

## Article

# Land Use Impact on Water Quality and Phytoplankton Community Structure in Danjiangkou Reservoir

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**Abstract:** The composition and intensity of land use significantly influence the aquatic ecological environment, further affecting the physicochemical attributes of the water body, and indirectly modulating the phytoplankton community structure. This study centers around the Danjiangkou Reservoir, investigating the correlation between land use, water environment, and phytoplankton alongside varying intensities of anthropogenic activities, based on the review of land use, phytoplankton, and water quality data of 2021. Firstly, an analysis was conducted over five circular buffer zones generated around sampling points with radii set at 500 m, 1000 m, 1500 m, 2000 m, and 2500 m, wherein the intensity of human activity was categorized into low, medium, and high, in accordance with the human activity intensity level score (HAILS). This study proceeded to explore the correlation between land use and the water environment across different scales, compared phytoplankton density and community structure differences across varied levels of human activity, and analyzed the association between phytoplankton communities in the Danjiangkou Reservoir and environmental variables under various intensities. The findings showed: The land use within the 500 m circular buffer zone has the greatest impact on the water quality of the Danjiangkou Reservoir, especially with the increase in human activities leading to elevated nutrient levels in the water, thereby promoting the growth and reproduction of algae, and increasing the risk of algal blooms. This research scrutinizes the relationship between land use, water environment, and plankton under varying human activity intensities, serving as a foundation for environmental management sectors to make informed decisions and promote the sustainable development of the catchment water environment.

**Keywords:** land use; phytoplankton; aquatic ecological environment; Danjiangkou Reservoir



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## 1. Introduction

In recent years, owing to the progressive intensification of human activities, the water quality of rivers has been progressively affected. Concurrently, there has been a surge in various pollutants, and the impact of land use on aquatic ecosystems has elicited widespread attention [1]. As primary producers in aquatic ecosystems, the community

structure of phytoplankton is a reflection of water quality [2]. The indirect influence of land use on the community structure of phytoplankton is brought about through the change in nutrients, toxic substances, and other physicochemical indicators present in water bodies.

The Danjiangkou Reservoir, denoted as a nationally significant source water protection area and the primary water source for the central route of China's South-to-North Water Diversion Project [3], holds immense importance. Thus, the stability of ecosystem of the reservoir is critical for ensuring water security in Northern China. The initiation of the South-to-North Water Diversion Middle Route Project, coupled with the dam-raising initiative at the Danjiangkou Reservoir, has brought about a substantial shift in the land use dynamics surrounding the reservoir area. An examination of the period from 2000 to 2020 reveals a consistent expansion in the area covered by bodies of water and human-made surfaces within the Danjiangkou Reservoir and its periphery [4]. Land use strongly influences the water environment and river water quality [1,5], and as the main carrier of pollutants, various types and scales of land use affect water quality by altering the hydrological process and nutrient migration within the watershed [6]. The correlation between land use and water quality has been extensively explored [7]; for instance, John Peter Obubu [8] found that different land use and land cover activities are strongly correlated with particular water quality parameters, for example, agriculture is strongly correlated with nutrients such as TP, TN and nitrate as well as turbidity, TSS, BOD and temperature. Zakariya Nafi' Shehab [9] conducted a study on the spatial variation effects of landscape pattern and land cover rate on water quality in an urbanizing watershed in Malaysia. The findings demonstrated a significant correlation between water quality, landscape patterns, and the land cover rate. Thandile T. Gule [10] stated that land use and land cover modifications are involved in the deterioration of water quality around the city. Chen [11] revealed that anthropogenic land use potentially contributed to the threats of aquatic micro-pollutants in Danjiangkou Reservoir.

Changes in land use within watersheds as a result of anthropogenic activities, and the corresponding decline in water quality, are deemed significant drivers influencing phytoplankton development [12]. Variations in water quality parameters can lead to direct effects on phytoplankton growth dynamics. For example, the study by Gonzalez-Camejo J. [13] showed that variations in the pH levels of water bodies could markedly affect the proliferation of phytoplankton communities. Additionally, Memet Varol [14] reported that phytoplankton growth and reproductive cycles were influenced by water temperature, with elevated temperatures fostering Cyanobacteria proliferation [15], whereas Bacillariophyta exhibited a preference for cooler conditions. Eutrophication characterized by nutrient-rich waters is commonly associated with enhanced phytoplankton blooming, elevated nutrient levels in aquatic ecosystems can facilitate an increase in phytoplankton populations [16]. However, the proliferation of these organisms can be hindered by various types of pollutants, including heavy metals and organic contaminants. These pollutants may adversely affect vital physiological and biochemical processes within the phytoplankton, such as photosynthesis and respiration [17,18]. Additionally, the impact of nutrient enrichment on phytoplankton varies with the type of nutrient involved; specifically, total nitrogen has been observed to influence the proliferation of cyanobacteria [19]. Moreover, changes in the aquatic environmental factors can lead to shifts in the phytoplankton community structure, marked by changes in species dominance and ecological succession [20].

This investigation focuses on the Danjiangkou Reservoir and examines the interconnections between land utilization patterns, water quality, and phytoplankton communities based on monitoring data collected in 2021. This study is designed to address several key research questions: (1). How do changes in land use patterns affect the quality of the aquatic environment in the Danjiangkou Reservoir? (2). How do different intensities of land use impact the composition of phytoplankton communities, through their influence on the water environment? (3). What is the relationship between environmental factors and the dynamics of phytoplankton communities in the Danjiangkou Reservoir?

## 2. Materials and Methods

### 2.1. Study Area

The Danjiangkou Reservoir, as the preeminent water control structure in the Han River basin, ranks among the most expansive reservoirs throughout Asia. Exerting control over the upper segments of the Han River and the Danjiang, the reservoir boasts a commanding catchment area that encompasses approximately 95,200 km<sup>2</sup>. It is located in central China (32°36′–33°48′ N; 110°59′–111°49′ E) [21,22].

