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Impact of Land Use Patterns on Transboundary Water Bodies: A Case Study of the Sino-Russian Erguna River Basin

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Abstract

The Erguna River, a Sino-Russian transboundary river, is vital for regional ecology, but land use impacts on its water quality remain unclear. This study aimed to reveal their response relationship. Using ArcGIS/ENVI, it classified land use in 2010 and 2016 into six types, and applied Pearson correlation to 10 monitoring sections' water quality data. Results showed land use–water quality correlations were temporally and spatially variable: correlations weakened with increasing buffer distance, with the strongest associations within 1000 m. From 2010 to 2016, grassland shifted from a positive (water-purifying) to negative (pollutant-source) impact on water quality (BOD_5 and arsenic), which was driven by area reduction and overuse; forestland transitioned from no significant effect to a positive (pollutant-intercepting) role, attributed to area expansion. Arable and construction land showed no significant correlations with water quality, due to low proportions of construction land in cross-border areas, and arable land is mostly distributed in areas far from the riverbank. This study provides critical scientific support for transboundary water resource cooperation and targeted ecological management of the Erguna River Basin.

Keywords: land use; water quality response; Sino-Russian; transboundary river; Erguna river

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1. Introduction

As important international water resources [1,2], transboundary rivers have far-reaching impacts on the socio-economy and environmental protection of riparian countries [3,4]. The Erguna River, a boundary river between China and Russia, is a critical transboundary water system in Northeast Asia [5]. The impact of land use change in its basin on water quality has become a core issue in regional environmental management [6,7]. With the intensification of human activities, transformations in land use patterns (such as agricultural expansion, urbanization, and deforestation) may significantly alter water quality through pathways like nutrient transport, sediment loading, and pollutant diffusion [8–13]. Research on water quality responses in transboundary basins not only involves ecological security but also concerns international cooperation and policy coordination [14,15].

In recent years, significant progress has been made in studies on the correlation between land use and water quality responses. Multiple studies have shown that agricultural land is closely linked to increased nitrogen and phosphorus concentrations in water bodies [16,17], while urbanization leads to heavy metal and organic pollution through

increased impervious surfaces and sewage discharge [18–20]. Additionally, the reduction in natural vegetation cover exacerbates soil erosion, thereby affecting river suspended sediment content and habitat stability [21–25]. However, existing research predominantly focuses on single countries or small watershed scales, and the only research on cross-border pollution focuses on the impact of land use change in cross-border watersheds on hydrological conditions [26], improvement of land use classification methods in cross-border areas [27], and the relationship between land use change and cross-border haze [28]. There is a lack of research on the impact of land use change in cross-border watersheds on cross-border water quality. Due to difficulties in data acquisition and differences in management systems, the impact mechanisms of land use changes on transboundary water quality in the Erguna River Basin remain unclear [5,29,30].

Although the development of remote sensing technologies and hydrological models (such as SWAT and InVEST) has provided new tools for transboundary basin research in recent years [31,32], current studies still have the following limitations: (1) Most models lack validation with high-resolution land use and hydrological data in transboundary basins [33]. (2) The absence of long-term monitoring data restricts the quantitative analysis of dynamic water quality responses to land use changes [34,35]. (3) Research on collaborative management strategies in the China-Russia transboundary region is insufficient, urgently requiring the construction of an integrated assessment framework combining remote sensing and field monitoring. This study aims to reveal the ecological effects of land use changes in the Erguna River Basin through the coupling of multi-temporal remote sensing interpretation and water quality models, providing a scientific basis for transboundary water resource cooperation. This study conducts the first research on the response relationship between land use and water quality in the Sino-Russian cross-border region, which greatly expands the previous research scope that only focused on a single country or small watershed.

2. Materials and Methods

2.1. Study Area

The Erguna River, commonly known as the main source of Heilongjiang River, originates from the western slope of the Greater Khingan Mountains in China. Its main stream is the boundary river between China and Russia, flowing in a southwest-northeast direction. The river is 898 km long and has a drainage area of approximately 153,100 square kilometers within China. The left bank of the basin is located within the territory of Russia, including Nerchensky Zavod, Karaga, Prialgonsk, Redstone City, and Post Baikalsk and Borja. The right bank of the basin is located within the territory of China, including Manzhouli City, Erguna City, Genhe City, Chenbalhu Banner, Xinbalhu Left Banner, and Xinbalhu Right Banner in Inner Mongolia Autonomous Region. It is separated from the Nenjiang River system, the upper source of the Songhua River, by the Greater Khingan Range as a watershed. The Hailar River is a primary tributary of the Erguna River, flowing roughly in an east–west direction. Its source is the Dayan River, with the left bank fed by the Miandu River and the Yimin River, and the right bank fed by the Teni River and the Moergle River. The river is 622 km long and has a drainage area of 54,810 square kilometers, covering Yakeshi City, Ewenki Autonomous Banner, Hailar District, and other areas. The Genhe River is one of the largest tributaries of the Erguna River, originating in the southwest of the Greater Khingan Mountains and generally running in a northeast-southwest direction. It flows through the cities of Genhe and Erguna and is joined by tributaries such as the Tuli River and Ituri River.

