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Response of Macroinvertebrate Community to Water Quality Factors and Aquatic Ecosystem Health Assessment in a Typical River in Beijing, China

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Abstract

Healthy aquatic ecosystems can offer basic ecological services for the sustainable development of humans and society. Water quality greatly influences the macroinvertebrate community in aquatic ecosystems and can alter the aquatic ecosystem's health status. However, the quantitative relationship between macroinvertebrate community and water quality factors in rivers remains unclear, particularly in urban rivers, which are strongly affected by human activities. Therefore, a new framework for the quantitative analysis between macroinvertebrate community and key water quality driving factors was developed in the study, meanwhile, the aquatic ecosystem health conditions were evaluated and validated by different methods. The framework was applied in a typical urban river, the North Canal River, which is regarded as the "mother river" of Beijing. Combined with the redundancy analysis (RDA) and the thresholds indicator taxa analysis (TITAN), the water quality driving factors and their indicator species were identified and the corresponding response threshold was determined. Based on the benthic index of biotic integrity (B-IBI), the multi-metric rapid bioassessment method and biological monitoring working party (BMWP) score, the aquatic ecosystem health condition in the basin was comprehensively evaluated. The results show that fluoride, biochemical oxygen demand, ammonia-nitrogen and total phosphorus were the key water quality driving factors influencing the community structure of macroinvertebrates. Four indicator species of ammonia-nitrogen were identified by the TITAN method with a threshold range of 1.09~6.94 mg·L^{-1}, and three indicator species of total phosphorus were identified with a threshold range of 0.48~1.27 mg·L^{-1}. According to the results of the aquatic ecosystem health assessment, the river ecosystem was generally unhealthy and the upstream was better than downstream; the health condition in the mountainous areas of Changping district was the best, while that in Chaoyang district and the central city area was the worst. The framework could provide a strong basis for ecological restoration and pollution control of the urban rivers and become an important tool for the rehabilitation of aquatic ecosystems.

Key words: Macroinvertebrate; thresholds indicator taxa analysis (TITAN); threshold; urban river; aquatic ecosystem health assessment

1 Introduction

Aquatic ecosystems and their biological assemblages have continued to degrade globally due to strong anthropogenic activities in recent decades. Among the anthropogenic activities, urbanization led to rapid economic development and population growth, accompanied by the increasing amount of impervious area and discharged wastewater, which has a negative impact on water quality and aquatic ecosystem health (Gal et al., 2019; Marshalonis and Larson, 2018; Tagliaferro et al., 2020).

The basic approaches to evaluate the health status of the aquatic ecosystems include indicator species, indices of community structure and multi-metric indices (Helson and Williams, 2013; Huang et al., 2015). The index of biotic integrity (IBI), a method based on multi-metric indices including taxonomical and ecological indicators, was applied widely to assess the health of river ecosystem by evaluating the biotic integrity of aquatic organisms, such as fish assemblages (Ganasan et al., 2010), macroinvertebrates (Zhao et al., 2019) and periphytons (Paller et al., 2017).

Macroinvertebrates play an important role in the aquatic ecosystem through nutrient cycling and pollutants detoxification. They have the characteristics of abundant species, few with long life cycles, weak migration ability, easy collection and distinguished sensitivity of different water pollution. Meanwhile, community structures, dominant species, species diversity and abundance of macroinvertebrates are affected by aquatic habitats, chemical and physical conditions, channel morphology, substrate type and aquatic vegetation, which make macroinvertebrates suitable as biological indicators species (Gal et al., 2019).

However, previous studies concerning macroinvertebrate communities mainly focused on marine ecosystems(Hines et al.,2000; Ekau et al.,2010; Borja et al.,2013; Francis, 2014; Li et al., 2018), and little attention was paid to freshwater ecosystems, especially for highly urbanized river ecosystems (Francis, 2014; Li et al., 2018). The B-IBI is usually applied in natural rivers rather than urban rivers, which has two main reasons, on one hand, it is difficult to determine the reference sites reflecting the natural conditions, for urban rivers are mostly affected by anthropogenic activities (Karr et al., 1986; Morley, 2000); on the other hand, under the influence of urbanization, many sensitive macroinvertebrate species will disappear while tolerant species will proliferate (Luo et al., 2018).

Beijing, the capital of China, is a highly urbanized city. The North Canal River, the mother river of Beijing, is a typical urban river with intensive pressure from human activities. The North Canal River basin has more than 70% population of Beijing and burdens most of the pollution emission of Beijing, which leads to worrying health status. Meanwhile, the river networks of the North Canal River in the central city area have been reformed to artificial channels, which differ a lot from natural rivers. As mentioned above, the standards for ideal reference sites in the North Canal River basin are quite different from those for natural river basins. Thus, exploring the proper standards for the reference sites is significant for aquatic ecological health assessment in the North Canal River basin and other urban river basins.

Water quality is deeply affected by the development of urbanization and intensive human activities, thus, aquatic organisms must adapt to environmental stress to survive. Many previous studies have shown that water quality has a great impact on the community structures, species diversity, species abundance and ecological function of macroinvertebrates (Azrina et al., 2006), however, few studies focused on the quantitative relationship between water quality and macroinvertebrate in urban rivers. Baker and King (2010) introduced a new technique called threshold indicator taxa analysis (TITAN), which is used to detect the changes in taxa distributions along an environmental gradient, and take the change points of the synchrony among taxa as evidence for community thresholds. The TITAN method has been widely applied to detect the thresholds for benthic invertebrates along an environmental gradient (Cao et al., 2016; Thi et al., 2018), and the specific thresholds of species offer an indication of whether and how species tend to be affected by changing environmental factors. Quantitatively identifying the impact of water quality on macroinvertebrates and the thresholds of key water quality factors are significant for determining the suitable water quality conditions for the aquatic ecosystem. The study would make up the shortcomings of qualitative research between environmental factors and aquatic organism communities, what’s more, it could provide a theoretical basis for aquatic ecological restoration and pollutant control in the North Canal River basin and offer a management strategy for protecting and restoring urban aquatic ecosystem structure and functions in other urban rivers.

In the study, we surveyed the macroinvertebrate communities and measured water quality conditions in Beijing’s North Canal River basin in 2015. Our goals of the study were (1) to explore the key factors of water quality affecting macroinvertebrate communities; (2) to identify the threshold of key water quality factors for macroinvertebrate communities; (3) to evaluate the health status of urban river ecosystem based on macroinvertebrate communities.

2 Study area and sampling methods

2.1 Study area

The North Canal River originates from Yan mountain in the north of Beijing and flows through 11 districts of Beijing, with a river length of 81 km and a catchment area of 4432 km^2. The North Canal River basin, with the highest urbanization level in Beijing, has the largest plain drainage area and the largest number of tributaries in Beijing. Hence, the river is known as Beijing's "Mother River". It has a warm and semi-humid continental monsoon climate with hot, rainy summers and dry, cold winters. The average annual temperature is 10-12℃, and the average annual rainfall is 500-600 mm, of which about 80% occurs between June and August. From 1961 to 1998, the average annual surface water outflow in the North Canal River basin was about 0.93 billion m^3/a, including 0.462 billion m^3 fresh water and 0.469 billion m^3 wastewater discharge (Shen et al., 2014). With the continuous development of urbanization, eco-environmental issues including water pollution, habitat destruction, and ecological imbalance have severely restricted social and economic sustainable development. According to the previous studies, most sections of the river didn't meet the requirements of river ecosystem function, and pollutants mainly came from industry, agriculture and residents living along the river (Qiu et al., 2021).