### 2.2. Land Use Data

The land use data for 2021 with a spatial resolution of 30 m were obtained and analyzed [23]. Based on these data, land use types were classified into six categories: farmland, forest, grassland, water body, unused land, and construction land. This classification system reflects the main land cover characteristics of the study area and can accurately assess land use patterns. Circular buffer zones with radii of 500 m, 1000 m, 1500 m, 2000 m and 2500 m were delineated around each sampling point using the ArcGIS spatial analysis tool. The area and proportion of each land use type within the buffer zones at different spatial scales were calculated. The human activity intensity level (HAILS) score of all circular buffer zones was calculated based on surface features [24]. Samples were divided into three equal intervals based on HAILS scores: low human activity intensity (lowest third of HAILS scores), medium human activity intensity (middle third), and high human activity intensity (highest third). The formula for calculating HAILS is as follows:

$$HAILS = \frac{S_{CLE}}{S} \times 100\%, \quad (1)$$

where *HAILS* is the human activity intensity score on land surface, *S<sub>CLE</sub>* is the equivalent area of construction land, and *S* is the total area of the region.

### 2.3. Phytoplankton Sample Collection, Identification, and Data Processing

In June 2021, phytoplankton samples and water quality surveys were conducted in Danjiangkou Reservoir, China, with 24 sampling sites covering different areas of the reservoir. Quantitative samples were collected using a water sampler to collect 1.5 L of water into quantitative sampling bottles at each site. The phytoplankton samples were immediately fixed with Lugol's solution at a concentration of 1.0–1.5% of the water sample volume. All fixed phytoplankton samples were transported to the laboratory for further processing and analysis.

Phytoplankton taxonomy identification referred to literature such as the Journal of Chinese freshwater algae [25–29], and phytoplankton were identified to genus. Quantitative analysis of phytoplankton used a pipette to extract 0.1 mL of homogenized sample and inject it into a phytoplankton counting chamber, covered with a cover slip and left to settle for a moment without bubbles. The chamber was then placed under a microscope for counting.

The dominance index was calculated following published methods to determine the dominance level of algal species, with an index exceeding 0.02 considered dominant [12]. The formula is as follows:

$$Y = \frac{n_i}{N} \times f_i, \quad (2)$$

where *Y* is the dominance index, *n<sub>i</sub>* is the number of individuals of a given species, *N* is the total number of individuals of all species, and *f<sub>i</sub>* is the ratio of sampling sites where the *i*th species appeared to the total number of sampling sites.

### 2.4. Water Quality Analysis

A YSI (Xylem) water quality analyzer was used to measure water quality parameters 0.5 m below the water surface at each sampling point, including water temperature (WT), pH, dissolved oxygen (DO) and conductivity (Cond). Turbidity (Turb) was determined us-

ing a turbidity meter, while total phosphorus (TP), total nitrogen (TN), ammonium nitrogen (AN), chemical oxygen demand (COD<sub>Mn</sub>), chlorophyll *a* (Chl.*a*) and other parameters were determined by standard methods [30]. Eight water quality variables—WT (°C), pH, Cond (ms/m), DO (mg/L), TN (mg/L), TP (mg/L), COD<sub>Mn</sub> (mg/L) and AN (mg/L)—were used to measure the water quality index (WQI) according to the following formula [31]:

$$WQI = \frac{\sum_{i=1}^n C_i \times P_i}{\sum_{i=1}^n P_i}, \quad (3)$$

where *n* is the total number of water quality parameters studied, *C<sub>i</sub>* is the normalized value of parameter *i*, and *P<sub>i</sub>* is the assigned weighting of the *i*th parameter. WQI values range from 0 to 100, and water quality is divided into five levels according to the WQI score: excellent (91–100), good (71–90), medium (51–70), poor (26–50) and very poor (0–25) [32].

### 2.5. Data Analysis

Redundancy analysis (RDA) was performed on land use types and environmental factors using the “vegan” package in R 4.3.1. Spearman’s rank correlation analysis was conducted and a heat map was plotted using the “corrplot” package in R 4.3.1 for land use types, human activity intensity and environmental factors. Rank sum tests were performed in R 4.3.1 on phytoplankton density in different human activity intensity areas of Danjiangkou Reservoir, and Mantel tests were conducted using the “vegan” package to analyze the relationship between phytoplankton communities and environmental factors.

