INVESTIGATION AND PROTECTION STRATEGY OF PLANKTON IN THE HARBIN SECTION OF THE SONGHUA RIVER, CHINA

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Abstract. In order to study the structural characteristics and influencing factors of plankton communities in different seasons in the Harbin section of the Songhua River, China, we conducted a plankton sampling survey in 8 sections of the water from 2011 to 2021. During the research period, we identified a total of 101 species of phytoplankton, belonging to 7 phyla and 61 genera, of which Chlorella and Diatom phylum were mainly present in spring, summer and autumn. At the same time, a total of 30 species of zooplankton was identified in 4 categories, mainly protozoa and rotifers in spring, summer and autumn. In terms of seasons, we found that the number of species, abundance and biomass of plankton in summer was lower than that in spring and autumn; while in space, the species of plankton downstream are higher than that in the upstream, and there are significant differences between the center and shore of the Songhua River. Based on the water quality evaluation results of the Shannon-Wiener (H') and Pielou (J') biodiversity index, the water quality of the research area of the Harbin section of the Songhua River is slightly polluted. Generally speaking, in the past 11 years, the species change in the Harbin section of the Songhua River had been relatively stable, the abundance and biomass had shown a trend of rising first and then falling, and the water quality had gradually improved.
Keywords: *Songhua River, phytoplankton, zooplankton, community structure, water quality evaluation*

Introduction

With the interference of human activities and changes in the global environment, water pollution and eutrophication of freshwater ecosystems occur frequently, and the protection and management of large water bodies such as rivers have become the guarantee and source of sustainable ecological, economic, and social development (Wang and Wang, 2017). In the river ecosystems, the change of phytoplankton community structure is closely related to the water ecological environment (Tian et al., 2012), and its quantitative distribution and species composition have an indicator effect on environmental level. Indicator organisms in river ecosystems include fish, plankton, benthic animals, etc. Among them, plankton is an important part of the river ecosystem as an important link in the food chain affecting the overall capacity of the river ecosystem and the consumption of biological resources. Plankton includes phytoplankton and zooplankton (Zhao et al., 2021), of which phytoplankton is the primary producer of the aquatic ecosystem and the basic link of the food chain (Zhang et al., 2021); Zooplankton, as secondary producers, feed on phytoplankton and organic detritus and are an important link in the food chain (Li et al., 2019). Plankton is more sensitive to changes in the water environment (Jiang et al., 2024). Once the water environment changes, plankton reacts quickly. Therefore, the water pollution and water eutrophication of rivers can be judged through the structure of plankton communities (Hao et al., 2020).

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The Songhua River is an important surface water resource in northern China. It has a variety of functions such as urban drinking water, industrial and agricultural water, and carrying industrial and agricultural domestic sewage discharge. After the Songhua River pollution incident in 2005, the biodiversity and ecosystem service functions of the Songhua River Basin were damaged to varying degrees (Lin et al., 2016). Organic pollution is the most important environmental problem of the Songhua River. Organic matter has been detected in all major river sections of the main stream, and organic pollution during the freezing period is more prominent (Li et al., 2024). Since the "Twelfth Five-Year Plan", the Songhua River Basin has been listed as an important part of the state's water pollution prevention and control plan for key river basins. The prevention and control of pollution in Zhejiang and the protection of water source has been strengthened, the quality of the water environment has been significantly improved, and the water ecosystem has been gradually restored. At present, the ecological status of water bodies is expounded based on the relationship between the characteristics of aquatic biological communities and the water environment, and the research to guide the ecological restoration of water bodies has been widely used in freshwater ecosystems such as rivers, lakes and reservoirs (Jiang and Dai, 2023; Deininger et al., 2017). At present, there is little research on the long-term evolution of plankton in the Harbin River basin of the Songhua River, and the succession law of the time scale can more realistically and intuitively reflect the change trend and governance effect of the quality of the water ecological environment in the river basin (Otten, 2010).

This study takes the Harbin section of the Songhua River as the research area. From the perspective of temporal and space-time distribution, it carries out an investigation of the community structure, abundance and biomass of plankton in the Harbin section of the Songhua River. From the spatial and temporal distribution characteristics of the biological community of environmental changes, the relationship between them is analyzed by using the Shannon-Wiener diversity index and the Pielou uniformity index, and analyzes and summarizes the community structure and inter-annual changes of plankton in the Harbin section of the Songhua River from 2011 to 2021, in order to provide a scientific basis and theoretical basis for the water environment management and the restoration of the ecological environment of the Harbin section of the Songhua River.

Materials and methods

Overview of the research area

The Harbin section of the Songhua River (124°02'E-128°03'E, 45°09'N-46°57'N) belongs to the middle reaches of the Songhua River, running through Harbin from southwest to northeast, with a total length of about 70 kilometers. The climate in this area belongs to the temperate continental monsoon climate. The precipitation and runoff show obvious seasonal changes, and the distribution is extremely uneven. The annual runoff is mainly concentrated from July to September, while the average temperature in winter is below zero degrees. The ground freezing period is from the end of September to the beginning of October, and it will not be solved until April or May of the following year. Freeze, the runoff is the most limited. The Harbin section of the Songhua River plays a key role in the industrial and agricultural production and domestic water supply of in Harbin, and its waters are rich in phytoplankton and

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zooplankton. These ecological resources not only maintain the rich species diversity in the Songhua River Basin, but also maintain the integrity of the overall water ecosystem.

Sampling time and place

The survey was conducted in three times, the specific time of 2011-2021 (*Table A1* in the *Appendix*). According to the ecological characteristics of the Harbin section of the Songhua River, China, taking into account the distribution of water quality monitoring points in the water source, the survey of phytoplankton and zooplankton was sampled in 8 sections, namely 1# (Daliangzi), 2# (Hulan Estuary), 3# (Sanjiazi Beach Protection Area), 4# (Cement Factory), 5# (Er Shuiyuan), 6# (Yangmingtan Reserve), 7# (Jinhewan Wetland Reserve), 8# (San Jiazi). The section is based on the import and export of the Harbin section of the Songhua River and the possible pollution sources. 1# and 8# are the downstream and upstream of the Harbin section of the Songhua River respectively; 2# the upstream is the Hulan River with large discharge of domestic sewage; 4# is a cement factory and one of the sewage factories along the coast of the Harbin section; 5# used to be the water source of Harbin City, but due to the comprehensive management of the change of the water source to the Mopanshan Reservoir in 2008. It is not as good as before; 7# Jinhewan Wetland Park has frequent activities; 3# and 6# are protected areas (*Fig. 1; Table 1*). The physico-chemical properties of the water as well as the water depth was measured and reported in the manuscript, as these factors significantly influencing the species composition and diversity in 2021 (*Tables A1* and *A3* in the *Appendix*).

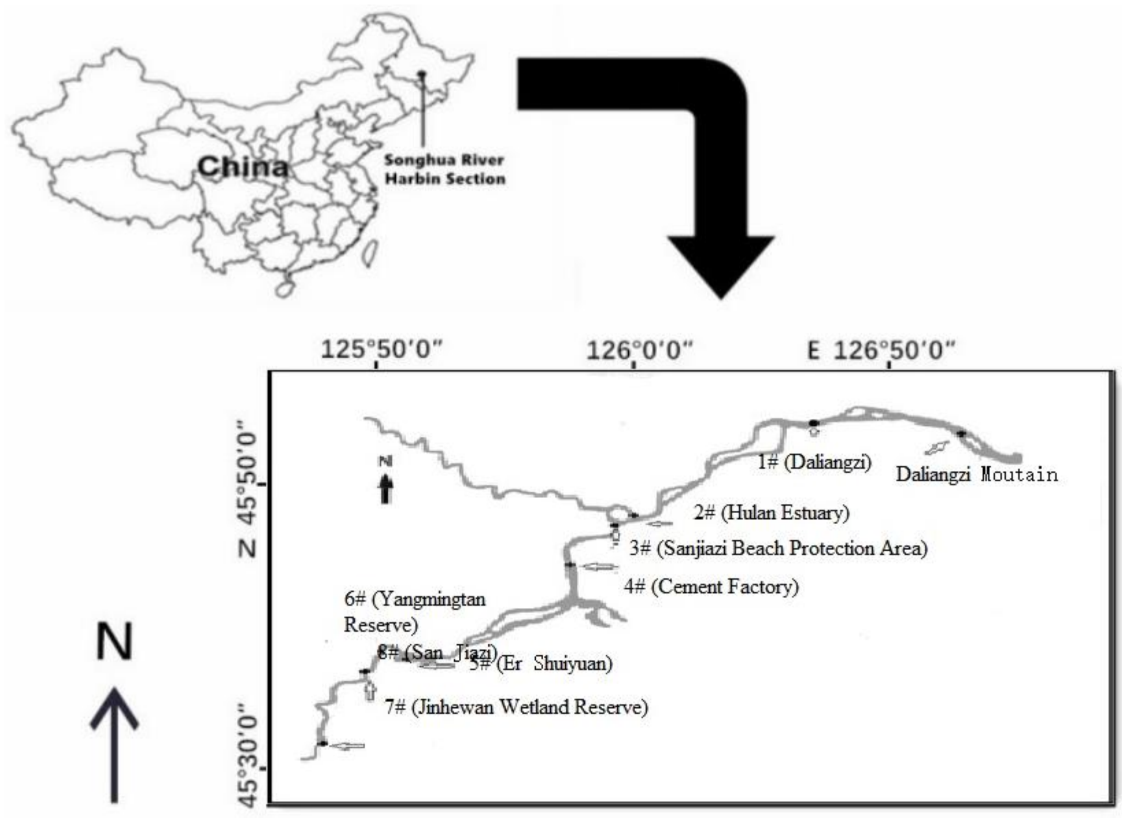

Figure 1. *Map showing sampling locations in the Songhua River, China*

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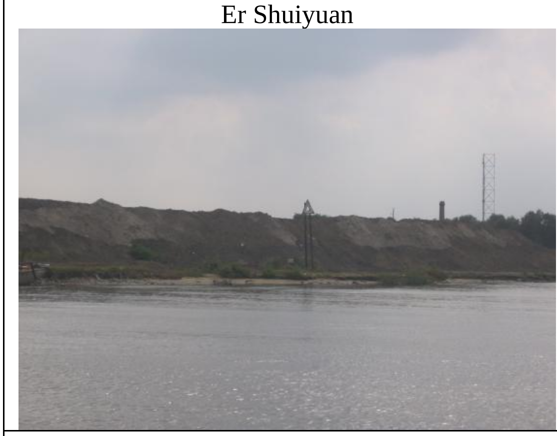
Table 1. *The photos of the sampling locations in the Songhua River, China*

Daliangzi 	Hulan Estuary 
Sanjiazi Beach Protection Area 	Cement Factory 
Er Shuiyuan 	Yangmingtan Reserve 
Jinhewan Wetland Reserve 	San Jiazi 

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Monitoring methods and contents

The large-scale fixed-point survey method in inland waters is adopted to select representative aquatic biological survey and monitoring points. The survey includes: phytoplankton and zooplankton.