Fig 1

2.2 Sampling methods

For this study, an extensive field investigation including macroinvertebrate communities and water quality investigation at 34 sampling stations in August 2015, coving the North Canal River basin of Beijing (Fig 1) was carried out, and the sampling stations were selected based on the degree of urbanization and variation of landscape characterization. For macroinvertebrates, the Peter Saint Mud Harvester was used to dig substrate sludge and a 60-mesh filter was used to wash the substrate sludge. Then, the macroinvertebrate was extracted and a 75% concentration alcoholic solution was added to a 200 ml plastic bottle. At last, the macroinvertebrate was classified and counted according to the aquatic organism atlas. For water quality, 12 physical and chemical factors were measured, including pH, fluoride (F^-), dissolved oxygen (DO), ammonia nitrogen (NH_3-N), permanganate index (COD_{Mn}), arsenic (As), zinc (Zn), total phosphorus (TP), total nitrogen (TN), electrical conductivity (Cond), biochemical oxygen demand (BOD) and chloride (Cl^-). Among them, pH and DO were measured on-site using a portable pH meter and portable water quality monitor, respectively, while the other water quality factors were measured in the laboratory.

3 Statistical analysis

3.1 Redundancy analysis

Redundancy analysis (Van Den Wollenberg, 1977) (RDA) was used to identify the key factors influencing the macroinvertebrate community, and the analysis was implemented via the "vegan" package in R. The degree of multicollinearity among the

11 water quality factors was examined by the variance inflation factors (VIFs). If the VIF values exceed 4, the RDA with forwarding selection was carried out and redundant variables were excluded until the VIFs of all remaining variables were lower than 4. The independent and relative importance of each water quality factor accounting for the total variations were distinguished by applying the hierarchical partitioning method via the “rdacca. hp” package in R (Lai et al., 2021). The statistical significance of each explanatory variable was validated by the Monte Carlo permutation tests with 999 permutations.

3.2 Threshold Indicator Taxa Analysis (TITAN)

TITAN is a method combining indicator species analysis and nonparametric change-point analysis. TITAN is used to detect the change points of individual taxa in frequency and abundance, and investigate the multiple taxa’s synchronous responses to a small change in nutrient enrichment gradient. TITAN was applied to the dataset using 1000 bootstrap replicates in the R package TITAN2, and taxa with occurrences <5 were not considered following the reference of Baker and King’s (2010). The TITAN splits taxa into two groups: taxa responding positively or negatively to the specific predictor variable in terms of z scores. This method is based on the IndVal (indicator values from species indicator analysis) (Dufrêne and Legendre, 1997) and incorporates a bootstrap procedure to find certain taxon responses (uncertainty <0.05), pure (purity ≥ 0.95) and reliable (reliability ≥ 0.95).

3.3 Benthic Index of Biological Integrity (B-IBI)

B-IBI is used for the assessment of ecosystem health by evaluating the integrity from the perspective of the compositions and structures of macroinvertebrate communities. First of all, the selection of reference sites is critical for the B-IBI index and the health assessment criteria (Ruaro and Gubiani, 2013), and most studies took conditions referring to physical, chemical, biological data to identify the minimally disturbed sites as the reference sites (Barbour et al., 1995; Li and Zeng, 2020). The qualitative conditions usually consider better riparian vegetation, no towns or human communities along the river, no wastewater discharges, no river modification. In addition, the reference sites should have a 100 m riparian buffer zone and more than 60% of the basin is forested, with the agricultural and urban land less than 20% of the total drainage area. While the North Canal River basin in Beijing is severely affected by human activities, the reference sites are difficult to meet such criteria. Combined with sampling conditions in the North Canal River basin, the reference sites are considered as the relatively unimpaired ones, and the criteria for the reference sites in the basin are mainly based on the investigation results of habitat and water quality (Flotemersch et al., 2006): ① habitat investigation score is above 80 and there is no point source pollution in the riparian zone; ② higher than Class III water quality criteria.

According to previous studies, biometric parameters sensitive to environmental change were selected from the perspective of community richness, community composition and community tolerance, and then their distribution range, discriminatory ability and correlation were analyzed (Qu et al., 2012; Zhang et al., 2012., Cai et al., 2014., Cui et al., 2019).

The detailed calculation method of the B-IBI can refer to relevant research (Karr et al., 1986). Firstly, core parameters of the B-IBI assessment were selected by the disturbance range analysis, boxplot method and correlation analysis. Then, the scores for those parameters were calculated through the ratio method, and the B-IBI value of each site is the sum of the standardized scores of parameters. At last, taking the 25th quantile of the B-IBI score distribution at the reference sites as a criterion for health assessment, the site with a B-IBI score greater than the 25th quantile was regarded as health status. The assessment index systems of the B-IBI are shown in Table 1.

Table 1

3.4 The multi-metric index for rapid bioassessment method

The rapid bioassessment index has been widely applied in the protection and management of river ecosystems because of its being cost-effective and efficient (Wang et al., 2015). The rapid bioassessment index is mainly divided into the following four types: based on the tolerance or sensitivity characteristics of macroinvertebrate; based on characteristics of taxa, such as Ephemeroptera + Plecoptera + Trichoptera (EPT), mollusk relative abundance, oligochaete relative abundance; based on various biodiversity indices and based on the functional group of community. The rapid bioassessment index can be used individually, or to construct a multi-metrics index for aquatic ecosystem health assessment.

Urban aquatic ecosystems are affected by various stresses like water pollution, habitat destruction and changes in land use, thus, the multi-metric index for rapid bioassessment is more suitable for urban aquatic ecosystem health assessment. Compared with natural rivers, pollution tolerant species are the absolute dominant species in urban rivers due to the higher pollution load (Nichols et al., 2016). Therefore, the multi-metrics would exclude indexes like EPT and prioritize biodiversity index and index based on the tolerance.

In the study, the multi-metric index for rapid bioassessment was applied in the North Canal River basin to validate the ecosystem health assessment result based on the B-IBI. Indices in Table 1 were selected by distribution range test and correlation test, and normalized by rules according to previous studies.

$$P_j = \frac{1}{m}\sum_{i=1}^{m} P_i \tag{1}$$

where, P_i and P_j are the normalized values of the i-th parameter and normalized values at the j-th sampling site (i=1, 2, …, m; j=1, 2, …, k); m is the total number of the selected parameters; k is the total number of the sampling sites.

3.5 The Biological Monitoring Working Party Score method

The Biological Monitoring Working Party Score method (BMWP) is a rapid biological health assessment method, and the BMWP score is calculated by counting the presence of sensitivity species. The higher the score, the more sensitive species, the lower impact of human activities, the better the ecosystem health.

According to the difference of pollution resistance characteristics of macroinvertebrates, sensitivity scores from 1 to 10 are given to macroinvertebrates species from the least sensitive to the most sensitive. The sensitivity scores (Table 2) adopted in this study are based on their original scores, referring to the relevant research in China (Hawkes, 1998; Luo et al., 2018).

