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RESEARCH ARTICLE

Impact of extreme oxygen consumption by pollutants on macroinvertebrate assemblages in plain rivers of the Ziya River Basin, north China

Yuekui Ding[1,2] · **Nan Rong**[1,2] · **Baoqing Shan**[1]

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Abstract The aim of the study was to estimate the impact of oxygen depletion on macroinvertebrate community structure in benthic space. Macroinvertebrate assemblages and potential of dissolved oxygen (DO) consumption were investigated simultaneously in the plain rivers of the Ziya River Basin. The degree of DO depletion was represented by sediment oxygen demand (SOD) and DO, chemical oxygen demand (COD_{Cr}), and ammonia nitrogen (NH_4^+-N) in the overlying water. The results showed an all-around hypoxia environment formed, and the values of DO, SOD, COD_{Cr}, and NH_4^+-N were separately 0.11–4.03 mg L^{-1}, 0.41–2.60 g m^{-2} day^{-1}, 27.50–410.00 mg L^{-1}, and 1.79–101.41 mg L^{-1}. There was an abnormal macroinvertebrate assemblage, and only 3 classes, Insecta, Gastropoda, and Oligochaeta, were found, which included 9 orders, 30 families, and 54 genera. The biodiversity was at a low level, and Shannon-Wiener index was 0.00–1.72. SOD, and NH_4^+-N had major impact on the macroinvertebrate community, and the former had negative effect on most taxa, for instance, *Nais*, *Branchiura*, *Paraleptophlebia*, etc., which were sensitive or had a moderate-high tolerance to pollution. NH_4^+-N had both positive and negative impacts on benthic animals, for instance, *Dicrotendipes*, *Gomphus*, *Cricotopus*, etc., for the former, and *Procladius*, *Limnodrilus*, *Hippeutis*, etc., for the latter. They all had a moderate-high tolerance to pollution. It is significant to improve DO condition and macroinvertebrate diversity in river harnessing and management.

Keywords Macroinvertebrate · Oxygen consumption · Ziya River Basin

Responsible editor: Philippe Garrigues

✉ Baoqing Shan
bqshan@rcees.ac.cn

Yuekui Ding
yuekuiding@163.com; yyytgtg@163.com

Nan Rong
rongnan420@163.com

[1] State Key Laboratory on Environmental Aquatic Chemistry, Research Center for Eco-Environmental Science, Chinese Academy of Science, Beijing 100085, People's Republic of China

[2] University of Chinese Academy of Science, Beijing 100049, People's Republic of China

Introduction

Dissolved oxygen (DO) is essential for survival of aquatic life. However, pollutants discharged into river channel can consume large amounts of oxygen during the process of form transformation, which results in hypoxia and a direct threat to aquatic organisms. Oxygen availability was proved to be an important factor in predicting aquatic invertebrate assemblages (Comte et al. 2010). Hypoxia induces changes in community structure and process (McNeil and Closs 2007; Ekau et al. 2010), behavior (Zhang et al. 2009; Riedel et al. 2014), and physiological features (Grieshaber et al. 1994; Urbina and Glover 2012) of aquatic organisms (fish, macroinvertebrate, zooplankton). Extreme lack of DO is likely to produce lethal effect on aquatic organisms (Nandan and Azis 1995; Rao et al. 2014), which threaten normal development of aquatic ecosystem.

