Ecological assessment of water quality in an urban river replenished with reclaimed water: the phytoplankton functional groups approach

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Abstract

Comprehensive water quality assessment plays a vital role in decision making for the sustainable management of urban rivers, and thus the exploration of integrated ecological assessment methods for water quality has become a major requirement. This study assessed the water quality of the North Canal River on the basis of its ecological status using the phytoplankton functional groups (PFGs) approach. The river runs through the megacities of the Beijing-Tianjin-Hebei region in China, and is mainly replenished with reclaimed water. The results showed that the PFGs approach is much better for evaluating the water quality of urban rivers than the conventional physicochemical index method and phytoplankton diversity metrics, because the PFGs approach is more sensitive to the spatiotemporal variations in the water quality of urban rivers. The average Q, index, for ecological status estimation in rivers, based on the PFGs of the North Canal River was 3.30, indicating 'good' water quality. In the dry season, the dominant PFG upstream was group D (Cyclotella spp.), whereas the major downstream PFGs had changed to group Y (Glenodinium spp., Cryptomonas ovata, and Cryptomonas erosa) and W1 (Euglena spp. and Gonium pectoral). While the dominant PFG throughout the river changed to T1: Melosira spp. in the wet season. The Q, at each site was one to two grades lower during the wet season than the dry season, indicating that water quality was worse in the wet than the dry season.

1. Introduction

As an important part of urban landscapes, urban rivers are very much influenced by rapid social and economic progress (Wang et al 2013), which has caused a series of environmental issues such as water shortages, water pollution, ecological degradation, and eutrophication (Dalu et al 2019, Zhong et al 2019). Such issues are particularly serious in the urban rivers of some cities in China, and it is becoming a challenge to sustainably meet the increasing demands of human and social development (Xu et al 2019, Zhang et al 2019). The importance of water environment protection and restoration in urban areas is widely recognized and the Chinese government considers it a priority (MWR 2008, 2018). Thus, a series of laws and regulations have been formulated, such as the Water Law (2002) and the Action Plan for Water Pollution Prevention and Control (2015). A large number of engineering projects have also been planned and implemented, such as river restoration, black-odorous water body treatment and remediation, the interception of wastewater along rivers, and construction of municipal wastewater treatment plants (WWTPs). It is well known that water quality assessment is crucial for the support
of the protection, restoration, and management of urban rivers; further that these play a vital role in the decision making required for sustainable river management (Shi et al. 2017). It is common in China that the surface water management is based on the water function zone objectives, according to the physicochemical indicators of Environmental Quality Standards for Surface Water (GB 3838-2002) (Lv et al. 2020). However, these methods only describe the physicochemical status of water bodies, and not their ecological status. Therefore, the development of water quality evaluation methods based on both aquatic ecological status and physicochemical status is thus becoming an urgent requirement, for sustainable river management in China.

Aquatic organisms, including benthic macroinvertebrates, macrophytes, diatoms, phytoplankton, and fish, are used to assess the ecological status of surface water bodies according to the EU Water Framework Directive (WFD) (Karaozuz et al. 2019). As a key component of aquatic ecosystems, phytoplankton plays an important role in responding rapidly to changes in their environment, and is thus considered a good indicator for water quality assessment (Vajravelu et al. 2018, Yang et al. 2019). There is a long history of using phytoplankton species composition as an indicator of biological water quality (Soumia 1978, Smith 1983, Shapiro 1997). Previous studies have reported that the spatial and temporal variations in phytoplankton distributions are widely affected by physical, chemical, and biological factors; for example, using phytoplankton as indicators, high correlations have been found between physicochemical indices and diatoms (Karaozuz et al. 2019), and between water resource vulnerabilities and human impact (Nankabirwa et al. 2019). Varol (2019) showed that NO$_3^-$, SiO$_2$ total phosphorus (TP), pH, and water temperature (WT) are the most important environmental factors controlling the species composition and diversity of phytoplankton communities in aquatic systems (Rosinska et al. 2017, Barrenha et al. 2018). In addition, these alterations in composition and diversity are widely accepted as highly sensitive early warning indicators of water quality status (Carvalho et al. 2013). Reynolds et al. (2002) reported that in response to well-defined environmental conditions, characteristic species associations occur in phytoplankton; these are defined as phytoplankton functional groups (PFGs). Based on this concept, a new ecological status estimation method (Q index) was developed for lake phytoplankton, and then for river phytoplankton ($Q_r$ index) (Borics et al. 2007). The PFGs approach and $Q_r$ ($Q$) indices that are highly correlated with natural physical constraints and disturbances in time and space have been widely studied in natural rivers and reservoirs (Borics et al. 2014, Frau et al. 2019). For instance, Abonyi et al. (2012) examined the application of the $Q_r$ index to the river Loire and Becker et al. (2010) assessed the ecological status of the Sau Reservoir using $Q_r$.