Phytoplankton investigation methods

The qualitative samples of phytoplankton are taken in a horizontal "∞" shape at 50 cm below the surface of the water with No. 25 plankton net; quantitative samples of phytoplankton is collected with a 1 L water harvester to collect 1 L of mixed water samples in the upper, middle and lower water layers. The sample is fixed with 1.5% iodine solution and brought back indoors. After precipitation and concentration, qualitative and quantitative analysis is performed with 40 times magnification by optical microscope (Motic BA210, Motic Inc., China) (V = 0.1 mL). Phytoplankton species were identified using the references from different literature (Hustedt, 1930; Prescott, 1954; Patrick et al., 1966; Komarek, 1983; Lange-Bertalot, 2001; Hu et al., 2006).

Zooplankton survey methods

The qualitative sample is obtained in a horizontal "∞" shape at 50 cm–100 cm under the surface of the No. 13 plankton net; the quantitative sample of zooplankton is taken with a 5 L glassiness water harvester to take 20 L mixed water samples in the upper, middle and lower layers, and then filtered and concentrated with No. 13 plankton net and brought back to the laboratory for optical display. Identification under the microscope. In the laboratory, zooplankton samples are identified using a microscope at 200×magnification (Motic BA210, Motic Inc., China) (V = 1 mL). In this study, we identified zooplankton species to use the references from different literature (Wang, 1961; Crustacean Research Group, 1979; Jiang and Du, 1979; Han and Shu, 1995).

Data processing

The diversity analysis of plankton survey data is calculated by Shannon-Wiener diversity index (*H′*), Pielou index (*J*), and advantage index (*Y*). The formula is as follows (Bureau of Fisheries et al., 2021):

$$H' = -\sum_{i=1}^{s} P_i \log_2 P_i$$
$$J = \frac{H'}{\log_2 S} \qquad \text{(Eq.1)}$$
$$Y = fi * pi$$

In the formula, S is the total number of species, *N* is the total number of individuals of all species, p_i is the proportion of the number of individuals of the *i* species in the total number of individuals (n_i/N), f_i is the frequency of the *i* species at each sampling time, and when $y > 0.02$, it is regarded as the dominant species. With reference to relevant literature (Yang et al., 2021; Lan et al., 2021; Chenn et al., 2022), the evaluation criteria of other indexes are shown in *Table 2.*

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Table 2. *Evaluation criteria for the Shannon-Wiener index and the Pielou index*

Shannon-Wiener diversity index (H')	Water quality type	Pielou uniformity index (J)	Water quality type
0	Severe pollution	$0 \leq J < 0.3$	Heavy pollution
$0 < H' \leq 1$	Heavy pollution eutrophic type	$0.3 \leq J < 0.5$	Medium pollution
$1 < H' \leq 2$	Medium pollution and medium nutrient type	$0.5 \leq J < 0.8$	Light pollution
$2 < H' \leq 3$	Nutrient type in light pollution	$0.8 \leq J < 1.0$	Clean
$H' > 3$	Clean and poor nutrient type		

Results and analysis

Species composition and horizontal distribution characteristics of phytoplankton

During the research period, a total of 7 phytoplankton species of 61 genera and 101 variants were detected in the Harbin section of the Songhua River, of which the largest number of Chlorophyta species, 44 species, accounting for 44%; Bacillariophyta followed by 32 species, accounting for 32%; 13 species of Cyanophyta, accounting for 13%; 8 species of Euglenophyta, accounting for 8%; 2 species of Cryptophyta, accounting for 2%; Chrysophyta there are 1 species of Dorus and 1 species of Pyrroptata, accounting for 1% respectively. Chlorophyta and Bacillariophyta are more suitable for nutrient-rich water bodies, and are usually regarded as one of the indicators of water eutrophication (Liu et al., 2023). It can be seen that the water bodies in the research area are polluted.

There are certain differences in the number of species of phytoplankton in different seasons. The sampling point with the largest number of phytoplankton species appears at the 7# sampling point in spring and the 6# sampling point in autumn, with 37 phytoplankton each; the sample point with the least number of phytoplankton species is the 7# sampling point in summer, and only 10 species of phytoplankton appear. This may be due to the possibility of excessive sunlight in summer, resulting in an increase in water temperature, which inhibits the growth of some phytoplankton (Wang et al., 2020). However, some studies have shown that in the Rhine River in the summer of 2003, due to the increase in water temperature, the number of phytoplankton in the water body increased significantly, and the risk of outbreaks also continued to increase (Hardenbicker et al., 2017), indicating that the temperature may decrease. The number of species of phytoplankton increases the number of dominant species (*Fig. 2*).

The abundance of phytoplankton and the horizontal distribution of biomass

The spring abundance value of phytoplankton in the Harbin section of the Songhua River is the highest, 166.62×10^4 ind./L, while the lowest abundance in summer is 62.31×10^4 ind./L; The biomass is the highest in autumn and the lowest in summer, with 2.20 mg/L and 0.71 mg/L respectively. The abundance and biomass of phytoplankton in the Songhua River Basin is quite different between 13 sampling points in the three seasons. The amenity in spring, summer and autumn changes at 19.20×10^4 Ind./L - 331.20×10^4 ind. Between/L, the highest is the 7# sampling point in spring, which is 331.20×10^4 ind./L, the lowest is the summer 7# sampling point, 19.20×10^4 ind./L. The biomass is between 0.21 mg/L and 4.21 mg/L throughout the year. The highest is the spring 7# sampling point, which is 4.21 mg/L, and the lowest is the summer 7# sampling point, which is 0.21 mg/L. The seasonal changes of abundance and biomass

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are obvious, and the summer is significantly lower than that of spring and autumn, which is consistent with the change trend of the number of phytoplankton species. Among the sampling points of the horizontal distribution, the center and shore of the Songhua River is significantly different (*Fig. 3*).

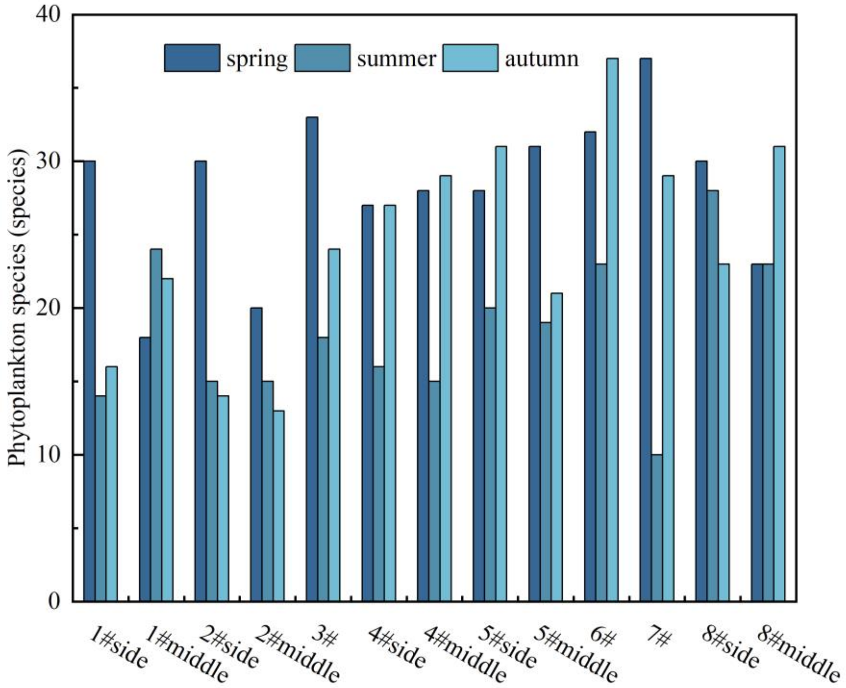

Figure 2. *Characteristics of the horizontal distribution of phytoplankton in 2021*

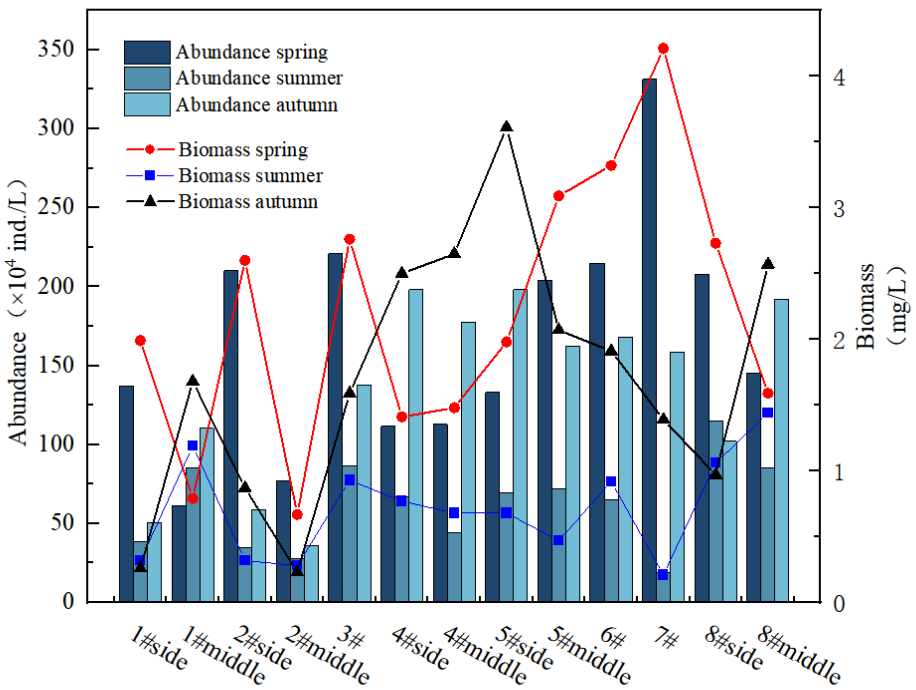

Figure 3. *Phytoplankton abundance (unit: $\times 10^4$ ind./L) and biomass (unit: mg/L) of phytoplankton sampling points in the Harbin section of the Songhua River, China in 2021*

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Advantageous and common species of phytoplankton

According to the frequency and abundance of phytoplankton, the dominant species is determined by the dominant species (y > 0.02). A total of 7 dominant species was found in the three seasons of the Harbin section of the Songhua River, including 3 species of Bacillariophyta: *Fragilaria capucina*, *Synedra acus* and *Cyclotella meneghinian*; 2 species of Chlorophyta: *Chlorella vulgaris* and *Chlamydomonas ovalis*; and *Chromulina elegans* of Chrysophyta and the fine-grained *Euglenophyta Trach* and *Elomonas granulosa* of the Euglenophyta.

It can be seen from *Table 3* that the dominant species do not change much with the season. There are 9 dominant species in spring, and 8 dominant species in summer and autumn. The dominant species in spring and summer are mainly diatom and Chlorella, and the dominant species in autumn are concentrated in diatom, *Chrysophyceae* and *Chlorella*. From the perspective of advantages, the advantages of spring, summer and autumn are not much different. The advantages of spring are between 0.03-0.21, the advantages of summer are between 0.02-0.22, and the advantages of autumn are between 0.02-0.23. The highest value of spring dominance occurs in the *Cyclotella meneghiniana* of the Bacillariophyta, which is 0.21; the highest value of the advantage in summer and autumn appears in the *Chrysophyta Chromulina elegans*, which is 0.22 and 0.23 respectively.

Table 3. *The dominant species of phytoplankton in each season in the Harbin section of the Songhua River, China in 2021*

Quarter	Dominant species		Dominance
Spring	Bacillariophyta	*Fragilaria capucina*	0.09
		Asterionella formosa	0.05
		Synedra acus	0.03
		Synedra amphicephala	0.03
		Cyclotella meneghiniana	0.21
	Chrysophyta	*Chromulina elegans*	0.19
	Chlorophyta	*Ankistrodesmus angustus*	0.03
		Chlorella vulgaris	0.03
		Chlamydomonas ovalis	0.08
Summer	Bacillariophyta	*Nitzschia palea*	0.05
		Synedra acus	0.02
		Cyclotella meneghiniana	0.20
	Chrysophyta	*Chromulina elegans*	0.22
	Euglenophyta	*Trachelomonas granulosa*	0.03
	Chlorophyta	*Chlorella vulgaris*	0.03
		Ulothris variabilis	0.02
		Chlamydomonas ovalis	0.06
Autumn	Bacillariophyta	*Synedra acus*	0.02
		Cyclotella meneghiniana	0.19
	Chrysophyta	*Chromulina elegans*	0.23
	Euglenophyta	*Trachelomonas granulosa*	0.08
		Trachelomonas cylindrica	0.02
	Chlorophyta	*Chlorella vulgaris*	0.02
		Chlamydomonas ovalis	0.13
		Chlamydomonas globosa	0.03

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According to the principle of frequency > 65%, it is determined as a common species, and the common species of phytoplankton in the Songhua River are shown in *Table 4*.

Table 4. *Common species of phytoplankton in the Harbin section of the Songhua River, China in 2021*

Quarter	Common species		Frequency
Spring	Bacillariophyta	*Navicula exigua*	0.77
		Fragilaria capucina	0.92
		Asterionella formosa	0.92
		Synedra acus	1.00
		Synedra amphicephala	0.92
		Synedra tabulata	0.85
		Cyclotella meneghiniana	1.00
	Chrysophyta	*Chromulina elegans*	1.00
	Euglenophyta	*Trachelomonas granulosa*	0.77
	Chlorophyta	*Chodatella quadriseta*	0.69
		Ankistrodesmus angustus	0.92
		Chlorella vulgaris	1.00
		Chlamydomonas ovalis	1.00
		Chlamydomonas globosa	0.77
Summer	Bacillariophyta	*Nitzschia palea*	1.00
		Cyclotella meneghiniana	0.92
		Melosira varians	0.69
	Chrysophyta	*Chromulina elegans*	1.00
	Euglenophyta	*Trachelomonas granulosa*	0.69
	Chlorophyta	*Chlorella vulgaris*	0.69
		Ulothris variabilis	0.69
		Chlamydomonas ovalis	0.92
		Chlamydomonas globosa	0.77
Autumn	Bacillariophyta	*Synedra acus*	0.77
		Cyclotella meneghiniana	1.00
	Chrysophyta	*Chromulina elegans*	1.00
	Euglenophyta	*Trachelomonas granulosa*	0.92
		Trachelomonas cylindrica	0.92
	Chlorophyta	*Chodatella quadriseta*	0.69
		Chlorella vulgaris	0.85
		Stichococcus bacillaris	0.85
		Ulothris variabilis	0.85
		Chlamydomonas ovalis	0.92
		Chlamydomonas globosa	0.92

Horizontal distribution of phytoplankton diversity

The Shannon-Wiener Diversity Index *(H')*, Pielou Uniformity Index (*J'*) and the water quality evaluation of water environments at different sampling points is shown in *Figure 4*. The highest point of the annual Shannon-Wiener index is at sampling point

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6#, the average is 3.84, the second highest point is at sampling point 8#, the average point is 3.64, the lowest point is at sampling point 7#, and the average is 3.40. The Shannon-Wiener index at the upstream sampling point is slightly lower than the downstream index, and the water quality evaluation shows light pollution. The highest point of Pielou uniformity index (*J'*) is at the sampling point 2#, the average point is 0.835, the second highest point is at the sampling point 1# and 4#, the average point is 0.805, the lowest point is at the sampling points 3# and 7#, the average point is 0.77, the upstream sampling point is slightly higher than the downstream index, water quality evaluation The price is shown as light pollution. Judging from the results of water quality evaluation, the water environment difference between the upstream and downstream of the Harbin section of the Songhua River is relatively small, and the whole is in the stage of mild pollution.

The seasonal difference of the Shannon-Wiener index is not significant. The range of change in spring is 3.22-4.16, and the average is 3.73; the range of change in summer is 2.85-3.96, and the average is 3.48; the range of change in autumn is 3.04-3.95, and the average is 3.48. Seasonal change is characterized by higher spring than summer and autumn. The seasonal difference of Pielou index changes significantly. The range of change in spring is 0.71-0.85, with an average of 0.78 in 2021; the range of change in summer is 0.75-0.96, with an average of 0.84 in 2021; the range of change in autumn is 0.72-0.82, with an average of 0.77 in 2021. It is characterized by full-youth pollution, and the summer is higher than that in spring and autumn. The results of the Shannon-Wiener index (*H'*) and Pielou index (*J'*) show that the environmental quality in spring and summer is better than that in autumn. In spring and summer, in the hydrological wet season, high water level, fast flow rate, strong water self-purification capacity. In the dry autumn season, the water level drops, and the flow rate is slow, which is not conducive to water self-purification.

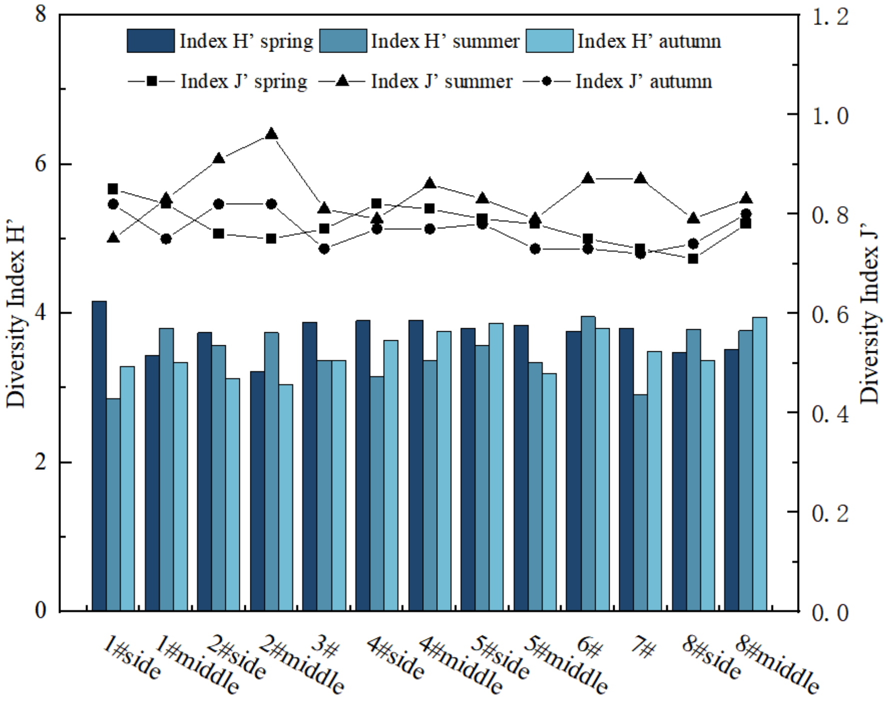

***Figure 4.** Pollution evaluation of diversity index H' and J' in the Harbin section of the Songhua River, China in 2021*

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Summary of the change law of phytoplankton in 2011-2021

In the past 11 years, a total of 137 species of phytoplankton has been identified in the Harbin section of the Songhua River, China, including 56 species of Chlorophyta, accounting for 40.9%; 55 species of Bacillariophyta, accounting for 40.1%; 11 species of Cyanophyta, accounting for 8.0%; 8 species of Euglenophyta, accounting for 5.8%; 2 species of Chrysophyceae and Cryptophyta, accounting for 1.5%. 1 species of Pyrroptata, accounting for 0.7%. Each year, 6-7 species of phytoplankton and 48-125 species were identified, with an average of 96 species, the lowest in 2013 and the highest in 2011 (*Fig. 5*).

The change trend of the number of species of phytoplankton takes 2013 as the demarcation point, and the shock decreases from 2013, and then shows a stable trend of change, basically maintaining about 100 species. According to the survey, there was a huge flood in 2013. The erosion of floods will bring sediment, nutrients and other substances into rivers and lakes. The environmental capacity of the water body will continue to change with the process of the flood, and may cause the concentration of pollutants in the water body to rise, causing the deterioration of water quality (Cheng et al., 2005).

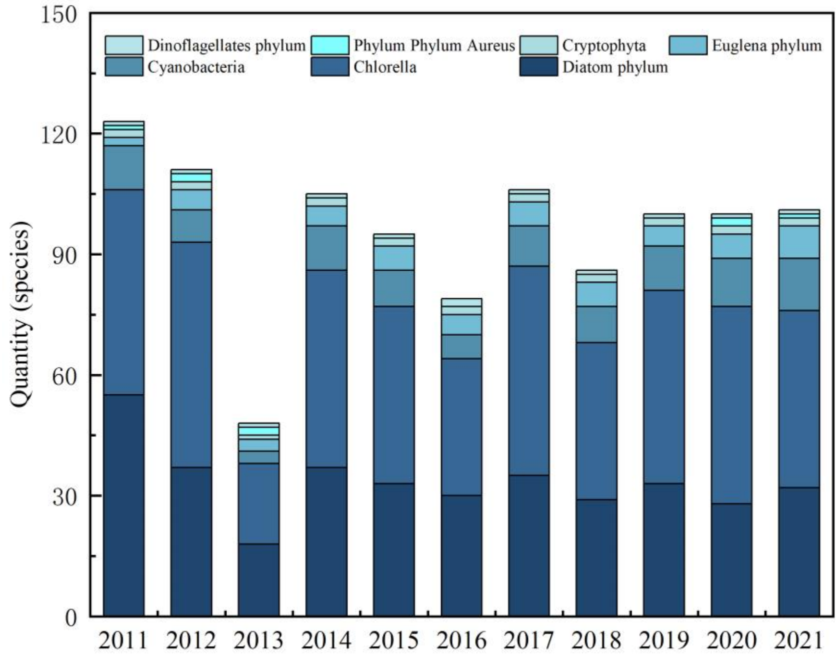

Figure 5. *Changes in the number of phytoplankton species from 2011 to 2021*

During the survey, the range of changes in the abundance of phytoplankton in spring, summer and autumn in the Harbin section of the Songhua River is 76.8-415.9 ind./L, 25.02-285.9 ind./L, 35.17-479.8 ind./L, the range of change in the average abundance is 45.66-353.6 ind./L, the highest average abundance of plankton in the past 11 years was 353.6 ind./L in 2015, the lowest value appeared in 2016 at 45.66 ind./L (*Fig. 6*). The overall change of abundance shows a trend of rising first and then decreasing. Among them, the abundance was at a high level from 2011 to 2015, and the abundance of phytoplankton varies significantly from year to year. The range of biomass changes of phytoplankton in the Harbin section of the Songhua River in spring, summer and

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autumn is 1.272-7.072 mg/L, 0.341-3.029 mg/L, and 0.601-2.525 mg/L respectively, and the average biomass change range is 0.873-3.407 mg/L, the highest average biomass of phytoplankton in the past 11 years was 3.407 mg/L in 2018, and the lowest value was 0.873 mg/L in 2016. The overall change of biomass has not changed much, of which the biomass is at a high level from 2017 to 2020 (*Fig. 7*).

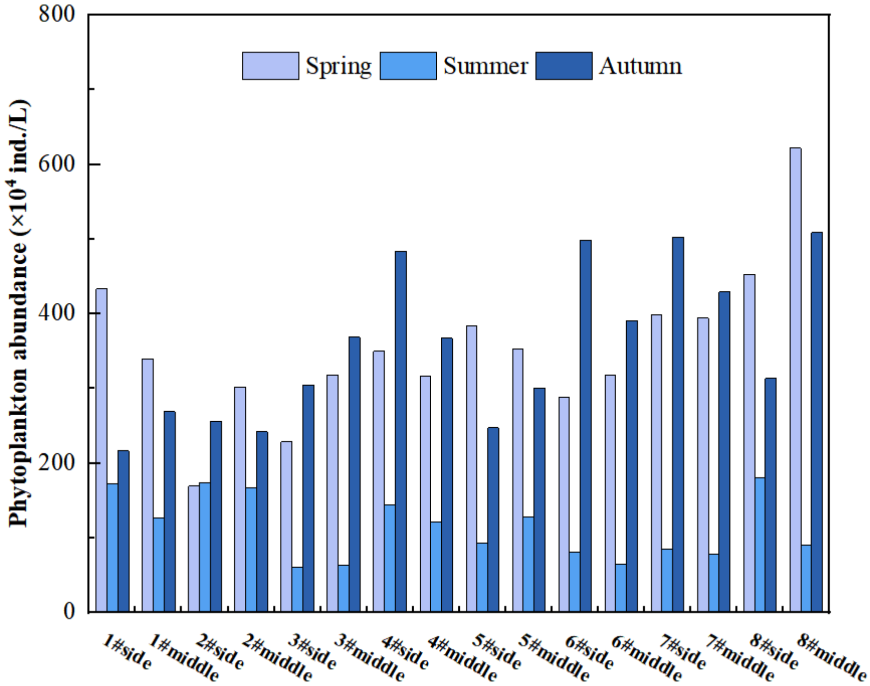

***Figure 6.** Changes in phytoplankton abundance from 2011 to 2021*

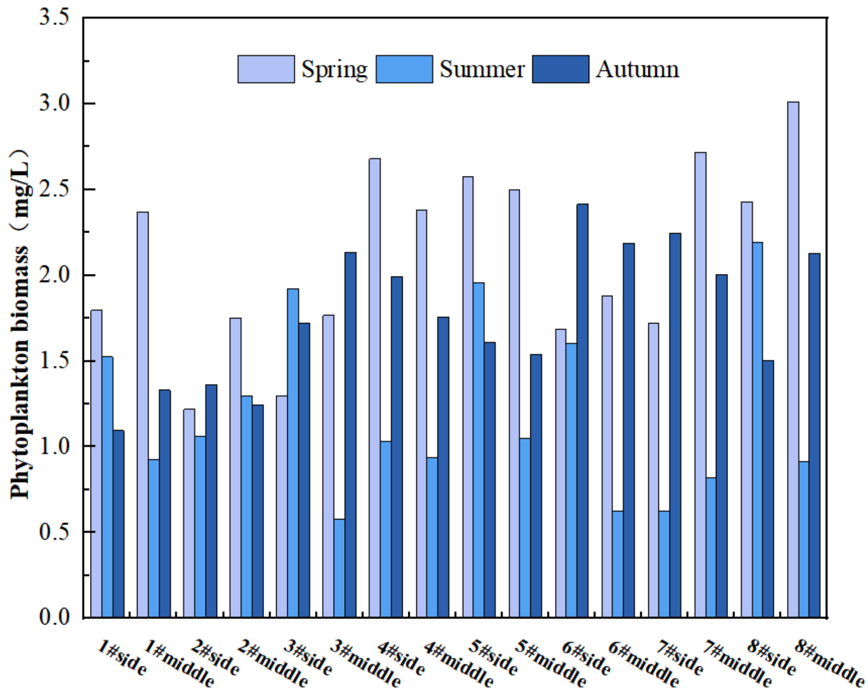

***Figure 7.** Changes in phytoplankton biomass from 2011 to 2021*

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In the past 11 years, the change of species diversity of phytoplankton in the Harbin section of the Songhua River is analyzed. The ecological environment of the Harbin section of the Songhua River gradually tends to be slightly polluted or pollution-free, but the pollution is serious in summer. The Shannon-Wiener index ranges 1.8557-3.807, the lowest in 2013 and the highest in 2020. The Shannon-Weave index of phytoplankton from 2017 to 2021 fluctuates less, and the shock range from 2012 to 2015. It is getting bigger, and the overall trend is decreasing first and then rising (*Fig. 8*). The Pielou index ranges from 0.365 to 0.813, the lowest in 2015 and the highest in 2020. There are certain fluctuations in each year, and it rises year by year from 2015 to 2021. It shows that the health status of the water ecological environment is being gradually improved (*Fig. 9*).

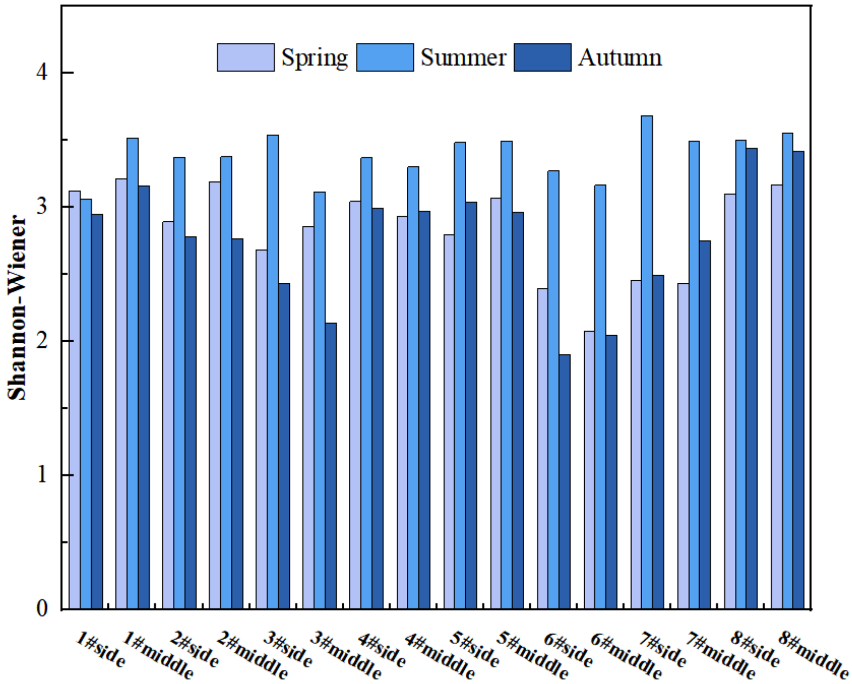

Figure 8. *Changing pattern of Shannon-Wiener index of phytoplankton from 2011 to 2021*

Species composition and horizontal distribution characteristics of zooplankton

During the survey, a total of 30 species of zooplankton was identified, including 6 genera and 8 species of protozoa, accounting for 27% of the total number of zooplankton; 12 species of 9 genera of rotifers, accounting for 40%, 6 species of 5 genera of cladoceran, accounting for 20%, and 4 species of 4 genera of copepods, accounting for 13%. Rotifers are more adaptable to nutrient-rich water bodies and are of great significance in the study of ecosystem structure, function and biological productivity (*Fig. 10*).

There are certain differences in the number of zooplankton species in different seasons, and the number of zooplankton species at each sampling point shows that the largest number of species is the sampling points of 7# and 8# in spring, which are 11 species respectively; followed by 6# sampling points in spring, which is 10 species; the 4 sampling points with the least number of species are 1# side and 5# side 5# middle and 8# side in summer, which are 3 species respectively. Studies have shown that

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temperature is the main factor affecting the species and number of zooplankton (Tao et al., 2004). Generally speaking, in summer and autumn, the water temperature is relatively high, the food source is relatively sufficient, their reproduction is fast, and the population grows rapidly (Zhong et al., 2011). Unlike the results of this study, it shows that temperature is not the only influencing factor.