The Erguna River basin belongs to a continental monsoon climate in the temperate zone, with strong winds and low temperatures in spring, mild and rainy summers, clear

and cool autumn, and severe winter. The frost-free period is about 100 days, and the maximum freezing depth is 2.5–3.8 m. The distribution of precipitation within the year is uneven, with summer precipitation accounting for over 70% of the annual precipitation, winter snow accounting for 10–20% of the annual precipitation, and an average annual precipitation of 350 mm. The average annual runoff depths of Shiwei and Qiqian are 133 cubic meters per second and 292 cubic meters per second, respectively. The interannual variation in precipitation in the Hailar River is significant, with an average annual precipitation of 287–337 mm. Influenced by the monsoon, precipitation is mainly concentrated in June to September, accounting for 80–84% of the annual precipitation. The average temperature decreases from west to east, with a multi-year average temperature of −1.3–2.6 °C. The annual evaporation is 1250–1533 mm, which is 3.2–5.1 times the average annual precipitation. The research area is located in an alpine region with a long ice period and a thick ice layer. There may be ice on the ice or even continuous freezing at the bottom, and even ice dams may form during the river opening period.

2.2. Data Sources

The research data mainly includes remote sensing image data and water quality data of the Erguna River Basin. The remote sensing image data are Landsat TM in 2010 with a resolution of 30 m, and high-resolution satellite remote sensing image data in 2016 with a resolution of 2 m. The water quality data is sourced from the Environmental Monitoring Center of Hulunbuir City, Inner Mongolia Autonomous Region, which includes water quality data from 10 monitoring sections in the Erguna River Basin. The water quality monitoring frequency is once a month, with 12 periods per year (of which the Yimu River section only samples one period due to high latitude). Due to the fact that there is only one period of data for the Yimu River section, this period of data is used as the annual average data, while the annual average data for other sections is the average of monthly monitoring data.

The monitoring points, indicators, monitoring frequency and detection methods are shown in Table 1.

Table 1. List of Monitoring Points and Monitoring Indicators.

No.	Point Name	Sampling Frequency	Monitoring Indicators	Methods	QA/QC Procedures
D1	Galoto	once a month	DO COD_{Mn} BOD_5 NH_3-N Arsenic (As)	DO: Electrochemical probe method, HJ 506-2009 [36] COD_{Mn}: GB 11892-89 [37] BOD_5: dilution and seeding method, HJ 505-2009 [38] NH_3-N: Salicylic acid spectrophotometry, HJ 536-2009 [39] As: Silver diethyldithiocarbamate spectrophotometric method, GB 7485-87 [40]	DO: Instrument calibration; linear inspection of instruments; maintenance of electrodes COD_{Mn}: Blank experiment; parallel experiment BOD_5: Blank sample; Parallel samples NH_3-N: Blank experiment; Cleaning of rectifier; Preparation of color reagents As: Preprocessing; Calibration; blank experiment
D2	Heishantou	once a month			
D3	Shiwei	once a month			
D4	Yimu River	once a year			
D5	No. 8 Pasture	once a month			
D6	Yakeshi	once a month			
D7	Taohai	once a month			
D8	Cuogang	once a month			
D9	Yuliang	once a month			
D10	Genhekou areas	once a month			

In this paper, we selected 10 water quality monitoring sections in the Erguna River Basin, among which there are 4 water quality monitoring sections in the main stream. From upstream to downstream, they are Galoto, Heishantou, Shiwei, and Yimu Rivers, all of which belong to state-controlled river sections. The Hailar River has four water quality monitoring sections, namely No. 8 Pasture, Yakeshi, Taohai, and Cuogang, all of which belong to the state-controlled river section. The Genhe River has two monitoring sections, from upstream to downstream are Yuliang and the Genhekou section. Yuliang belongs to the municipal-controlled river section, while the Genhekou section belongs to the municipal-controlled river section. The specific distribution of each water quality monitoring section is shown in Figure 1. For the convenience of representation, D1, D2, D3, D4, D5, D6, D7, D8, D9, and D10 are used to represent 10 monitoring sections within the

Galoto, Heishantou, Shiwei, Yimu River, No. 8 Pasture, Yakeshi, Taohai, Cuogang, Yuliang, and Genhekou areas, respectively.

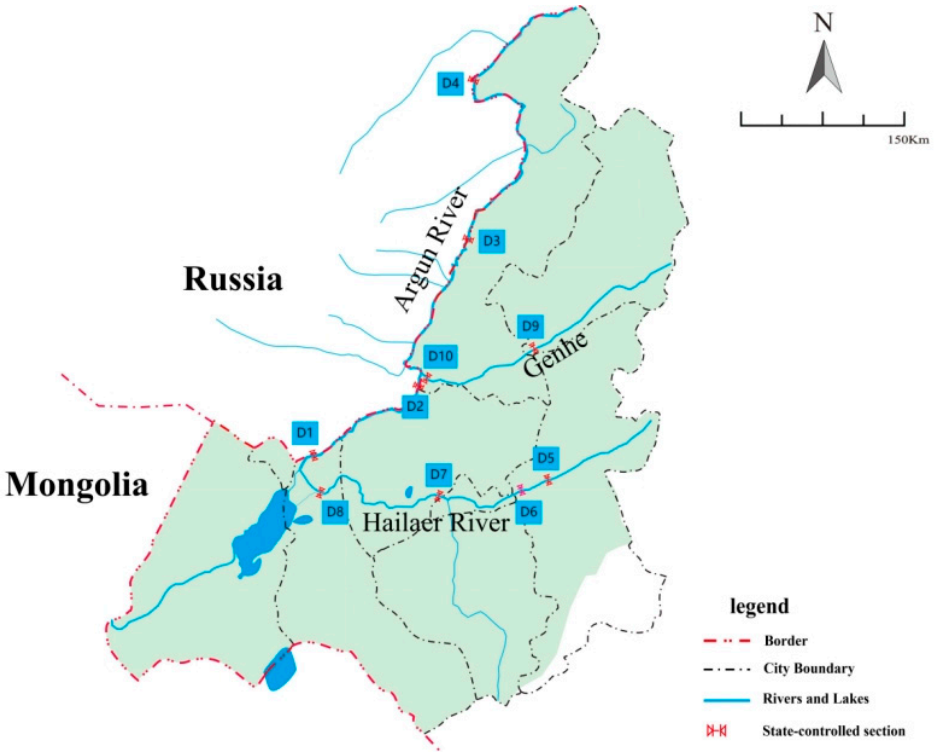


Figure 1. Distribution of Monitoring Sections in the Erguna River (Argun River) Basin.