## 3. Results

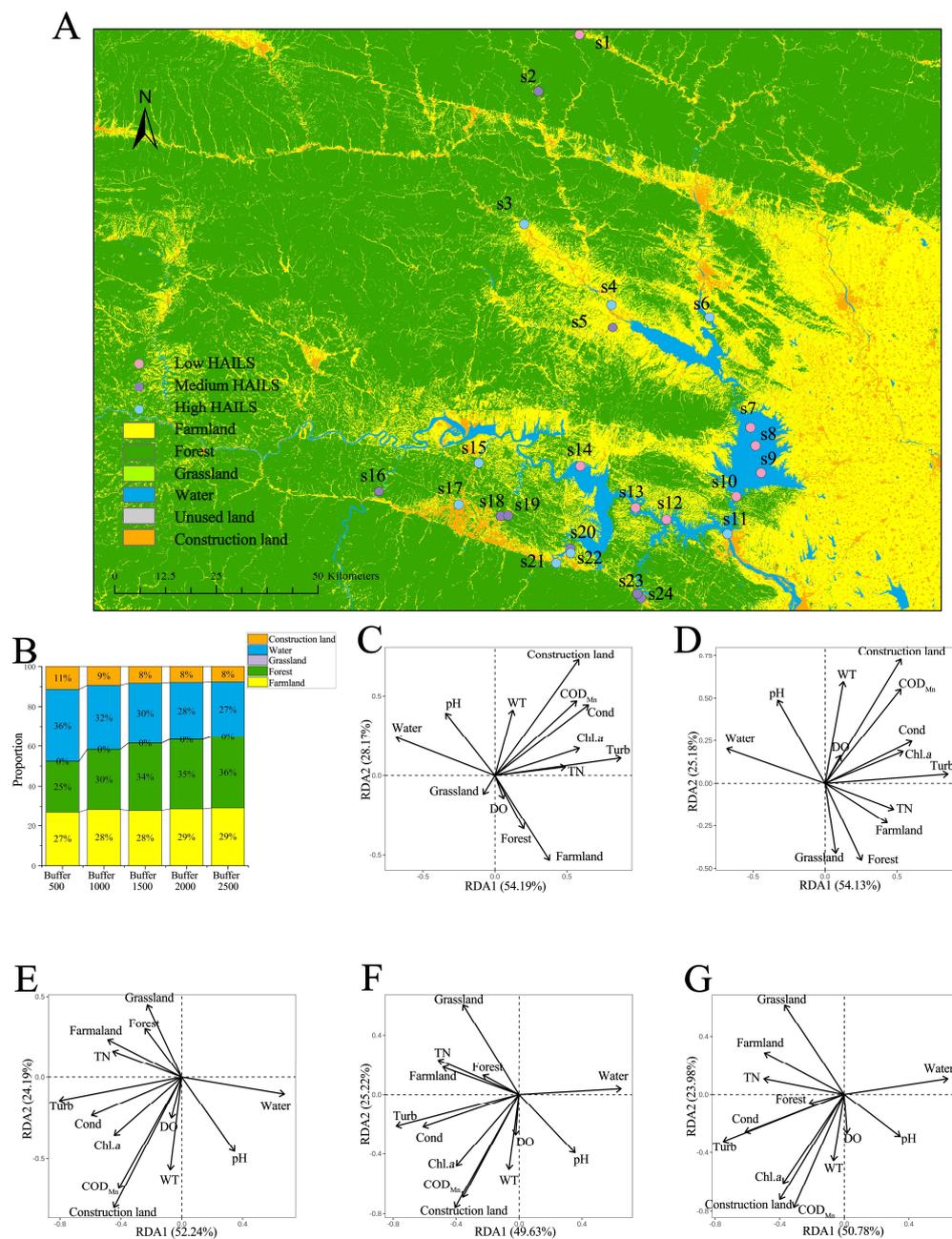
### 3.1. Land Use Pattern around Danjiangkou Reservoir

The land use composition within circular buffers with radii of 500–2500 m from the reservoir is shown in Figure 1A,B and Table 1. In general, the main land use types are cropland, forest and water body. With the expansion of buffer radii, the proportion of construction land shows a decreasing trend, while the area of forest increases and the areas of farmland and grassland show overall increasing trends.

Using redundancy analysis (RDA), we assessed the impact of land use types on water quality indicators at different scales. The results (Figure 1C) indicate that the 500 m circular buffer best explains the changes in water quality, with the first two axes (RDA1 and RDA2) accounting for 82.36% of the environmental variables, denoting a good explanatory effect. As the buffer scale expands, the capacity to explain water quality changes declines with the decline ranging from 3.05% to 7.6%.

Specifically (Figure 1C), forest was positively correlated with Cond, Turb, TN, COD<sub>Mn</sub> and Chl.*a*, and negatively correlated with WT, pH and DO. At most scales, farmland was negatively correlated with pH and COD<sub>Mn</sub>, and positively correlated with WT, DO, Cond, Turb, TN and Chl.*a*. Grassland was positively correlated with Cond, Turb, TN and negatively correlated with WT, pH, DO, COD<sub>Mn</sub> and Chl.*a*. Water was positively correlated with pH and negatively correlated with other environmental factors. Construction land was positively correlated with all environmental factors.

A comparative analysis of the main environmental factors influencing water quality at the five scales (Figure 1C–G) showed that Cond, Turb, COD<sub>Mn</sub> and Chl.*a* were the primary impact factors within the 500 m, 2000 m and 2500 m buffers, while Cond, Turb and COD<sub>Mn</sub> were the main factors within the 1000 m and 1500 m buffers. The results from the five scales were generally consistent in identifying Cond, Turb and COD<sub>Mn</sub> as the primary influencing factors.



**Figure 1.** Relationship between land use and water quality in Danjiangkou Reservoir. (A) Schematic diagram of land use in Danjiangkou Reservoir; s1–s24 represents point names; (B) percentage of land use types in Danjiangkou Reservoir. Ordination diagrams of redundancy analysis results in Danjiangkou Reservoir: (C) 500 m; (D) 1000 m; (E) 1500 m; (F) 2000 m; (G) 2500 m.