Table 2

4 Results and analysis

4.1 Spatial distribution of macroinvertebrate in the North Canal River basin

There are 29 species of macroinvertebrate observed in the North Canal River basin, and the community structure is relatively single, with 13 molluscs, 13 aquatic insects and 3 annelids. Among them, pollution-tolerant species are the absolute dominant species, while the sensitive species with poor tolerance to pollution, such as the chironomids, which feed on bacteria and algae and play an important role in water purification. It can be seen from Figure 2 that only 3 of all the sampling sites have more than 10 species, while 9 sampling sites have single species. Generally speaking, compared with natural rivers, the aquatic habitats, chemical and physical conditions, river channel morphology, substrate type and aquatic vegetation in the urban rivers are suffering from directly and indirectly influenced by human activities, resulting in relatively poor aquatic ecosystem conditions: lower total taxa, lower diversity, few sensitive species and dominant pollution-tolerant species.

Figure 2

However, it can be seen from Figure 3 that the spatial distribution of macroinvertebrates in the northern mountainous area of the North Canal River basin is not entirely superior to that in the highly urbanized area. From the perspective of administrative regions, the sampling sites with lower benthic taxa and lower diversity index are concentrated in Haidian District, Chaoyang District, Dongcheng District and Xicheng District, while there are some sampling sites with good condition simultaneously. The conditions of macroinvertebrate in Changping District is overall better than other districts, except for Changping Bridge and Zhuishikou sites. According to the results of aquatic ecological survey records, it is found that obvious potential pollution sources and severe watershed erosion are around the Zhuishikou site; and the bottom quality of the Changping Bridge is simple, the habitat complexity is low and the riparian zone is distributed with residential and commercial land.

Figure 3

4.2 Key water quality driving factors affecting the macroinvertebrate

The relationship between the monitored water quality parameters and macroinvertebrate were analyzed by the redundancy analysis, and the results showed that 12 water quality parameters explained 54.2% of the total variation in the macroinvertebrate community structure. The explained variance and its proportion of each parameter obtained by the hierarchical segmentation method are shown in Figure 4, among them, F^-, NH_3-N, TP and BOD passed the replacement test at a significance level of 0.01, indicating that the four parameters are the key water quality driving factors affecting the distribution of macroinvertebrate in the North Canal River basin in Beijing.

Figure 4

Figure 5 showed the spatial distribution of the four water quality key driving factors in the basin. NH_3-N and TP mainly reflect the concentration of nutrients like nitrogen and phosphorus in the water body, which are in high spatial consistency characterized as high value mainly distributed in the south of Changping District and the south of the basin. Biochemical oxygen demand mainly reflects the concentration of organic pollutants in the water body, of which the high value was mainly distributed in the south of Changping District; fluoride has strong reducibility and mainly reflects the concentration of dissolved oxygen in the water body, of which the high value was mainly distributed in Changping District and Haidian District.

Figure 5

4.3 Responses of taxon and assemblages to key water quality driving factors

On the strength of the TITAN for evaluating variation in the taxonomic composition of the macroinvertebrate community in response to the gradients of key water quality driving factors, the results revealed that $F^-$and BOD doesn't have indicator species, while NH_3-N has 5 positive indicator species (increase as the NH_3-N gradient rise) and TP has 3 positive indicator species. The indicator species of NH_3-N include Chironomidae and Lymnaeidae, and the threshold concentration of Lymnaeidae is greater than that of Chironomidae. It can be seen from Figure 6 that the threshold concentration range of NH_3-N is 1.09~6.94 $mg \cdot L^{-1}$, in another word, when the ammonia nitrogen concentration in the water body reaches 6.94 $mg \cdot L^{-1}$, except for the two positive Lymnaeidae indicator species, most species are out of tolerance and the community no longer has a significant response.

Figure 6

The indicator species of TP also include Chironomidae and Lymnaeidae, similar to those of NH_3-N, the threshold concentration of Lymnaeidae is greater than that of Chironomidae. It can be seen from Figure 7 that the threshold concentration range of TP is 0.48~1.27 $mg \cdot L^{-1}$, indicating that when the TP concentration in the water body reaches 1.27 mg·L^{-1}, except for the two positive Lymnaeidae indicator species, most species are out of tolerance and the community no longer has a significant response.

Figure 7

4.4 Aquatic ecological health assessment in the North Canal River

4.4.1 Aquatic ecological health assessment based on the B-IBI

According to the criteria for reference sites in the basin related to habitat investigation and water quality evaluation, four of 34 sites were selected as reference sites for aquatic ecological health assessment in the North Canal River. Of the 22 metrics in Table 1 tested by the B-IBI, 12 metrics were eliminated because either their medians were zero or the distribution range was very narrow. For other metrics, the discriminant analysis was performed for the IQ value, and five metrics were rejected because of their lower separation power (IQ<2). Then, the result of Spearman rank correlation analysis among the five remaining metrics (NM, SWI, PDO, PTD, PTU) showed that there were three pairs of highly correlated metrics ($r \geq |0.90|$, $p=0.01$) (Table 3).

Table 3

Finally, we selected the three qualified metrics: NM, SWI, PTU, which stand for richness, composition, and abundance and normalized the scoring criteria of each metric based on quadrisection system, which was interpreted as good (≥2.41), moderate (1.93~2.41), poor (1.14~1.93) and very poor (<1.14). Figure 8 (a) showed the results of aquatic ecological health assessment based on the B-IBI, in which seven sites are in good, seven sites are in moderate, eight sites are in poor and eleven sites are in very poor. It was found that the water ecological health of the northern area is better, and the water ecological heath of highly urbanized central areas is generally poor. For the good water ecological health assessment results in the central areas, it may be related to the ecological water replenishment or other aquatic restoration measures of the river section.

4.4.2 Aquatic ecological health assessment based on the rapid bioassessment

By comparing the distribution range of candidate metrics in Table 1, 12 metrics were eliminated because either their medians were zero or the distribution range was very narrow. The results of the correlation analysis between the metrics with proper distribution range were shown in Table 2. There was a significant correlation between NT, NC and NTO, meanwhile, NA, NC and PCH were with significant correlation; NC, PCH, NTO were also significantly correlated with each other, while NA and NT were significantly correlated. The chironomid with strong pollution tolerance is the dominant taxon in the North Canal River basin, thus, SWI, PDO and PTD were highly correlated with each other. Finally, NT and PCH were retained for detail and non-redundant information, and NT, PCH, NM, SWI, PO, PCM and BI were selected for the multi-metric rapid bioassessment index.

The index scores were calculated according to the scoring rules of each index and the comprehensive score was the average of the seven indices. Aquatic ecological health level was divided into four levels by the equal-ration method and the results were shown in Figure 8 (b). Most of the sampling sites are in moderate states, 4 are in good states, 2 are in poor states and 1 is in very poor states. It was found that the sites with relatively poor water ecological health results are in central areas, and the overall water ecological health assessment results of the basin by the multi-metric index for rapid bioassessment method are relatively good than the results by the B-IBI method.

Figure 8

Comparing the results of aquatic ecological health assessment by the B-IBI method and the multi-metric rapid bioassessment index method, which showed that 35.3% of all the sites have the same result of aquatic ecological health assessment, and the B-IBI method is more sensitive to good and very poor health assessment levels. Based on the results of aquatic ecological health assessment by the multi-metric rapid bioassessment index method, sampling sites with good states are distributed in Changping District, Chaoyang District and Daxing District. The results of aquatic ecological health assessment by the B-IBI method showed that the sampling sites with good states were mainly distributed in Changping District, Chaoyang District, Haidian District and Xicheng District, while the sampling sites with very poor states were mainly distributed in the central city and Chaoyang district. In general, the aquatic ecological system in the North Canal River basin of Beijing is considered to be in a moderate-poor state in 2015.