2.3. Remote Sensing Image Processing

With the support of ENVI 5.0, remote sensing image data is preprocessed through correction, registration, and stitching to obtain remote sensing image maps of the Erguna River Basin. In this study, the maximum likelihood supervised classification method [41] was used to extract the land use information of the study area in combination with visual interpretation to obtain the land use type classification data of each year and produce the land use map of the study area. According to the principles of land use classification, the land use status of the Erguna River Basin, and research needs, the land use types are classified into six major categories: water bodies, forest land, grassland, cultivated land, construction land, and other land (the kappa coefficients for 2010 and 2016 were 0.88 and 0.91, respectively). Considering that there is no practical significance between the water body and water quality of the river itself, the water body in the land use type studied in this article refers to the part that removes the water surface of the river.

2.4. Establishment of Riverbank Zones in Cross-Border Areas

Firstly, establish a monitoring section, load the document of monitoring section coordinate points in ArcGIS 10.1 based on the longitude and latitude coordinates of each monitoring section, and assign them to their geographic coordinate system. Establish a 5 km buffer zone with the monitoring section as the center, perpendicular to the river channel, and upstream towards the river. Establish river buffer zones of 100, 300, 500, 1000, 2000, and 4000 m on both sides of the river surface. Intersect the established monitoring section buffer zone with the actual river water surface buffer zone to obtain buffer zones of different scales for each monitoring section. Erase the river surface based on the established buffer zone. In order to ensure that the buffer zones of each monitoring section are a single surface, feature fusion is carried out on the buffer zone after erasing the river water surface, mainly to prevent the same land use type from appearing multiple times when

the river buffer zone intersects with land use. Intersect the buffer zones of each fused monitoring section with land use data to obtain land use data for each monitoring section buffer zone. Assign projection coordinates to the data, calculate the area of land use types, and separately calculate the land use type area of each monitoring section in different buffer zones.

2.5. Analysis Method for Correlation Between Water Quality and Land Use

Correlation analysis can help study the correlation between random variables and explore their direction and degree of correlation. The water quality indicators and land use type parameters in each buffer zone in this article satisfy a normal distribution. Therefore, Pearson correlation analysis is used to reveal the response relationship between water quality indicators and land use changes. The water quality monitoring data adopts the monthly average value throughout the year (excluding the Yimu River section).

3. Results

3.1. Basic Situation of Water Quality in Cross-Border Areas

Figure 2 reflects the changes in the annual average content of DO (dissolved oxygen), COD_{Mn} (chemical oxygen demand), BOD_5 (five-day biochemical oxygen demand), ammonia nitrogen (NH_3-N), and As (arsenic) at various sections of the Erguna River from 2010 to 2016. From the figure, it can be seen that from 2010 to 2016, except for D3, the average annual value of DO in each section showed an overall upward trend, ranging from 7.5 to 9.0 mg/L. Although the COD_{Mn} content fluctuated significantly during this period, it showed an overall downward trend, all below 9.0 mg/L; BOD_5 showed significant differences and changes in various sections, but its peak value is below 3 mg/L. The overall NH_3-N content also shows a downward trend, with the content at each section being below 0.4 mg/L in 2016. The overall As content is low, and the upward trend is not obvious.

3.2. Temporal and Spatial Changes in Land Use Structure of Riverbank Zones in Cross-Border Areas

Land use data of different types from two periods (2010 and 2016) were selected to first classify and then statistically analyze the land use types in the riparian buffer zones of 10 monitoring sections in the Erguna River Basin. The riparian zone is a buffer zone established by tracing the monitoring section 5 km upstream of the river, and a buffer zone of 4000 m is established on both sides of the river surface.

Use a single land use dynamic index K to quantitatively reflect changes in land use types. The formula is as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

In the formula: K is the dynamic index of a certain land use type; U_a and U_b represent the area of land use types at the beginning and end of the research period, T represents the research period, and when T is measured in years, K represents the annual change rate of a certain land use type.

The changes in land use structure of the Erguna River riparian zone in 2010 and 2016 are shown in Table 2. From the table, it can be seen that grassland and forestland are the main land use types in the Erguna River riparian zone, with grassland area accounting for about 50% and forest land area accounting for over 20%.