The Hai River Basin (HRB), located in northern China, is one of China's seven major river basins and is an important center of politics, economy, and culture. However, with the economic development speeding up, river pollution increases. Combined with water shortage due to local anthropogenic activities (Tang et al. 2015), the HRB has become one of the most polluted basins in China (Liu et al. 2010). There are eight sub-river basins in the HRB, of which the Ziya River Basin (ZRB) is the most polluted one. The ZRB is located in the southwest of the HRB and has more than 60 cities and counties, most of which gathers in plain area. The plain area includes Shijiazhuang city that is the provincial capital of Hebei and other major cities such as Xingtai city, Hengshui city, and Handan city. Accordingly, there is a large population in the plain area. Shijiazhuang city, Xingtai city, and Hengshui city have a population of 1.02×10^8, 7.10×10^6, and 4.34×10^6 people, respectively (National Bureau of Statistics 2010). As the economy develops, emission of pollutants increases and water pollution has become one of the major problems. Water and sediment are polluted simultaneously, and the proportion of blackwater river increases rapidly. Dry rivers and polluted rivers have dominated the ZRB (Zhu 2014). Water quality in most river sections is worse than grade V in the Ziya River and its main branch, Fuyang River (Li et al. 2012). Wastewater discharges affect the DO in water column (Antanasijevic et al. 2014). Especially in the plain area of the ZRB, ammonia nitrogen (NH_4^+-N), which has great potential for oxygen consumption, has become the major excessive pollutant (Wang and Shan 2012).Oxygen depletion has become one of the prominent problems of rivers in the ZRB, which severely impacts aquatic organisms. Zhu claimed that aquatic animals and plants had almost become extinct in the ZRB (Zhu 2014). However, this is just a qualitative description and lacks support of quantitative research.

This study focused on DO consumption and macroinvertebrate assemblages in the plain rivers of the ZRB. We proposed the following hypotheses: (1) there was an oxygen-deprived benthic environment all around in plain rivers of the ZRB; (2) variables related with oxygen consumption had significant impact on community composition of benthic animals. Extreme hypoxic environment would support few pollution-tolerant species. Hypoxia condition was determined both in sediment and overlying water. We measured DO and two major substances of oxygen consumption, NH_4^+-N and chemical oxygen demand (COD) of water and sediment oxygen demand (SOD). In parallel, macroinvertebrates were investigated.

Material and methods

Study area and sampling sites

The ZRB, located in north China, is bounded on the north by the Daqing River Basin, on the west by the Taihang Mountain, on the east by the Bohai Sea, and on the south by the Zhangwei River Basin (Fig. 1). It stretches across Hebei Province, Shanxi Province, and Tianjin Municipality and supports 19 million populations. The basin has an area of 46,868 km^2, 66 % and 34 % of which are mountain area and plain area respectively (The Hai River Basin (vol.1), 1997). This study focused on the plain area due to its heavy pollution and oxygen depletion. The basin, the area of northern temperate continental monsoon climate, has an annual average rainfall of 550 mm. Nevertheless, rivers with blackwater and odors have dominated the plain area of the basin, and oxygen depletion has become a prominent problem due to sewage discharge. Based on the previous study, NH_4^+-N, an important substance consumed by DO, was highlighted as the main pollutant in the Ziya river system (Li et al. 2012; Zhao et al. 2014).

The Ziya river system has two big branches: the Hutuo River and the Fuyang River. Sampling sites were set in the Fuyang River and its important tributaries, considering that most river segments of the Hutuo River has dried up and even been abandoned in the whole years. Sampling sites were set based on the following principles: (1) considering the areas of the river systems and complexity of the river network, river systems with larger areas had more sampling sites, and fewer sites were set in river systems with small areas and simple river networks. (2) Sampling sites were set both on major and branch channels to study the differences and relationships between them. (3) Sites were set upstream and downstream of sewage outlets. (4) For those reaches with uniform characteristics, comparatively fewer sites were set. Twenty-four sampling sites were set in the plain rivers of the ZRB (Fig. 1), with rivers flowing down from Shijiazhuang city and Xingtai city. At the intersections of tributaries, sites were set specially.

