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A study on the phytoplankton community structure in the Diaohe River section of the Middle Route of the South-to-North Water Diversion Project in winter

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ABSTRACT

As the first span and aqueduct of the Middle Route of the South-to-North Water Diversion Project, Diaohe Aqueduct has brought good engineering and social benefits since its completion. In order to understand the present water quality of the Diaohe River section of the route, four samplings were conducted at Diaohe Aqueduct in the winter of 2018. The main results of this study are as follows: 62 species (or variants) of phytoplankton belonging to 32 genera, 22 families and six phyla were identified during the study period, among which Bacillariophyta are the most dominant species. The identified phytoplankton fall into eight indicator grades: os; ps, αm; ps, αm, βm; αm; αm, βm; αm, βm, os; βm; and βm, os. A total of 17 functional groups are detected, among which TB is the absolute dominant functional group. Based on the composition characteristics of phytoplankton, the water quality trophic state of Diaohe Aqueduct is mesotrophic. However, other physical indexes show that the water quality of the Middle Route of the South-to-North Water Diversion Project is good. The conclusions drawn using phytoplankton alone as the evaluation index may not be comprehensive. In future research, how to build a comprehensive index system combining other water quality indexes for the Middle Route of the South-to-North Water Diversion Project needs yet to be improved and tested.

Key words | community structure, Diaohe Aqueduct, functional groups, phytoplankton, water quality

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HIGHLIGHTS

- Sixty-two species of phytoplankton were measured in Diaohe Aqueduct of MPR in winter.
- A diatom, such as *Fragilaria*, *Cymbella*, was the main dominant species.
- TB functional group is the absolute dominant functional group.
- The water quality trophic state of the Diaohe Aqueduct is mesotrophic.
- The water quality in the Diaohe Aqueduct during the study period is clean.

INTRODUCTION

As the largest inter-basin water diversion project in the world, the Middle Route of the South-to-North Water Diversion Project (MRP) is a major strategic infrastructure for alleviating water shortages in northern China, reasonably allocating water resources, ensuring sustainable economic and social development, and comprehensively building a well-off society in China. Since the MRP provides domestic and industrial water to northern China (e.g. Beijing), the water quality in the MRP is required to meet the Grade II Chinese Environmental Quality Standard for Surface

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Water (GB3838-2002; Tang *et al.* 2011). However, the MRP is composed of a long canal and complex hydraulic structures, and transfers drinking water to Beijing, Tianjin and other cities in open channels, which has caused a certain threat to the MRP water quality (Tang *et al.* 2016; Zhu *et al.* 2019). Therefore, it is particularly important to monitor the water quality in the MRP.

Phytoplankton is the principal primary producer in aquatic ecosystems, it is highly sensitive and responds rapidly to environmental changes (Yuan *et al.* 2018), and the changes of its community structure have a direct or indirect impact on other aquatic organisms, and can even affect the stability of the aquatic ecosystem. Learning phytoplankton structure could obtain a comprehensive and real understanding of the status of an aquatic ecosystem (Suikkanen *et al.* 2007). Many researchers determine the water quality of a study area by studying phytoplankton communities and environmental variables, for example, Gharib *et al.* (2011) determined the water quality of Matru Beach in the Mediterranean Sea in southeastern Egypt by studying environmental variables and the abundance and community structure of phytoplankton during 2009–2010. Zaghloul *et al.* (2020) studied the species composition and abundance of phytoplankton weekly from 16 June 2011 to 30 May 2012 in the Eastern Harbor, and divided the aquatic system into oligotrophic, mesotrophic and eutrophic water types. However, due to the short running time of the MPR, there are few studies on determining water quality by studying phytoplankton community. Therefore, it is necessary to monitor the water quality in the MRP by studying the phytoplankton community.

Known as 'the first span of the massive water diversion project', Diaohe Aqueduct is the first aqueduct for water conveyance in the MRP, and it has brought good engineering and social benefits since its completion. As the beginning section of the Middle Route of the South-to-North Water Diversion Project, the water quality of the Diaohe River section has a direct impact on the condition of drinking water for residents in the following areas receiving the water supply. Therefore, this paper investigates the phytoplankton in the Diaohe River section of the Middle Route of the South-to-North Water Diversion Project, with the aim of providing an important basis for the ecological protection of the water of this main canal (Diaohe River section) in the Middle Route.