4.4.3 Aquatic ecological health assessment based on the BMWPS

Four health levels including “good, moderate, poor and very poor” were set to compare with other aquatic ecological health assessment results in the North Canal River basin. Table 4 showed the specific division criteria.

Table 4

The aquatic ecological health of the North Canal River basin was evaluated by BMWP scores, and figure 8 (c) showed the results, in which 10 sites are in good, 5 sites are in moderate, 5 sites are in poor and 14 sites are very poor. Compared with the health assessment results by the B-IBI, 64.7% of the health level assessment results are the same, on the whole, the health level assessment results of the BMWP are better than the results of the B-IBI for the rest 35.3% of the health level assessment results.

5 Discussion

Human activities cause changes in water quality, significantly influencing the structure and composition of the macroinvertebrate community. The distribution of macroinvertebrates is influenced by their response to multiple stressors including temperature increment, flow alterations, high metal pollution and increase in nutrient loads. In the study, the RDA and the hierarchical partitioning method was applied to isolate the influence of particular water quality factors on macroinvertebrate. The results showed that F-, NH_3-N, TP and BOD are the key water quality driving factors affecting the distribution of macroinvertebrates in the North Canal River basin in Beijing. The combined effect of water quality led to a reduction in taxon richness by the exclusion of sensitive species and the increase of tolerant taxa densities.

The prosperity of pollution tolerant species means higher phosphate levels and lower dissolved oxygen. The accumulation of nitrogen and phosphorus is an important factor causing water eutrophication, which influences macroinvertebrate communities by influencing primary productivity. The increased productivity from eutrophication increases oxygen consumption in the system, which can lead to low-oxygen (hypoxic) or oxygen-free (anoxic) water bodies, reduce macroinvertebrates' diversity and change the ecological structure and function. Firstly, the occurrence of hypoxic and anoxic water leads to the mortality of less mobile or more sensitive taxa, reduction of suitable habitat and shifts in the food web. Secondly, the frequency and duration of the hypoxia and anoxic events play a major role in the response of species to reduced oxygen availability (Pearson, 1978; Richards,1993; Board, 2000). At last, the hypoxia and anoxic water environment lead to the transformation of dominant species from large long-lived species to small short-lived species, and long-term anoxia limits the community succession.

The selection of reference sites is vital for the calculation of the B-IBI for aquatic ecological health assessment, which facilitates the comparison with impacted sites to observe the deviations from the natural community composition and the construction of scoring criteria. Reference sites are ought to be the minimally impacted sites, however, it is difficult to define the reference conditions in urban rivers strongly affected by human activities, especially in the North Canal River basin in Beijing, even the sites with a high percentage of natural land use were not entirely undisturbed by human activities. According to the “relatively unimpacted” rules and the actual situation in the North Canal River basin in Beijing, the sites characterized as surface water quality better than grade III, integrated habitat assessment index scored greater than 80 and no point source pollution and cultivation in the riparian zone were suitable for the selection of reference sites in the study area. Under the comprehensive consideration of the actual water quality condition, ecological condition and impactive condition, four sites were chosen as the reference sites, which are not all distributed in the northern mountainous area and it is the difference between urban rivers and mountainous rivers in the selection of the reference sites. According to the calculation results of the B-

IBI, 3 of the 4 reference sites were evaluated as health status, indicating that the selection of the reference sites in this study is relatively appropriate.

Under field conditions, some factors such as sediment, hydrodynamic condition and river network connectivity have impacts on the biological indicators, which lead to some uncertainties in this study. Therefore, laboratory tests to supplement in-situ or sublethal does test could be adopted to further improve our research. Meanwhile, in future study, we could also carry out quantitative research on the water quality driving factors of other aquatic organisms such as phytoplankton and fish. Based on the comprehensive and suitable demand level of water quality by various aquatic organisms, a total amount of river pollutants control system could be constructed to guide the control of the total amount of pollutants and ecological restoration in the North Canal River basin.

6 Conclusions

In this study, the community structures of macroinvertebrates and water quality conditions in the North Canal River basin of Beijing in 2015 were surveyed. Subsequently, a new framework for the quantitative analysis between macroinvertebrate community and key water quality driving factors was developed, the key factors of water quality affecting macroinvertebrate communities were determined by the RDA method and the threshold of them for macroinvertebrate communities were identified by the TITAN method. At last, the aquatic ecological health was assessed by the B-IBI method and the multi-metric index for the rapid bioassessment method. The results can be summarized as follows.

(1) The macroinvertebrate community in the aquatic ecological system in the North Canal River basin of Beijing is dominated by pollution-tolerant species including aquatic insects and mollusks. A total of 5 classes and 11 families have been identified and the average number of species taxa is 5.47. The average value of the Shannon - Wiener index is 0.40 and the average value of the BI index is 6.95. Compared with mountainous areas, the community structure of macroinvertebrates in urban river systems is more single with fewer sensitive species and dominant pollution-tolerant species.

(2) Fluoride, biochemical oxygen demand, ammonia nitrogen and total phosphorus are identified as the key water quality driving factors of the macroinvertebrate community in the North Canal River basin of Beijing. Based on the TITAN method, Fluoride and biochemical oxygen demand don't have indicator species, while ammonia nitrogen has 5 positive indicator species with the threshold range of 1.09~6.94 $mg \cdot L^{-1}$, and total phosphorus has 3 positive indicator species with the threshold range of 0.48~1.27 $mg \cdot L^{-1}$.

(3) By comparing the results of aquatic ecological health assessment by the B-IBI, the rapid bioassessment method and the BMWP score, it is found that the aquatic ecological health condition of the North Canal River basin in Beijing is relatively poor, the areas with better aquatic ecological health conditions are mainly located in the mountainous areas of Changping District, while those of Chaoyang District and the central city area is suffering the worst aquatic ecological health conditions.

Figure Captions

Figure 1 The Location of the study area with aquatic ecosystem sampling stations

Figure 2 Distribution of macroinvertebrates in the North Canal River basin of Beijing

Figure 3 Spatial distribution of characteristics parameters of macroinvertebrates in the North Canal River basin of Beijing

Figure 4 Water quality impactive factors of macroinvertebrates in the North Canal River basin of Beijing

Figure 5 Spatial distribution of key water quality driving factors in the North Canal River basin

Figure 6 Indicator species and thresholds of ammonia in the North Canal River basin of Beijing by the TITAN analysis

Figure 7 Indicator species and thresholds of total phosphorus in the North Canal River basin of Beijing by the TITAN analysis

Figure 8 Results of aquatic ecosystem health assessment in North Canal River basin by the B-IBI method, multi-metric index for rapid bioassessment method and BMWP Score method