Macroinvertebrates investigation

In August 2013, macroinvertebrates were sampled at each site. Although the rivers in the study area were mostly with slow flow and blackwater, macroinvertebrate sampling procedures were conducted in various habitat (run, riffle, pool, backwater, drop water, etc.). Quantitative and qualitative samplings were combined. Qualitative samples were taken using a standard D-net with 0.5-mm mesh. A surber with an area of 0.3 m × 0.3 m was used for quantitative sampling. Large rocks, woody debris, and leaves were scrubbed to dislodge organisms clinging to these substrates. There were at least four samples at a site. Samples were preserved with 10 % formalin in the field, and then transformed to 75 % ethanol in the laboratory. Organisms were sorted with forceps in white china plate. Samples were identified to the lower practicable taxonomic level (normally genus) possible.

Measurement of sediment oxygen demand

Sediment constitutes the main habitat for macroinvertebrate. However, polluted sediment has a high potential to consume DO. Sediment oxygen demand (SOD) has been found to

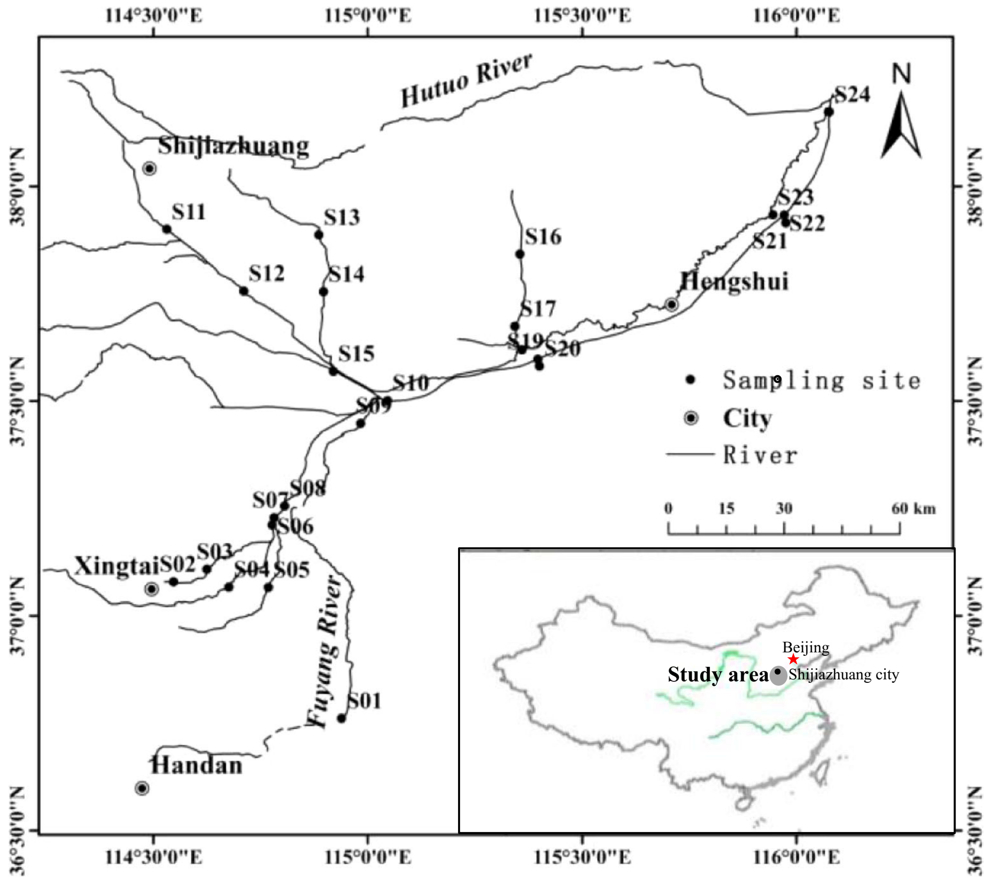

Fig. 1 The location of Ziya River Basin and sampling sites

contribute significantly to oxygen consumption in river and plays a primary role in the water quality (Hanes and Irvine 1966; James 1974; Hu et al. 2001). We measured SOD specially to determine the potential of sediment to consume DO. To ensure accuracy of laboratory experiment, two measurements were conducted. In August and October 2013, sediment samples were collected from the top 20 cm of the riverbed using a dredge sampler at each site. This was because the top 20 cm represent the most biologically active depositional layer for relatively slow flowing streams (Hickey 1988). At each site, three parallel samples were collected and then stored in polyethylene tubes with air isolating cock to protect sediments from oxidation during the preservation. Sediment samples were placed in a refrigerator at 8 °C (a representative hypolimnetic temperature). After delivery to the laboratory, the SOD of samples was measured as soon as possible.