However, urban rivers are very different from natural rivers because they have shallow depths and are highly artificial, with more established dams than in natural rivers; thus, urban rivers should be carefully managed to address the various needs of policymakers, including recreation, irrigation, and flood control (Rose et al. 2019). Due to water shortages in China, non-conventional water resources such as reclaimed water from WWTPs have become important water replenishment resources for urban rivers (Petts 2009, Liu et al. 2018, Zhong et al. 2019); in 2017, approximately 92% of reclaimed water in Beijing was used to replenish lakes and rivers (Lv et al. 2020). The discharge standard for water pollutants from WWTPs in Beijing (DB 11/890-2012) specifies that the total nitrogen (TN) and total phosphorus (TP) concentration limits for Grade A effluent should be 10 mg l$^{-1}$ and 0.2 mg l$^{-1}$, respectively, and that the N/P ratio (m/m) of effluent should be 50. Such high effluent N/P ratios affect water quality and aquatic ecosystems in any receiving water bodies (Barrenha et al. 2018). Compared with natural rivers which get replenished by natural water sources, it is of paramount importance to comprehensively monitor the water quality and ecological status of urban rivers replenished with reclaimed water, to support their sustainable management; critical factors include phytoplankton diversity, PFGs, and relationships with environmental variables. To the best of our knowledge, to date, no study has assessed the water quality of urban rivers replenished with reclaimed water using the PFGs approach.

The North Canal River originates in Beijing and flows through the megacity areas of the Beijing-Tianjin-Hebei region. Located in the northern part of the dry North China Plain, it is managed by different local governments. Its basin area is approximately 6166 km$^2$, with a main channel length of approximately 186 km, and 17 flood control sluices (Zhang et al. 2020). The upstream portion of the North Canal River in Beijing is known as the Wenyu River. The Wenyu River basin encompasses the central area of Beijing City, accounting for almost 70% of the population and 80% of Beijing’s GDP; it accounts for 90% of the drainage from the central Beijing region, which is heavily affected by urbanization (Wang et al. 2013, Liu et al. 2018). With great effort and the implementation of the water pollution control action plan in 2015, the water quality in the Wenyu River has improved significantly; the main water pollutant changed from ammonia nitrogen (NH$_4^+$-N) in 2010 to TN in 2018, and the dominant species of phytoplankton changed from Cyanophyta in 2011 to Bacillariophyta in 2018 (Yu et al. 2012, Zhu et al. 2020). The 80% section of the North Canal River thus achieved grade IV standard water quality (GB3838-2002) in 2019 (BMEE 2020). As the physicochemical status of water bodies improves, the sustainable management of urban rivers presents new demands for aquatic ecosystem restoration. However, the traditional water quality assessment by the physicochemical index method cannot meet with its increasing sustainable management requirements for ecological restoration of urban rivers, such as its responsibility, investment and operation & maintenance of local governments due to river across through different
administration areas along with carrying out ecological civilization in China. Therefore, the North Canal River was selected for this study, with the purpose of exploring the feasibility of evaluating the ecological status and water quality of the urban river in the dry and wet seasons using the PFGs approach and Q$_r$ index method; to provide support for decision makers of urban river restoration and sustainable management.

2. Materials and methods

2.1. Study area

The North Canal River runs through the Jing-Jin-Ji Urban Economic Circle, the political and cultural center of China; as shown in figure 1. It originates in the southern part of Yan Mountain, located in the Changping district of Beijing, and flows progressively south-east through the Tongzhou district of Beijing, the Langfang city of Hebei province, and Tianjin City. The Beiguan sluice in the Tongzhou district is upstream of the North Canal River, in a 47.5 km long section known as the Wenyu River. The Qing and Ba rivers are the main tributaries of the Wenyu River, with annual runoff accounting for 40.65% and 30.03% of its total runoff, respectively (Wang et al. 2013). Below the Beiguan sluice, the North Canal River runs downstream for a distance of 95.5 km until its confluence with the Ziya River, and eventually draining into the Hai River (Xu et al. 2019). Therefore, in the Jing-Jin-Ji Urban Economic Circle, the North Canal River is mainly replenished with reclaimed water from WWTPs (Wang et al. 2013). In 2019, a total of 692.5 million m$^3$ of reclaimed water was discharged upstream of the North Canal River, accounting for 74.91% of the annual runoff from the Beiguan sluice (figure S1 (available online at stacks.iop.org/ERC/3/115006/mmedia)). The quality of the reclaimed water meets Grade A of the discharge standard of water pollutants for WWTPs in Beijing (DB 11/890-2012), as shown in table S1. The North Canal River basin has a temperate zone monsoon climate with an annual mean rainfall of approximately 643 mm. The wet season usually spans from June to September, with approximately 84% of the annual rainfall, while the dry season spans between October and May (Zhang et al. 2019).