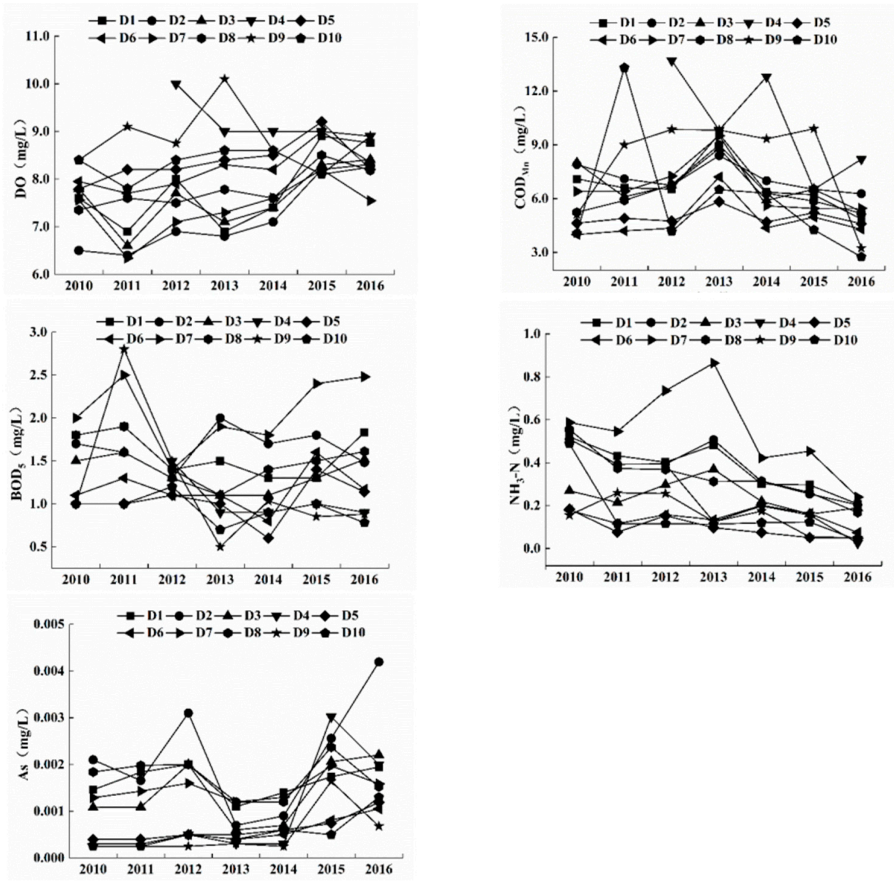


Figure 2. Water quality changes at various monitoring sections of the Erguna River Basin from 2010 to 2016.

Table 2. Time variation in land use structure in the Erguna River riparian zone.

Land Type	2010	2010	2016	2016	2010~2016
	Area (km^2)	Proportions (%)	Area (km^2)	Proportions (%)	K (Annual Rates of Change)
grassland	319.36	58.25	270.36	48.35	−2.56
forestland	120.08	21.90	134.27	24.01	1.97
water bodies	19.16	3.49	31.35	5.61	10.61
arable land	44.20	8.06	69.34	12.40	9.48
Construction land	34.10	6.22	22.52	4.03	−5.66
Other land	11.38	2.08	31.36	5.61	29.28

From 2010 to 2016, there was no significant change in the land use structure of the riparian zone, but each land use type showed varying degrees of increase or decrease. The main changes in quantity are as follows: the grassland area has decreased, from 319.36 km^2 in 2010 to 270.36 km^2 in 2016, and its proportion has also decreased from 58.25% to 48.25%. The area of forestland has increased, with its proportion increasing from 21.90% in 2010 to 24.01%. The water bodies, arable land area, and other land use have also increased, while other land use has increased significantly. The area of construction land has decreased.

From the perspective of change dynamics, the most significant change is in other land use types, with an annual change rate of nearly 30%. The changes in other types are relatively small, except for water bodies where the annual change rate is greater than 10%; all other types have an annual change rate of less than 10%.

Figures 3 and 4 show the proportion of land use types in the buffer zone of the Erguna River, Hailar River, and Genhe River in 2010 and 2016, respectively. The comparison shows that the grassland area in the buffer zone of the Erguna River, Hailar River, and Genhe

River has decreased, while other land use types have changed to varying degrees. The grassland area of section D1 in the Erguna River Basin has decreased, while the water bodies and other land areas have increased, mainly influenced by human activities. The D2 section is mainly characterized by a decrease in arable land area, while the land use structure of sections D3 and D4 remains basically unchanged.

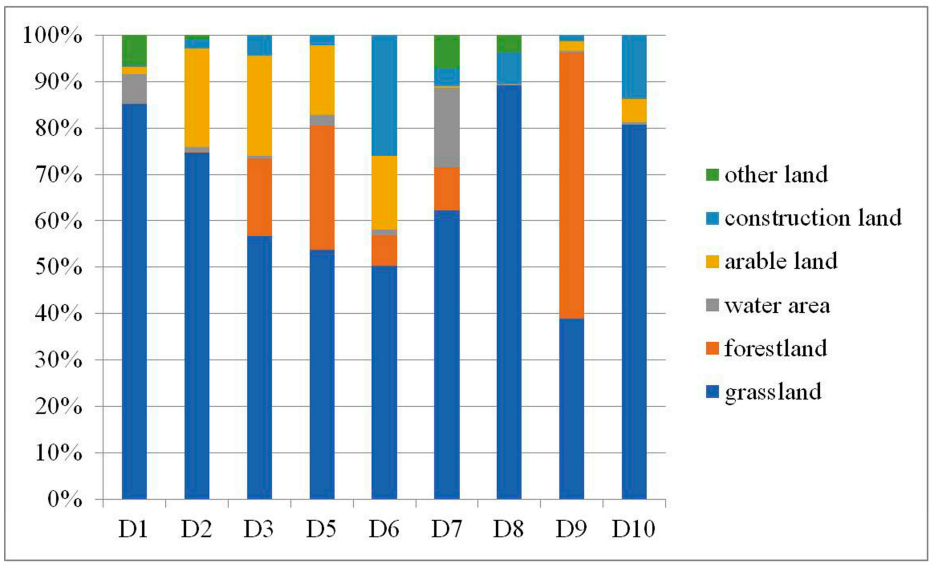


Figure 3. The proportion of land use types in the riparian zones of each monitoring section in 2010.