A method of laboratory core incubation was applied. Sediment was incubated in cylindrical perspex cores with 6-cm internal diameter and 28-cm height. Sediment cylinders were 10 cm deep and with 14 cm overlying water. Sediment cores were incubated, at 25 °C in dark, for 24 h or longer until the DO concentration in the overlying water dropped to 2 mg L^{-1}. The rate of oxygen consumption was calculated based on the slope along the DO versus time profiles and the area of the sediment-water interface. SOD was expressed in terms of grams per square meter per day (g O_2 m^{-2} day^{-1}). Mathematically, the SOD rate of core incubation can be formulated as

$$\mathrm{SOD} = (24\mathrm{S}\cdot\mathrm{V})/10^3\mathrm{A} \quad (1)$$

where

SOD sediment oxygen demand, g m^{-2} d^{-1}
S slope of liner portion of usage curve, mg L^{-1} h^{-1}
V volume of the overlying water, litters
A area of the core incubator, m^2

The specific formula for the core incubator in this study was

$$\mathrm{SOD} = 3.360\mathrm{S} \quad (2)$$

Measurement of oxygen consumption in water

The characteristics of overlying water have inevitable effects on macroinvertebrate assemblages (Maul et al. 2004; Heatherly et al. 2007; Holland et al. 2015). During the field survey of macroinvertebrates and sediment, DO concentration in the overlying water was simultaneously measured using a portable DO analyzer (HACH/HQ30d, America). Water samples were collected in polythene bottles with 100 mL, acidified with sulfuric acid to pH < 2, and stored in car refrigerator at 2–5 °C. The COD was determined with the reactor digestion method (HACH/DR2800, America), and the ammonia was determined with the phenol-hypochlorite colorimetric method (State Environmental Protection Agency 2002).

Data processing

Analysis on macroinvertebrate community was conducted, and pollution levels of rivers were evaluated with DO, SOD, COD, and NH_4^+-N as indicators followed by the investigation of their relationships. Microsoft Excel was used for drawing histogram and scatterplot. Map of sampling sites was produced by ArcGIS 10.0. Ordination analyses were performed using Canoco 5.0 which was a professional statistic software applied in ecology.

Results

Macroinvertebrate assemblages

The survey result showed that the macroinvertebrate community in the plain area of the Ziya river system had an abnormal structure. Benthic taxa were incomplete; only three classes, Insecta, Gastropoda, and Oligochaeta, appeared, while other taxa, such as Crustacea and Lamellibranchia disappeared. There were 9 orders, 30 families, and 54 genera. Aquatic insects were dominant in each taxon, of which Chironomidae was the major component. A total of 19 genera in Chironomidae were found, accounting for 35 % of the total taxa in the plain area of the basin (Table 1). The Ziya river system had a low density of macroinvertebrate generally. There was a large range of density which was from 11.11 to 3022.22 ind m^{-2} (Fig. 2). This was due to the differences of taxa that occurred between the sites. For instance, those sites with the most aquatic insects or Oligochaeta had a high density, while the sites with macroinvertebrate groups dominated by Gastropoda had a low density. The average and the median of the density were 328.31 ± 406.68 and 61.11 ind m^{-2}, respectively. Similarly, the biomass was also at a low level, with an average of 0.40 ± 0.47 g m^{-2} and the median of 0.11 g m^{-2}. The biomass had a wide range from 0.0009 to 2.57 g m^{-2} (Fig. 2). There were few taxa in each site, and obviously, those sites with Gastropoda had a large biomass, while the sites occupied by Chironomidae or Tubificidae had a small biomass.

Benthic community had an abnormal structure in the plain rivers of the Ziya river system. There were very low richness and low abundance at each site, coupled with a sparse distribution. It was often difficult to find benthic organisms. Several sampling processes for obtaining one sample and the

Table 1 Macroinvertebrate taxa in plain rivers of the Ziya river system

Classes	Orders	Families	Genera
Insecta	Diptera	Tabanidae	
		Stratiomyidae	
		Culicidae	*Chaoborus*
		Psychodiae	
		Stratiomyidae	
		Ephydridae	
		Ptychopteridae	*Ptychoptera*
		Chironomidae	*Chironomus*
			Tanypus
			Enfieldia
			Procladius
			Tanytarsus
			Glyptotendipes
			Stictochironomus
			Dicrotendipes
			Harnischia
			Cricotopus
			Lipiniella
			Nilothauma
			Parachironomus
			Cladopelma
			Microchironomus
			Acalcarella
			Boreochlus
			Cryptochironomus
			Micropsectra
	Odonata	Gomphidae	*Gomphus*
		Libellulidae	*Crocothemis*
		Aeshnidae	*Anax*
			Aeshna
		Coenagrionidae	*Ischnura*
	Coleoptera	Psephenidae	
		Dytiscidae	*Dytiscus*
			*Noter*us
			Hydaticus
		Hydrophilidae	Hydrobius
			Hydrosous
		Sphaeridiinae	
	Hemiptera	Belostomatidae	*Kirkaldyia*
		Veliidae	
	Trichoptera	Polycentropidae	
		Rhyacophiloidae	*Rhyacophila*
		Corixidae	*Corixa*
Gastropoda	Pulmonata	Lymnaeidae	*Radix*
		Onchidiidae	*Hippeutis*
		Lymnaeidae	
		Physidae	*Physa*
	Prosobranchia	Hydrobiidae	*Alocinma*
Oligochaeta	Tubificida	Tubificidae	*Limnodrilus*
			Branchiura
			Tubifes
		Naididae	*Nais*
			Paranais
	Ephemerida	Oligoneuriidae	
		Leptophlebiidae	*Paraleptophlebia*

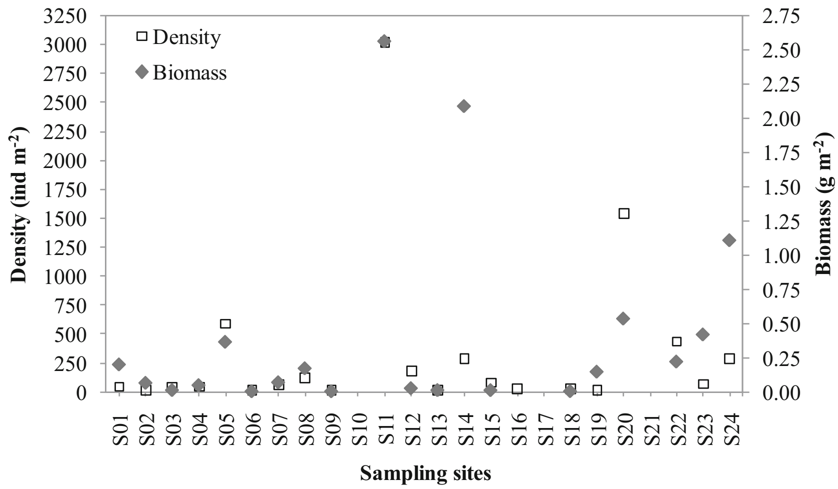

Fig. 2 Density and biomass of macroinvertebrate in plain rivers of the Ziya river system

communities were dominated by only one or two taxon. Shannon-Wiener index, which could simultaneously reflect biodiversity and evenness, was calculated for each site. The results showed that the plain rivers in the Ziya river system had a lower biodiversity. Values of the Shannon-Wiener index were from 0.00 to 1.72 (Table 2). There were up to nine sites with a "zero" level of biodiversity, and the reasons were as follows: (a) only one species was found in quantitative samples at site, such as S02, S06, S09, S13, and S14, and (b) no organisms were found at site, such as S10, S17, S18, and S21. The average and the median of the index value were respectively 0.62 ± 0.60 and 0.65, representing a low biodiversity.

Due to fewer species in quantitative samples, it was easy to determine the dominant species. We just applied the cumulative percentage of several species which had a relative large number of individuals in quantitative samples. The cumulative percentages of the species were above 70 %, 12 of which were 100 %(Table 2). This was because there were only one or two species that appeared in the quantitative samples, and these survivals dominated the corresponding locations obviously. The dominant taxa were mainly Chironomidae, followed by Tubificidae and Gastropoda. Adaptable or tolerable habitats for the dominant species were mainly lentic, polluted, eutrophic, hypoxia water, or sediments. For instance, *Chironomus* lived in lentic habitat and could bear high pollution; *Radix* preferred the sediments with rich organic matters and could tolerate anoxia; *Tubificidae* often survived in polluted and anoxic waters. Most dominant species had tolerance to moderate or high pollution, and the tolerance values were 3–7 or ≥7 (Table 2).

Oxygen content and consumption potential

Measurement of water column in situ showed that the DO in the Ziya river system was at a low level. The range of DO concentration was 0.11–4.03 mg L^{-1}, and the average value was 1.35 ± 0.95 mg L^{-1}. There were five sites with extremely low values of DO (<0.5 mg L^{-1}). They were S09 (0.21 mg L^{-1}), S10 (0.11 mg L^{-1}), S15 (0.21 mg L^{-1}), S19 (0.44 mg L^{-1}), and S20 (0.17 mg L^{-1}) (Fig. 3b). S10 and S15, located at the confluences of several branches, had low DO, indicating that convergence of pollutants did more contribution to oxygen depletion (Fig. 1). S19 and S20 were in the downstream location near the confluence and with a low level of DO. S09 was set in the reach that flows across a large area of rural space (Fig. 1), which received large amounts of household garbage and had a lot of potential to consume oxygen.

Pollutants in sediment and overlying water both contribute to DO consumption, and we measured both SOD and COD_{Cr} and NH_4^+-N in the overlying water. Water column in the Ziya river system had high COD_{Cr} (Fig. 3b). There was a big range of COD_{Cr}, which was 27.50 to 410.00 mg L^{-1}. The average and median of COD_{Cr} at the sites were 76.08 ± 80.46 and 54.50 mg L^{-1} respectively, indicating a high potential to consume oxygen during its transformation. Four sites, S13, S16, S19, and S23, which were with the COD_{Cr} contents even exceeded 100 mg L^{-1} (Fig. 3b). NH_4^+-N had similar situation with COD_{Cr}. The range of NH_4^+-N concentration was 1.79–101.41 mg L^{-1}, and the average and the median were 27.41 $\pm$ 14.45 and 22.11 mg L^{-1} respectively. Three sites, S16, S19, and S23, had higher NH_4^+-N, which were in accordance with the rule of COD_{Cr} (Fig. 3b).

Overall, SOD in summer was higher than in autumn, and the ranges of SOD were 0.41–2.60 g m^{-2} day^{-1} in summer and 0.22–1.23 g m^{-2} day^{-1} in autumn, respectively. Combining the summer and autumn, the average and the median of SOD were 0.97 ± 0.34 and 0.63 ± 0.24 g m^{-2} day^{-1}(Fig. 3a). Most sites reflected a similar change trend of SOD from summer to autumn. Nevertheless, there were individual sites with a different law, which perhaps related with the pulse of pollution discharge. For instance, SOD of the site S18 was 2.60 g m^{-2} day^{-1} in summer, but 0.22 g m^{-2} day^{-1} in autumn

Table 2 Biodiversity and dominant taxa in plain rivers of the Ziya river system

Sampling sites	Shannon-Wiener index	Cumulative percentage of *n*/*N*	Dominant taxa	Habitat	Tolerance values
S01	1.00	86 %	Lymnaeidae	Lentic or tranquil-flow	3–7 or >7
S02	0.00	100 %	Tabanidae	Waters of moor or forest	3–7
S03	0.94	75 %	*Limnodrilus hoffmeisteri*	Extremely polluted waters	>7
S04	1.04	100 %	*Tubifex*, *Alocinma longicornis*, *Radix auricularia*	Polluted and anoxic water	>7 (*Tubifex* and *Radix auricularia*); 3–7 (*Alocinma longicornis*)
S05	0.89	99 %	*Chironomus pallidivittatus*, *Chironomus riparius*	Lentic-littoral and profundal, lotic-depositional	>7
S06	0.00	100 %	*Limnodrilus hoffmeisteri*	Extremely polluted waters	>7
S07	1.63	75 %	*Tanypus punctipennis*, *Chironomus pallidivittatus*, *Chironomus riparius*	Lentic-littoral and profundal, lotic-depositional	>7
S08	1.43	93 %	*Chironomus pallidivittatus*, *Parachironomus*	Lentic-littoral and profundal, lotic-depositional	>7
S09	0.00	100 %	*Cladopelma*	Lentic-littoral	<3 or 3–7
S10	0.00				
S11	0.48	92 %	*Glyptotendipes tokunagai*	Eutrophic sediment	>7
S12	1.69	70 %	Parachironomus, *Boreochlus thienemanni, Cryptochironomus*, *Cricotopus*, *Chironomus pallidivittatus*	Lotic-erosional; lentic-littoral and profundal; lotic-depositional; lentic-vascular hydrophytes and lotic-erosional and depositional	3–7or >7(*Cricotopus*); 3–7(*Boreochlus thienemanni*); >7(others)
S13	0.00	100 %	Psephenidae	Lotic and rock	3–7
S14	0.00	100 %	Lymnaeidae	Lentic or tranquil-flow	3–7 or >7
S15	0.60	100 %	*Tubifex*, *Limnodrilus hoffmeisteri*	Polluted and anoxia water	>7
S16	0.69	100 %	*Cladopelma*, *Dicrotendipes*	Lentic-littoral	>7
S17	0.00				
S18	0.00	100 %	*Chironomus pallidivittatus*, *Glyptotendipes cauliginellusa*	Lentic-littoral and profundal; lotic-depositional; eutrophic water	>7
S19	0.69	100 %	*Chironomus flaviplumus*	Lentic-littoral and profundal; lotic-depositional	>7
S20	0.26	100 %	*Chironomus pallidivittatu*, *Glyptotendipes cauliginellusa*	Lentic-littoral and profundal; lotic-depositional; eutrophic water	>7
S21	0.00				
S22	1.72	82 %	*Glyptotendipes tokunagai*, *Procladius*, *Tubifex tubifex*	Eutrophic sediment; lentic-profundal; lotic-depositional; extremely-polluted water	>7
S23	0.89	100 %	*Corixa substriata*	Eutrophic sediment	≥7
S24	0.93	98 %	*Tanypus punctipennis*, *Chironomus pallidivittatu*	Lentic-littoral and profundal; lotic-depositional	>7

Note: habitats for dominant species are cited from John et al. (1994), Zhao (2005), and Liu et al. (1979); tolerant values are cited from John et al. (1994), Lenat (1993), Hilsenhoff (1998), Wang and Yang (2004), especially, tolerant value of Lymnaeidae is cited from Leunda et al. (2009), Wang et al. (2003), and tolerance of *Corixa substriata* is cited from Xing et al. (2012) and Wang et al. (2003)

(Fig. 3a). This was because S18 was just at the reach running through a village, and a pollution event occurred probably when sampling.