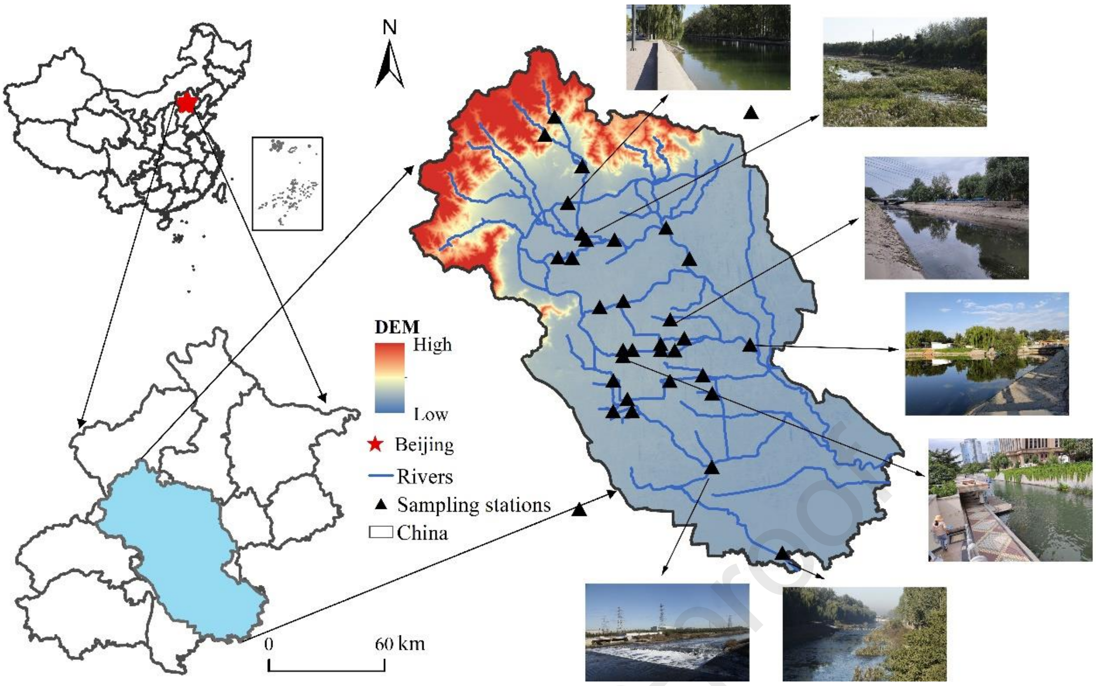


Figure 1 The Location of the study area with aquatic ecosystem sampling stations

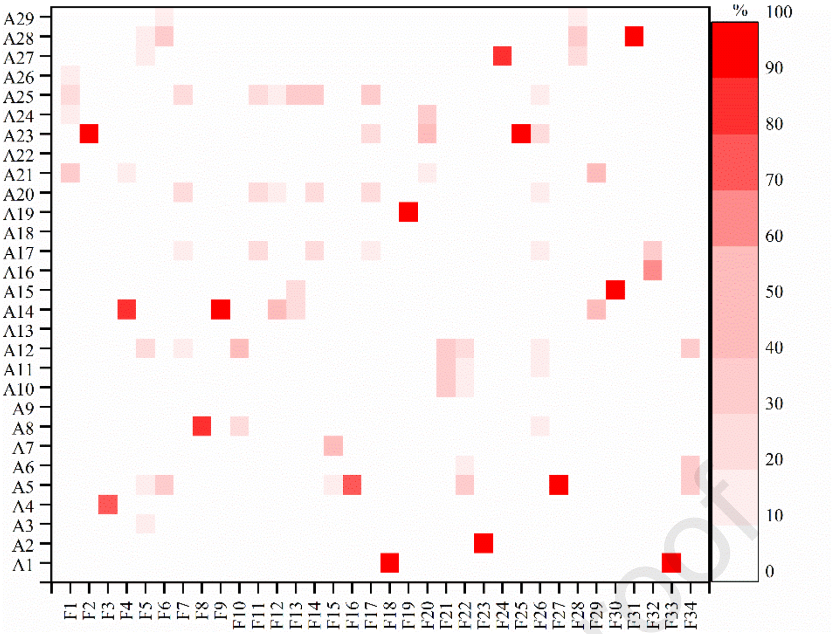


Figure 2 Distribution of macroinvertebrates in the North Canal River basin of Beijing

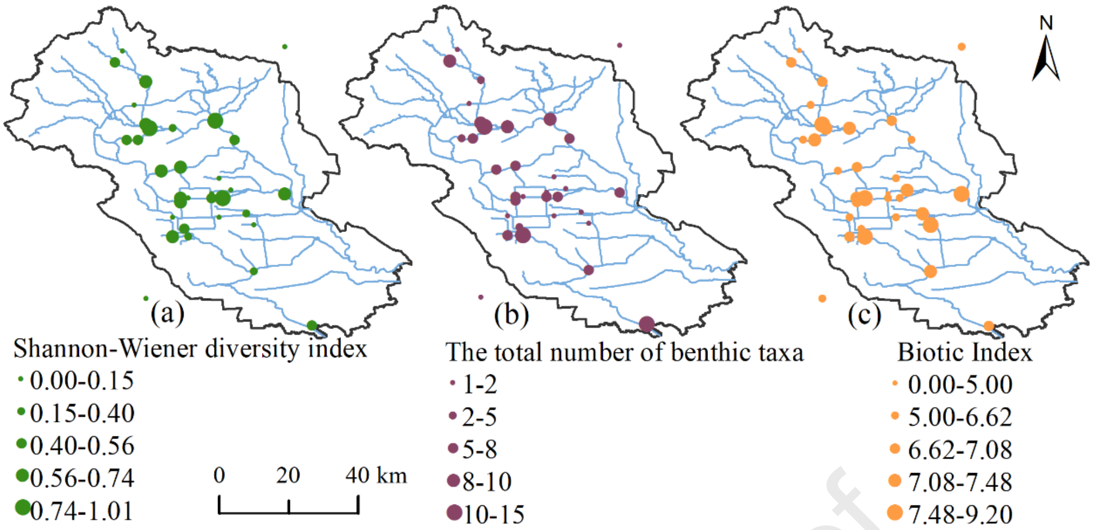


Figure 3 Spatial distribution of characteristics parameters of macroinvertebrates in the North Canal River basin of Beijing

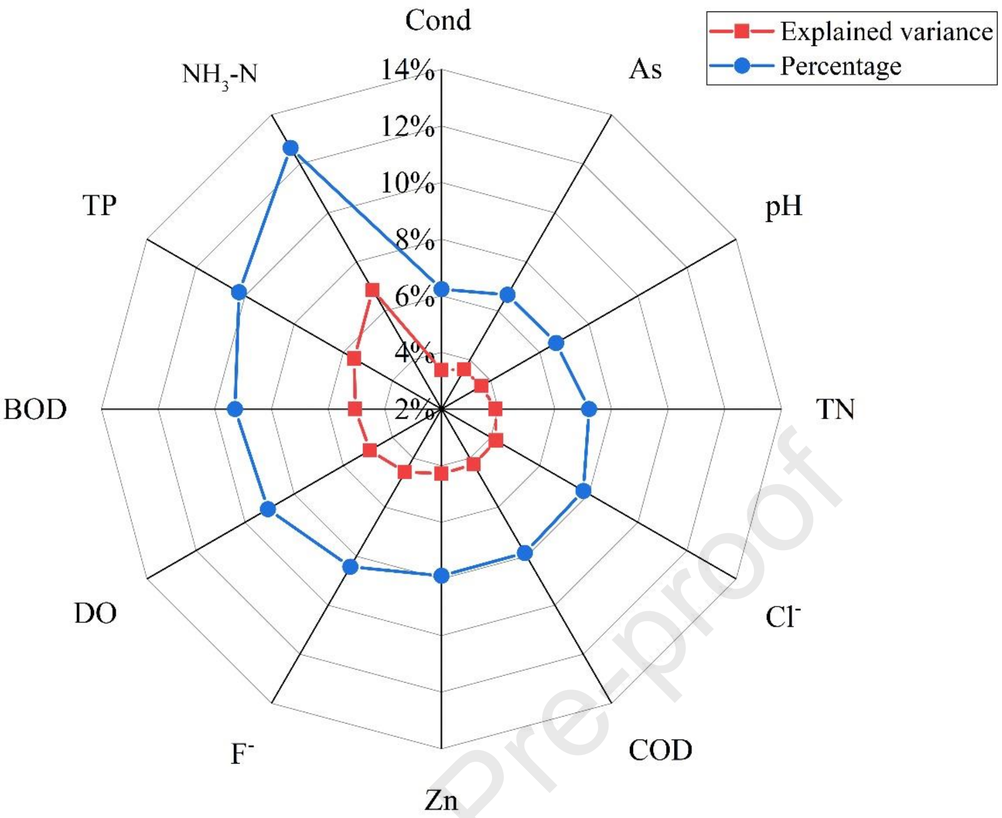


Figure 4 Water quality impactive factors of macroinvertebrates in the North Canal River basin of Beijing