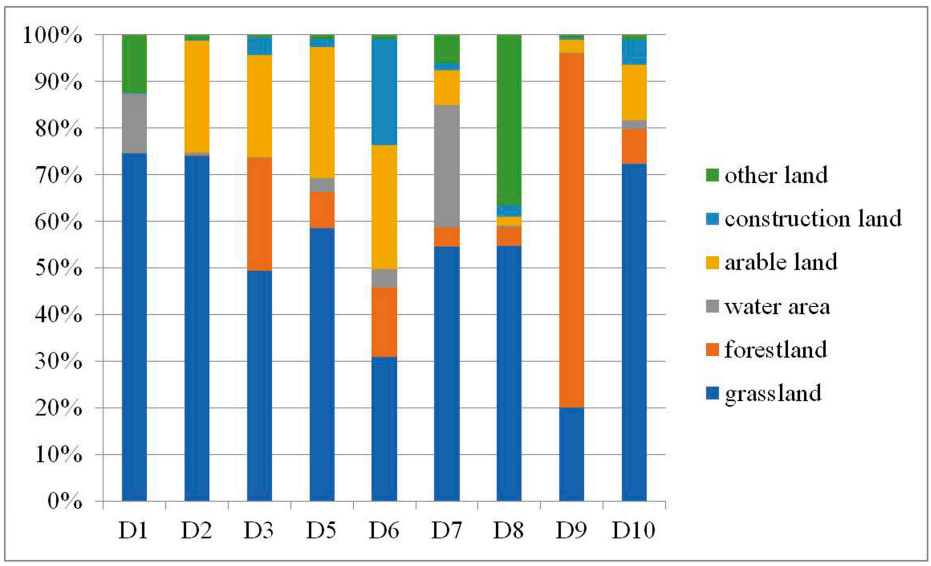


Figure 4. The proportion of land use types in the riparian zones of each monitoring section in 2016.

The forestland area of section D5 in the Hailar River Basin has decreased, while the arable land area has increased. The grassland area of section D6 has decreased, while the arable land area has increased. The water bodies and arable land area of section D7 have increased. The grassland area of section D8 has decreased, while other land areas have significantly increased. Overall, the significant characteristics of this region are a decrease in grassland area, an increase in arable land area, and an increase in other land use with significant increases.

The forestland area of section D9 in the Genhe River Basin has increased, while the grassland area has decreased. In recent years, the government of Genhe City has strengthened afforestation and mountain closure for afforestation, and the increase in

forestland area may be the result of the evolution of low shrubs into tree forests. The arable land area of D10 section has increased, while the construction land area has decreased.

3.3. Correlation Analysis Between Land Use Types and Water Quality

Pairwise correlation analysis was conducted on the average water quality indicators of the 9 monitoring sections in 2010 and 2016, except for the D4 section of the Yimu River, and the land use area of different buffer zones at different distances. The results are shown in Tables 3 and 4.

Table 3. Correlation analysis between water quality and land use type (2010).

Buffer Area /(m)	Water Quality Indicator	Type of Land Use					
		Grassland	Forestland	Water Bodies	Arable Land	Construction Land	Other Land
100	DO	0.585	−0.406	−0.641	0.172	−0.076	−0.287
	COD_{Mn}	−0.397	0.125	0.326	0.318	0.513	0.686 *
	BOD_5	−0.675 *	0.537	0.661	−0.032	0.011	0.301
	NH_3-N	−0.506	0.368	0.405	0.151	0.263	0.504
	As	−0.082	−0.136	−0.046	0.292	0.769 *	0.819 **
300	DO	0.627	−0.461	−0.754 *	0.223	−0.097	−0.703 *
	COD_{Mn}	−0.326	0.119	0.331	0.200	0.240	0.641
	BOD_5	−0.705 *	0.567	0.755 *	−0.018	0.029	0.707 *
	NH_3-N	−0.487	0.361	0.465	0.119	0.122	0.661
	As	0.040	−0.169	−0.049	0.095	0.184	0.511
500	DO	0.614	−0.445	−0.754 *	0.213	−0.125	−0.764 *
	COD_{Mn}	−0.284	0.085	0.293	0.139	0.184	0.559
	BOD_5	−0.669 *	0.535	0.744 *	−0.083	0.072	0.781 *
	NH_3-N	−0.434	0.311	0.451	0.016	0.101	0.654
	As	0.098	−0.210	−0.062	0.002	0.030	0.342
1000	DO	0.507	−0.168	−0.766 *	0.170	−0.184	−0.648
	COD_{Mn}	−0.165	−0.135	0.285	0.070	0.090	0.537
	BOD_5	−0.513	0.241	0.745 *	−0.179	0.061	0.880 **
	NH_3-N	−0.256	0.014	0.450	−0.131	0.039	0.738 *
	As	0.264	−0.386	−0.063	−0.098	−0.125	0.180
2000	DO	0.304	0.208	−0.755 *	0.126	−0.120	−0.650
	COD_{Mn}	0.093	−0.330	0.291	0.204	−0.289	0.453
	BOD_5	−0.153	−0.172	0.759 *	−0.233	−0.261	0.847 **
	NH_3-N	0.132	−0.334	0.467	−0.175	−0.314	0.671 *
	As	0.487	−0.484	−0.062	0.101	−0.330	0.038
4000	DO	−0.160	0.416	−0.627	0.048	−0.123	−0.359
	COD_{Mn}	0.247	−0.399	0.306	0.361	−0.344	0.395
	BOD_5	0.283	−0.378	0.827 **	−0.237	−0.333	0.872 **
	NH_3-N	0.420	−0.465	0.556	−0.030	−0.414	0.726 *
	As	0.393	−0.468	−0.037	0.516	−0.312	0.057

Notes: ** Significantly correlated at the 0.01 level (two-sided). * Significantly correlated at the 0.05 level (two-sided).

Table 3 reflects the correlation between water quality and land use in 2010.

(1) Within the buffer zones of 100, 300, and 500 m, there is a significant negative correlation between grassland and BOD_5 at the 0.05 level, with the most significant correlation at the 300 m buffer zone, indicating that the increase in grassland is beneficial for improving water quality.

(2) Within the buffer zones of 300, 500, 1000, and 2000 m, there is a significant negative correlation between water bodies and DO, a significant positive correlation between water bodies and BOD_5 at buffer zones of 300, 500, 1000, and 2000 m, and a highly significant positive correlation between water bodies and BOD_5 at buffer zones of 4000 m.

(3) There is a significant positive correlation between construction land and arsenic only in the 100 m buffer zone, and there is no significant correlation with other water quality indicators.

(4) In terms of other land use, within a 100 m buffer zone, there is a significant correlation with COD_{Mn} and arsenic. Within a buffer zone of 300 and 500 m, there is a significant correlation with DO and BOD_5. Within the buffer zones of 1000, 2000, and 4000 m, there is a significant correlation with BOD_5 and NH_3-N.

(5) The correlation between forest land, cultivated land, and various water quality indicators is not significant in each buffer zone.

Table 4. Correlation analysis between water quality and land use type (2016).

Buffer Area /(m)	Water Quality Indicator	Type of Land Use					
		Grassland	Forestland	Water Bodies	Arable Land	Construction Land	Other Land
100	DO	0.336	0.061	−0.810 **	−0.609	−0.043	−0.368
	COD_{Mn}	0.528	−0.815 **	0.287	0.212	−0.202	0.293
	BOD_5	0.335	−0.721 *	0.714 *	0.333	−0.209	0.282
	NH_3-N	0.595	−0.917 **	0.377	0.017	−0.304	0.313
	As	0.711 *	−0.739 *	−0.149	−0.249	−0.274	0.014
300	DO	0.387	0.143	−0.802 **	−0.179	−0.053	−0.279
	COD_{Mn}	0.403	−0.845 **	0.274	0.205	−0.041	0.264
	BOD_5	0.191	−0.747 *	0.682 *	0.049	−0.084	0.236
	NH_3-N	0.467	−0.911 **	0.340	−0.002	−0.136	0.243
	As	0.692 *	−0.737 *	−0.146	−0.138	−0.197	−0.030
500	DO	0.390	0.244	−0.780 *	−0.148	0.010	−0.236
	COD_{Mn}	0.287	−0.852 **	0.271	0.197	0.038	0.239
	BOD_5	0.062	−0.750 *	0.699 *	0.020	−0.071	0.215
	NH_3-N	0.343	−0.899 **	0.358	−0.022	−0.053	0.218
	As	0.686 *	−0.745 *	−0.142	−0.144	−0.122	−0.054
1000	DO	0.271	0.406	−0.728 *	−0.166	0.002	−0.198
	COD_{Mn}	0.195	−0.791 *	0.253	0.194	0.078	0.227
	BOD_5	−0.024	−0.687 *	0.734 *	−0.012	−0.049	0.242
	NH_3-N	0.241	−0.791 *	0.402	−0.093	−0.016	0.241
	As	0.698 *	−0.691 *	−0.141	−0.160	−0.120	−0.067
2000	DO	0.057	0.533	−0.654	−0.193	−0.009	−0.169
	COD_{Mn}	0.250	−0.631	0.265	0.179	−0.153	0.220
	BOD_5	0.064	−0.562	0.790 *	−0.119	−0.218	0.279
	NH_3-N	0.327	−0.593	0.489	−0.253	−0.258	0.273
	As	0.726 *	−0.552	−0.099	−0.118	−0.27	−0.074
4000	DO	−0.248	0.559	−0.563	−0.182	−0.042	−0.116
	COD_{Mn}	0.333	−0.506	0.250	0.208	−0.222	0.240
	BOD_5	0.266	−0.457	0.807 **	−0.284	−0.256	0.330
	NH_3-N	0.393	−0.446	0.533	−0.248	−0.349	0.327
	As	0.591	−0.448	−0.078	0.27	−0.307	−0.058

Notes: ** Significantly correlated at the 0.01 level (two−sided). * Significantly correlated at the 0.05 level (two−sided).

Table 4 reflects the correlation between various water quality indicators and different land use types in 2016.

(1) Water quality factors and grasslands. Within the buffer zones of 100, 300, 500, 1000, and 2000 m, the water quality factor arsenic was significantly positively correlated with the grassland at the 0.05 level, while the other water quality factors DO, COD_{Mn}, BOD_5, NH_3-N were not significantly correlated with the grassland in each buffer zone.

(2) Water quality factors and forest land. Within the buffer zones of 100, 300, and 500 m, there was a significant negative correlation between forest land and COD_{Mn} and NH_3-N at the 0.01 level, and the correlation with COD_{Mn} increased with the increase in buffer zone distance, while the correlation with NH_3-N decreased with the increase in buffer zone distance. Within a 1000 m buffer zone, there is a significant negative correlation with COD_{Mn}, NH_3-N, BOD_5, and arsenic at the 0.05 level.

(3) Water quality factors and water bodies. The correlation with DO gradually decreases as the buffer distance increases, with a significant negative correlation in 100 and 300 m buffers and DO at the 0.01 level, and a significant negative correlation in 500 and 1000 m buffers at the 0.05 level. BOD_5 showed a significant positive correlation

at the 0.05 level in the buffer zone waters of 100, 300, 500, 1000, and 2000 m, and a significant positive correlation at the 0.01 level in the buffer zone waters of 4000 m.

(4) The correlation between water quality factors and cultivated land, construction land, and other land use in each buffer zone is not significant.

4. Discussion

4.1. Interpretation of Water Quality Evaluation Results of the Erguna River

In accordance with the Environmental Quality Standards for Surface Water of China (GB3838-2002) [42], the contents of DO, permanganate index (COD_{Mn}), five-day biochemical oxygen demand (BOD_5), and arsenic in each monitoring section of the Erguna River in 2016 all met the Class I water quality standard, while the highest content of ammonia nitrogen (NH_3-N) also complied with the Class II standard. All indicators can also meet the EU Water Framework Directive and related standards (in a "good" state). Compared with the water quality in 2010, the overall water quality of the river showed an improving trend. This result indicates that, as a cross-border river between China and Russia, the Erguna River currently maintains a good water quality base without obvious pollution accumulation. This may be attributed to the relatively low intensity of human activities in the basin and the strong natural purification capacity of the river ecosystem.

4.2. Characteristics of Land Use Changes in the Erguna River Basin

From a temporal perspective, the overall land use structure of the basin remained stable during 2010–2016 (with the core order of grassland > forest land > arable land > other land types). However, the area of grassland and construction land decreased, while the area of other land types increased. This phenomenon is consistent with the "grassland degradation—expansion of other land uses" pattern observed in similar semi-arid basins by Xiang et al. [43] and Liang et al. [44]. The primary cause of grassland reduction is desertification, and the recent climate conditions of rising temperatures and decreasing precipitation. The reduction in construction land may be directly related to the overall relocation policy for herdsmen in areas severely affected by grassland desertification, reflecting the coordinated adjustment between regional ecological protection and human residential needs.

From a spatial perspective, along the main stream of the Erguna River from upstream to downstream, the proportion of grassland decreases while that of forest land increases. This spatial pattern is closely associated with the topographic differences in the basin: the upstream area is dominated by mountains, while the downstream area has flat and open terrain, which is more suitable for grassland distribution. Additionally, the high proportion of arable land in the D2 and D3 sections (near Heishantou Town and Shiwei Town) and the high proportion of construction land in the D6 section (Yakeshi City) both reflect the "match between land use types in human activity-concentrated areas and population density as well as the intensity of production activities". In contrast, the tributary Genhe River exhibits the spatial characteristic of "more forest land in the upstream and more grassland in the downstream", which further verifies the decisive role of topography (mountains in the upstream and open plains in the downstream) in the spatial differentiation of land use.

4.3. Correlation Mechanism Between Land Use Types and Water Quality in the Erguna River Basin

4.3.1. Grassland and Water Quality: Transition from "Improvement" to "Negative Impact"

In 2010, grassland showed a significant negative correlation with BOD_5, indicating that grassland had a certain purification effect on water quality at that time. However, in 2016, grassland exhibited a strong positive correlation with arsenic and no significant positive

correlation with other water quality indicators. This result contradicts the traditional perception that "grassland improves water quality" but is consistent with the conclusions of Xiang et al. [43] and Liang et al. [44] that "grassland may serve as a source of pollutants in water bodies". The core mechanism lies in the fact that the Erguna River Basin is an important animal husbandry base in China (with nearly 100 million mu of usable natural grassland), and arsenic compounds are widely used in animal husbandry to promote livestock growth and enhance disease resistance [45]. The feces of grazing livestock tend to remain on the surface under semi-arid climatic conditions (where temperature and moisture affect fecal decomposition) and enter the river through surface runoff. Meanwhile, if the livestock carrying capacity per unit area of grassland exceeds the limit, the decomposition of a large amount of feces can lead to point source pollution [46,47]. The transition of grassland's impact on water quality from "positive" to "negative" between 2010 and 2016 is also related to the significant reduction in grassland area. Blind pursuit of economic growth and improper management practices have weakened the grassland's ability to intercept pollutants, leading to increased loss of nutrients such as nitrogen and ultimately exerting a negative impact on water quality.

4.3.2. Forest Land and Water Quality: Temporal and Spatial Differences in the "Sink" Effect

In 2016, within the 1000 m buffer zone, forest land showed a significant negative correlation with COD_{Mn}, BOD_5, NH_3-N, and arsenic, demonstrating a "sink" effect of forest land on pollutants. This is consistent with other research results [48–50]—the permeable underlying surface of forest land can intercept the migration of pollutants, and its roots can absorb pollutants, thereby alleviating water pollution. Notably, there was no significant correlation between forest land and water quality indicators in 2010. This may be due to the small area of forest land or the underdeveloped forest stand structure (e.g., tree species, canopy density) in 2010, which had not yet formed an effective purification capacity, reflecting the "time lag" in the water quality improvement effect of forest land.

4.3.3. Water Bodies and Water Quality: Stable "Negative Impact"

From 2010 to 2016, water bodies (mainly wetlands such as inland tidal flats, pond water surfaces, and swamp lands) showed a negative correlation with DO and As, and a positive correlation with COD_{Mn}, BOD_5, and NH_3-N (with significant correlations with DO and BOD_5). This indicates that water bodies generally exert a negative impact on water quality. Although wetlands have the functions of water storage, regulation, and pollutant absorption [51], the annual increase in water body area in this study did not change the strength of its correlation with water quality indicators. This may be because the water bodies in the basin are dominated by "stagnant wetlands", where pollutants accumulate and are then input into the river through runoff. Additionally, the purification capacity of wetlands probably has reached saturation, so the increase in area cannot further enhance the purification effect.