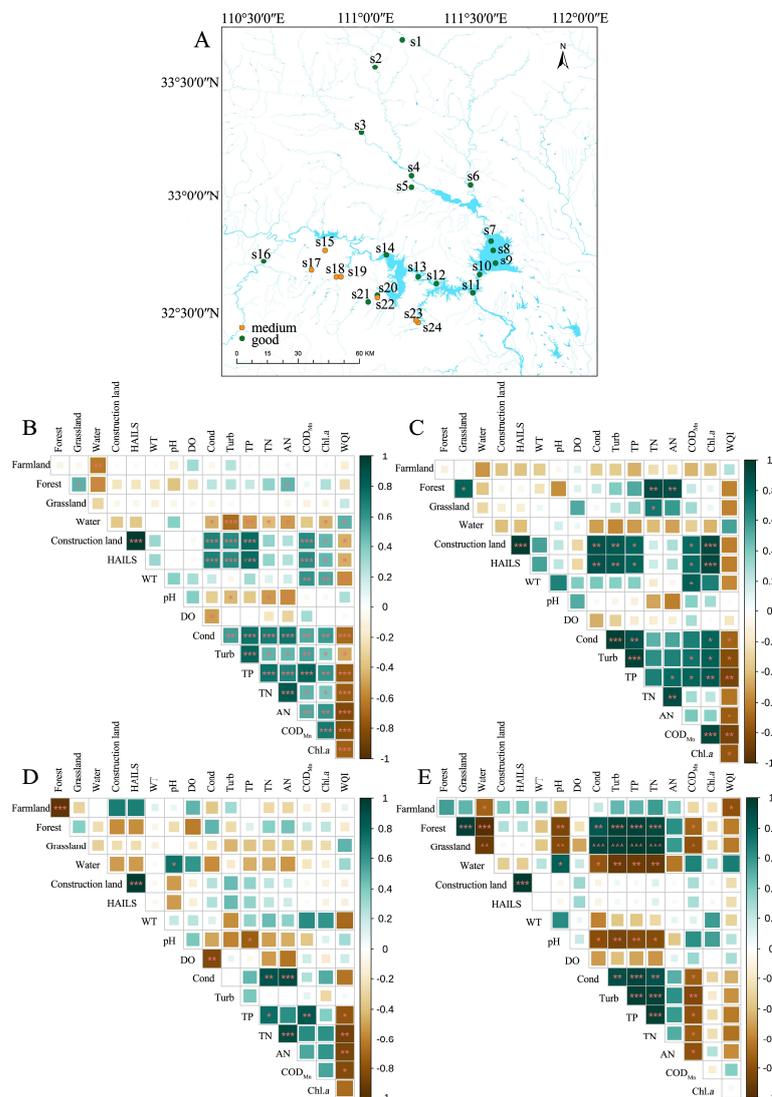
**Table 1.** Land use type proportions at different scales.

	Farmland	Forest	Grassland	Water	Construction Land
500 m circular buffer	27.11%	25.24%	0.11%	36.12%	11.42%
1000 m circular buffer	28.44%	29.93%	0.08%	32.13%	9.42%
1500 m circular buffer	27.93%	33.58%	0.10%	29.99%	8.39%
2000 m circular buffer	28.73%	34.64%	0.17%	28.49%	7.97%
2500 m circular buffer	29.19%	35.51%	0.22%	27.34%	7.74%

### 3.2. Impact of Land Use on Water Quality around Danjiangkou Reservoir

WT ranged from 18.6 to 31.4 °C, and the pH demonstrated fluctuations between 7 and 9.39. DO concentration fluctuated between 5.81 and 14.52 mg/L. Conductivity showed variation in the range of 18.6–80.4 ms/m. Turbidity was relatively stable at 0.64–30.1. TP and TN, which are key indicators for assessing reservoir eutrophication levels [33], exhibited concentrations from 0.005 to 0.268 mg/L and 0.24 to 12.32 mg/L, respectively. AN and COD<sub>Mn</sub> levels varied between 0.0125 and 0.641 mg/L and 1–7.7 mg/L, respectively. Chl.a concentration fluctuated in the range of 0.5–29.4 µg/L across all sampling sites.

The sampling sites were divided into three levels based on HAILS: low, medium and high human activity intensity (Figure 2A). The WQI values at sites with low human activity intensity varied between 78.75 and 83.75 with an average of 81.64, indicating good water quality. Sites with medium and high human activity intensity had WQI values in the range of 51.25–89.375 and 61.25–82.5, with averages of 73.83 and 71.48, respectively, indicating moderate to good water quality.



**Figure 2.** Impact of land use on water quality in Danjiangkou Reservoir. (A) Schematic diagram of WQI distribution of sampling points in Danjiangkou Reservoir; s1–s24 represent point names (B–E) Spearman’s analysis between land use, human activity intensity and water quality factors in Danjiangkou Reservoir, (B) represents Danjiangkou Reservoir; (C) represents a high human activity intensity area; (D) represents a medium human activity intensity area; (E) represents a low human activity intensity area; \*\*\* indicates  $p < 0.001$ , \*\* indicates  $p < 0.01$ , and \* indicates  $p < 0.05$ .

As shown in Figure 1C, the 500 m circular buffer explained water quality variation best. Based on this buffer, Spearman's correlation analysis between land use types, human activity intensity and water quality factors under different intensities was conducted (Figure 2B). Results showed that grassland and water were significantly negatively correlated. Forest was significantly positively correlated with grassland and AN but negatively with water. Water was significantly negatively correlated with Cond, Turb, TP, TN, AN and Chl.*a* but positively with WQI. Construction land was significantly positively correlated with HAILS, Cond, Turb, TP, COD<sub>Mn</sub> and Chl.*a* but negatively with WQI. HAILS was significantly positively correlated with Cond, Turb, TP, COD<sub>Mn</sub> and Chl.*a* but negatively with WQI.

Under a high human activity intensity, forest was significantly positively correlated with grassland, TN and AN. Grassland was significantly positively correlated with TN. Construction land was significantly positively correlated with HAILS, Cond, Turb, TP, COD<sub>Mn</sub> and Chl.*a*. HAILS was significantly positively correlated with Cond, Turb, TP, COD<sub>Mn</sub> and Chl.*a*, indicating high human activity could lead to increased TP concentration. Under medium intensity, water was significantly positively correlated with pH, and farmland was significantly negatively correlated with forest. Under a low intensity, farmland was significantly negatively correlated with water and WQI, while forest was significantly positively correlated with grassland, Cond, Turb, TP, TN but negatively correlated with water, pH and COD<sub>Mn</sub>. Grassland was significantly negatively correlated with water, pH and COD<sub>Mn</sub> but positively with Cond, Turb, TP, TN. Water was significantly negatively correlated with Cond, Turb, TP, TN but positively with pH.