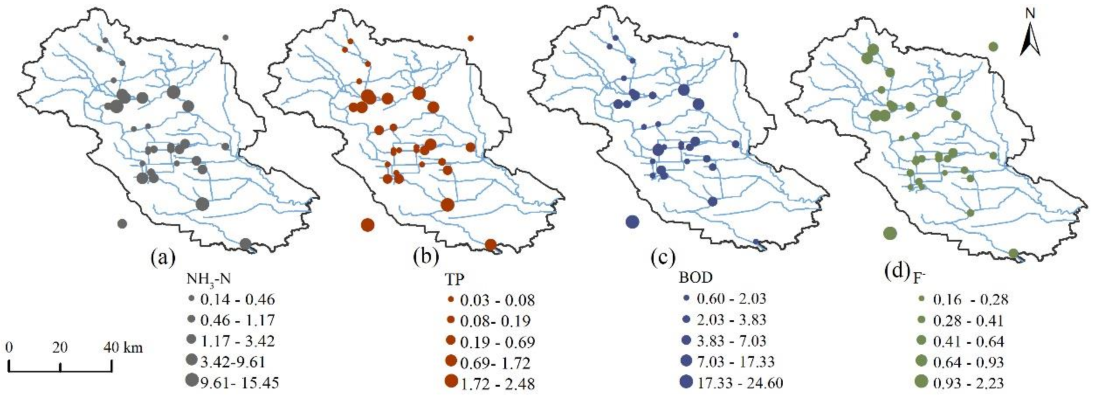
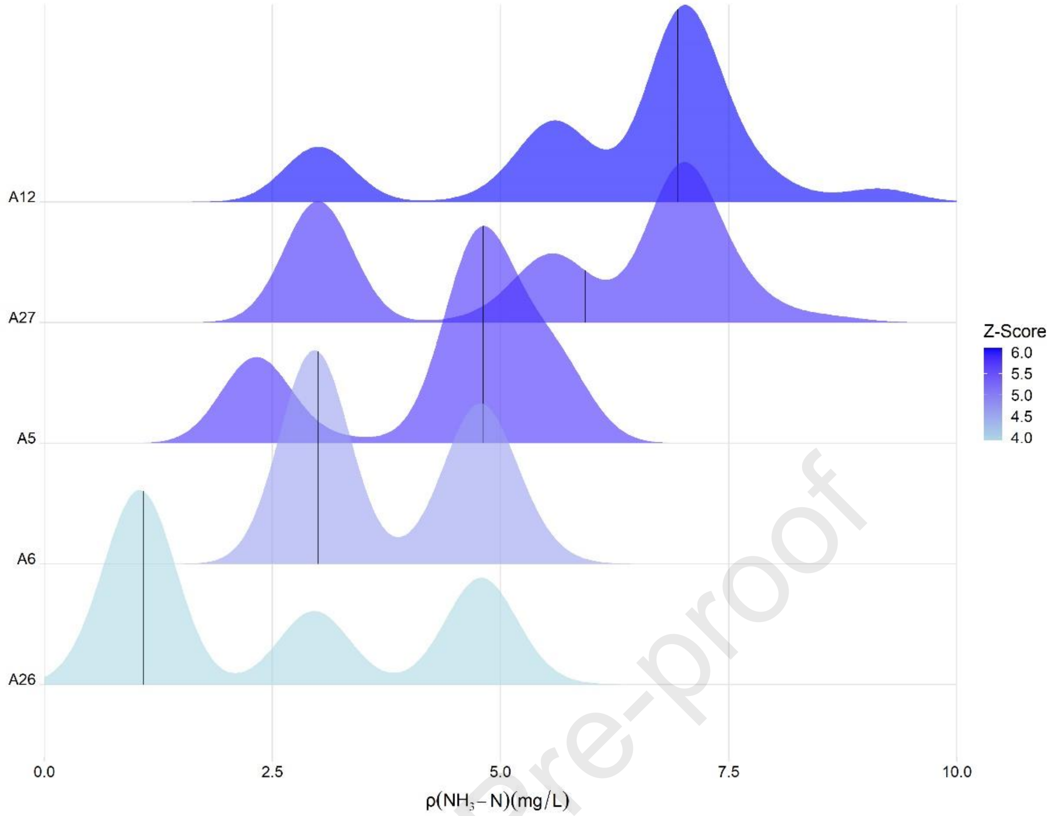


Figure 5 Spatial distribution of key water quality driving factors in the North Canal River basin



502

503 Figure 6 Indicator species and thresholds of ammonia in the North Canal River basin

504 of Beijing by the TITAN analysis

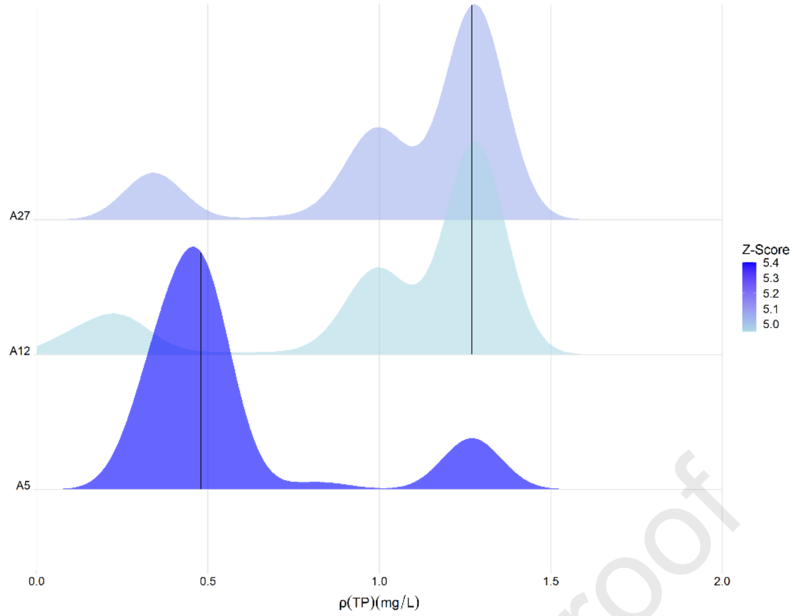


Figure 7 Indicator species and thresholds of total phosphorus in the North Canal River basin of Beijing by the TITAN analysis