2.2. Sampling and analysis

In this study, 14 sites in the main channel of the North Canal River were selected for water sampling; of which S1 to S7 were upstream and S8 to S14 were downstream (figure 1 and table S2). Among the 14 sites, the seven upstream sites and the downstream site S14 were all located in urban areas and mainly influenced by human activities. The other six downstream sites were located in rural areas and were mainly influenced by agricultural nonpoint source pollution (table S2). Samples were collected bi-monthly using a Ruttner sampler, from July 2018 to May 2019, except in January 2019, due to the rivers being frozen. Water samples were collected from a depth of 0.5 m below the surface at each sampling site and transported to the laboratory in an insulated icebox. Sampling was completed within 1–2 days at all 14 sampling sites. Physical parameters, including water temperature (WT), dissolved oxygen (DO), electroconductivity (EC), and pH were measured in situ using a multi-parameter instrument (HQ43d WTW, Germany). Chl a ($\mu$g l$^{-1}$) concentrations were measured using a Hydrolab DSS (HACH, USA). Chemical parameters, including chemical oxygen demand (COD$_{cr}$), TP, NH$_4^+$ -N, and TN were determined according to standard procedure (EPAC 2002).
One-liter phytoplankton samples were collected simultaneously with the water samples, fixed in situ in polyethylene bottles with alkaline Lugol’s solution, and transported to the laboratory in the water samples. In the laboratory, the samples were stored in 1 l funnel flasks in the dark for 3–5 days prior to taxonomic analysis and the counting of phytoplankton. Sedimented phytoplankton were transferred to smaller bottles until approximately 30 ml of phytoplankton samples were obtained. The identification of phytoplankton species followed the methods described by Hu and Wei (2006) and Guiry and Guiry (2021). The biovolume of the dominant species was determined by measuring the dimensions of 5–30 individuals and calculating biovolume from the closest geometrical figure (Hillebrand et al. 1999). Assuming a mean density of 1 g cm−3, the biovolume was transformed into biomass (Bahnwart et al. 1998). Sedgwick rafter counting chambers in conjunction with an inverted microscope was used to count and identify species (Olympus CKX-41) to at least the genus level, but mostly at the species level. Phytoplankton taxa were classified into PFGs according to previously published methods (Padišák and Reynolds 1998, Reynolds et al. 2002, Borics et al. 2007, Padišák et al. 2009, Abonyi et al. 2020). PFGs accounted for more than 5% of the total phytoplankton biomass and were classified as the predominant groups.

The dominance index (Y), Shannon-Wiener diversity index (H′), Margalef richness index (M), and Pielou evenness index (J) were used to calculate phytoplankton community metrics. A species was considered dominant when \( Y \geq 0.02 \). It has become common practice to use the following index values to assess water quality: \( 3 < H', 0.5 < J', \) or \( 5 < M \) indicates mild or no contamination, \( 1 < H' < 3, 0.3 < J < 0.5, \) or \( 3 < M < 5 \) indicates moderate contamination, and \( 0 < H' < 1, 0 < J < 0.3, \) or \( M < 3 \) indicates serious contamination (Xu et al. 2017). These indices are calculated using the following equations (Shannon and Weaver 1998, Varol 2019):

**Dominance index:**

\[
Y = \frac{n_i}{N} \times f_i \quad (1)
\]

**Shannon-Wiener diversity index:**

\[
H' = -\sum_{i=1}^{S} p_i \ln p_i \quad (2)
\]

**Margalef richness index:**

\[
M = \frac{S - 1}{\ln N} \quad (3)
\]

**Pielou evenness index:**

\[
J = \frac{H'}{\ln S} \quad (4)
\]

where \( n_i \) is the individual number of species \( i; f_i \) is the frequency of species \( i; p_i = \frac{n_i}{N}; \) \( N \) is the total number of individuals; and \( S \) is the total number of species.

The \( Q_i \) index was used as a water quality metric for the predominant PFGs. This index reflects potential threats to water quality, such as eutrophication and organic pollution, based on a compound factor (F) (table S4) for each PFG (Borics et al. 2007). The index is calculated using the following equation:

\[
Q_i = \sum_{i=1}^{S} P_i \times F_i \quad \text{where} \quad P_i = \frac{nb_i}{NB} \quad (5)
\]

where \( nb_i \) is the biomass of the \( i \)-th group, \( NB \) is the total biomass, and \( F \) is the factor number assigned to each PFG. The theoretical maximum \( Q_i \) is 5 and the minimum is 0. For water quality grading scale, 0–1 indicates ‘bad’, 1–2 ‘tolerant’, 2–3 ‘medium’, 3–4 ‘good’, and 4–5 ‘excellent’ water quality (Borics et al. 2007).

### 2.3. Statistical analysis

The differences in the spatial and temporal distribution of environmental variables in the North Canal River were analyzed by pooling data across sampling months (March, May, July, September, and November) using t-test and one-way analysis of variance (ANOVA). For the analysis, the data were transformed into Log10(x+1) to obtain a normal distribution of the data. Principal coordinates (PCO) analysis was performed on the data, pooling the data from the sampling months, and analyzing them using the Bray-Curtis distance measure. This analysis was used to characterize differences in sampling sites by examining PFG preferences, such as nutrient status and water turbulence. A permutational multivariate analysis of variance (PERMANOVA) was performed alongside the PCO analysis, to verify the statistical significance of each PCO \( p < 0.05 \). All statistical analyses were performed in IBM SPSS Windows v. 25.0 and CANOCO v. 5.0 (ter Braak and Smilauer 2012). Figures were plotted using OriginPro 9.0 (OriginLab, USA) and R ggplot (R version 3.5.2).
3. Results

3.1. Changes of water quality with physicochemical parameters

In this study, there was no significant spatial variation ($p > 0.05$, t-test) between the upstream and downstream values of the physicochemical variables measured in the North Canal River (figure S2, table 1). However, some parameters exhibited significant seasonal differences ($p < 0.05$, ANOVA). As expected, WT values were lower in November (9.40°C) and higher in July (31.50°C). The mean annual DO concentration was 11.11 ± 2.28 mg l$^{-1}$. The mean EC values of the upstream (901.66 ± 188.26 μS cm$^{-1}$) were lower than that of the downstream (1162.85 ± 411.60 μS cm$^{-1}$) ($p > 0.05$, t-test). The mean pH value was 8.51 ± 0.65, with the highest pH value of 9.64 at sampling site S1, in September. pH values exceeded 9 at sites S1, S5, and S7 (upstream) during the wet season (July and September), and S8, S11, and S13 (downstream) during the dry season (November), respectively. ANOVA showed that the pH values were significantly different between months ($p < 0.05$). The annual mean Chl a concentration was 59.31 ± 38.19 μg l$^{-1}$, with lower concentrations at sampling points S3, S6, and S14.

The monthly variation in COD$_{cr}$ concentration was significantly different ($p < 0.05$, ANOVA) with an average value of 43.83 ± 26.63 mg l$^{-1}$. The COD$_{cr}$ concentration was lower downstream than upstream ($p > 0.05$, t-test) (table 1). Deviating from the trend of the COD$_{cr}$, the average concentration of NH$_4^+$-N was the highest in March (2.17 ± 0.47 mg l$^{-1}$), with the mean value of 1.42 ± 0.15 mg l$^{-1}$. The monthly variation in NH$_4^+$-N concentration was significantly different ($p < 0.05$, ANOVA). The annual average concentration of TN was 5.85 ± 1.28 mg l$^{-1}$, with a decreasing trend further along the river and no significant temporal variations ($p > 0.05$, ANOVA). The TN concentrations at the upstream sites were significantly higher than that at the downstream sites ($p > 0.05$, t-test) (table 1). The annual mean TP concentration was 0.26 ± 0.05 mg l$^{-1}$ (table 1).

3.2. Changes of phytoplankton community

A total of 112 phytoplankton species were observed at 14 sites in the North Canal River, comprising diverse taxa from seven phyla (figure 2(a)). Chlorophyta (39 species; 35.16%) was the most diverse phylum, followed by Bacillariophyta (31 species; 27.93%), Cyanophyta (22 species; 19.82%), and Euglenophyta (11 species; 9.91%). Pyrrophyta, Cryptophyta, and Chrysophyta were represented by five species (4.50%), two species (1.80%), and one species (0.09%), respectively (figure 2(a)). The number of phytoplankton species was higher in September and lower in March.

The average phytoplankton biomass in the North Canal River was 95.27 mg l$^{-1}$, and the monthly phytoplankton biomass varied significantly ($p < 0.05$, ANOVA). The highest and lowest phytoplankton biomasses, September and March 161.49 mg l$^{-1}$ and 47.98 mg l$^{-1}$, were observed in September and March, respectively (figure 2(b)). Bacillariophyta algae (52.28 mg l$^{-1}$) were the most biomass taxon, with an average contribution of 53.88% to the total biomass. Euglenophyta algae (11.92 mg l$^{-1}$) were the second most biomass taxon, with an average contribution of 12.51% to the total biomass, and Chlorophyta algae (7.84 mg l$^{-1}$) were the third most biomass taxon, accounting for 8.22% of the total biomass (figure 2(b)).

The dominant species and their dominant index ($Y$) values are summarized in table S3. During the wet season (July and September), Oscillatoria tenuis, Arthrosira platensis, and Merismopedia elegans (from Cyanophyta) were the dominant species. They were observed in most of the upstream sites, especially in July. In September, Bacillariophyta and Cyanophyta were the dominant species in the North Canal River.

| Variables | unit | Upstream | Downstream | Wet season | Dry season |
|-----------|------|----------|------------|------------|------------|
| WT | °C | 20.23 ± 6.97 | 19.77 ± 7.52 | 26.32 ± 5.37 | 15.95 ± 5.59 |
| DO | mg l$^{-1}$ | 11.11 ± 2.28 | 9.88 ± 2.62 | 10.62 ± 3.31 | 10.43 ± 1.30 |
| EC | μS cm$^{-1}$ | 901.66 ± 188.26 | 1162.85 ± 411.60 | 949.26 ± 285.42 | 1082.50 ± 366.84 |
| pH | | 8.51 ± 0.65 | 8.42 ± 0.42 | 8.66 ± 0.50 | 8.34 ± 0.48 |
| Chl.a | μg l$^{-1}$ | 62.34 ± 51.88 | 54.44 ± 43.78 | 61.66 ± 43.86 | 56.38 ± 45.14 |
| COD$_{cr}$ | mg l$^{-1}$ | 45.83 ± 27.95 | 41.76 ± 23.55 | 44.56 ± 28.55 | 43.36 ± 20.47 |
| NH$_4^+$-N | mg l$^{-1}$ | 1.35 ± 1.09 | 1.49 ± 1.34 | 1.11 ± 1.06 | 1.61 ± 1.08 |
| TN | mg l$^{-1}$ | 7.31 ± 1.87 | 4.35 ± 2.21 | 5.75 ± 2.57 | 5.91 ± 2.35 |
| TP | mg l$^{-1}$ | 0.24 ± 0.13 | 0.29 ± 0.28 | 0.30 ± 0.21 | 0.24 ± 0.17 |
| N/P ratio (m/m) | | 40.50 ± 29.01 | 32.88 ± 24.30 | 25.79 ± 22.61 | 36.84 ± 29.43 |
| $H'$ | | 1.78 ± 0.67 | 2.02 ± 0.51 | 2.02 ± 0.47 | 1.82 ± 0.61 |
| $M$ | | 2.93 ± 0.96 | 2.18 ± 0.97 | 2.44 ± 0.82 | 2.63 ± 1.49 |
| $J$ | | 0.57 ± 0.20 | 0.71 ± 0.16 | 0.66 ± 0.15 | 0.62 ± 0.21 |

Table 1. Environmental factors and phytoplankton biodiversity indices in the North Canal River and seasons.
Discostella stelligera (Bacillariophyta) was mainly observed upstream, while Oscillatoria tenuis (Cyanophyta) was mainly observed downstream. During the dry season, fewer previously dominant species were observed, with dominance shifting to Bacillariophyta, such as Discostella stelligera and Cyclotella meneghiniana. In March and May, Discostella stelligera was observed at all upstream sites, with the highest Y value (0.147) at S7. In November, the dominant species were observed at only three upstream sampling sites, represented by the dominant species Merismopedia elegans, Cyclotella meneghiniana, and Tetrastrum glabrum, belonging to Bacillariophyta and Chlorophyta, respectively.

The annual average values of diversity metrics $H'$, $M$, and $J$ were $1.90 \pm 0.56$, $2.56 \pm 1.26$ and $0.64 \pm 0.18$, respectively, which indicated a river water quality of 'moderate contamination' (figure 3). T-test results showed that the diversity metrics $H'$, $M$, and $J$ were not significantly spatially or seasonally different in the upstream and downstream sections of the North Canal River (table 1).

3.3. Changes of Phytoplankton functional groups
In this study, phytoplankton taxa were classified into 23 functional groups (table S4) (Reynolds et al 2002, Borics et al 2007, Padisák et al 2009, Abonyi et al 2020). Nine functional groups (C, W1, D, Y, T_B, X2, G, J, and T_C) contributed to more than 5% of the total phytoplankton biomass at each sampled site, and were classified as the predominant groups in the North Canal River. Therefore, these nine functional groups were used for the analysis of phytoplankton community composition and dynamics (figure 4).

Functional group Y was the only group that exceeded 10% of the total phytoplankton biomass during the study period, with contributions of 14.09% and 15.37% in the dry and wet seasons, respectively (figure 4). During the dry season, functional group D was dominant (44.61% on average), while functional groups W1, Y, and T_B were subdominant with average contributions of 14.31%, 14.09%, and 11.17%, respectively. However, in the wet season, the biomass of group D decreased significantly, to 10.72%, while the functional group biomass of T_B and Y continued to increase, resulting in co-dominance at 25.67% and 15.37%, respectively. Meanwhile, the functional group T_C emerged as sub-dominant, accounting for 13.87% of the total biomass.

According to the PERMANOVA results, the differences in the measurements at the upstream and downstream sites were statistically significant ($p < 0.05$), except during September, when $F = 1.726$ and $p = 0.091 > 0.05$. As shown in figure 5, the first and second principal axes represented by PCO1 and PCO2 in each month were well-distinguished from the characteristic of PFGs arrangement at different sites during the dry and wet seasons. The plane formed by the first axis alone explained more than 50% of the differences in these

Figure 2. Composition (a) and biomass (b) of Phytoplankton community in the North Canal River.
observations. During the dry season, the PFGs arrangement differed between the upstream and downstream sites of the North Canal River. The upstream sites were characterized by the PFG (D) characteristics associated with shallow and mid-mixed waters, whereas the downstream groups (C, G, Y, and W1) represented eutrophic, standing, and highly organic waters. During the wet season (July), the PFGs in the upstream sites indicated highly eutrophic waters (TC and TB), while the downstream sites indicated mixed, inorganic turbid, and eutrophic waters (X2 and J) (figure 5 and table S4).

3.4. Water quality assessment by the PFGs approach

The water quality assessments associated with the $Q_i$ of each PFG are depicted in figure 6. The average $Q_i$ index of the North Canal River was 3.30, indicating ‘good’ water quality. Overall, the average $Q_i$ index at the upstream sites (3.57) was higher than that at the downstream sites (3.02), indicating that the water quality was better upstream. In the dry season, the water quality at the upstream sites was ‘good,’ with an average $Q_i$ index of 3.77.
The Qr indices of S3 and S6 in March and S4 and S6 in May were >4, exhibiting the best water quality during the study period. In the wet season, downstream sampling site, S11, represented a state of pollution tolerance (Qr < 2). Clearly, the Qr index at each site in the North Canal River decreased by one or two grades during the wet season, indicating that the water quality worsened during the wet season, compared to the dry season.

Pearson correlation analysis was carried out on the environmental factors, phytoplankton diversity metrics, the nine predominant PFGs, and Qr indices; network analysis was also performed using indicators, with significant correlations found (p < 0.05) (figure 7). The results showed that diversity, $H'$, was positively correlated with pH and EC, M had positive correlations with TP and TN, and that J was positively correlated with WT and EC, respectively. The Qr index was negatively correlated with pH and WT, and exhibited a significantly

**Figure 4.** Variation in relative biomass (%) of the phytoplankton functional groups in the North Canal River.

**Figure 5.** Principal coordinates analysis (PCO) for each month: March (triangle), May (star), July (circle), November (square). (The upstream sites are in green and downstream sites are in red).
positive correlation with TN. There were no significant correlations between the predominant PFGs and NH$_4^+$-N. Group C had a positive correlation with TN, while Y and TC had a negative correlation with TN. Groups G and X2 were positively correlated with pH and COD$_{Cr}$ levels. Group T$_8$ had a significantly positive correlation with COD$_{Cr}$.
Table 2. Distribution of municipal WWTPs in the upstream of the North Canal (MEE, 2020).

| Design treatment capacity (10^3 m³ d⁻¹) | Number | Discharge standard of water pollutants | Actual volume of water treated in 2019 (10^3 m³ d⁻¹) |
|-----------------------------------------|--------|----------------------------------------|--------------------------------------------------|
| <20                                     | 27     | Grade A of discharge standard of water pollutants for WWTPs in Beijing (DB 11/890-2012) | 10.7375                                          |
| 20–50                                   | 17     |                                        | 83.0771                                           |
| 50–100                                  | 8      |                                        | 103.7003                                          |
| >100                                    | 3      |                                        | 494.9433                                          |

4. Discussion

4.1. Response of phytoplankton and PFGs to the aquatic environment quality

Sustainable river management requires adequate environmental flow (Potts 2009). Non-conventional water sources are highly promising resources for the alleviation of urban water scarcity, especially in arid and semiarid regions. For example, the largest-scale and most successful water reuse project in China is in Beijing (Chen et al. 2015); the amounts of reclaimed water were at 1.2 billion m³ in 2020 (BWA 2021).

The North Canal River is a typical urban river replenished with reclaimed water resources. Based on the list of Beijing centralized municipal wastewater treatment facilities (MEE 2020), approximately 57 WWTPs were constructed upstream of the North Canal River, 13 of which were designed to treat ≥50,000 m³ of municipal wastewater every day (figure S1). The actual total volume of treated water in 2019 was 692.5 million m³, accounting for 74.91% of the annual runoff from the Beiguan sluice in 2018 (table 2); reclaimed water contributed to approximately 70% of the upstream river flow. Yu et al. (2012) previously reported that the ratios of annual effluent to river runoff in the two main upstream sluices of the North Canal River, the Shahe Sluice and the Beiguan Sluice, were 55% and 84%, respectively; indicating that reclaimed water accounts for more than half of the upstream outflow. Based on the measured physicochemical parameters, the characteristics of reclaimed water as a main supply source makes no significant difference to the upstream and downstream water quality in the North Canal River (table 1). This is consistent with the results of Liu et al. (2018), who reported on the traceability of nitrogen in North Canal River water by using a dual stable isotope approach. It is difficult to distinguish differences in the water from different river segments based on the assessment of water quality using the physicochemical index method, making it impossible to reasonably implement independent urban river management strategies.

The ecologically competitive nature of phytoplankton results in it being exceptionally sensitive to changes in nutrient forms, such as ammonia nitrogen (NH₄⁺-N) and nitrate nitrogen (NO₃⁻-N), in the water environment (Reynolds 2006, Vajravelu et al. 2018, Zhong et al. 2019). Reed et al. (2016) demonstrated that nitrogen can effectively increase phytoplankton density, which was consistent with the conclusions of Sitta et al. (2018). Leruste et al. (2019) showed that NH₄⁺-N can promote the growth of Cyanophyta, whereas diatoms and dinoflagellates preferentially use nitrate nitrogen. In this study, the water quality of the North Canal River had characteristics typical of reclaimed water with high total nitrogen (TN) and low total phosphorus (TP), due to the high percentage of reclaimed water (table 1). For example, the average NH₄⁺-N:TN ratio in the river water was 0.28:1, showing more nitrate nitrogen, which resulted in Bacillariophyta (average 52.28 mg l⁻¹) being the taxa with the highest average biomass contribution (53.88%) to the total biomass (figure 2b). The dominant Bacillariophyta species with indices of Y ≥ 0.02, such as Discostella stelligera, Cyclotella meneghiniana, and Aulacoseira granulate, were more dominant upstream, while the Cyanophyta species (e.g., Oscillatoria tenuis) were more dominant downstream (table S3). The results clearly show that spatiotemporal differences in water quality can be delineated based on phytoplankton compositions, which are more sensitive than physicochemical parameters (table 1 and figure S2). Nankabiirwa et al. (2019) found that the use of phytoplankton indices facilitates the clustering analysis of crater lakes. Zhong et al. (2019) evaluated the outcomes of remediation projects by monitoring phytoplankton communities.

Figures 5 and 7 indicate that PFGs arrangement and their corresponding biomass are closely associated to seasonal conditions and water environments, and spatiotemporal variation was evident along the North Canal River. Table 3 shows the PFGs variability exhibited by most PFGs biomass at each site during the study period. The distributions in most of the PFGs (Tb, Y, C, N, D, G, J, and TC) biomasses are dynamic, and more diverse in the wet season than in the dry season (D, C, Tb, Y, and W1). This shows that most PFGs arrangement and biomass can be representative of different conditions along the river (figure 5). We found that one main functional group (D: Cyclotella spp.) characterized the upstream phytoplankton community during the dry season, but that the downstream functional groups were substantially different (Y: Glenodinium spp.,...
Table 3. Distribution of the most biomass PFGs at sampling sites in the North Canal River.

| Season | Month | Upstream | Downstream |
|--------|-------|----------|------------|
| Wet    | Sep.  | C TB B Y C TB Y T B TB Y C T B | S8 TB Y T B Y C T B |
|        | Jul   | TB B C N T C N Y T B D T B C G Y T B | S9 Y T B |
| Dry    | Nov.  | D D D C D TB D T C C Y Y Y C | S10 T B Y D |
|        | May   | D X2 D D D TB Y W1 W1 W1 T B Y D | S11 W1 W1 T B Y D |
|        | Mar   | D D D W1 T B D W1 T B Y D | S12 W1 W1 T B Y D |

Cryptomonas ovata, and Cryptomonas erosa, W1: Euglena spp. and Gonium pectoral). In contrast, TBB: Melosira spp. became the dominant PFG along the river during the wet season.

Such time- and segment-related changes in phytoplankton and PFGs in natural rivers have been emphasized in the literature (Abonyi et al. 2012, Xu et al. 2017, Frau et al. 2019, Zhong et al. 2019). For example, Bolgovics et al. (2017) revealed that diatoms were the dominant phytoplankton component in the upper river segments in terms of both taxa richness and relative abundance. Borics et al. (2007) assessed the ecological status of different segments of large rivers using the PFGs approach and showed that the ecological status was better upstream than downstream. In this study, the upstream sections that were supplied mainly by reclaimed water had stable and similar water qualities during the dry season, resulting in the domination of a single functional group, D, which is sensitive to mixing and the seasonal occurrence of near-surface nutrients. However, downstream tributary inflow became more complex, allowing the colonization of multiple functional groups (Y and W1). The North Canal River is the main drainage river in the urban area, and large volumes of runoff and WWTP effluent enter the river, making the water environment similar to that during the wet season. As a result, the relative biomass of TBB, representing mixed aquatic habitats, became dominant and was distributed throughout the river (figure 4 and table 3). Abonyi et al. (2020) reported that in rivers, groups J and TBB thrive in more eutrophic environments.

The results of this study, presented in table 3 and figure 6, confirm this; indicating that the downstream sections of the North Canal River require more water quality control management during the wet season. These results clearly show that the PFG approach is highly sensitive to the replenishment of urban rivers with reclaimed water and that it is a useful tool for monitoring the environmental water quality of the different segments of the North Canal River.

4.2. Assessment of ecological status and water quality

Previous studies have successfully applied the Q or Q′ index to assess the ecological status of various types of natural aquatic ecosystems (Borics et al. 2007, Wang et al. 2011). Padisák et al. (2006) developed the Q index to assess the ecological status of the different lake types established by the WFD. Becker et al. (2010) used the Q index to indicate that the Sau Reservoir had good overall ecological conditions, which was the first application of the index to a European water supply reservoir. Overall, the index is very sensitive to the occurrence of species and has proved to be a promising tool in monitoring processes. In this study, the application of the Q index to assess water quality of the North Canal River indicated that the river’s ecological status was ‘good’ during the study period, showing better water quality in the dry season than in the wet season. The ecological status of the upstream sections was found to be better than those of the downstream sections, due to the policies and actions of Beijing river management bodies (MWR 2008, Chen et al. 2015).

In this study, phytoplankton diversity metrics were also determined, to validate that the Q index is effective for evaluating water quality. Diversity metrics have been frequently used to indicate the overall ecological conditions of most phytoplankton communities and to assess the ecological status of aquatic ecosystems (Shannon and Weaver 1998, Reynolds 2006, Xu et al. 2017, Varol 2019). Based on the degree of water pollution reflected by the diversity metrics, we found that the ecological status of the North Canal River had a ‘moderate’ state of pollution. However, the differences in the spatiotemporal gradients of H′, J, and M were less significant than those of the Q′ index (figures 3 and 6). Diversity metrics are commonly based on the number of species in a community, while Q′ is based on the relative biomass of each species, and provides qualitative values independently of total biomass, and which provided a better representation of species richness (Abonyi et al. 2012). Borics et al. (2014) investigated the limitations of diversity metrics as ecological indicators and reported that the application of diversity metrics to assess large rivers should rely on the biomasses of phytoplankton species rather than total phytoplankton quantity. Pearson correlation analysis has also been used to verify that the Q′ index is more closely linked to environmental factors (figure 7). Changes in phytoplankton diversity are expressed as structural changes in the community, but are not sensitive to environmental differences. In contrast, PFGs preference analysis, such as trophic state and water turbulence, can characterize differences in the
ecological status of the sampling sites (figure 5). In summary, the Q index method can be a useful tool to evaluate the water environmental quality of urban rivers supplied by reclaimed water, and it is helpful for enhancing decision makers’ understanding and management of rivers, based on their ecological status.

4.3. Application of the PFGs approach in the sustainable urban river management

As mentioned above, it is difficult to distinguish spatiotemporal differences in water quality using physicochemical indicators and phytoplankton diversity metrics in the Beijing-Tianjin-Hebei section of the North Canal River, owing to the high proportions of reclaimed water. The variables of COD$_{Cr}$, NH$_4^+$-N, TN, and TP were not significantly different between the upstream and downstream sections (p>0.05, t-test) (table 1), while the results of the PCO and Q indices delineated clear spatiotemporal variations in the water environment (figures 5 and 6). These results clearly indicate that the PFGs approach was able to reflect the remarkable achievements Beijing has made, such as the three ‘Three-year Action Plans,’ in improving the quality of the aquatic ecology and environment in the Wenyu River basin. In addition, researchers have reported that PFGs can be used as indicators of human impact. Abonyi et al (2012) showed that different human stressors are associated with different PFGs arrangements. Frau et al (2019) identified the main pollutants using the PFGs at different sites. This will be further explored in future research on the North Canal River, which will identify the different stressors in each river section, and target the improvement of river management strategies.

5. Conclusions

The results of this study demonstrate that the PFGs approach and Q index method can provide a much better understanding of the ecological status and water quality of urban rivers replenished with reclaimed water, compared with water quality assessment using the physicochemical index method and phytoplankton diversity metrics. The ecological status of the North Canal River was classified as ‘good’ and exhibited better water quality in the dry season than in the wet season. Nine functional groups (C, W1, D, Y, T$_B$, X2, G, J, and T$_C$) were predominant in the North Canal River. The dominant upstream PFG biomass comprised group D during the dry season, and Y and W1 were dominant downstream. However, during the wet season, T$_B$ (25.67%) became the dominant functional group along the river. The PFGs method can clearly reflect the spatiotemporal environmental status of an urban river. This was the first application of the Q index to urban rivers supplied by reclaimed water, helping to ascertain the environmental conditions of the river and improve its sustainable management.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author’s contributions

All authors contributed to the work presented in the manuscript. Liying Zhu: Conceptualization, Methodology, Data analysis, Writing—original draft & editing. Yuanyuan Chen: Investigation, Data curation. Yawei Wang: Formal analysis, Data curation. Chunrong Wang: Project administration, Writing—review. Yuansong Wei: Conceptualization, Supervision, Writing—review & editing, Funding acquisition. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare no competing interests.

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13