MATERIALS AND METHODS

Study area

The beam-type Diaohe Aqueduct is located on the river 500 m away from Yaoying Village, Jiulong Town, Dengzhou City, Henan Province, 2.5 km south from Dengzhou–Zhechuan Highway. The main structures of the aqueduct include 115.1 m of surplus escape, 40 m of inlet transition, 26 m of inlet controlling sluice, 20 m of inlet connection, 350 m of aqueduct, 20 m of outlet connection, 15 m of outlet maintenance chamber, 70 m of outlet transition, and 3.9 m of outlet open channel, with the total length being 660 m. The span arrangement of the aqueduct body is 8*40 m + 1*30 m, the upper structure of which is a pre-stressed box-type simply supported beam arranged in double lines and double troughs. The net width of a single trough is 13.0 m, with a maximum cross-sectional area of 83.98 m^2, a designed water depth of 5.75 m, and an increased water depth of 6.46 m. The trough is 15 m wide at the top, 15.1 m at the bottom, the inner wall spacing between the two troughs is 5.0 m, and a sidewalk slab is laid between them. The full width of the double-line aqueduct is 33.0 m wide at the top and 33.1 m wide at the bottom. Diaohe Aqueduct is the first water conveyance aqueduct on the main canal of the Middle Route of the South-to-North Water Diversion Project, known as 'the first span of the massive water diversion project'. From December 12, 2014, when the Middle Route of the South-to-North Water Diversion Project was officially put into use, to October 1, 2017, the total cumulative amount of water entering the canal has reached 10 billion m^3. The aqueduct has yielded good engineering and social benefits.

Sampling time and sites

In this experiment, four samplings were conducted at the Middle Route (Diaohe section) of the South-to-North Water Diversion Project in November 2018 (on November 7, 14, 20, and 27, 2018, respectively). The monitored canal section (Diaohe section) is in two different channel shapes: straight and curved. The light intensity varies on different sides of it, and the curved section has concave and convex banks which lead to different flow velocities.

All these factors will affect the growth and distribution of algae. As a result, three sampling points were set up after comprehensively considering the above circumstances and the operability on the site. They are located on the left and right banks of the pontoon bridge of Diaohe Aqueduct (straight section) and the water quality sensitive position of Diaohe Aqueduct (curved section), as shown in Figure 1.

Sample collection and analyses

Environmental factor analyses

The pH, water temperature (WT), dissolved oxygen (DO), and conductivity, oxidation–reduction potential (ORP) were measured by YSI 6600EDS at 0.5 m below the water surface. At the same, a deep water sampler was used to collect the mixed water sample for an additional index at 0.5 m below the water surface, and 500 ml of mixed water was extracted and put into a polyethylene plastic bottle, then the water samples were transported to the laboratory within 24 h, and stored in a refrigerator at 4 °C before being analyzed.

Additional indexes included the total phosphorus, orthophosphate, total nitrogen, ammonia nitrogen, nitrate nitrogen, permanganate index, chemical oxygen demand and chlorophyll *a*. These indexes were measured according to Chinese standard methods (see Wei *et al.* (2002) for details).

Algae sample collection and identification

Collection of samples for qualitative analysis: use the plankton net no. 25 (mesh diameter being 0.064 mm) to collect the sample. Specifically, drag the net slowly at a speed of 20–30 cm/s by making a '∞' shape repetitively for 3–5 min in the space between the water surface and 0.5 m deep below the water surface. Add Lugol's solution into the collected sample for fixation, label the sample bottle, and make various records (Jin & Tu 1990). To perform qualitative analysis of the phytoplankton, classify the plankton samples, make them into temporary specimens for microscope slides and then identify them. In this process, the phytoplankton need to be photographed and preserved, and identified by authoritative books (Shi 2004; Zhou & Chen 2004; Wang *et al.* 2008).

Collection of samples for quantitative analysis: use the plexiglass water sampler to collect the sample by holding it still at about 0.5 m below the water surface, collect 1 L of water, put it into the sampling bottle that has been soaked with nitric acid and cleaned beforehand, and then immediately add 15 ml of Lugo's solution with a mass fraction of 15‰ into the collected sample for fixation. After taking the sample back to the laboratory, shake it thoroughly and transfer it into a 1,000 ml separatory funnel. After leaving the separatory funnel still for 24 h, aspirate the supernatant from it by siphoning (using a siphon) until 250 ml of the sample is left, and remove the remaining liquid to a small container. Leave the sample still for 24 h again, and then pipette the supernatant until 30 ml of the sample is left. After shaking the remaining liquid thoroughly, pipette 0.1 ml of the shaken sample into a phytoplankton counting box (0.1 ml) and count the phytoplankton under a microscope with a 10 × 40 magnification lens (Liu *et al.* 2019). The cell count on each slide is no less than 200, and the average of the counts of three slides is taken for each specimen. Since the specific gravity of phytoplankton is close to 1, the volume of phytoplankton can be directly converted to biomass (wet weight). That is, the biomass of phytoplankton is equal to the number of phytoplankton multiplied by their average volume, and the unit is mg/L. The biomass of unicellular organisms is mainly obtained by measuring their individual shape (Jin & Tu 1990).

Statistical analysis

The following equations of three diversity indices are used to calculate community metrics of phytoplankton. These are the Shannon–Wiener diversity index (Shannon & Weaver 1949) (shown in Equation (1)), Margalef richness index (Margalef 1958) (shown in Equation (2)), the Pielou evenness index (Pielou 1969) (shown in Equation (3)):

$$H' = -\sum_{i=1}^{S} p_i \ln p_i \tag{1}$$

$$d = 1 - \sum_{i=1}^{S} p_i^2 \tag{2}$$

$$J = \frac{H'}{\ln S} \tag{3}$$

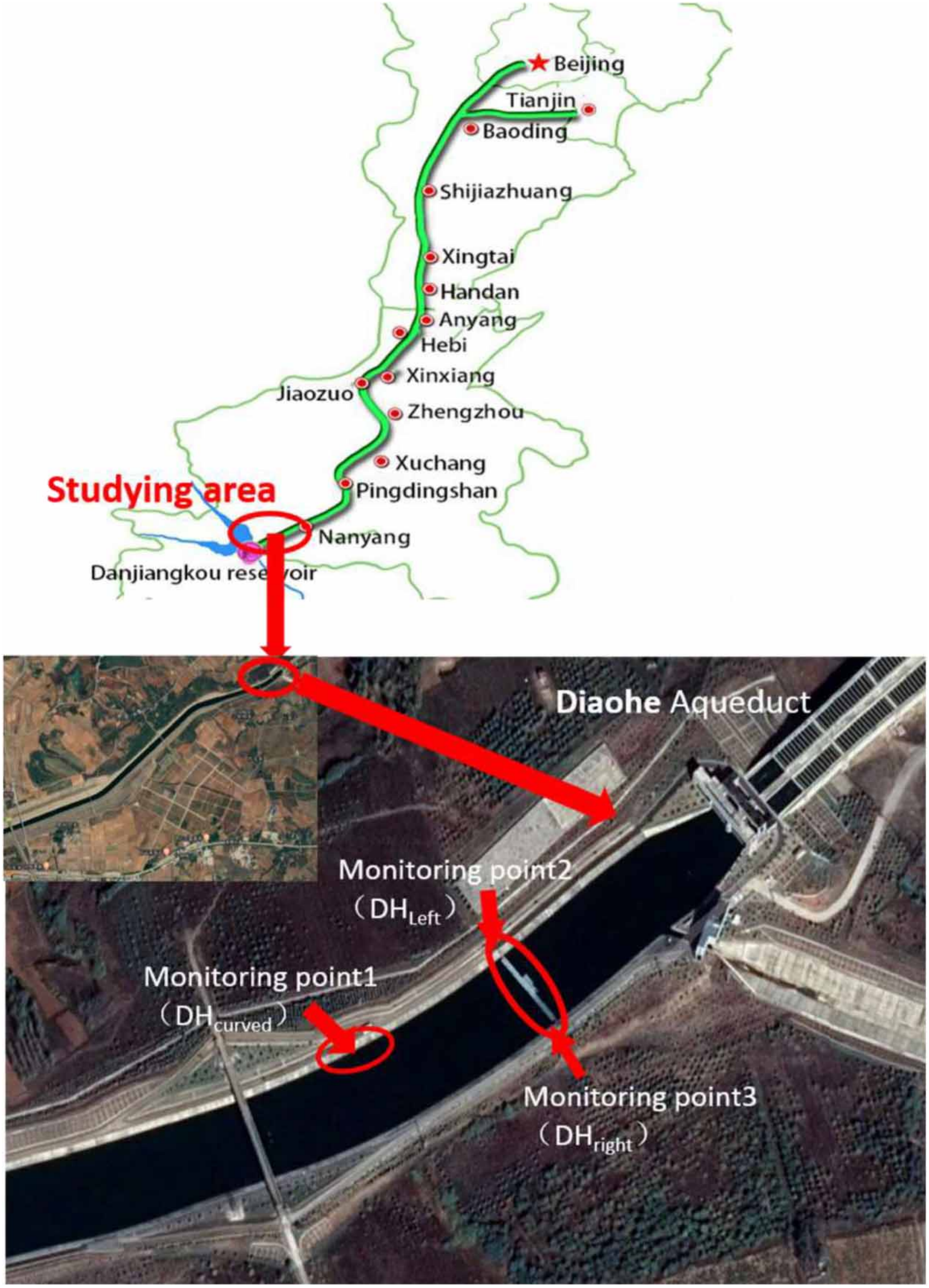

Figure 1 | Algae sampling points at Diaohe Aqueduct.

where H' is the Shannon–Wiener index, d is the Margalef richness index, J is the Pielou evenness index, p_i is the ratio of the individual number of the species i and total individual number (N), and S is the number of species within the given sample; and Excel is used in the following statistical analyses.

RESULTS AND DISCUSSION

Water quality indexes

The water quality indexes in Diaohe Aqueduct during the study period are summarized in Table 1. During the study period, the water temperature was maintained at about 14 °C, and pH was maintained at about 8.5. Chlorophyll *a* is an index that characterizes the content of algae; comparing the content of chlorophyll *a* at different times in the same place, it is found that as time goes by, the content of chlorophyll *a* shows a downward trend, while the content of nutrients and organic matter both show a downward trend, and the water temperature does not change. It is inferred that the phytoplankton had begun to enter a dormant period. Comparing with the Chinese Environmental Quality Standard for Surface Water (G3838-2002), it is found that the content of all water quality indexes meet the Grade II Chinese Environmental Quality Standard for Surface Water, that means the water quality in the Diaohe Aqueduct during the study period is clean.

Composition of phytoplankton community

In the samples collected at Diaohe Aqueduct in November 2018, Chlorophyta, Cyanophyta, Bacillariophyta, Pyrrophyta, Euglenophyta and Cryptophyta are identified. There are 62 species (or variants) of phytoplankton under 32 genera, 22 families and six phyla, including 30 species (or variants) of Bacillariophyta under 12 genera, accounting for 48.39% of the total phytoplankton; 16 species of Chlorophyta under 11 genera, accounting for 25.81%; nine species of Cyanophyta under four genera, accounting for 14.52%; two species of Pyrrophyta under two genera, accounting for 3.23%; one species of Euglenophyta under one genus, accounting for 1.61%; and four species of Cryptophyta under two genera, accounting for 6.45% (Figure 2 shows the composition of phytoplankton and Table 2 lists the phytoplankton species during the study period).

Composition of phytoplankton pollution indicator species

As early as 1908, German scientists Kolkwitz and Marsson (Kolkwitz & Marsson 1908) used algae to monitor the environmental quality of water bodies, and they were the first to propose a sewage biological system indicating

Table 1 | Water quality indexes in the Diaohe Aqueduct during the study period (except for WT and pH, all indexes are in mg/L)

Sampling time	Monitoring point	pH	WT	DO	COD_{cr}	I_{Mn}	TP	PO_4^{3-}-P	NH_4^+-N	NO_3^--N	Chla
2018/11/6	DH_{left}	8.3	14.4	8.1	13.54	1.75	5.75×10^{-3}	3.47×10^{-3}	0.028	0.657	2.14
2018/11/6	DH_{right}	8.5	15.3	8.08	10.53	1.62	5.25×10^{-3}	3.10×10^{-3}	0.031	0.495	2.10
2018/11/6	DH_{curved}	8.4	14.6	8.1	12.04	1.51	5.47×10^{-3}	2.87×10^{-3}	0.022	0.627	3.56
2018/11/13	DH_{left}	8.5	13.8	8.24	12.36	2.76	5.47×10^{-3}	2.65×10^{-3}	0.04	0.582	1.40
2018/11/13	DH_{right}	8.5	14.0	8.2	11.22	2.08	6.07×10^{-3}	3.06×10^{-3}	0.032	0.545	2.14
2018/11/13	DH_{curved}	8.6	14.4	8.26	11.60	2.17	4.42×10^{-3}	2.60×10^{-3}	0.014	0.539	1.84
2018/11/20	DH_{left}	8.4	13.5	8.1	11.20	1.29	6.16×10^{-3}	3.47×10^{-3}	0.016	0.545	1.54
2018/11/20	DH_{right}	8.4	14.3	8.08	12.60	1.20	5.79×10^{-3}	4.56×10^{-3}	0.029	0.506	2.13
2018/11/20	DH_{curved}	8.4	12.5	8.13	13.21	1.63	4.93×10^{-3}	3.88×10^{-3}	0.029	0.552	1.20
2018/11/27	DH_{left}	8.1	14.1	8.08	9.67	1.58	5.79×10^{-3}	3.06×10^{-3}	0.017	0.496	2.13
2018/11/27	DH_{right}	8.5	13.7	8.1	9.15	1.55	7.25×10^{-3}	4.84×10^{-3}	0.028	0.371	1.93
2018/11/27	DH_{curved}	8.2	14	8.11	9.57	1.58	6.34×10^{-3}	3.56×10^{-3}	0.017	0.513	2.25

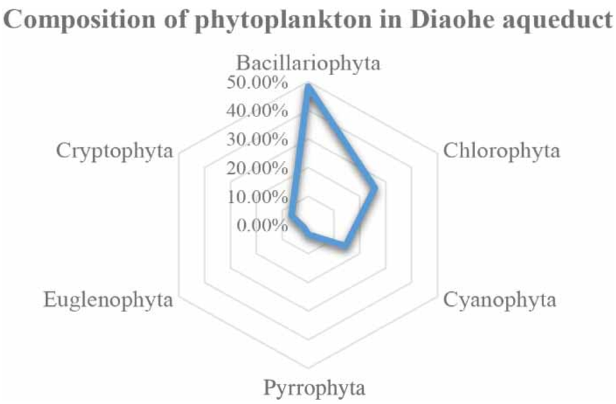

Figure 2 | Composition of phytoplankton in the Diaohe Aqueduct.

organic pollution in rivers. It pointed out different types of 'indicator organisms' for different pollution zones, and these were low pollution zone, β medium pollution zone, α medium pollution zone and multi-contamination zone. Through the changes of 'indicating organisms' in different water bodies, the water quality of the water body can be judged. Since the concept of 'indicating organisms' was proposed, it has been used by many scholars and has been continually revised and improved.

In the samples collected at Diaohe Aqueduct in November 2018, 62 species (or variants) of phytoplankton under 32 genera, 22 families and six phyla are identified, and they fall into eight indicator grades: os (oligotrophic); ps (p hypertrophic), αm (α medium eutrophic); ps, αm, βm (β mesotrophic); αm; αm, βm; αm, βm, os; βm; and βm, ps. Among them, there are one species of os phytoplankton under one genus, accounting for 5.56% of the total indicator species; two species of αm phytoplankton under two genera, accounting for 11.11%; four species of βm phytoplankton under four genera, accounting for 22.22%; four genera of βm, ps phytoplankton under three genera, accounting for 22.22%; and two species of α-β-o mesotrophic phytoplankton under two genera, accounting for 11.11%. The phytoplankton pollution indicator species and their quantity in Diaohe Aqueduct are shown in Figure 3.

In this experiment, the identified pollution indicator species fall into six phyla, namely Chlorophyta, Cyanophyta, Bacillariophyta, Pyrrophyta, Euglenophyta and Cryptophyta. The Bacillariophyta include *Cyclotella meneghiniana* Kütz., *Gomphonema* sp., *Melosira granulata* (Ehr.) Ralfs, and *Synedra ulna* (Nitzsch) Ehr.; the *Pyrrophyta* include *Ceratium* sp.; the Cyanophyta include *Microcystis robusta* (Clark) Nygaard, and *Aphanizomenon flos-aquae* (L.) Ralfs; the Euglenophyta include *Euglena viridis* Ehr.; the Chlorophyta include *Phacotus lenticularis* (Ehr.) Stein, *Eudorina* sp., *Oocystis* sp., *Pediastrum simplex* Meyen, *Planktosphaëria gelatinosa* G. M. Smith, *Radiococcus nimbatus* (Wild.) Schm., *Pediastrum duplex* Meyen, and *Staurastrum manfeldtii* Delp.; and the Cryptophyta include *Cryptomonas erosa* Ehr., as shown in Table 3.

Phytoplankton diversity

The Shannon–Wiener diversity index (H') is a single-factor index for representing the relationship between the number and species of biomes with multiple kinds of organisms. The biodiversity in communities reflects the complexity of biomes or habitats. This index is widely used to monitor changes of marine benthos (Noman *et al.* 2019), and it also can be used as a main indicator to evaluate water quality. As shown in Table 4 (Table 4 shows water quality and ecological evaluation standards), the Shannon–Wiener diversity index (H'), the Margalef richness index (d) and the Pielou evenness index (J) were applied to evaluate the water quality and ecological environment of Diaohe Aqueduct (Figure 4 shows the changes in the biodiversity index for each sampling points during the study period).

Water quality evaluation with the Shannon–Wiener diversity index

The Shannon–Wiener diversity index of phytoplankton in Diaohe Aqueduct ranges from 1.42 to 1.66. The biggest value 1.66 was recorded at the curved section, followed by 1.56 at the monitoring point on the left bank, and the smallest value 1.42 on the right bank. The range of changes is relatively small, and the pollution level is rated medium (Miao *et al.* 2019).

Water quality evaluation with the Margalef richness index

The Margalef richness index indicates the richness of species in a biological community. Generally speaking, the

Table 2 | List of phytoplankton species in the Diaohe Aqueduct

Phyla	Genera	Species
Chlorophyta	*Pediastrum* Meyen	*Pediastrum simplex* Meyen
Chlorophyta	*Pediastrum* Meyen	*Pediastrum duplex* Meyen
Chlorophyta	*Planktosphaëria*	*Planktosphaëria gelatinosa* G.M. Smith
Chlorophyta	*Staurastrum* Meyen	*Staurastrum planctonicum* Teiling
Chlorophyta	*Staurastrum* Meyen	*Staurastrum planctonicum*
Chlorophyta	*Radiococcus* Schmidle	*Radiococcus nimbatus* (Wild.) Schm.
Chlorophyta	*Pediastrum* Meyen	*Pediastrum clathratum* (Schroeter) Lemmermann
Chlorophyta	*Phacotus*	*Phacotus lenticularis* (Ehr.) Stein
Chlorophyta	*Eudorina*	*Eudorina* sp.
Chlorophyta	*Oocystaceae*	*Oocystis* sp.
Chlorophyta	*Staurastrum* Meyen	*Staurastrum manfeldtii* Delp.
Chlorophyta	*Scenedesmus* Meyen	*Scenedesmus bijuga* (Turp.) Lag.
Chlorophyta	*Coelastrum* Nägeli	*Coelastrum reticulatum*
Chlorophyta	*Chlamydomonas* Ehrenherg	*Chlamydomonas* sp.
Chlorophyta	*Scenedesmus* Meyen	*Scenedesmus* sp.
Chlorophyta	*Mougeotia* Meyen	*Mougeotia* sp.
Cyanophyta	*Oscillatoria* Vaucher	*Oscillatoria tenuis* Ag.
Cyanophyta	*Oscillatoria* Vaucher	*Oscillatoria* sp.
Cyanophyta	*Anabaena* Bory	*Anabaena* sp.
Cyanophyta	*Aphanizomenon* Morr	*Aphanizomenon* sp.
Cyanophyta	*Aphanizomenon* Morr	*Aphanizomenon flos-aquae* (L.) Ralfs
Cyanophyta	*Microcystis* Kütz.	*Microcystis* sp.
Cyanophyta	*Microcystis* Kütz.	*Microcystis densa* G.S.West
Cyanophyta	*Microcystis* Kütz.	*Microcystis ichthyoblabe* Kütz.
Cyanophyta	*Microcystis* Kütz.	*Microcystis robusta* (Clark) Nygaard
Bacillariophyta	*Gyrosigma* Hassal	*Gyrosigma* sp.
Bacillariophyta	*Gyrosigma* Hassal	*Gyrosigma acuminatum* (Kütz.) Raben.
Bacillariophyta	*Fragilaria* Lyngbye	*Fragilaria* sp.
Bacillariophyta	*Fragilaria* Lyngbye	*Fragilaria capucina* Desmaziéres
Bacillariophyta	*Fragilaria* Lyngbye	*Fragilaria intermedia* (Grun.) Grun.
Bacillariophyta	*Diatoma* De Candolle	*Diatoma vulgare* Bory
Bacillariophyta	*Diatoma* De Candolle	*Synedra tenue* Agardh
Bacillariophyta	*Nitzschia* Hassall	*Hantzschia* sp.
Bacillariophyta	*Nitzschia* Hassall	*Nitzschia sigmoidea* (Nitzsch.) Wm. Smith
Bacillariophyta	*Cymbella* Agardh	*Cymbella* sp.
Bacillariophyta	*Cymbella* Agardh	*Cymbella aspera*
Bacillariophyta	*Cymbella* Agardh	*Cymbella affinis* Kuetz
Bacillariophyta	*Achnanthes* Bory	*Achnanthes* sp.
Bacillariophyta	*Cyclotella* Kützing	*Cyclotella* sp.
Bacillariophyta	*Cyclotella* Kützing	*Cyclotella hubeiana* Chen et Zhu

(*continued*)

Table 2 | continued

Phyla	Genera	Species
Bacillariophyta	*Cyclotella* Kützing	*Cyclotella meneghiniana* Kütz.
Bacillariophyta	*Asterionella* Hassall	*Asterionella* sp.
Bacillariophyta	*Gomphonema* Ehrenberg	*Gomphonema* sp.
Bacillariophyta	*Gomphonema* Ehrenberg	*Gomphonema subclavatum*
Bacillariophyta	*Synedra* Ehrenberg	*Synedra* sp.
Bacillariophyta	*Synedra* Ehrenberg	*Synedra acus* Kütz.
Bacillariophyta	*Synedra* Ehrenberg	*Synedra ulna* (Nitzsch) Ehr.
Bacillariophyta	*Melosira* Agardh	*Melosira varians* Agardh
Bacillariophyta	*Melosira* Agardh	*Melosira granulata* (Ehr.) Ralfs
Bacillariophyta	*Melosira* Agardh	*Melosira granulata* var. *angustissima* Müll.
Bacillariophyta	*Melosira* Agardh	*Melosira granulata* var. *angustissima* f. *spiralis* Hustedt
Bacillariophyta	*Navicula* Bory	*Navicula* sp.
Bacillariophyta	*Navicula* Bory	*Navicula radiosa* Kuetz
Bacillariophyta	*Navicula* Bory	*Navicula cincta* (Ehr.) Ralfs
Bacillariophyta	*Navicula* Bory	*Navenacea*
Pyrrophyta	*Certium* Schr.	*Ceratium* sp.
Pyrrophyta	*Gymnodinium* Stein	*Gymnodinium* sp.
Euglenophyta	*Euglena* Ehrenberg	*Euglena viridis* Ehr.
Cryptophyta	*Cryptomonas* Ehr.	*Cryptomonas ovata* Ehr.
Cryptophyta	*Cryptomonas* Ehr.	*Cryptomonas erosa* Ehr.
Cryptophyta	*Chroomonas*	*Chroomonas acuta* Uterm.
Cryptophyta	*Chroomonas*	*Chroomonas caudata* Geitler

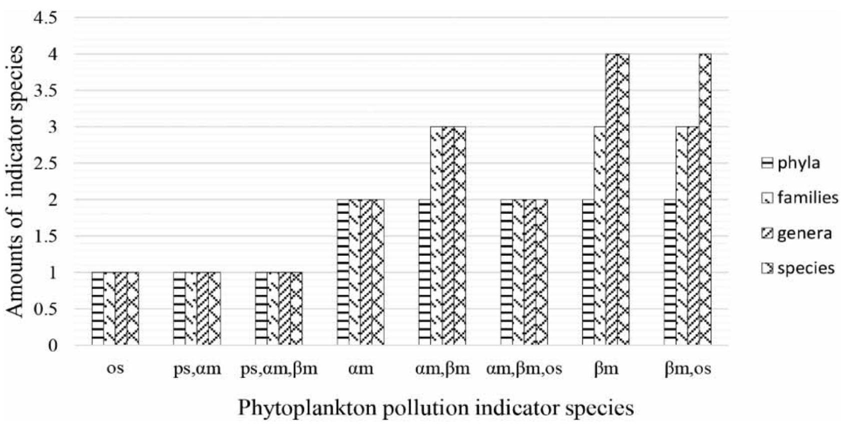

Figure 3 | Amounts of phytoplankton pollution indicator species.

number of species is high in a healthy environment, and the number of species is low in a polluted environment (Ma 2012).

The Margalef richness index of phytoplankton in Diaohe Aqueduct ranges from 6.98 to 7.21. The range of changes is big, with the characteristics of index changes in

Table 3 | Composition of phytoplankton pollution indicator species

Phytoplankton pollution indicator species	Monitoring point			Indicator grade
	DH_{left}	DH_{right}	DH_{curved}	
Synedra ulna (Nitzsch) Ehr.	+	+	+	os
Gomphonema sp.	+	+	+	αm
Cyclotella meneghiniana Kütz.		+		αm, βm, os
Melosira granulata (Ehr.) Ralfs	+	+	+	βm
Ceratium sp.			+	βm, os
Aphanizomenon flos-aquae (L.) Ralfs	+	+	+	αm, βm
Microcystis robusta (Clark) Nygaard	+	+	+	αm, βm
Euglena viridis Ehr.		+		ps, αm
Phacotus lenticularis (Ehr.) Stein	+			αm
Eudorina sp.			+	αm, βm
Oocystis sp.			+	αm, βm, os
Pediastrum simplex Meyen		+		βm
Planktosphaëria gelatinosa G.M.Smith	+			βm
Radiococcus nimbatus (Wild.) Schm.	+			βm
Pediastrum duplex Meyen	+	+	+	βm, os
Staurastrum planctonicum Teiling	+			βm, os
Staurastrum manfeldtii Delp.		+	+	βm, os
Cryptomonas erosa Ehr.	+			ps, αm, βm

space being left bank> water quality sensitive point> right bank. The index at all the three monitoring points is greater than 6, so the water quality is relatively healthy and the pollution level is clean.

Water quality evaluation with the Pielou evenness index

The Pielou evenness index gives a good representation of the distribution uniformity of the individuals of phytoplankton species. The value range of J is 0–1. When this value is big, it indicates that the distribution of individuals among the species is uniform; when this value is small, it suggests uneven distribution of individuals among the species (Ma 2012).

The Pielou evenness index of phytoplankton in Diaohe Aqueduct ranges from 0.42 to 0.51, and the changes are stable, so the pollution level is rated as medium-light pollution. The value at the monitoring point on the right bank is small, while that on the left bank is large.

The spatial variation of the Pielou evenness index of phytoplankton in Diaohe Aqueduct is characterized as water quality sensitive point > left bank > right bank. The water quality at the monitoring points on the left and right banks is worse than that at the water quality sensitive point. Their pollution level is medium pollution, with the water quality on the left bank better than that on the right bank and rated as light pollution. Generally speaking, the distribution of individuals among the phytoplankton species in Diaohe Aqueduct is uniform.

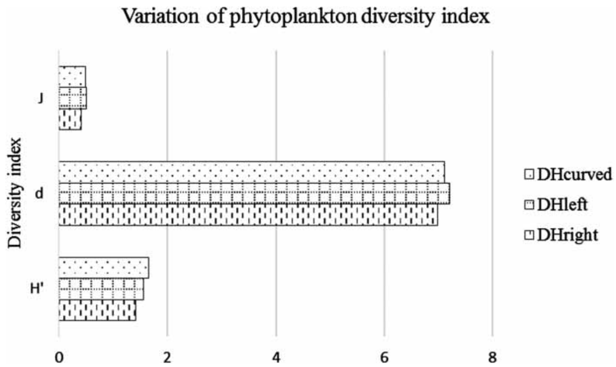

Figure 4 | Spatial variations of phytoplankton diversity indexes.

Classification of phytoplankton into functional groups

The composition of phytoplankton functional groups can be analyzed according to the physiological and growth

Table 4 | Water quality and ecological evaluation standards

Biodiversity index	Serious pollution	Heavy pollution	Medium pollution	Light pollution	Oligosaprobic (clean)
H'		<1	1–2	2–3	>3
D	0–1	1–2	2–3	3–4	>4
J		0–0.3	0.3–0.5	0.5–0.8	0.8–1

characteristics of phytoplankton and the mechanism of their environmental adaptability as proposed by Reynolds *et al.* (2002) and Padisák *et al.* (2009). The identified phytoplankton were classified into different groups according to their functions. As shown in Table 5, the phytoplankton in Diaohe Aqueduct can be divided into 17 functional groups, namely: B, C, D, F, G, H1, J, LO, M, MP, N, P, T, TB, W1, WO, and X2.

If the dominance of a certain functional group is $\geq$0.02, its status in the water is dominant and we call it the dominant functional group (Wang *et al.* 2018). The monitoring results on the left bank of Diaohe River register the most species of Bacillariophyta, in which *Fragilaria*, *Cymbella*, *Navicula* and *Diatoma vulgare* Bory (in the order of dominance from large to small, the same below) are absolutely dominant. On the right bank of Diaohe River, *Fragilaria*, *Navicula* and *Cymbella* are absolutely dominant, and at the water quality sensitive point, *Navicula*, *Fragilaria*, *Cymbella* and *Oscillatoria* are absolutely dominant.

In the monitoring period, the degree of dominance of the TB functional group in all the four sampling investigations is $\geq$0.02, which makes it the absolute dominant functional group in the Diaohe section of the middle water diversion route. The TB functional group includes *Fragilaria* and *Navicula*, and the secondary functional groups are P and MP, which mainly include *Diatoma*,

Table 5 | Classification of phytoplankton in Diaohe Aqueduct into functional groups

Functional group	Representative species (genus)	Physiological characteristics
B	*Cyclotella* Kützing	Small and medium-sized mesotrophic lakes, sensitive to stratification
C	*Cyclotella hubeiana* Chen et Zhu, *Cyclotella meneghiniana* Kütz., *Asterionella* sp.	Small and medium-sized mesotrophic lakes, sensitive to stratification
D	*Synedra ulna* (Nitzsch.) Ehr., *Synedra acus* Kütz.	Shallow turbid rivers
F	*Oocystis* Nägeli, *Planktosphaëria gelatinosa* G. M. Smith	Deep mesotrophic and eutrophic lakes, thermocline
G	*Eudorina* sp.	Small eutrophic lakes, river basins or reservoirs
H1	*Anabaena* sp., *Aphanizomenon* sp., *Aphanizomenon flos-aquae* (L.) Ralfs	Shallow eutrophic, stratified, low-nitrogen lakes
J	*Pediastrum* Meyen, *Pediastrum simplex* Meyen, *Scenedesmus* Mey., *Scenedesmus bijuga* (Turp.) Lag.	Mixed shallow, highly eutrophic waters
LO	*Radiococcus nimbatus* (Wild.) Schm., *Gymnodinium* sp., *Gyrosigma* Hassal	Broad adaptability
M	*Microcystis* Kütz., *Microcystis densa* G.S.West, *Microcystis robusta* (Clark) Nygaard	Stable mesotrophic and eutrophic waters with transparency not too low
MP	*Oscillatoria* Vauch., *Cymbella* Agardh	Frequently disturbed, non-organic, shallow turbid lakes
N	*Staurastrum planctonicum* Teiling, *Staurastrum manfeldtii* Delp.	Mixed layer of mesotrophic waters,
P	*Diatoma* De Candolle, *Melosira* Agardh	Shallow highly mixed mesotrophic and eutrophic waters
T	*Mougeotia* sp.	Thermocline of uniformly mixed deep waters
TB	*Navicula* Bory, *Fragilaria* Lyngb., *Nitzschia* Hassall, *Achnanthes* Bory	Abominable streams and rivers
W1	*Euglena* Ehrenberg	Waters rich in organic matter or agricultural wastewater and domestic sewage
WO	*Chlamydomonas* Ehrenherg	Rivers and ponds highly rich in organic matter
X2	*Cryptomonas* Ehr., *Phacotus*	Shallow highly mixed, mesotrophic and eutrophic waters

Cymbella and *Oscillatoria*. All the three functional groups are between mesotrophic and eutrophic. In this study, since the TB, P, and MP functional groups are the dominant functional groups in Diaohe Aqueduct in winter, it is inferred that the nutritional state of Diaohe Aqueduct may be mesotrophic.

Discussion

During the study period, although the β-p hypertrophic phytoplankton indicator and β mesotrophic phytoplankton indicator dominated in the Diaohe Aqueduct, considering the phytoplankton diversity index (including the Shannon–Wiener index, the Magalef richness index and the Pielou evenness index) and the study of phytoplankton functional groups, it can be inferred that the water quality of the Diaohe section was mesotrophic. The Middle Route of the South-to-North Water Diversion Project diverts water from Danjiangkou Reservoir to Beijing, Tianjin and other cities. As Wan *et al.* (2020) reports, the water quality of Danjiangkou Reservoir in 2018 was in a mesotrophic state, and the Diaohe Aqueduct is only a section of the MRP, so it is speculated that the mesotrophic state of water quality in the Diaohe Aqueduct during the study period may be related to the water quality of the Danjiangkou Reservoir. However, the conclusions drawn using phytoplankton alone as the evaluation index may not be comprehensive, and needs to be further combined with other indexes for comprehensive consideration. So in the future the water quality index and the phytoplankton need to be considered comprehensively.

CONCLUSION

By analyzing the water quality monitoring data, it is found that the water quality of the Diaohe Aqueduct is relatively clean, which meets the Grade II Chinese Environmental Quality Standard for Surface Water (G3838-2002). The phytoplankton population in the Diaohe section of the Middle Route in winter consists of 62 species of phytoplankton under 32 genera, 22 families and six phyla, and the main dominant species or genera are *Cyclotella*, *Navicula*, *Fragilaria*, *Diatoma* and *Cymbella* under Bacillariophyta and *Oscillatoria* under Cyanophyta. Considering the pollution indicator species, dominant functional groups and diversity index of phytoplankton in the Diaohe Aqueduct, it is inferred that the water quality of the Diaohe section was mesotrophic in the winter of 2018. Although the conclusions analyzed by phytoplankton community may not be comprehensive, it is recommended that the local government should pay more attention to changes in the phytoplankton community while carrying out long-term water quality monitoring.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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