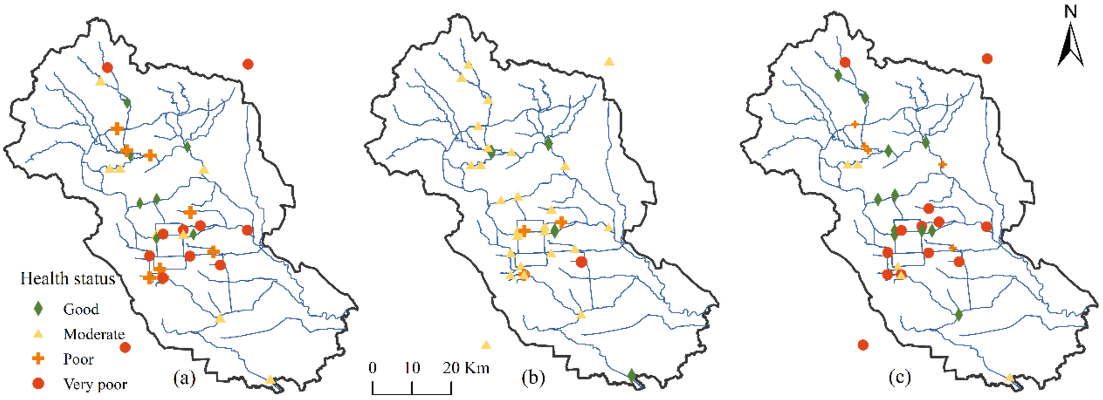


Figure 8 Results of aquatic ecosystem health assessment in North Canal River basin by the B-IBI method, multi-metric index for rapid bioassessment method and BMWP Score method

Table captions

Table 1 Candidate metrics and their expected direction of response to disturbance

Table 2 The sensitive values of family level for macroinvertebrate in sampling sites in North Canal River basin

Table 3 Results of spearman rank correlation analysis among candidate metrics

Table 4 Health assessment grading standards of B-IBI in North Canal River basin

Table 1 Candidate metrics and their expected direction of response to disturbance

Serial number	Categories	Metric name	Metric code	Response to disturbance
M1	Richness	No. total taxa	NT	Decrease
M2		No. EPT taxa	NEPT	Decrease
M3		No. Aquatic insect taxa	NA	Decrease
M4		No. Mollusca taxa	NM	Decrease
M5		No. Chironomidae taxa	NC	Decrease
M6		Shannon-Wiener index	SWI	Decrease
M7		Evenness index	EI	Decrease
M8	Composition and abundance	Dominant taxon	PDO	Increase
M9		Three most Dominant taxon	PTD	Increase
M10		Trichoptera	PT	Decrease
M11		Ephemeroptera	PE	Decrease
M12		Plecoptera	PP	Decrease
M13		Tubifex	PTU	Increase
M14		Chironomidae	PCH	Increase
M15		Diptara taxa	PD	Increase
M16		Oligochaeta	PO	Increase
M17		Crustacea + Mollusca	PCM	Decrease
M18		Legless taxa	PL	Increase
M19	Tolerance	Intolerant taxa	NI	Decrease
M20		Tolerant taxa	NTO	Increase
M21		Intolerant taxa	PI	Decrease
M22		Biotic index	BI	Increase

Table 2 The sensitive values of family level for macroinvertebrate in sampling sites in North Canal River basin

Family	Tubificida	Chironomidae	Lymnaeidae	Baetidae	Libellulidae	Unionidae
Sensitive Score	1	2	3	4	8	6
	Viviparidae	Costellae	Macrospiridae	Bithyniidae	Corbiculidae	
	5	6	5	6	6	

Table3 Results of spearman rank correlation analysis among candidate metrics

	M1	M3	M4	M5	M6	M8	M9	M13	M14	M16	M17	M20	M22
M1	1.00												
M3	0.78**	1.00											
M4	0.63**	0.09	1.00										
M5	0.83**	0.97**	0.16	1.00									
M6	0.79**	0.47**	0.65**	0.53**	1.00								
M8	-0.74**	-0.35*	-0.72**	-0.42*	-.95**	1.00							
M9	-0.75**	-0.48**	-0.64**	-0.52**	-0.93**	0.82**	1.00						
M13	0.42*	0.50**	-0.19	0.53**	0.31	-0.24	-0.28	1.00					
M14	0.61**	0.82**	0.09	0.85**	0.31	-0.24	-0.30	0.22	1.00				
M16	0.42*	0.50**	-0.19	0.53**	0.31	-0.22	-0.28	1.00**	0.22	1.00			
M17	-0.29	-0.71**	0.38*	-0.62**	-0.03	-0.08	0.06	-0.53**	-0.63**	-0.53**	1.00		
M20	1.00**	0.79**	0.63**	0.83**	0.79**	-0.74**	-0.75**	0.42*	0.61**	0.42*	-0.29	1.00	
M22	0.33	0.35*	0.03	0.39*	0.21	-0.12	-0.24	0.55**	0.33	0.55**	-0.37*	0.33	1.00

Table 4 The grading standards of aquatic ecological health assessment based on the B-IBI in the North Canal River basin of Beijing

Health levels	Good	Moderate	Poor	Very poor
Scores for the B-IBI method	>2.41	1.93~2.41	1.14~1.93	<1.14
Scores for the multi-metric index for rapid bioassessment method	>62.76	49.97-62.76	45.17-49.97	<45.17
Scores for the BWMP	>21	14-21	7-14	<14

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References

Azrina MZ, Yap CK, Ismail AR, Ismail A, Tan SG. (2006). Anthropogenic impacts on the distribution and biodiversity of benthic macroinvertebrates and water quality of the Langat River, Peninsular Malaysia. ECOTOX ENVIRON SAFE, 64(3), 337-347. doi: 10.1016/j.ecoenv.2005.04.003

Baker ME, King RS. (2010). A new method for detecting and interpreting biodiversity and ecological community thresholds. METHODS ECOL EVOL, 1(1), 25-37. doi: 10.1111/j.2041-210X.2009.00007.x

Barbour MT, Stribling JB, Karr JR. (1995). Multimetric approach for establishing biocriteria and measuring biological condition. Biological assessment and criteria: Tools for water resource planning and decision making, 63-77

Borja, A., Chust, G., Del Campo, A., Gonzalez, M., Hernandez, C. (2013). Setting the maximum ecological potential of benthic communities, to assess ecological status, in heavily morphologically-modified estuarine water bodies. MAR POLLUT BULL 71, 199-208. doi: 10.1016/j.marpolbul.2013.03.014

Cao X, Wang J, Liao J, Sun J, Huang Y. (2016). The threshold responses of phytoplankton community to the nutrient gradient in a shallow eutrophic Chinese lake. ECOL INDIC, 61(2), 258-267. doi: 10.1016/j.ecolind.2015.09.025

Cui W, Guo S, Meng X, Kong F. (2019). Application of adapted Benthic Index of Biotic Integrity (B-IBI) for river ecosystem health assessment in Zhanghe River Watershed, China. POL J ECOL, 66(4), 407-415. doi:10.3161/15052249PJE2018.66.4.008

Dufrêne M, Legendre P. (1997). Species assemblages and indicator species: the need for a flexible asymmetrical approach. ECOL MONOGR, 67(3), 345-366. doi:10.1890/0012-9615(1997)067[0345:SAAIST]2.0.CO;2

Ekau, W., Auel, H., Portner, H.O., Gilbert, D. (2010). Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). BIOGEOSCIENCES 7, 1669-1699. doi: 10.5194/bg-7-1669-2010

Flotemersch, J. E., Stribling, J. B., & Paul, M. J. (2006). Concepts and Approaches for the Bioassessment of Non-wadeable Streams and Rivers. Washington, DC: US Environmental Protection Agency, Office of Research and Development.