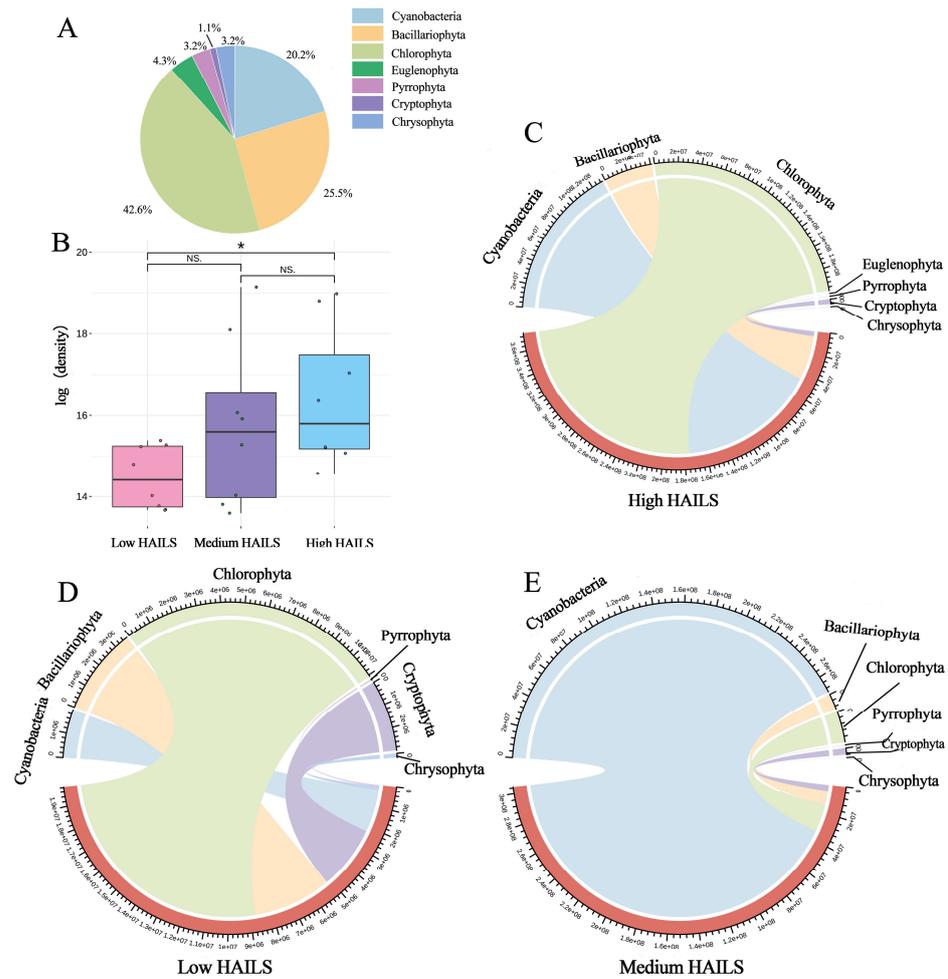
### 3.3. Phytoplankton Community Structure

A total of 94 genera belonging to 7 phyla were monitored in the Danjiangkou Reservoir, including 40 genera of Chlorophyta, 24 genera of Bacillariophyta, 19 genera of Cyanobacteria, and 11 genera of other algae (including Euglenophyta, Cryptophyta, Pyrrophyta and Chrysophyta) (Figure 3A), see Appendix A for a list of all phytoplankton.

The densities of phytoplankton under different human activity intensities were compared (Figure 3B). The results showed that as the human activity intensity increased, the density of phytoplankton tended to increase accordingly, with significant differences between high and low intensities.

Across the entire Danjiangkou Reservoir (Figure 3C–E), Cyanobacteria had the highest abundance, followed by Chlorophyta and Bacillariophyta. Cyanobacteria and Chlorophyta were the dominant phyla. Under a high human activity intensity, Chlorophyta had the highest abundance, followed by Cyanobacteria and Bacillariophyta, which were the dominant phyla. Under a medium intensity, Cyanobacteria had the highest abundance, followed by Chlorophyta, Bacillariophyta and Cryptophyta, with Cyanobacteria being the dominant phylum. Under a low intensity, Chlorophyta had the highest abundance, followed by Bacillariophyta, Cryptophyta and Cyanobacteria, with Chlorophyta, Bacillariophyta, Cryptophyta and Cyanobacteria being the dominant phyla.

Taking a dominance of >0.02 as the dominant genera, the dominant genera in Danjiangkou Reservoir are shown in Table 2. The main dominant genera in the entire reservoir area included *Cyclotella* with a dominance of 0.0313, *Scenedesmus* with a dominance of 0.2545, *Pseudanabaena* with a dominance of 0.0468 and *Microcystis* with a dominance of 0.2283. The dominant genera under a high human activity intensity included *Cyclotella* with a dominance of 0.0251, *Scenedesmus* with a dominance of 0.2495, *Pseudanabaena* with a dominance of 0.0454, and *Microcystis* with a dominance of 0.0227. The dominant genus under a medium intensity was *Microcystis* with a dominance of 0.2046. No obvious dominant genus was found under a low intensity. In summary, the dominant genera of phytoplankton under a high intensity included *Cyclotella*, *Scenedesmus*, *Pseudanabaena* and *Microcystis*; the dominant genus under a medium intensity was *Microcystis*; no obvious dominant genus was found under a low intensity.



**Figure 3.** Phytoplankton community structure. (A) Species composition of phytoplankton throughout Danjiangkou Reservoir; (B) differences in phytoplankton density at different human intensities areas in Danjiangkou Reservoir; (C) community composition of phytoplankton at high human activity intensity areas; (D) community composition of phytoplankton at low human activity intensity areas; (E) community composition of phytoplankton at medium human activity intensity areas. \* indicates  $p < 0.05$ ; NS. indicates not significant.

**Table 2.** Dominant genera in Danjiangkou Reservoir.

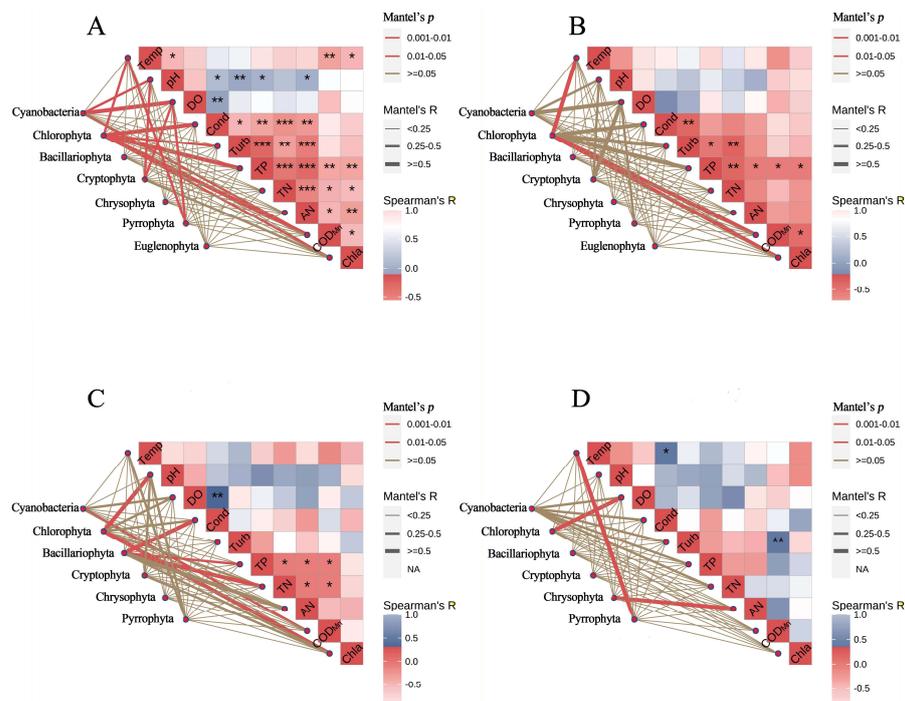
	Genera	Dominance
High HAIL Area	<i>Cyclotella</i>	0.0251
	<i>Scenedesmus</i>	0.2495
	<i>Pseudanabaena</i>	0.0454
Medium HAIL Area	<i>Microcystis</i>	0.0227
	<i>Microcystis</i>	0.2046
Low HAIL Area	-	-

3.4. Relationship between Phytoplankton and Environmental Factors under Different Intensities

The phytoplankton community in the Danjiangkou Reservoir basin was mainly composed of Chlorophyta and Cyanobacteria. To understand the driving factors affecting the succession and distribution of phytoplankton communities, Mantel tests were performed between phytoplankton assemblages and environmental factors in the Danjiangkou River basin and under different intensities, respectively.

The results showed (Figure 4A) that in the Danjiangkou Reservoir basin, Cyanobacteria was closely related to pH, DO and COD<sub>Mn</sub>, Chlorophyta was closely related to Temp, Cond,

Turb, TP, COD<sub>Mn</sub> and Chl.*a*, Cryptophyta was closely related to pH and DO, Pyrrophyta was closely related to Temp and DO. Spearman’s correlation between environmental factors showed that Temp was significantly positively correlated with pH, COD<sub>Mn</sub> and Chl.*a*, pH was significantly negatively correlated with Cond, Turb, TP and AN, DO was significantly negatively correlated with Cond, Cond was significantly positively correlated with Turb, TP, TN and AN, Turb was significantly positively correlated with TP, TN and AN, TP was significantly positively correlated with TN, AN, COD<sub>Mn</sub> and Chl.*a*, COD<sub>Mn</sub> was significantly positively correlated with Chl.*a*.



**Figure 4.** Relationship between phytoplankton community and environmental factors in Danjiangkou Reservoir. (A) Danjiangkou Reservoir; (B) high human activity intensity area; (C) medium human activity intensity area; (D) low human activity intensity area; \*\*\* indicates  $p < 0.001$ , \*\* indicates  $p < 0.01$ , \* indicates  $p < 0.05$ ; red line indicates significant correlation; green line indicates non-significant correlation; Temp. indicates water temperature.

Under a high intensity (Figure 4B), Chlorophyta was closely related to Temp, COD<sub>Mn</sub> and Chl.*a*, and Spearman’s correlation showed that COD<sub>Mn</sub> was significantly positively correlated with TP and Chl.*a*. Under a medium intensity (Figure 4C), Cyanobacteria was closely related to COD<sub>Mn</sub>, Chlorophyta was closely related to pH and Chl.*a*, Bacillariophyta was closely related to Cond, TN and TP, and Spearman’s correlation showed that Cond was significantly negatively correlated with DO, TP was significantly positively correlated with TN, AN and COD<sub>Mn</sub>, TN was significantly positively correlated with AN and COD<sub>Mn</sub>. Under a low intensity (Figure 4D), Chlorophyta was closely related to DO, Chrysophyta was closely related to AN, Pyrrophyta was closely related to Temp, and Spearman’s correlation showed that Temp was significantly negatively correlated with Cond.

#### 4. Discussion

##### 4.1. Relationship between Land Use and Water Quality

Land use, a primary carrier of pollutants, significantly influences water quality by modifying watershed hydrologic processes and nutrient migration, thereby engendering surface pollution [6]. Various land use types each contribute distinctively within this discipline. Urbanized landscapes elevate TN and TP concentrations in water bodies, primarily induced by domestic waste and livestock excretion produced from anthropogenic activities, which subsequently reinforce the eutrophication of water bodies and act as pollutant

“sources”. Alternatively, forests and grasslands efficaciously obstruct the migration of N, P, and organic matter via plant absorption, serving as significant mitigators of pollution [34]. An examination of land use data across a myriad of scales within the Danjiangkou Reservoir Basin produced congruent outcomes. As the spatial extent enlarges, the proportion of “sink” land categories, such as grasslands, exhibits an upward trend, while “source” land types, namely construction land, demonstrate a contrary decline. It is thereby suggested that anthropogenic activities exert the highest impact within 500 m circular buffer zones, instigating paramount effects on water quality, a finding that aligns with the outcomes of the RDA analysis (Figure 1C). Specifically, the 500 m circular buffer zones offer the optimal explanation for water quality variation. However, the explicatory capability of these zones diminishes as their scales grow larger.

Within the Danjiangkou Reservoir Basin, forests showed a positive correlation with total nitrogen (TN) and the permanganate index ( $\text{COD}_{\text{Mn}}$ ), likely due to the rich humic substances in the surrounding forest soil that influence the nutrient concentrations via surface runoff [35]. In various types of watersheds, humic substances exhibit a strong association with total nitrogen, total phosphorus, nitrates, and phosphates [35–37]. Grasslands demonstrated a negative correlation with temperature, pH, DO,  $\text{COD}_{\text{Mn}}$ , and chl.*a* across multiple scales, underscoring their role in enhancing water quality [10]. Conversely, construction land were predominantly positively correlated with all assessed environmental factors. This trend might be attributed to the growing presence of impervious surfaces associated with urbanization, which facilitates the conveyance of urban refuse, animal waste, nutrients, and heavy metals into aquatic systems through runoff, thereby intensifying the urban pollution load [38].

RDA analysis indicated that land use significantly influences conductivity, turbidity, and permanganate index within the reservoir basin, which may be attributed to the relatively large fraction of farmland, comprising 27.11–29.19% of the area. Studies have shown that turbid water bodies are mainly surrounded by arable land [39]. The high proportion of arable land in the reservoir basin affected water turbidity. Chemicals such as pesticides and fertilizers used in agricultural production enter water bodies through rainwater wash-off, leading to increased permanganate index. Organic matter and other pollutants in domestic sewage from urban residents are also discharged into water bodies after treatment, also causing increased permanganate index.

The results from Spearman’s correlation analysis depicted in Figure 2B–D indicate that in regions subjected to a high human activity intensity, there is a significant positive correlation between construction land cover and the intensity of these human activities with concentrations of total phosphorus, permanganate index, and chlorophyll *a*. Conversely, such correlations were not observed in zones characterized by medium to low human activity levels. The observed trend suggests that escalated anthropogenic actions enhance the translocation of nutrients from urban expanses to aquatic systems, thereby augmenting the potential for eutrophication.

In agreement with the aforementioned findings, water quality assessments presented in Figure 2A demonstrated that locales of low human activity generally maintain superior water quality. In contrast, regions with medium to high levels of human activity intensity somewhat diminished water quality, categorized as either good or medium. Thus, the intensification of human activities is closely linked with the increased risk of nutrients being transported from construction land to water bodies, which in turn leads to a decline in water quality. It is inferred that lower human activity intensity may correspond to a reduced risk of water pollution, which could potentially improve water environmental quality.

#### 4.2. Differences in Phytoplankton Community Structure under Different Human Activity Intensities

By comparing the phytoplankton community structures under three intensities (low, medium, high) (Figure 3C–E), it was found that under a low intensity, the phytoplankton species were more diverse and the densities of different algal classes were more evenly

distributed. This indicates that compared with medium and high intensities, the impact of human activities on water bodies was relatively low and the aquatic ecological environment remained relatively stable. However, with the increase in human activity intensity from low to medium and high, the density of phytoplankton showed an increasing trend (Figure 3B), and the algal densities under high and low human activity intensities showed significant differences. With the increase in human activity intensity, the algal density increased accordingly, but the algal richness showed a decreasing trend. Specifically (Table 2), under a high intensity, the dominant phytoplankton classes included *Scenedesmus*, *Microcystis*, *Pseudanabaena* and *Cyclotella*, while *Microcystis* was the dominant class under a medium intensity, and no obvious dominant species was found under a low intensity. Among these dominant classes, *Scenedesmus* are commonly found planktonic algae that thrive in eutrophic still waters [40]. *Pseudanabaena* is also a representative species of harmful algal blooms in subtropical reservoirs, belonging to toxic species [41]. *Microcystis* is also the most common bloom-forming cyanobacteria [42]. These algae prefer eutrophic water bodies to survive. The growth and reproduction of these algae in water bodies demonstrate that the enhancement of human activity intensity leads to an increase in the nutrient (such as TN and TP) content of water bodies, increasing the potential risk of eutrophication and benefiting the massive growth and reproduction of *Scenedesmus*, *Pseudanabaena* and *Microcystis*, leading to their increased density and dominance, and increasing the risk of algal blooms in water bodies.

#### 4.3. Correlation between Phytoplankton and Water Environment

Phytoplankton serve as primary producers in aquatic ecosystems, displaying a heightened sensitivity to environmental factors such as water quality, hydrology, and climate. Their community structure directly reflects the water quality status [2]. The dominant phytoplankton classes in the Danjiangkou Reservoir Basin were mainly chlorophyta and Cyanobacteria. Both chlorophyta and Cyanobacteria in the Danjiangkou Reservoir Basin were closely related to permanganate index, which was a significant factor affecting the growth of chlorophyta and Cyanobacteria. The influence of environmental factors also differed under different human activity intensities. For example, chlorophyta were significantly correlated with permanganate index under medium and high intensities, while Cyanobacteria were significantly correlated with permanganate index under a medium intensity.

The permanganate index is a critical indicator for assessing water pollution levels, where elevated values signify heightened organic contamination [43]. Sources such as domestic wastewater, agricultural runoff, and livestock discharges contribute to the increased permanganate values in aquatic systems. Furthermore, phytoplankton proliferation exacerbates oxygen consumption and organic pollution through the release of their metabolic byproducts [44]. Studies within the Danjiangkou Reservoir Basin reveal a significant positive correlation between the permanganate index and several environmental parameters: WT, TP, TN, AN, and chl.*a*. Under medium- to high-intensity conditions, there is a noteworthy positive association with nutrient indicators pertinent to trophic status, like TN and TP; such a pattern is absent at low intensities. Higher water temperatures bolster the degradation of organic substances in water, thus spurring more redox reactions that raise the permanganate index [45]. Moreover, nutrients such as TP, TN, and AN—integral for algal growth—are implicated in shifts in the algal community structure [16]. Concurrently, elevated TN and TP levels are primary drivers of eutrophication and subsequent algal blooms [33]. All algae contain chlorophyll *a*, which is an important component of algal cells [46]. Under medium and high intensities, green algae were closely related to chlorophyll *a*, indicating that green algae were one of the main sources of chlorophyll *a* in water bodies. Genera such as *Scenedesmus* and *Coelastrum* are high-content chlorophyta, especially *Scenedesmus*, which prefers to grow and reproduce massively in nutrient-rich still water environments [41]. The permanganate index is the main environmental factor driving the changes in the algal community distribution in the Danjiangkou Reservoir area.

The intensification of human activities has led to an increase in the TN (Total Nitrogen) and TP (Total Phosphorus) content of the water body being transferred. The content of nutrients such as TN and TP can affect the permanganate index of the water, which in turn affects the growth of phytoplankton.

## 5. Conclusions

- (1) At a 500 m radius circular buffer zone, land use has the highest explanatory power for water quality. RDA analysis revealed that conductivity (Cond), turbidity (Turb), and the permanganate index ( $COD_{Mn}$ ) were the predominant environmental factors influenced by land use. Spearman's correlation analysis showed that the lower the intensity of human activities, the lower the risk of water body pollution and the higher the water environmental quality.
- (2) Escalation of human activities contributes to an elevated content of TN and TP in the water body, indirectly influencing the permanganate index. This permanganate index is the principal environmental driver altering the algal community distributions in the Danjiangkou Reservoir area, further impacting the growth of phytoplankton.
- (3) Increased human activity intensity led to higher nutrient levels in water bodies, increasing the potential risk of eutrophication. This is conducive to massive growth and reproduction of algae such as *Scenedesmus*, *Pseudanabaena* and *Microcystis*, leading to increased density and dominance, raising the risk of algal blooms in water bodies.

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## Appendix A

### Genera Detected in the Phytoplankton of Danjiangkou Reservoir

<i>Cyclotella</i>	<i>Chlamydomonas</i>	<i>Dictyosphaerium</i>	<i>Peridinium</i>
<i>Asterionella</i>	<i>Pteromonas</i>	<i>Hydrodictyon</i>	<i>Gymnodinium</i>
<i>Fragilaria</i>	<i>Chlorogonium</i>	<i>Westella</i>	<i>Ceratium</i>
<i>Staurastrum</i>	<i>Tetrablepharis</i>	<i>Staurastrum</i>	<i>Euglena</i>
<i>Synedra</i>	<i>Spermatozopsis</i>	<i>Cosmarium</i>	<i>Phacus</i>
<i>Navicula</i>	<i>Treubaria</i>	<i>Gonatozygon</i>	<i>Strombomonas</i>
<i>Cymbella</i>	<i>Microspora</i>	<i>Dimorphococcus</i>	<i>Trachelomonas</i>
<i>Achnanthes</i>	<i>Planctonema</i>	<i>Tetrastrum</i>	<i>Dinobryon</i>
<i>Gomphonema</i>	<i>Spirogyra</i>	<i>Oscillatoria</i>	<i>Kephyrion</i>
<i>Nitzschia</i>	<i>Stigeoclonium</i>	<i>Planktothrix</i>	<i>Synura</i>
<i>Surirella</i>	<i>Nephrocytium</i>	<i>Phormidium</i>	<i>Gomphosphaeria</i>
<i>Diatoma</i>	<i>Quadrigula</i>	<i>Spirulina</i>	<i>Golenkinia</i>
<i>Cocconeis</i>	<i>Chodatella</i>	<i>Cylindrospermopsis</i>	<i>Melosira</i>
<i>Rhizosolenia</i>	<i>Ankistrodesmus</i>	<i>Anabaenopsis</i>	<i>Coelosphaerium</i>
<i>Attheya</i>	<i>Tetraëdron</i>	<i>Cuspidothrix</i>	<i>Schroederia</i>

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**Genera Detected in the Phytoplankton of Danjiangkou Reservoir**


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<i>Amphora</i>	<i>Kirchneriella</i>	<i>Aphanizomenon</i>	<i>Ulothrix</i>
<i>Eunotia</i>	<i>Selenastrum</i>	<i>Dactylococcopsis</i>	<i>Actinastrum</i>
<i>Diploneis</i>	<i>Mougeotia</i>	<i>Raphidiopsis</i>	<i>Cryptomonas</i>
<i>Hantzschia</i>	<i>Scenedesmus</i>	<i>Pseudanabaena</i>	<i>Oocystis</i>
<i>Meridion</i>	<i>Chlorella</i>	<i>Merismopedia</i>	<i>Eudorina</i>
<i>Cymatopleura</i>	<i>Crucigenia</i>	<i>Anabaena</i>	<i>Lyngbya</i>
<i>Ceratoneis</i>	<i>Coelastrum</i>	<i>Chroococcus</i>	<i>Limnothrix</i>
<i>Gyrosigma</i>	<i>Closterium</i>	<i>Microcystis</i>	<i>Pandorina</i>
<i>Amphiprora</i>	<i>Pediastrum</i>		

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