4.3.4. Arable Land, Construction Land, Other Land, and Water Quality: Uncertainty of Impacts

Overall, there was no significant correlation between arable land, construction land, and water quality indicators. This differs greatly from the conclusions of Zhang et al. [52] and Iqbal et al. [53] that "arable land and construction land exacerbate water quality deterioration". The main reason is that the proportion of construction land in the cross-border area of the study is low and decreasing year by year, while arable land is mostly distributed in areas far from the riverbank, making it difficult for pollutants to enter the river through runoff. In 2016, there was no significant correlation between other land uses and water quality indicators, indicating that other land uses have a limited impact on

water quality. This may be because other land uses (e.g., unutilized land) are dominated by "non-polluting land types" and account for a small area, failing to form large-scale pollution input.

4.3.5. Impact of Buffer Zone Distance on the "Land Use–Water Quality" Correlation

When the buffer zone exceeds 1000 m, the correlation between water quality and land use is generally weak; within 1000 m, the correlation is more significant. This conforms to the general law of "distance decay effect" in the impact of land use on water quality—the closer the land use type is to the riverbank, the easier it is for pollutants to enter the river through runoff, leaching, and other processes. Specifically, in 2016, the correlation between grassland and As was the highest in the 100 m nearshore buffer zone and 2000 m buffer zone, indicating that grassland in these two regions is an important "source" of As. The forest land in the 300 m buffer zone showed the highest overall correlation with water quality indicators, suggesting that afforestation in this area has the optimal effect on improving water quality, providing a clear spatial reference for ecological restoration in the basin.

4.4. Limitations of the Study

Temporal Scale Limitation: This study only compares data from two time points (2010 and 2016), failing to reflect the long-term dynamic changes in the correlation between land use and water quality (e.g., interannual fluctuations, seasonal differences). It may also miss the interference of abnormal climate years (e.g., extreme precipitation, drought) on the correlation between the two.

Indicator Coverage Limitation: Only five water quality indicators (DO, COD_{Mn}, BOD_5, NH_3-N, arsenic) were selected, excluding other key pollutants such as total nitrogen, total phosphorus, and heavy metals (e.g., cadmium, lead). This may underestimate the potential pollution contribution of some land use types (e.g., arable land). Additionally, land use types were not further subdivided (e.g., grassland was not divided into natural grassland and artificial grassland, and forest land was not divided into coniferous forest and broad–leaved forest), making it difficult to accurately identify the differential impacts of different subtypes on water quality.

Depth Limitation of Mechanism Research: The correlation between land use and water quality was only inferred through correlation analysis, without combining field in situ observations (e.g., monitoring of pollutant migration flux) and laboratory simulation experiments (e.g., pollutant leaching rate under different land use types). The interpretation of the correlation mechanism remains at the "phenomenal correlation" level, lacking quantitative verification. In the future, scientists from China and Russia can jointly conduct field experiments and research and establish a data exchange mechanism.

5. Conclusions

5.1. Main Research Findings

Water Quality Status: In 2016, the core water quality indicators (DO, COD_{Mn}, BOD_5, arsenic) in each monitoring section of the Erguna River met the Class I standard, and NH_3-N met the Class II standard. The overall water quality was good and showed an improving trend compared with 2010.

Land Use Changes: From 2010 to 2016, the overall land use structure of the basin remained stable (with grassland and forest land as the dominant types). However, the area of grassland and construction land decreased (the main cause of grassland reduction was desertification and climate drought), and the area of other land types increased. Spatially, along the main stream from upstream to downstream, the proportion of grassland decreased

and that of forest land increased, while the opposite trend was observed in the tributary Genhe River. Topography was the main driving factor for these changes.

"Land Use–Water Quality" Correlation: Grassland transitioned from a "water quality improver" in 2010 to an important "source" of arsenic in 2016. Within the 1000 m buffer zone, forest land exhibited a significant "sink" effect on pollutants, and afforestation in the 300 m buffer zone had the optimal effect on improving water quality. Water bodies exerted a stable negative impact on water quality. Arable land, construction land, and other land uses had limited impacts on water quality. The "land use–water quality" correlation decayed with buffer distance, and the correlation was much significant within 1000 m.

5.2. Scientific and Policy Significance

This study reveals the temporal and spatial heterogeneity of the "land use–water quality" correlation in semi-arid cross-border basins, verifies the "pollution source" effect of grassland under high livestock carrying capacity, the "pollution sink" effect of forest land, and the "decay effect" of buffer zone distance. It provides a reference paradigm for studies on the "land use–water quality" correlation in similar basins (e.g., other cross-border rivers in the northeastern border of China).

It clarifies the key directions for ecological protection in the basin. To alleviate grassland degradation and arsenic pollution input, it is necessary to reduce grazing pressure and optimize grassland management. Afforestation projects should be prioritized in the 300 m nearshore buffer zone to strengthen the interception and purification of pollutants by forest land. Meanwhile, considering that the Erguna River is a cross-border river between China and Russia, China is located in the upstream area, and Russia has slightly stricter water quality standards [54], it is essential to strengthen the supervision of the ecological environment in the basin to ensure cross-border water quality safety and maintain the friendship of ecological cooperation between China and Russia.

5.3. Future Research Directions

Long-term continuous monitoring data should be added, and water quality indicators such as total nitrogen, total phosphorus, and multiple heavy metals should be supplemented.

Combining field monitoring of pollutant flux and laboratory simulation experiments, the migration rate and transformation efficiency of pollutants under different land use types should be quantitatively analyzed to clarify the quantitative mechanism of the "land use–water quality" correlation. Hydrological models (e.g., SWAT model) could be introduced to simulate water quality changes under different land use scenarios, providing predictive support for land use planning in the basin.

Joint investigations on land use and water quality in the entire Erguna River Basin (both Chinese and Russian sides) could be conducted with Russia to compare and analyze the differential characteristics and coordinated protection needs of the two sides, providing a scientific basis for the coordinated ecological governance of cross-border basins.

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