Francis RA. (2014). Urban rivers: novel ecosystems, new challenges. WIRES WATER, 1(1), 19-29. doi: 10.1002/wat2.1007

Gal B, Szivak I, Heino J, Schmera D. (2019). The effect of urbanization on freshwater macroinvertebrates - Knowledge gaps and future research directions. ECOL INDIC, 104, 357-364. doi: 10.1016/j.ecolind.2019.05.012

Hawkes H A. (1998). Origin and development of the biological monitoring working party score system[J]. Water Res, 32(3): 964-968. doi: 10.1016/S0043-1354(97)00275-3

Helson J E, Williams DD. (2013). Development of a macroinvertebrate multimetric index for the assessment of low-land streams in the neotropics. ECOL INDIC, 29, 167-178. doi: 10.1016/j.ecolind.2012.12.030

Hines, M.E., Horvat, M., Faganeli, J., Bonzongo, J., Barkay, T., Major, E.B., Scott, K.J., Bailey, E.A., Warwick, J.J., Lyons, W.B. (2000). Mercury biogeochemistry in the Idrija River, Slovenia, from above the mine into the Gulf of Trieste. ENVIRON RES, 83, 129-139. doi: 10.1006/enrs.2000.4052

Huang Q, Gao J, Cai Y, Yin H, Gao Y, Zhao J, Liu L, Huang J. (2015). Development and application of benthic macroinvertebrate-based multimetric indices for the assessment of streams and rivers in the Taihu Basin, China. ECOL INDIC, 48, 649-659. doi: 10.1016/j.ecolind.2014.09.014

Karr J R, Fausch K D, Angermeier P L, Yant P R, Schlosser I J. (1986). Assessing biological integrity in running waters: a method and its rationale[M]. Illinois Natural History Survey Special Publication no. 05. http://hdl.handle.net/2142/111662

Li S, Yang W, Wang L, Chen K, Xu S, Wang B. (2018). Influences of environmental factors on macroinvertebrate assemblages: differences between mountain and lowland ecoregions, Wei River, China. ENVIRON MONIT ASSESS, 190(1523). doi: 10.1007/s10661-018-6516-7

Li Z, Zeng B. (2020). Health assessment of important tributaries of Three Georges Reservoir based on the benthic index of biotic integrity. SCI REP-UK, 10(1), 1-11. doi: 10.1038/s41598-020-75746-7

Luo K, Hu X, He Q, Wu Z, Cheng H, Hu Z, Mazumder A. (2018). Impacts of rapid urbanization on the water quality and macroinvertebrate communities of streams: A case study in Liangjiang New Area, China. SCI TOTAL ENVIRON, 621, 1601-1614. doi: 10.1016/j.scitotenv.2017.10.068

Marshalonis D, Larson C. (2018). Flow pulses and fine sediments degrade stream macroinvertebrate communities in King County, Washington, USA. ECOL INDIC, 93, 365-378. doi: 10.1016/j.ecolind.2018.04.060

Matthew E. Baker, Ryan S. King. (2010). A new method for detecting and interpreting biodiversity and ecological community thresholds. Methods Ecol. Evol, 1(1), 25-37. doi:10.1111/j.2041-210X.2009.00007.x

Morley S A. (2000). Effects of urbanization on the biological integrity of Puget Sound lowland streams: restoration with a biological focus[D]. University of Washington.

Nichols J, Hubbart JA, Poulton BC. (2016). Using macroinvertebrate assemblages and multiple stressors to infer urban stream system condition: a case study in the central US. URBAN ECOSYST, 19(2), 679-704. doi: 10.1007/s11252-016-0534-4

Paller MH, Kosnicki E, Prusha BA, Fletcher DE, Sefick SA, Feminella JW. (2017). Development of an Index of Biotic Integrity for the Sand Hills Ecoregion of the Southeastern United States. T AM FISH SOC, 146(1), 112-127. doi:

10.1080/00028487.2016.1240104

Pearson T H. (1978). Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr. Mar. Biol. Ann. Rev, 16: 229-311.

Qiu Y, Jin Y, Su Z, Di Y, Zhao D, Guo X. (2021). Analysis of the Spatial Changes in Bacterial Communities in Urban Reclaimed Water Channel Sediments: A Case Study of the North Canal River. ES, 42(5), 2287-2295. doi: 10.13227/j.hjkx.202008246

Richards C, Host G E, ARTHUR J W. (1993). Identification of predominant environmental factors structuring stream macroinvertebrate communities within a large agricultural catchment. FRESHWATER BIOL, 29(2), 285-294. doi: 10.1111/j.1365-2427.1993.tb00764.x

Ruaro R, Gubiani ÉA. (2013). A scientometric assessment of 30 years of the Index of Biotic Integrity in aquatic ecosystems: applications and main flaws. ECOL INDIC, 29, 105-110. doi: 10.1016/j.ecolind.2012.12.016

Shen, Z., Hou, X., Li, W., Aini, G. (2014). Relating landscape characteristics to non-point source pollution in a typical urbanized watershed in the municipality of Beijing. LANDSCAPE URBAN PLAN, 123, 96-107. doi: 10.1016/j.landurbplan.2013.12.007

Tagliaferro M, Giorgi A, Torremorell A, Albarino R. (2020). Urbanisation reduces litter breakdown rates and affects benthic invertebrate structure in Pampean streams. INT REV HYDROBIOL, 105(1-2), 33-43. doi: 10.1002/iroh.201902000

Thi HTN, Forio MAE, Boets P, Lock K, Ambarita MND, Suhareva N, Everaert G, Van der Heyden C, Elvin Dominguez-Granda L, Thu HTH, Goethals P. (2018). Threshold Responses of Macroinvertebrate Communities to Stream Velocity in Relation to Hydropower Dam: A Case Study from The Guayas River Basin (Ecuador). WATER, 10(11959). doi: 10.3390/w10091195

Van Den Wollenberg AL. (1977). Redundancy analysis an alternative for canonical correlation analysis. PSYCHOMETRIKA, 42(2), 207-219. doi:10.1007/BF02294050

V. Ganasan and R. M. Hughes. (1998). Application of an index of biological integrity (IBI) to fish assemblages of the rivers Khan and Kshipra (Madhya Pradesh), India. Freshwater Biol, 42(2), 367-383. doi:10.1046/j.1365-2427.1998.00347.x

Wang X, Zheng B, Liu L, Wang L. (2015). Development and evaluation of the lake multi-biotic integrity index for Dongting Lake, China. J LIMNOL, 74(3), 594-605. doi: 10.4081/jlimnol.2015.1186

Zhang Y, Wang B, Wang W, Li W, Huang J, Deng S, Wang Y, Yu G. (2016). Occurrence and source apportionment of Per- and poly-fluorinated compounds (PFCs) in North Canal Basin, Beijing. SCI REP-UK, 6, 36683. doi: 10.1038/srep36683

Zhao C, Shao N, Yang S, Ren H, Ge Y, Zhang Z, Zhao Y, Yin X. (2019). Integrated assessment of ecosystem health using multiple indicator species. ECOL ENG, 130, 157-168. doi: 10.1016/j.ecoleng.2019.02.016

Zhao, C.S., Yang, S.T., Zhang, H.T., Liu, C.M., Sun, Y., Yang, Z.Y., Zhang, Y., Dong, B.E., Lim, R.P. (2017). Coupling habitat suitability and ecosystem health with

AEHRA to estimate E-flows under intensive human activities. J HYDROL, 551, 470-483. doi: 10.1016/j.jhydrol.2017.05.047

Declaration of interests

xThe authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: