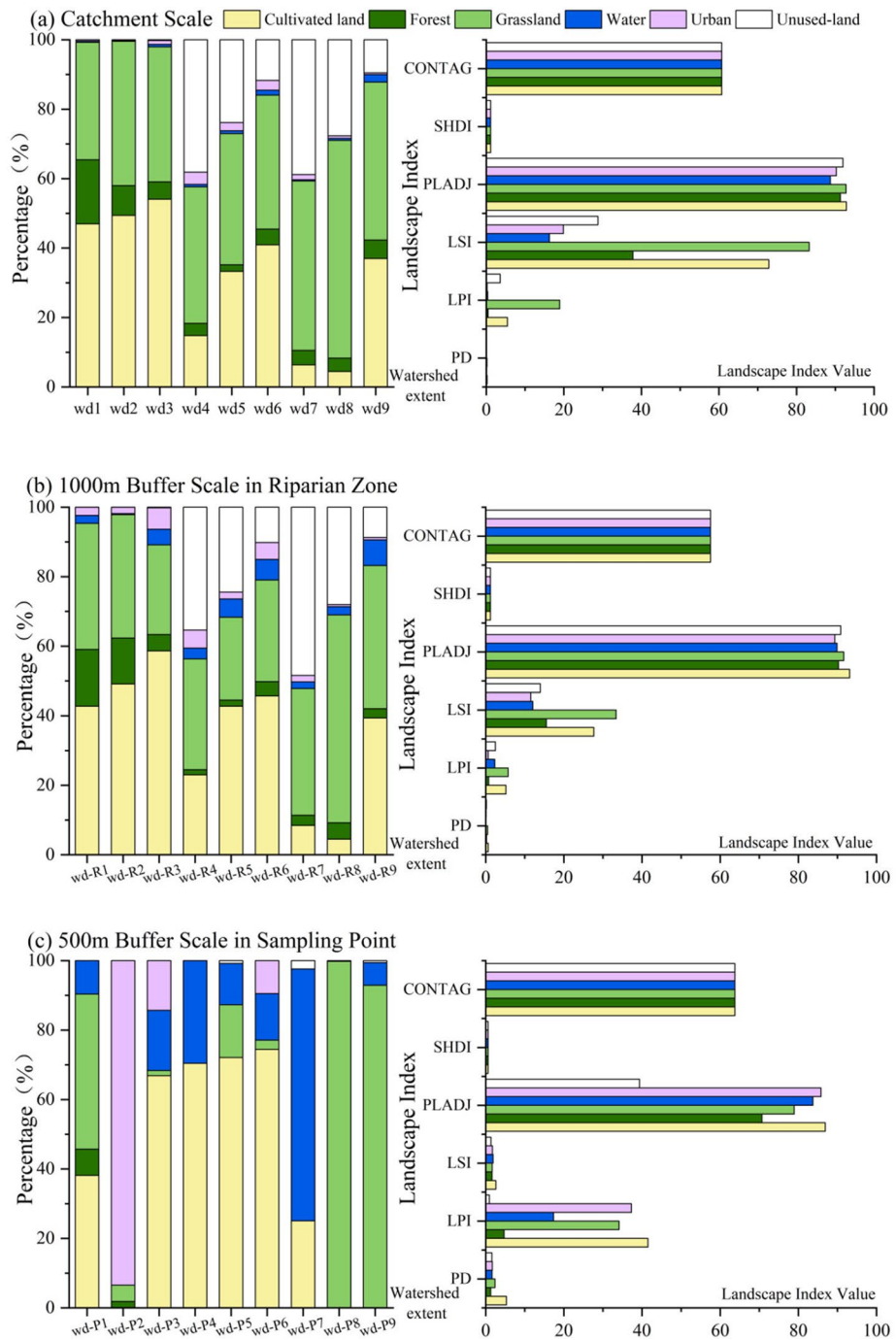
According to the landscape pattern index of different land types (Fig. 3), at the catchment scale (Fig. 3a), the LSI of grassland and cultivated land was 82.3 and 72.9, respectively, indicating that the complexity of patch shape at the sub-watershed scale is significant. The highest LPI of grassland reached 18.9, indicating that the occupancy degree of large patches in grassland was prominent compared with that of other land categories. The PLADJ of different regions was relatively close (approximately 90), indicating that the

connectivity between different local patches was high; the PD of each region was also proximate, indicating that the plaques are relatively complete and the fragmentation degree was low, all below 0.3. At the 1000-m buffer scale of the riparian zone (Fig. 3b), the LSI of grassland and cultivated land was 33.4 and 27.6, respectively, compared with that at the sub-basin scale. The LPI of grassland and cultivated land was higher than that of other land categories, but the overall level was not high, with the highest value being only 5.7. This result is consistent with that at the sub-watershed scales. At the 500-m buffer scale in sampling point (Fig. 3c), the LPI of cultivated land, construction land, and grassland was high, with values of 41.5, 37.3, and 34.1, respectively, indicating that the occupation of large patches of the three land types was more prominent, the degree of landscape fragmentation was relatively low, and only the PD (5.3) of cultivated land was significantly higher than that of other land categories.

Analysis of the spatial and temporal variation of river water quality

According to the comparison of water quality at the sampling sites in WDRB (Fig. 4), the WDR water was weakly alkaline and DO in the dry season was significantly higher than that in the wet season; F^- in the rainy season was

Fig. 3 Landscape pattern index of different land types. (a) Catchment scale; (b) 1000 m Buffer Zone in Riparian Zone; (c) 500 m Buffer Zone at Sampling Point. Note: The abscissa title in the figure explains wd1 refers to the spatial scale of watershed 1, wd-R1 refers to the spatial scale of 1000 m buffer in the riparian zone of watershed 1; wd-P1 refers to the 500 m buffer scale at the control point of watershed 1, and other numbers are the same as above



significantly higher than that in the dry season. The remaining water quality indices were relatively balanced in the two seasons, in line with the local reality.

According to the comparison of water quality at the sampling points (Fig. 5), TP, BOD, COD, COD_{Mn}, and NH₃-N in the middle reaches of the WDR were significantly higher than those in the upstream and lower reaches.

The concentration level of DO in rain and drought was relatively high in the whole basin; the BOD in the dry season of wd7 sub-basin was 2 times higher than that of the rainy

season, whereas the COD in the dry season was 1.76 times that of the rainy season. The TN of the wd9 sub-basin was 3.76 times that of the dry season; S²⁻ index is small both in dry season and rainy season, which can be considered no contamination of this indicator in WRDB. The water quality in this study period basically meets the water quality requirements of centralized domestic and drinking water surface water source protection areas, fish and shrimp wintering grounds, migration channels, aquaculture areas and other fishery waters, and swimming areas.

Table 1 Ecological significance of landscape pattern index

Scale	Index type	Index name	Index meaning
Class metrics	Area index	Largest patch index (LPI)	The entire landscape is occupied by large patches
	Shape index	Landscape shape index (LSI)	The patch-shape complexity that makes up the landscape
	Dispersion index	Patch density (PD)	Degree of landscape fragmentation
	Cluster index	Proportion of like adjacency (PLADJ)	Connectivity between the landscape patches
Landscape	Diversity indices	Shannon’s diversity index (SHDI)	How many various elements of landscape elements changes in the proportion of the proportion
	Convergence index	Contagion Index (CONTAG)	Different types of patches in the landscape reunion degree or extension trend

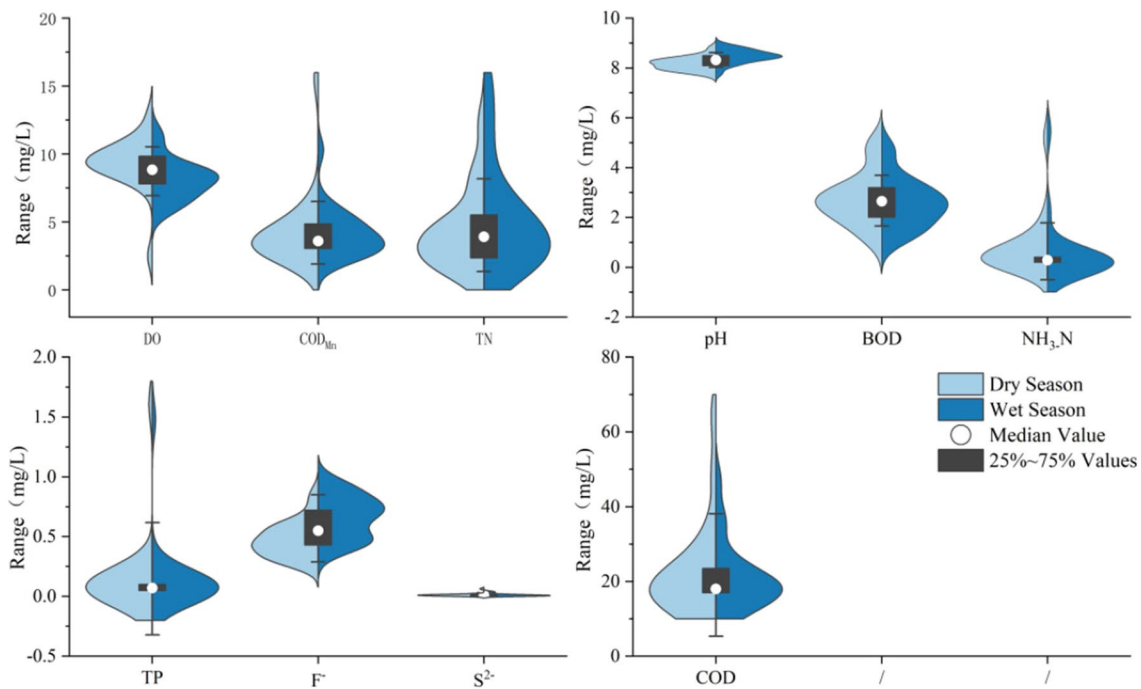


Fig. 4 Seasonal comparison chart of water quality indicators

Analysis of the correlation of water quality indicators

Analysis of the correlation between different spatial scales and water quality indicators

According to the correlation analysis of water quality in different seasons and at different spatial scales (Table 2), a distinct positive correlation was present between the sub-basin spatial scale and water quality index, where the positive correlation of F⁻ (0.619) was high; negative correlation was observed between the riparian buffer scale and water chemical indicators, where the positive correlation of F⁻ (0.615) was high; the pH index showed a notable

positive correlation at the sub-basin scale (0.589), but not at the riparian buffer scale (−0.584). In the rainy season, the positive correlation between the control point buffer scale and water quality was higher when compared with that at other spatial scales, where the positive correlation between TN (0.691) was significant. With the narrowing of the spatial scale, the correlation between the TN index and spatial scale ranged from a negative correlation (−0.325) to a significant positive correlation, whereas that between the COD_{Mn} index and spatial scale ranged from a negative correlation (−0.124) to positive correlation (0.528). This result suggests nutrient salt pollution and organic matter pollution in the study area.

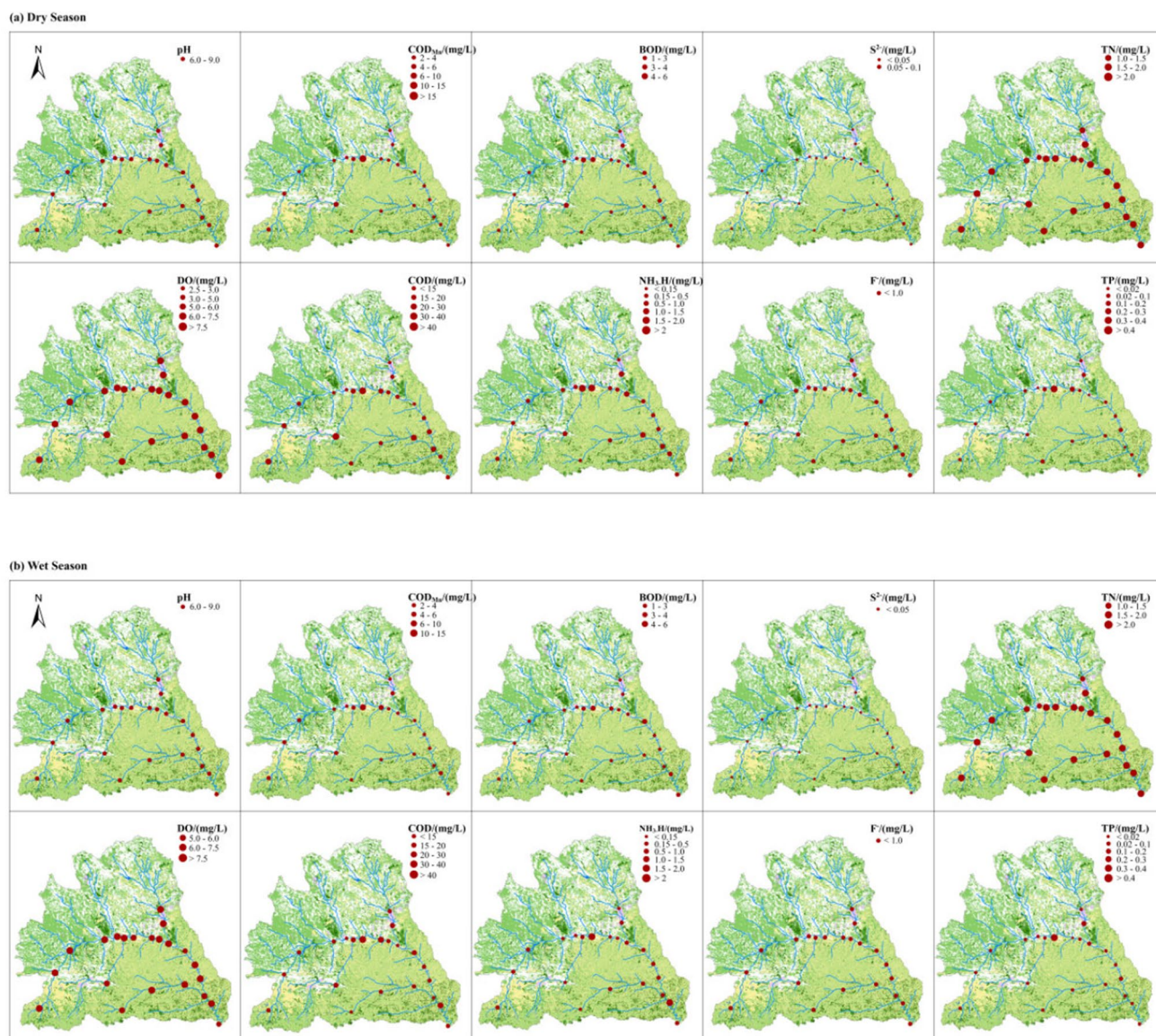


Fig. 5 The spatial distribution of water quality. (a) Dry season; (b) Wet season

Analysis of the correlation between different land categories and water quality indicators

According to the correlation analysis of water quality in different seasons (Table 3), in the dry season, water quality indices S^{2-} (0.802) and DO (0.700) and forest land were significant; the positive correlation coefficient between TN and cultivated land was 0.668, while the negative correlation coefficient with grassland was -0.684 . The negative correlation between pH (-0.747) and water was significant, whereas the positive and negative correlations between water and other land classes were not distinct. In the rainy season, the negative correlation between BOD (-0.810) and grassland was significant, and so were the positive correlations

between water and F^{-} (0.684) and S^{2-} (0.695), which was related to the higher pollutant flux in water caused by the large water quantity in the rainy season. In different land types, forest land and grassland have relatively significant interception and absorption of pollutants to improve water quality, and their impact on water quality is reflected in the large change of buffer water quality.

Correlation analysis of water quality indicators at multiple spatial scales

Water quality indices with high correlations and different land-class landscape indices (Table 4) were selected according to the SPSS linear regression for the RDA. The accuracy

Table 2 Correlation analysis of water quality parameters and spatial scales in different season

	Catchment scale	1000-m buffer scale in riparian zone	500-m buffer scale in sampling point
Dry season			
pH	0.589*	−0.584	−0.584
DO			
COD _{Mn}			0.360*
BOD			
NH ₃ -N	0.346	−0.347	
COD			
TN	0.503*	−0.506	0.526
TP	0.389	−0.391	0.345
F [−]	0.619**	−0.615	−0.474
S ^{2−}			0.599
Wet season			
pH			
DO	−0.445**	0.443	
COD _{Mn}			0.528
BOD			0.562
NH ₃ -N	0.381	−0.384	0.515*
COD	0.397*	−0.400	0.491
TN	−0.325	0.320	0.691**
TP	0.327	−0.329	
F [−]			0.619*
S ^{2−}	−0.412*		0.550

* At level 0.05 (double-tailed), the correlation is significant

** At level 0.01 (double-tailed), the correlation is significant

of the regression model was better in the dry than in the rainy season, indicating that the duration of the rainy season was large, which caused more water quality fluctuations, and the relationship with different land types was complex.

At the catchment scale, woodland PD and LSI were the core characteristics that affected water quality change in the dry season; LPI and woodland PD were the core characteristics that affected the change in water quality during the rainy season. At the riparian buffer scale, the LSI of construction land was the key feature that influenced water quality change in the dry season, whereas the LSI of construction land, water area, and grassland were the key features that influenced water quality change in the rainy season. At control point scale, the PLADJ of unused land was the primary feature affecting water quality during the dry season.

In this study, the response variable matrix was a 26-item landscape index, and the explanatory variable matrix consisted of 10 water quality indicators. During the dry and rainy seasons, six corresponding explanatory variable matrices were present at different spatial and temporal scales of the sub-basins, riparian buffer, and sampling point buffer, and six RDA analyses were conducted. Based on the results

of the SMLR analysis, the first and second RDA sorting axes were selected to draw six corresponding two-dimensional maps (Fig. 6). The cumulative interpretation of the horizontal and vertical combinations was > 80% (Table 5), the average interpretation of each combination was 88.59%, and the average interpretation of the first axis was 81.82%. In the ranking diagram of the sub-basin scale in the rainy season, the first axis (92.80%) and biaxis (94.62%) were the highest, followed by the first axis (68.07%) at the control point, and the lowest (80.61%) in the dry season.

Figure 5 shows the degree of contribution and difference in land use components and landscape configuration to the overall water pollution in the buffer zones of each scale (Liu et al. 2021). Specifically, the length of the arrow reflects the degree of contribution; the longer the arrow, the stronger the contribution of the land use component or landscape pattern characteristics. The angle between the arrows indicates the correlation between variables; the larger the angle, the larger the contribution of the two variables to water pollution.

The correlation at the same spatial scale varied between the dry and rainy seasons. In the dry season, the number of related landscape exponents in the buffer zone was greater than the number of sub-watershed scales, and included the LPI and LSI, indicating large patches with relatively large occupations at different scales, and the shape complexity was notable. Therefore, reasonable regulation of the proportion of the main subjects and the distribution of patches is conducive to inhibiting water pollution in the basin. In the rainy season, the number of relevant water quality indicators gradually increased with a reduction in spatial scale, including BOD, TN, and S^{2−}, whereas the rainy season included LPI3. At the sub-basin scale, the number of related water quality indicators during the rainy season was lower than during the dry season. The relationship between COD_{Mn} and LPI4 was unchanged; BOD and CONTAG had positive correlations in the dry season and negative correlations in the rainy season. Under the buffer scale of the sampling point, the related water quality indicators in the rainy season were higher than those in the dry season, and the correlation between other water quality indices was similar; TN, S^{2−}, and LPI4 showed a positive correlation in the dry season but a negative correlation in the rainy season.

Discussion

Spatial influence of land use structure and landscape pattern on water quality

Differences in the correlation between land use structure, landscape pattern characteristics, and degree of water pollution exist at different spatial scales (Zhang et al. 2019). In the WDRB, the proportions of cultivated land, grassland,

Table 3 Correlation analysis of water quality parameters and land use in different seasons

	Cultivated land	Forest	Grassland	Water	Urban	Unused land
Dry season						
pH				−0.747*		
DO		0.700**				−0.319
COD _{Mn}		−0.439		0.341		0.350
BOD		−0.347	−0.317		0.642**	0.424
NH ₃ -N		−0.312	−0.455		0.585	
COD	−0.324					0.364
TN	0.668*	0.626	−0.684*			−0.590
TP		−0.359			0.320	
F [−]			−0.455	−0.501		
S ^{2−}	0.314	0.802**	−0.402			−0.384
Wet season						
pH	0.510		−0.505			−0.425
DO		0.308		0.433		
COD _{Mn}				0.431		
BOD	0.591*	0.320	−0.810**		0.349	−0.394
NH ₃ -N			−0.457			
COD			−0.399			
TN		0.411		0.533	−0.611**	−0.417
TP		−0.365			0.419	
F [−]	0.373			0.684*	−0.349	−0.463
S ^{2−}			0.403	0.695**	−0.478	

Only show that the correlation index is not between −0.300 and 0.300

*At level 0.05 (double-tailed), the correlation is significant

**At level 0.01 (double-tailed), the correlation is significant

and construction land had relatively stronger correlations with water pollution. Among them, the proportion of building land, proportion of mainland, and degree of patch spread could aggravate water pollution, whereas the proportion of vegetation could inhibit the degree of water pollution to a certain extent, which further illustrates the importance of reasonable allocation of artificial land and vegetation for WDRB water pollution control. At each spatial scale, the interaction between land use and spatial patterns played an essential role in driving water quality changes, particularly in sub-basins with the highest contribution to water quality (Xu, et al. 2020). Through spatial heterogeneity analysis of the correlation between water quality and land use in the WDRB, the selection basis of the type of buffer zone and scale was clarified by analyzing the correlation between water quality and land use.

As listed in Table 4, the best data fits were present at sub-watershed spatial scales. The types of land use and their spatial distribution at the sub-basin scale affected water pollution, and a significant correlation existed between them. Several studies focusing on the Dongjiang River Basin, the Sarapu River Basin, and the Oregon State River demonstrated that sub-watershed scales explain the distribution characteristics of water quality at spatial scales better than

riparian scales (De Mello, et al. 2018; Ding et al. 2016; Nash, et al. 2009). Owing to the divergences in land use mode and human activity intensity, the pollutant loads of different land use types vary. The pattern and process theory of landscape ecology account for the spatial differences between different water quality parameters (Ren et al. 2022).

When land use heterogeneity exists in different sub-basins, its influence on the corresponding river water quality also differs (Wu and Lu 2021). The water qualities of each spatial scale and LSI and LPI both have a strong correlation; thus, frequent human activities can cause land use plaque shape complexity and easily cause water quality deterioration. Different types of land use affect the catchment water pollution load, and spatial patterns affect the pollutants in the river hydrological process (Ding, et al. 2016). Therefore, the influence of spatial patterns of land use on the river water environment must be considered.

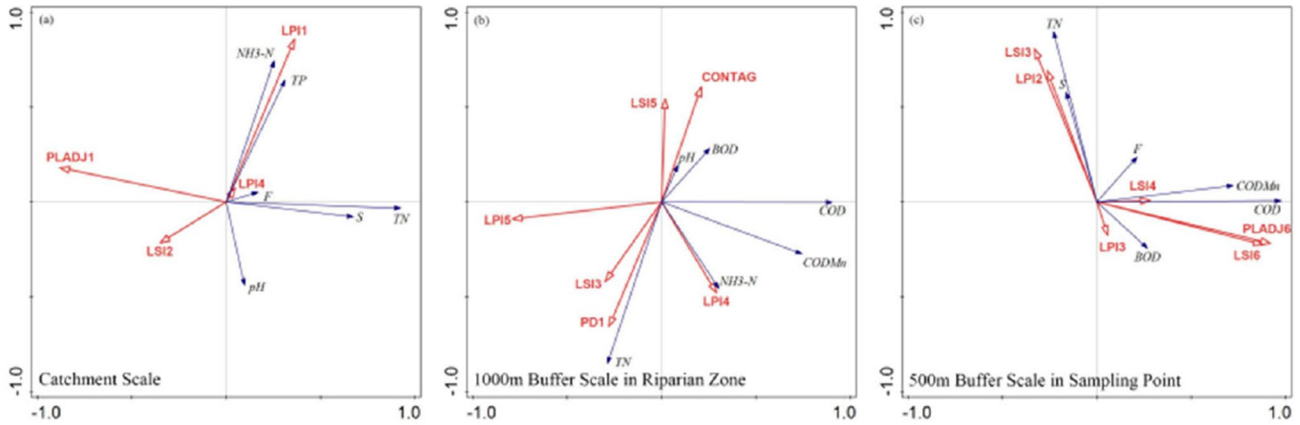
According to the analysis of land use structure around the river, nutrient salt pollution mainly originates from the point source of domestic sewage and the non-point sources of agriculture and breeding poultry, whereas organic pollution originates from industrial wastewater and living organic matter along the coast (Pan et al. 2022). Woodlands and grasslands can reduce surface runoff and soil erosion,

Table 4 Analysis of a single water quality parameter by stepwise multiple linear regression model in different seasons at different spatial scales

Period	Watershed scale			1000-m buffer zone in riparian zone			500-m buffer zone at sampling point			
	Water quality index	Catchment scale Landscape index (standardization coefficient B)	Adjusted R ²	VIF	Landscape index (standardization coefficient B)	Adjusted R ²	VIF	Landscape index (standardization coefficient B)	Adjusted R ²	VIF
Dry season	pH	LPI4 (-0.672)	0.373	1.000	LSI3 (0.687)	0.397	1.000	-	-	-
	DO	-	-	-	-	-	-	-	-	-
	COD _{Min}	-	-	-	LPI4 (0.693)	0.406	1.000	LSI6 (0.754)	0.506	1.000
	BOD	-	-	-	LSI5 (0.822)	0.628	1.000	LSI4 (0.864)	0.711	1.000
	NH ₃ -N	LPI1 (0.731)	0.467	1.000	CONTAG (-0.676)	0.379	1.000	-	-	-
	COD	-	-	-	LPI5 (-0.716)	0.443	1.000	PLADI6 (0.895)	0.772	1.000
	TN	PLADI1 (-0.872) LSI2 (-0.427)	0.804	1.015	PD1 (0.772)	0.539	1.000	LSI3 (0.785)	0.562	1.000
	TP	LPI1 (0.708)	0.430	1.000	-	-	-	-	-	-
	F ⁻	LPI4 (-0.691)	0.403	1.000	-	-	-	LPI3 (-0.860)	0.702	1.000
	S ²⁻	LSI2 (-0.808) PD2 (0.521)	0.978	1.005	-	-	-	LPI2 (0.855)	0.693	1.000
Wet season	pH	-	-	-	LPI5 (0.677)	0.382	1.000	PLADI5 (0.757)	0.512	1.000
	DO	-	-	-	-	-	-	-	-	-
	COD _{Min}	-	-	-	LPI4 (0.741)	0.484	1.000	PLADI5 (-0.667)	0.366	1.000
	BOD	CONTAG (-0.749)	0.499	1.000	CONTAG (-0.851)	0.684	1.000	SHDI (0.758)	0.514	1.000
	NH ₃ -N	-	-	-	-	-	-	-	-	-
	COD	-	-	-	-	-	-	PD1 (0.744)	0.490	1.000
	TN	LPI4 (0.800) PD5 (-0.566)	0.896	1.002	LSI5 (-0.672) LSI4 (0.401) LPI3 (0.387)	0.943	1.575	LPI3 (0.746)	0.493	1.000
	TP	-	-	-	-	-	-	-	-	-
	F ⁻	LPI4 (0.880) LPI3 (0.438) PD2 (0.212)	0.979	1.067	LPI3 (0.835)	0.653	1.000	PLADI3 (0.720)	0.449	1.000
	S ²⁻	-	-	-	-	-	-	PD6 (0.859)	0.701	1.000

Only the regression model of relative importance ($p < 0.05$) is listed; -means that no suitable regression model is found; B is the standard partial regression coefficient; adjusted R² refers to the adjustment coefficient of multiple decisions; the highest adjusted R² is expressed in bold in different periods; land use categories 1 (cultivated land), 2 (forest), 3 (grassland), 4 (water), 5 (urban), and 6 (unused land)

Dry Season



Wet Season

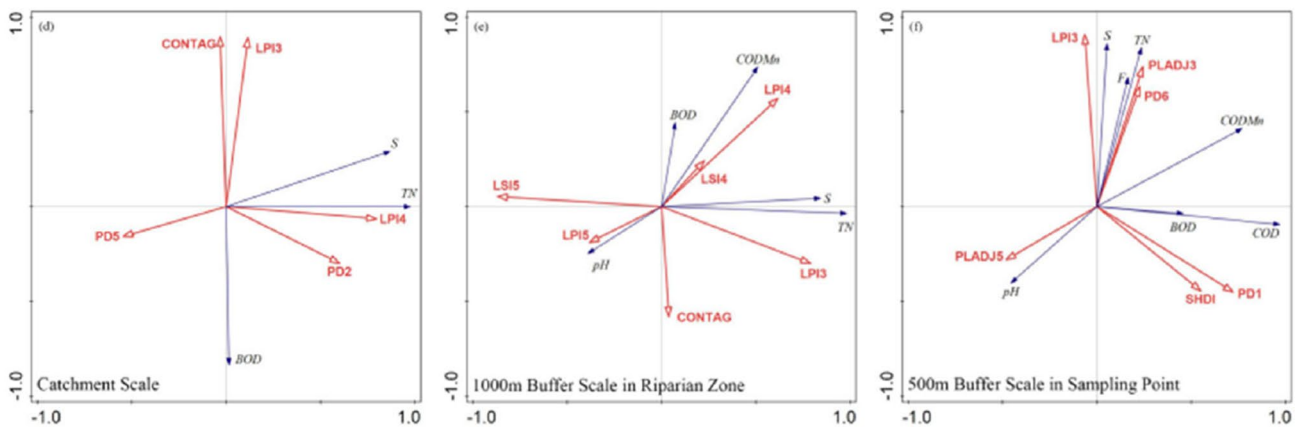


Fig. 6 Redundancy analysis results

Table 5 Results of redundancy analysis (RDA) in different seasons

Season	Scale	Explained variation (%)			Explanatory variables elected by the final MRL model
		Axis 1	Axis 2	All axis	
Dry season	Catchment scale	73.00	7.96	80.96	LSI2, LPI1, LPI4, PLADJ1
	1000-m buffer zone in riparian zone	77.98	2.64	80.61	CONTAG, PD1, LSI3, LSI5, LPI4, LPI5
	500-m buffer zone at sampling point	90.80	2.58	93.38	PLADJ6, LSI3, LSI4, LSI6, LPI2, LPI3
Wet season	Catchment scale	92.80	1.82	94.62	CONTAG, LPI3, LPI4, PD2, PD5
	1000-m buffer zone in riparian zone	88.26	5.06	93.31	CONTAG, LPI3, LPI4, LPI5, LSI3, LSI4
	500-m buffer zone at sampling point	68.07	20.59	88.67	SHDI, PLADJ3, PLADJ5, LPI3, PD1, PD6

thereby reducing the release of solid and dissolved pollutants into rivers following precipitation (Han et al. 2021; Ren et al. 2023). The nitrogen and phosphorus released during agricultural activities led to a rapid increase in water content. The discharge of industrial and domestic wastewater from living and production activities drives the rapid spread of organic pollutants in river basins (Schürings et al. 2024). The added non-ecological land in the watershed, such as construction land and farmland, transfers solid and dissolved nutrients to

local water and soil resources (Chang et al. 2021; Rodriguez-Espinosa et al. 2023; Xiao et al. 2019).

In addition, an increase in water area has a positive effect on water quality, whereas the development of urbanization will reduce water areas, thereby further reducing water quality (Deng 2020). In general, reasonable planning of the WDRB, especially the proportion of vegetation and artificial building land in a large spatial scale basin, will be conducive to the effective control of water pollution. Meanwhile,

under the comparison of gradually shrinking spatial scales, cultivated land, grassland, and built-up areas have a strong water quality interpretation ability.

Seasonal influence of land use structure and landscape pattern on water quality

The results of stepwise multivariate linear and RDA indicated that river water quality showed seasonal differences under different spatial scales and land class scenarios. The land used of woodland and grassland has a positive effect on water quality in the rainy season, whereas cultivated and construction lands have a negative effect on water quality in the dry season (Shu et al. 2022; Wang et al. 2023a). Rainy season runoff has a significant influence on solute concentrations (Zhang, et al. 2019). In WDRB, especially in the rainy season, surface pollutants may be deposited, absorbed or precipitated when they flow through different land use types, and eventually enter the river water with the surface runoff, which may cause a certain degree of pollution migration.

In Table 4, comparing the control indices of the rainy and dry seasons, TN, as the key to the water quality index, reflects the influencing factors of land use and landscape patterns at different spatial scales in different seasons. The control characteristics are mainly the mutual combination of woodland, grassland, and water areas, and PD, LPI, and LSI, suggesting that the complex changes in landscape types will vary with seasonal changes (Fernandes et al. 2021). In the rainy season, the natural water supplement runoff increases, and in urban land, a large amount of impure water is permeable to the surface and underground runoff, which increases the number of urban land landscape indices as the control feature in the rainy season (Chen et al. 2023; Nash, et al. 2009). For the management of river courses and groundwater, attention should be paid to seasonal differences and geographical location factors, and farmland fertilization and urban sewage discharge on both sides of the river should be strictly controlled (Wang et al. 2023b).

Pollution prevention and control in river basins

The WDRB has wide coverage, and its topographic features vary by region. The levels of urban development and population density are not consistent. The protection and treatment of water should consider the different effects of spatial scale and season. The WDRB is situated in an erosional area of the Loess Plateau, and the terrain is relatively complex and comprises deserts, river sources, and loess hills. In hilly and mountainous areas, by reasonably adjusting the proportion of grassland and forest areas, the concentration of organic matter in river water can be effectively reduced, along with the impact of soil erosion on rivers in areas with relatively moderate terrain, promoting the development of

cluster agriculture. Using the buffer effect of riverbank vegetation can improve the water quality of river basins (Xue et al. 2023). Point source pollution (such as wastewater discharge) and agricultural nonpoint source pollution are the main anthropogenic factors that influence water quality parameters, and they can provide a basis for local land use types to improve water quality management. Developing green agriculture, adjusting the land use structure around the riverbank, and improving the coverage rate of riparian woodland can improve water quality in the river basin. Consequently, relevant water resource management units should consider spatial scale planning in watershed water quality management, and communicate and cooperate between the upstream and downstream areas, focusing on ecological protection measures in the riparian zone to ensure that the sewage and wastewater generated by agricultural activities and urban development satisfy reasonable discharge standards and requirements.

In conclusion, to improve water quality in developing areas, relevant watershed management agencies must focus on the discharge of sewage and wastewater. In areas where agricultural activities are relatively concentrated, adopting modern agricultural methods and using high-quality fertilization are important measures to reduce pollution from nonpoint sources (Qiu and Turner 2015). However, in mountainous areas with severe soil erosion, increasing vegetative cover is an important method to reduce the negative impact on water quality (De Mello et al. 2020). The management of river basin involves the functions of water resources in the main and tributaries, flood control and flood fighting, water pollution prevention, river management, and ecological construction and protection. Fundamentally, the water quality management of water resource supervision units should emphasize riparian landscape planning, reasonably develop rivers, and construct healthy watershed ecosystems.

Conclusion

For the WDRB, which is affected by natural factors and human disturbances, the results show that the variation in seasonal alternation, spatial scale, and landscape indicators determine the influence of land use structure on water quality changes. The influence of land use type on water quality parameter variables was more notable in the rainy season than in the dry season, and the main sensitive water quality parameters were BOD, TN, and S^{2-} . The catchment scale had the highest overall interpretation and comprised the most important factor affecting the water quality of rivers. The rainy season is the key period affecting river water quality owing to the different land use and landscape patterns.

The protection and management of water quality in the WDRB should focus on landscape planning at the

sub-watershed scale. Simultaneously, by exploring the spatial effects and seasonal changes of different landscape characteristics on river water quality, the main factors affecting river water quality under different spatial and temporal conditions can be determined to prevent water environment pollution and control river basin management.

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