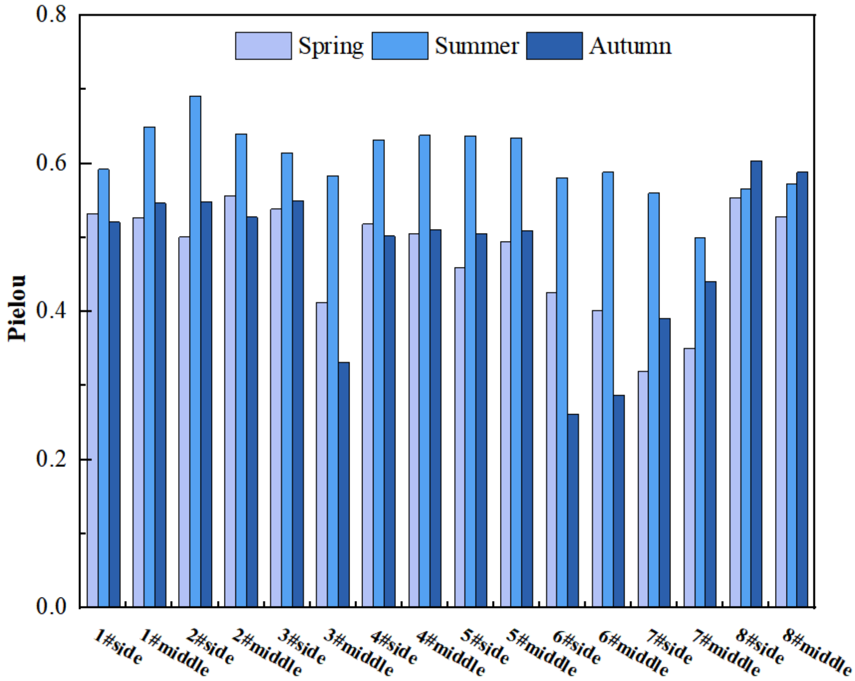

Figure 9. *Changes pattern of Pielou index of phytoplankton from 2011 to 2021*

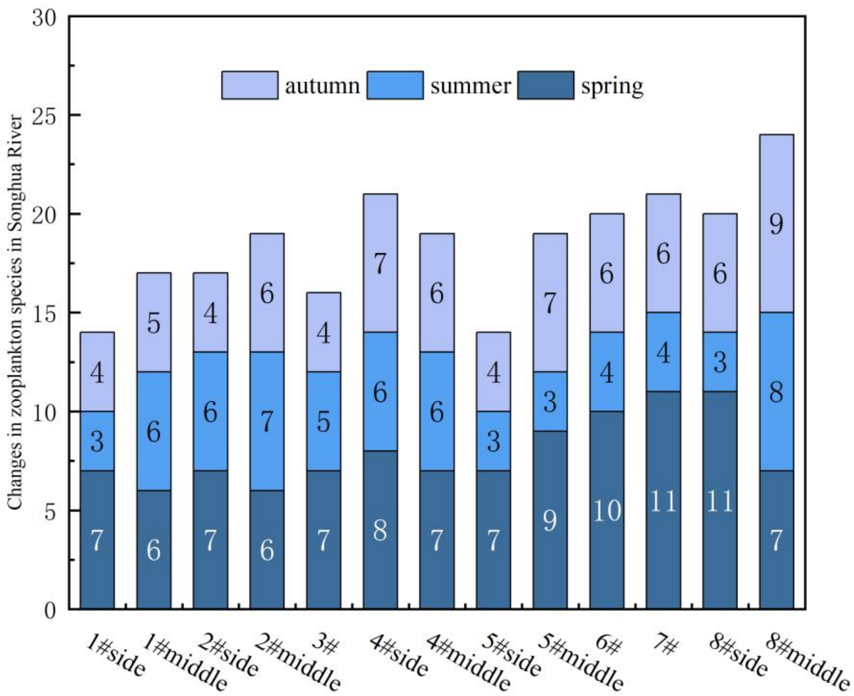

Figure 10. *Horizontal distribution characteristics of zooplankton in 2021*

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Distribution of zooplankton abundance and biomass levels

As can be seen from *Figure 11*, the abundance value of zooplankton in the Harbin section of the Songhua River is the highest in spring, which is 1392.80 ind./L, and the abundance of summer is the lowest, 358.56 ind./L; The biomass is the highest in spring and the lowest in autumn, 0.56 mg/L and 0.08 mg/L respectively. There are significant differences among the 13 sampling points of zooplankton and biomass in the Songhua River Basin during the three seasons. The abundance of spring, summer and autumn varies by 31.05 ind./L-3210.15 ind./L. Between the highest is the sampling point in spring 8#, which is 3210.15 ind./L, the lowest is the summer 3# sampling point, which is 31.05 ind./L. The biomass ranges from 0.0228 mg/L to 1.6696 mg/L throughout the year, with the highest sampling point in 8# in spring, which is 1.6696 mg/L, followed by the sampling point of 7# in spring, which is 1.2966 mg/L, and the lowest is the side sampling point of 5# in summer, which is 0.0228 mg/L. The sub-low is the sampling point of 5# in summer, which is 0.0291 mg/L. The seasonal changes of abundance and biomass are obvious. Spring is significantly higher than that of summer and autumn, which is consistent with the change of phytoplankton species. Among the sampling points of the horizontal distribution, the center of the Songhua River and the shore are significantly different.

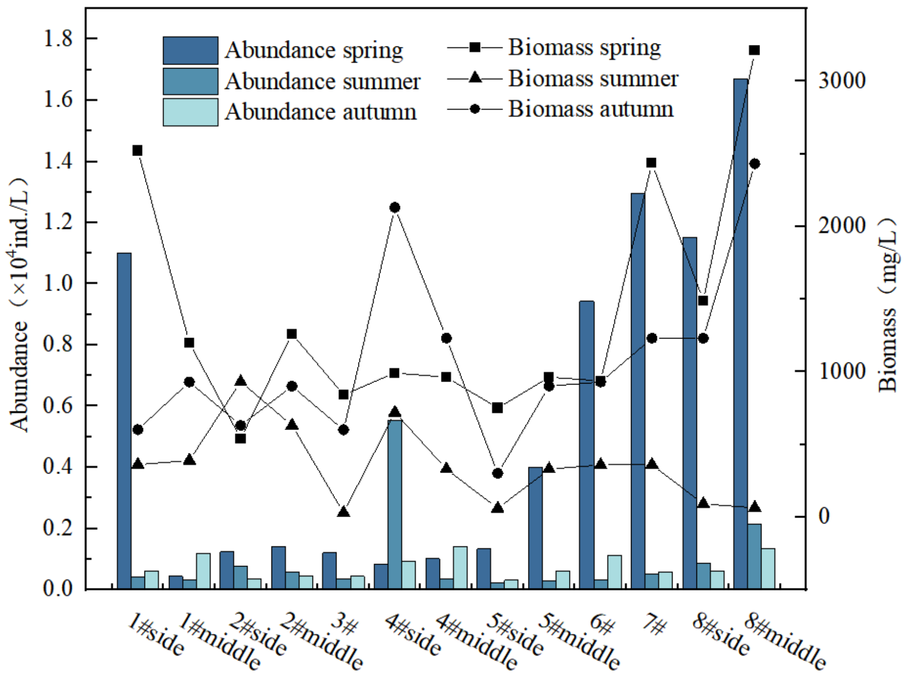

Figure 11. *Abundance and biomass of zooplankton in Songhua River, China in 2021*

Advantageous and common species of zooplankton

According to the frequency and abundance of zooplankton, the dominant species are determined by a dominance y > 0.02 as the boundary. A total of 8 dominant species are found in three seasons of the Harbin section of the Songhua River, including 3 species of protozoa, *Strombidium viride* and *Strobilidium velox* and *Vorticella microstoma*; 2 species of rotifer, *Polyarthra trigla* and *Keratella cochlearis*; 1 species of Cladocera, *Bosmina longirostris*; 2 species of Copepods, *Microcyclops javanus* and *Nauplii*.

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As can be seen from *Table 5* that the dominant species do not change much with the seasons. The dominant species are the most in autumn, with 6 species, 5 species in spring and 4 species in summer. In spring, the dominant species are mainly Rotifers, Cladicornis and Copepods. In summer, the dominant species are mainly Rotifers and Copepods. In autumn, the dominant species are Protozoa, Cladicornis and Copepods. From the perspective of advantages, the advantages of spring, summer and autumn are not much different. The advantages of spring is between 0.02-0.69, the advantages of summer are between 0.02-0.15, and the advantage in autumn are between 0.03-0.32. The highest advantage in spring is found in the Copepods, which is 0.69; the highest value of the advantage in summer and autumn is found in the Copepods, *Nauplii* and Microcyclops, which are 0.15 and 0.32 respectively.

Table 5. *Dominant species of zooplankton in the season in Songhua River, China*

Quarter	Dominant species		Dominance
Spring	Rotifer	*Polyarthra trigla*	0.02
		Keratella cochlearis	0.02
	Cladocera	*Bosmina longirostris*	0.03
	Copepods	*Microcyclops javanus*	0.08
		Nauplii	0.69
Summer	Rotifer	*Polyarthra trigla*	0.07
		Trichocerca ousilla	0.02
	Copepods	*Microcyclops javanus*	0.14
		Nauplii	0.15
Autumn	Protozoa	*Strombidium viride*	0.05
		Strobilidium velox	0.03
		Vorticella microstoma	0.03
	Cladocera	*Bosmina longirostris*	0.03
	Copepods	*Microcyclops javanus*	0.32
		Nauplii	0.16

According to the occurrence frequency of more than 65% throughout the year, it is determined as a common species, and the common species of zooplankton this year are shown in the following *Table 6*.

Table 6. *Common species of zooplankton in the Songhua River, China*

Quarter	Common species		Frequency
Spring	Protozoa	*Vorticella microstoma*	76.92%
	Rotifer	*Polyarthra trigla*	84.62%
		Keratella cochlearis	69.23%
	Cladocera	*Bosmina longirostris*	69.23%
	Copepods	*Microcyclops javanus*	92.31%
		Nauplii	92.31%
Summer	Rotifer	*Polyarthra trigla*	69.23%
	Copepods	*Microcyclops javanus*	69.23%
		Nauplii	69.23%
Autumn	Copepods	*Microcyclops javanus*	92.31%
		Nauplii	84.62%

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Summary of the changes of zooplankton from 2011 to 2021

In the past 11 years, a total of 71 species of zooplankton from 4 categories have been identified in the Harbin section of the Songhua River, including 6 Copepods; 6 species of *Cladicornis*; 43 species of Rotifers; and 16 species of Protozoa, with the largest species of Rotifers. The number of species of zooplankton identified in the past 11 years has decreased.

According to the zooplankton data from 2011 to 2021, 18-58 species of zooplankton were identified each year, with an average of 36 species. The number of species identified in 2011 was relatively high, and there were certain fluctuations in other years. The main group was Rotifers, with an average of 19 species each year. Among them, zooplankton continued to decrease from 2011 to 2013 and fluctuate greatly. The main factor was the huge flood in 2013 (*Fig. 12*). The flood caused the water level to rise, and the connection of the lake and the exchange rate of nutrients changed, which affected the composition and distribution of community structure of phytoplankton and zooplankton (Mac Donagh et al., 2009). From 2013 to 2014, the number of zooplankton gradually increased, and from 2014 to 2018, the number of zooplankton gradually decreased to 2019, but it did not change much.

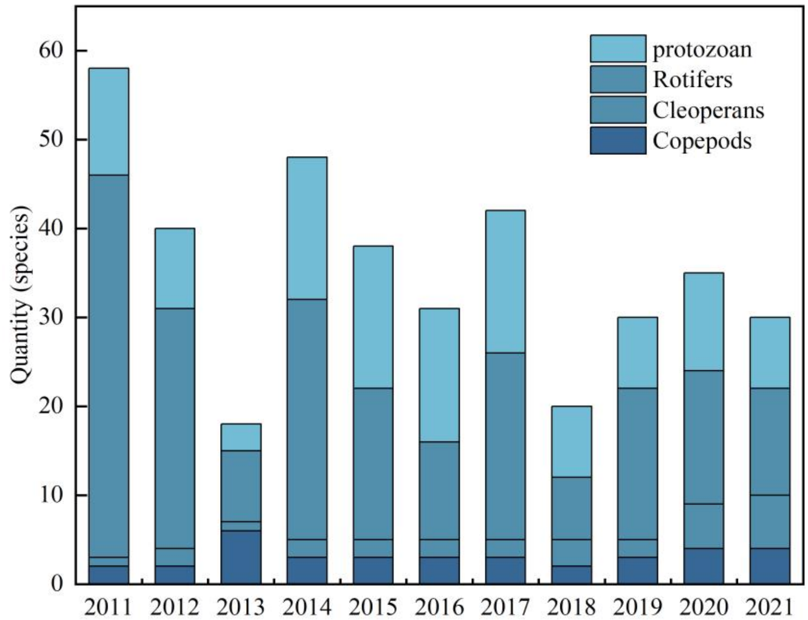

Figure 12. *Summary of zooplankton changes from 2011 to 2021*

During the investigation, the range of spring, summer and autumn abundance changes of zooplankton in the Harbin section of the Songhua River was 572.7-2275 ind./L, 15.25-4188 ind./L, 337.4-7310 ind./L, the average abundance change range is 443.4-4160 ind./L (*Fig. 13*). The highest average abundance of plankton in the past 11 years was 4160 ind./L in 2011, the lowest value in 2019 was 433.4 ind./L. The overall change of abundance shows a downward trend, among which the abundance in 2011 was at a high level. In the past 11 years, the highest average biomass of zooplankton was 1.242 mg/L in 2011, and the lowest value was 0.079 mg/L in 2012. The overall change of biomass shows a downward trend, among which biomass was at a high level in 2011 (*Fig. 14*).

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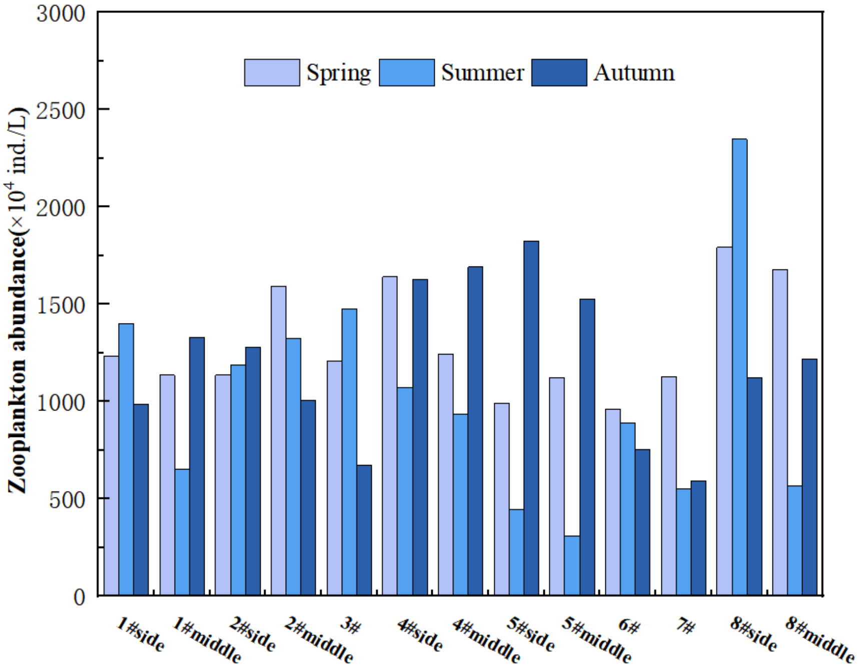

Figure 13. *Summary of zooplankton abundance changes from 2011 to 2021*

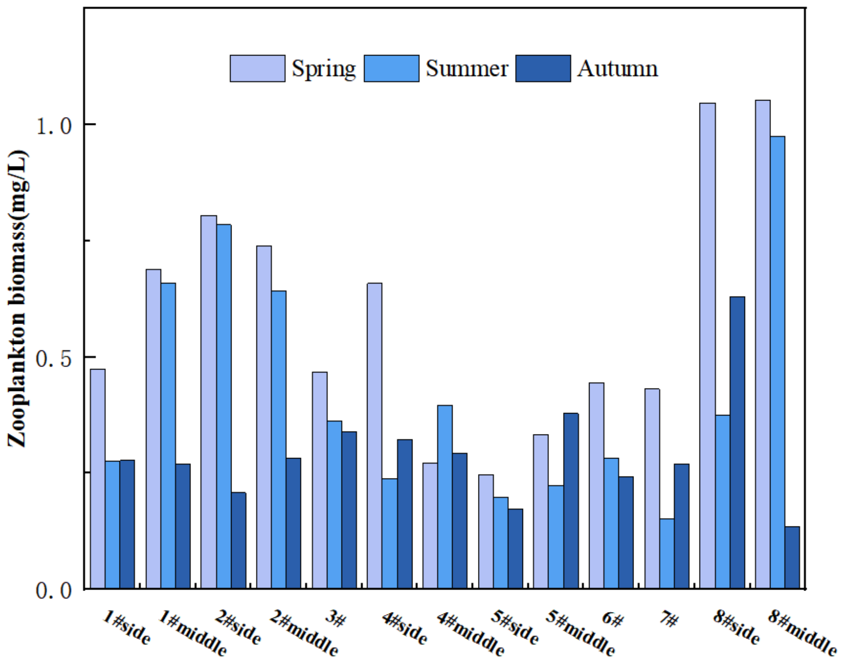

Figure 14. *Summary of zooplankton biomass changes from 2011 to 2021*

Discussion

Characteristics of phytoplankton community structure

In the monitoring of phytoplankton in the Harbin section of the Songhua River, a total of 101 species and variants of 71 genera were identified, including the largest

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number of Chlorophyta, followed by Bacillariophyta. Studies have shown that rivers with Bacillariophyta as dominant species and common species indicate that their degree of pollution is moderately polluted, and rivers with Cyanophyta as dominant species and common species are in severe pollution (Zhao et al., 2020a).

The change rules of horizontal distribution are as follows: the species, abundance and biomass of downstream phytoplankton are all higher than those of upstream phytoplankton. The upstream of the Harbin section of the Songhua River originates from Daliangzi, which is less affected by human factors, and the downstream is gradually disturbed by human factors. This study shows that phytoplankton exhibit characteristics of less species, quantity and biomass in water bodies of upstream rapids. Some studies show that in water bodies with high eutrophication, the types of pollut-resistant species increase, and the number and biomass will increase exponentially (Li and Yu, 2013). 8# (Sanjiazi) monitoring section will be affected by the industrial wastewater from the second Songhua River and Nenjiang River upstream. At the same time, due to the destruction of vegetation along the coast, the surface runoff injects organic substances such as *fertilisers*, pesticides and other ground pollutants in the soil into the Songhua River, forming a relatively serious surface source pollution; 5# (Er Shuiyuan) was originally the entrance of Harbin drinking water source of Songhua River, but the water source has been changed to the source of MopMountain drinking water, and the treatment degree is not as strict as before. The pollution mainly comes from human activities such as fishing and fishing. It can be seen that the problem of eutrophication caused by man-made is becoming more and more serious (Bennett et al., 2001; Paerl, 2006).

The seasonal pattern is that the average number, abundance and biomass of phytoplankton species are lower in summer than in spring and autumn. During the affluent period, the retention time of the water body is short, and the flow rate is relatively faster during the flat water period and the abundant period. These environmental conditions are not conducive to the abundance of phytoplankton and the accumulation of matter (Ren et al., 2023). The shorter retention time of the water body will lead to a decline in the productivity of phytoplankton (Burford et al., 2012). This survey of the Songhua River shows that the abundance of phytoplankton is relatively high during the dry period and the water period, while the abundance period is relatively low.

The temporal change rule is as follows: in the past 11 years, the common and dominant species of phytoplankton are mainly Bacillariophyta and Chlorophyta with extremely high cold resistance, and are in a dominant position in abundance and abundance (Ren et al., 2017). This is the same as the research results of the Sanjiang Plain, which is also located in the cold area of our province. Common and dominant species are Cyclotella meneghiniana (Eversheds, 2016). Yu et al. (2021) and others investigated and studied the structural characteristics of algae-spied communities in the main stream of the Songhua River in the summer of 2014-2019, and identified a total of 6 classes, 17 orders, 26 families and 58 genera, including 28 genera of Bacillariophyta, accounting for 48.28% of the total; 17 genera of Chlorophyta, accounting for 29.31% of the total amount. And the changes in the average biomass and abundance in the past 11 years are relatively consistent. The trend is to increase first and then decrease, both of which reached the lowest value in 2016, the highest in 2015, and the highest in biomass in 2018. During the period from 2015 to 2017, the degree of water pollution in the Harbin section of the Songhua River was mild. In 2018, the degree of water pollution was low and the water quality was excellent (Xie, 2020).

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Characteristics of zooplankton community structure

In the monitoring of zooplankton in the Harbin section of the Songhua River, a total of 30 species of zooplankton was identified, of which the largest number of Rotifera species, 9 genera and 12 species, accounting for 40%. The horizontal distribution rules are as follows: the species of phytoplankton located in the downstream are higher than the species of phytoplankton in the upstream, and the abundance and biomass show a trend of high on both sides and low in the middle. This is different from the change trend of phytoplankton. The reason may be that the nutrient level in the upstream waters of the Harbin section of the Songhua River is low, or there is insufficient light, and the growth of phytoplankton may be limited, resulting in low abundance. And zooplankton may be more adapted to a low nutrient-level environment, because they can use different sources of organic substances as energy sources. At the same time, the rapid flow of upstream water may affect the growth and settlement of phytoplankton, and zooplankton can better adapt to this fast-flowing environment.

In terms of seasons, the abundance and biomass of phytoplankton and zooplankton vary significantly, and summer is significantly lower than that of spring and autumn. This may be due to the fact that there are many tributaries and a wide basin area in the upper reaches of the Harbin section of the Songhua River, while the rising water level and increasing the amount of water during the abundance period, diluting nutrients, and improving the transparency of the water body during the affluent period, thus diluting the density and biomass of phytoplankton; the rainfall in autumn is less and the water temperature suitable, stable water level. Protozoa and Rotiferas can eat humus and decompose organic matter (Calbet and Landry, 2004). This is also the reason why the summer phytoplankton density and biomass distribution are relatively average between different sampling points. The autumn sampling points are quite different, which is more affected by the surrounding water environment, showing that the upstream is greater than the downstream characteristics. At the same time, the erosion of lake water caused by violent fluctuations in the water level to cause the re-suspension of lake sediments (Lü et al., 2020). High concentration of suspended matter will affect the growth of phytoplankton and directly hinder the feeding of zooplankton, thus affecting the community structure of plankton (Zhou and Chen, 2015).

In terms of time, the zooplankton in the Harbin section of the Songhua River in the past 11 years has always been dominated by *carousins* and protozoa. This study is similar to the characteristics of zooplankton species in the Nenjiang River (Huo, 2013), Heilongjiang (Zhao et al., 2020b) and the main stream of the Wusuli River (Su et al., 2005), all of which are mainly small groups, among which Rotiferas have the most species and are vivid. Secondly, there are fewer species of Copepods and Cladocera, which is similar to the structure of many known river zooplankton communities in China (Hong and Chen, 2002). Compared with the northern rivers, because the Rotifera has a unique reproductive mode of solitary female, it can achieve high abundance in a very short time, and quickly adapt to the changes in the physical and chemical environment and the fluctuation of hydrological conditions in the river. In the past 11 years, the average biomass and abundance has shown a downward trend. In 2011, the biomass and abundance reached the highest value, the abundance reached the lowest value in 2019, and the biomass reached the lowest value in 2012. A large amount of industrial, agricultural and domestic sewage along the Harbin section of the Songhua River was discharged, which was moderately polluted in 2011 (Li, 2024); the water body of the Harbin section of the Songhua River was at a moderate nutrient level and

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moderate pollution in 2012 (Ju et al., 2017); the water body improvement effect was significant in 2019 (Eversheds, 2016). This indicates that there is a complex interaction between water quality conditions and biomass in the body, and there is not necessarily a direct causal relationship. Water with good water quality usually contains fewer nutrients (such as nitrogen, phosphorus, etc.), which may limit the growth of phytoplankton, thus reducing biomass. On the contrary, water with poor water quality may be rich in nutrients, which promotes the reproduction of phytoplankton and leads to an increase in biomass. the water body may contain pollutants, such as heavy metals, organic matter, etc., which may have toxic effects on some organisms in 2012. The combination of different environmental factors determines the distribution and abundance of biomass in the water.

Water quality evaluation based on phytoplankton diversity index

Species diversity can not only reflect the basic situation of community structure, but also reveal water quality. Therefore, the diversity index of phytoplankton is widely used in the water quality evaluation of various water bodies (Li et al., 2005). In this study, the annual average value of Shannon-Wiener index and Pielou index of phytoplankton in the Harbin section of the Songhua River is at a high level, indicating that the water quality of each sampling point in the region is light pollution. This shows that there are many species of phytoplankton in Poyang Lake, and the number of various types of individuals is evenly distributed (Lenz et al., 2005). The Shannon-Wiener index reflects the characteristics of the distribution within and between species in the community (Wang et al., 2019), and the Pielou index reflects the uniformity of the abundance of each species in the community. The value of the Shannon-Wiener index in spring is higher than that in summer and autumn, indicating that the water quality in spring is better than that in autumn and summer; the index of Pielou in summer is higher than that in spring and autumn, indicating that the abundance of various species in the summer community is more uniform and the competitive pressure is less. The reason is that spring is the season for the reproduction and growth of many biological populations, with high biodiversity. This high biodiversity may lead to a higher value of the Shannon-Wiener index. Summer is usually a season of high water temperature and high light intensity. and the biological activity is relatively active in summer. The appropriate temperature and light conditions may enable various plankton to make more extensive use of habitat resources, thus improving the Pielou index. From the analysis of the changes in the biodiversity index from 2011 to 2021, the Shannon-Wiener index and Pielou index in the Harbin section of the Songhua River continue to rise as a whole, and the ecological environment gradually tends to be mildly polluted or pollution-free.

Water ecological environment protection strategy

The vegetation on both sides of the Songhua River should be comprehensively investigated, and key areas for protection should be defined, especially in the key upstream sampling points in autumn (such as sampling points of 6#, 4# and 2#), and vegetation restoration and protection should be strengthened. For river reaches without protection requirements, reduce human disturbance, and maintain the natural form of rivers and banks. Through appropriate measures of vegetation restoration and wetland diversity protection, a healthy and stable ecological environment of Harbin section of Songhua River will be constructed.

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We will prevent and control pollution sources. For the main pollution sources in Harbin section, the monitoring and control should be strengthened, and the responsibilities of all departments should be defined to ensure the efficient coordination of remediation work. Strengthen the sense of responsibility of all departments, establish a joint law enforcement mechanism, and increase the punishment for illegal acts such as excessive discharge and illegal discharge. At the same time, increase the number and frequency of the river inspection, timely clean up the river garbage, to prevent the garbage from causing secondary pollution to the water body.

Real-time water ecological environment monitoring will be carried out. Quickly establish a river and lake health assessment system, improve the construction of water ecology laboratory, introduce advanced monitoring equipment and technology, and improve the accuracy and reliability of monitoring data. We will accelerate the establishment of a river and lake health assessment system, formulate evaluation standards and methods, and regularly evaluate the health status of rivers and lakes. Comprehensive physical and chemical monitoring and biological monitoring methods are used to comprehensively reflect the quality of water environment, realize the dynamic monitoring and comprehensive perception of water-related information, and improve the real-time monitoring level of rivers and risk early warning ability.

In the urban tourism planning, the needs of river regulation and storage function and environmental protection of landscape ecological characteristics should be fully considered to ensure the combination of urban development and ecological protection. In the process of project development of ecotourism industry, the principle of ecological priority should be adhered to to ensure the sustainable utilization of water ecological environment.

Strengthen the publicity of water environment protection, and improve the public’s awareness and participation in water environment protection. Carry out water environment protection knowledge popularization activities to improve the public’s awareness of environmental protection and self-restraint ability. A public reporting mechanism should be established to encourage the public to actively participate in the water environment protection work and jointly maintain a good water ecological environment.

Conclusion

A total of 101 species and variants of 71 genera of 7 phytoplankton were identified in the Harbin section of the Songhua River, of which the largest number of species are Chlorophyta and Bacillariophyta. From a spatial point of view, the species, abundance and biomass of phytoplankton downstream are higher than that of phytoplankton species, abundance and biomass of upstream; from the perspective of seasons, the average number of phytoplankton species, abundance and biomass in summer are lower than that in spring and autumn. The Shannon-Wiener index and Pielou index of the phytoplankton is at a high level, and the water quality at each sampling point is light pollution. In the past 11 years, the common and dominant species of phytoplankton is mainly Bacillariophyta and Chlorophyta with extremely cold resistance, which are in a dominant position in terms of richness and abundance. The number of species changes is relatively stable, and the abundance and biomass as a whole show a trend of rising first and then decreasing, but the distribution of species abundance is more uniform.

A total of 30 species of wheel animalcule have been identified in the Harbin section of the Songhua River, China, mainly Rotifera and Protozoon. From a spatial point of view, the species of phytoplankton located downstream are higher than the upstream phytoplankton species, and the abundance and biomass show a trend of high on both sides and low in the middle. From the perspective of seasons, the abundance and biomass of wheel animal *culevaries*y significantly, and the summer is significantly lower than that in spring and autumn. In the past 11 years, the zooplankton in the Harbin section of the Songhua River has always been dominated by Rotifera and Protozoon, and the average biomass and abundance has shown a downward trend as a whole.

With the strengthening of water pollution control and management in the Songhua River, China, the overall water ecological state of the basin has been gradually restored, and the water quality of the Harbin section of the Songhua River is mild pollution throughout the year.

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APPENDIX

Table A1. *Sampling time of the Harbin section of the Songhua River from 2011 to 2021*

Survey time	Spring	Summer	Autumn
Year 2011	6/17	8/18	10/22
Year 2012	5/18	7/17	10/26
Year 2013	5/22	7/23	9/21
Year 2014	5/24	8/18	10/16
Year 2015	5/23	8/18	10/19
Year 2016	5/27	8/18	10/21
Year 2017	5/21	8/19	10/27
Year 2018	5/5	7/22	10/6
Year 2019	5/23	7/21	10/4
Year 2020	5/24	7/27	10/20
Year 2021	5/25	7/26	10/21

Table A2. *The mean value (± standard error) of environmental factors varies with seasonal changes in this chart in the Harbin section of Songhua River, China in 2021*

Sampling location	Water depth (m)	Velocity of flow (m/s)	Transparency (cm)	Dissolved oxygen (mg/L)	Turbidity (mg/L)	Chlorophyll-a (mg/L)
1#middle	19.43±6.29	1.22±1.17	19.67±4.62	8.15±1.8	7.74±0.17	221.27±55.19
1#side	1.27±0.29	0.26±0.15	18.67±1.15	8.19±1.81	7.65±0.27	213.93±58.08
2#middle	4.1±3.81	1.02±0.39	16.33±0.58	8.43±1.69	7.98±0.04	301.67±37.53
2#side	1.7±0	0.03±0.02	17.33±0.58	8.23±1.78	7.86±0.07	303.67±5.77
3#	1.2±0.17	0.89±0.2	20±0	8.48±1.5	8.03±0.15	211.13±59.64
4#middle	7.37±1.85	1.37±0.78	20±0	8.22±1.84	7.7±0.2	210.73±59.12
4#side	1.97±0.46	0.34±0.54	15±3.46	8.39±1.69	7.81±0.07	214.87±57.27
5#middle	12.1±0	1.83±0.32	15.33±4.04	8.24±2.14	7.62±0.44	210.8±61.66
5#side	2.4±1.56	0.17±0.14	14.67±2.89	7.99±2.23	7.62±0.38	210.53±61.03
6#	15.1±10.74	0.85±0.62	18.67±1.15	8.71±1.57	7.89±0.14	211±60.62
7#	7.8±0.35	2.22±0.31	20.67±1.15	7.86±2.26	7.61±0.3	212.27±60.39
8#middle	4.13±1.44	1.26±0.18	19.33±1.15	7.75±2.34	7.69±0.33	212±57.16
8#side	0.3±0	0.15±0.08	13.67±1.15	8.11±1.93	7.75±0.27	213.67±56.58

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Table A3. *Seasonal variation in environmental variables from 2012 to 2021 (p values were from One-way ANOVA test. Differences between the seasons were tested by Tukey HSD ANOVA)*

		2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**P**
	WT (℃)	11.13±11.4a	14.83±9.12a	16.53±2.85a	15.33±8.08a	16.50±5.77a	14.40±6.32a	17.56±8.86a	17.83±9.93a	13.73±6.13a	17.50±0.5a	0.986
	pH	7.86±0.93a	7.56±0.22ab	8.11±0.64a	7.94±0.16a	7.85±0.29a	7.60±0.28ab	5.04±4.41b	7.43±0.38ab	7.83±0.42a	7.89±0.08a	0.393
	DO (mg/L)	10.2±3.36a	7.37±3.15a	6.27±0.46a	10.07±1.27a	9.03±2.29a	9.43±1.81a	10.03±0.60a	7.00±2.11a	8.43±2.58a	8.03±0.10a	0.271
	CODMn (mg/L)	7.81±2.06ab	7.33±1.51ab	5.95±0.49bc	4.85±0.54c	4.48±0.16c	5.84±0.97bc	4.61±1.51c	8.56±1.27a	4.37±0.33c	4.64±1.95c	0.002
	CODCr (mg/L)	23.33±6.81a	17.13±6.30a	18.97±16.00a	20.63±13.14a	12.97±2.37a	16.80±3.27a	12.07±2.12a	17.73±6.34a	13.37±2.29a	12.97±2.37a	0.688
Spring	BOD5 (mg/L)	5.93±1.14a	1.73±1.67c	1.80±0.87c	4.90±1.54ab	2.53±0.49bc	4.20±2.46abc	3.50±1.44abc	1.13±0.31c	2.63±0.78bc	5.20±3.14ab	0.017
	NH4 + -N (mg/L)	0.71±0.56abc	0.53±0.29abc	0.11±0.04c	0.72±0.46abc	0.36±0.14abc	0.24±0.09bc	0.44±0.40abc	0.94±0.16a	0.25±0.10bc	0.89±0.61ab	0.006
	TP (mg/L)	0.08±0.03bc	0.12±0.03ab	0.11±0.01abc	0.12±0.05abc	0.07±0.02bc	0.11±0.07abc	0.03±0.01c	0.15±0.06ab	0.07±0.02bc	0.17±0.09a	0.039
	TN (mg/L)	1.50±0.52b	1.60±0.10ab	1.77±0.61ab	2.42±0.58a	1.72±0.42ab	2.05±0.35ab	1.87±0.87ab	1.33±0.06b	1.86±0.42ab	1.63±0.06ab	0.032
	NO3- (mg/L)	0.69±0.33c	1.39±0.34ab	1.44±0.11ab	1.09±0.23bc	1.25±0.36abc	1.51±0.37ab	0.98±0.46bc	0.92±0.19bc	1.49±0.28ab	1.75±0.45a	0.023
	Fe3 + (mg/L)	0.53±0.48ab	1.92±1.67ab	0.98±0.70ab	0.46±0.10ab	0.29±0.33b	0.50±0.55ab	0.28±0.20b	2.41±1.10a	0.53±0.55ab	2.29±2.18a	0.077
	WT (℃)	25.63±2.87a	24.17±3.61a	21.37±5.85a	21.67±2.08a	24.00±3.46a	23.87±5.17a	22.1±3.01a	22.67±2.36a	23±1.73a	25.17±2.75a	0.854
	pH	7.65±0.22abc	7.32±0.19c	7.4±0.24bc	7.75±0.18ab	7.57±0.07abc	7.3±0.17c	7.88±0.25a	7.35±0.15c	7.61±0.17abc	7.64±0.13abc	0.012
	DO (mg/L)	6.53±1.1bcd	5.87±0.9bcd	4.47±1.2d	7.1±0.98abc	7.07±1.15abc	6.8±0.85abc	8.8±1.8a	4.97±1.75cd	6.77±0.64abc	7.8±0.36ab	0.008
	CODMn (mg/L)	7.87±1.28a	7.97±2.08a	7.49±2.86ab	4.77±0.8bc	4.19±0.53c	4.93±1.01bc	6.51±0.93abc	6.64±1.52abc	5.11±0.92bc	3.95±0.64c	0.011
	CODCr (mg/L)	46.33±49.08a	19.63±4.47ab	18.7±6.06ab	12.4±0.96b	11.83±0.8b	11.43±4.42b	13.47±0.28b	12.574.02±b	13.27±0.41b	11.2±1.76b	0.266
Summer	BOD5 (mg/L)	2.87±1.17abc	1±0.52c	1.93±0.57bc	2.37±0.68abc	2±0.52bc	2.4±0.34abc	3.63±1.59ab	2.03±0.6abc	4.07±2.37a	1.63±0.2bc	0.067
	NH4 + -N (mg/L)	0.39±0.11bcd	0.81±0.36a	0.19±0.1bcd	0.46±0.3abc	0.17±0.07bcd	0.24±0.1bcd	0.22±0.16bcd	0.13±0.04cd	0.53±0.31ab	0.07±0.02d	0.006
	TP (mg/L)	0.13±0.07ab	0.17±0.03a	0.13±0.05ab	0.11±0.08ab	0.06±0.01b	0.09±0.05ab	0.06±0.02b	0.13±0.03ab	0.14±0.03ab	0.06±0.01b	0.094
	TN (mg/L)	1.6±0.36a	1.5±0.26a	1.7±0.51a	1.81±0.39a	1.74±0.11a	2.26±0.75a	1.88±0.65a	1.84±0.4a	2.02±0.52a	1.4±0.03a	0.541
	NO3- (mg/L)	1.58±0.98a	1.14±0.45a	1.2±0.24a	1.12±0.42a	1.43±0.15a	1.5±0.44a	0.82±0.12a	1.22±0.21a	1.18±0.66a	1.24±0.09a	0.1
	Fe3 + (mg/L)	1.13±0.57b	2.38±1.12ab	3.69±2.05a	1.32±0.85b	0.55±0.5b	1.45±1.85b	0.69±0.54b	2.06±0.96ab	1.18±1.18b	0.45±0.34b	0.063
	WT (℃)	6.40±5.21ab	4.97±3.99b	11.00±0.40ab	8.33±1.53ab	12.33±1.15a	10.10±4.25ab	9.97±2.00ab	6.93±5.70ab	10.00±3.46ab	8.20±1.22ab	0.277
	pH	7.98±0.66ab	7.54±0.17ab	7.58±0.17ab	7.86±0.03ab	7.73±0.08ab	7.42±0.21ab	5.18±4.49b	8.10±0.57a	8.02±0.25ab	7.73±0.29ab	0.455
	DO (mg/L)	11.53±1.81a	10.00±1.40a	7.57±1.37b	11.10±0.96a	10.20±0.62a	9.23±1.95ab	9.60±0.44ab	11.40±1.71a	11.27±0.40a	11.27±0.45a	0.018
	CODMn (mg/L)	8.51±0.94a	6.85±0.82b	4.19±1.49d	5.07±0.79cd	4.11±0.65d	6.27±0.98bc	4.08±0.00d	4.83±0.49cd	5.31±0.20cd	5.52±0.42bcd	0
	CODCr (mg/L)	18.33±15.89ab	13.10±3.94ab	12.97±1.15ab	15.00±3.80ab	9.73±0.40b	15.27±2.22ab	10.67±0.91b	9.00±7.81b	24.70±9.83a	15.77±1.87ab	0.241
Autumn	BOD5 (mg/L)	4.13±2.37a	1.87±0.31ab	1.17±0.72b	3.63±1.29ab	2.40±0.56ab	2.83±1.52ab	1.97±0.31ab	3.40±2.03ab	3.63±1.50ab	3.60±0.75ab	0.176
	NH4 + -N (mg/L)	0.43±0.05abc	0.76±0.20ab	0.05±0.00c	0.56±0.43abc	0.17±0.14bc	0.45±0.31abc	0.33±0.46abc	0.86±0.74a	0.77±0.21ab	0.07±0.01c	0.063
	TP (mg/L)	0.13±0.03a	0.11±0.03ab	0.04±0.01c	0.08±0.04abc	0.06±0.01abc	0.08±0.06abc	0.11±0.07abc	0.10±0.04abc	0.11±0.04abc	0.05±0.00bc	0.106
	TN (mg/L)	1.70±0.66bc	1.77±0.51bc	1.36±0.03c	2.13±0.47abc	1.79±0.41bc	2.16±0.26abc	2.08±0.62abc	1.88±0.75abc	2.72±0.17a	2.36±0.39ab	0.11
	NO3- (mg/L)	0.80±0.49b	1.58±0.58a	1.29±0.02ab	1.33±0.31ab	1.47±0.31a	1.47±0.41a	1.37±0.14ab	1.05±0.31ab	1.30±0.08ab	1.65±0.07a	0.13
	Fe3 + (mg/L)	0.77±0.82b	1.62±0.08a	0.41±0.04b	0.31±0.11b	0.65±0.18b	0.58±0.46b	0.64±0.13b	0.50±0.29b	0.40±0.15b	0.93±0.06b	0.005

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