Impact of oxygen depletion on macroinvertebrate taxa

The relationship between macroinvertebrate community and oxygen consumption potential was investigated by statistical tests. Response data (macroinvertebrates) were first analyzed by DCA to decide the methods used for the following analysis. It was shown that the response data had a gradient of 6.8 SD units long, so linear method was not appropriate and unimodal method was chosen (Lepx and Smilauer 2003). Ordination of macroinvertebrates was conducted on the basis of genus abundance. The eigenvalues for the four axes were separately 0.9584, 0.7910, 0.6636, and 0.2242, and of which the sum of eigenvalues of the first two axes accounted for 66.34 %. The samples represented by the sites could be

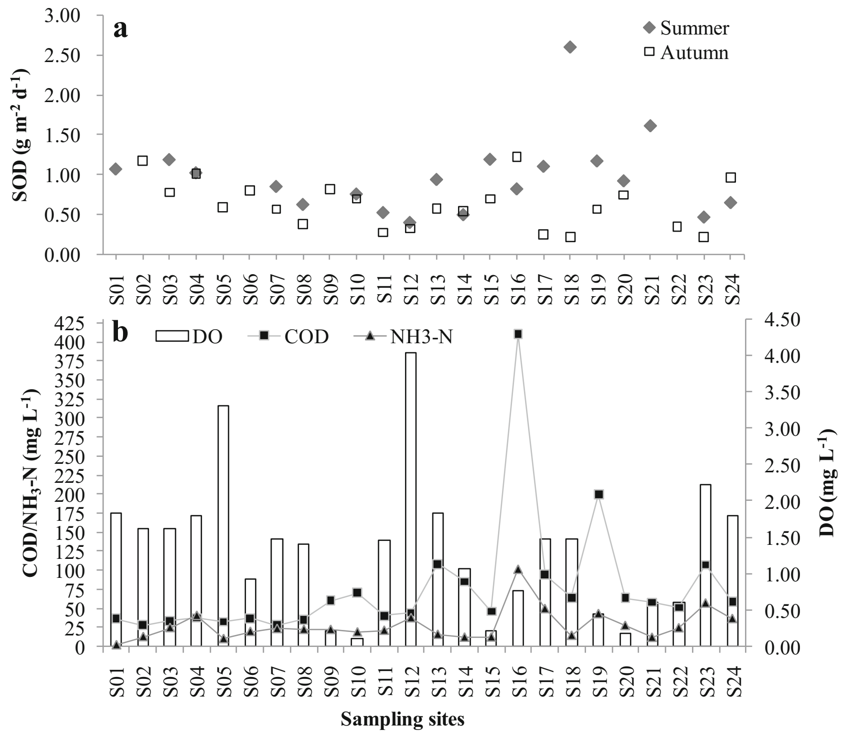

Fig. 3 Indicators measured for the potential of DO consumption

classified into four groups, and each group had its special macroinvertebrate taxa. The first three groups were S01-S14, S02-S11-S09, and S03-S06-S15, which were with three to six genera. The remaining samples with more genera constituted the fourth group (Fig. 4a).

Ordination of macroinvertebrate genera and environmental variables was conducted by CCA (Fig. 4b). The eigenvalues of four axes were respectively 0.7936, 0.4257, 0.2291, and 0.9233. The proportion of the sum of eigenvalues of the first two axes was 51.41 %. The four environmental variables, DO, SOD, COD_{Cr}, and NH_4^+-N, were divided into two categories. The arrows represented that DO and SOD almost appeared as one, indicating that they had a close correlation. Similarly, the angle between the arrows characterized COD_{Cr}, and NH_4^+-N was acute, and they were closely related. Conversely, the angle between the above two sets of variables were obtuse which showed a low correlation. SOD and NH_4^+-N, represented by long arrows, had the main contribution to the distribution of macroinvertebrates, while COD_{Cr} had a smaller contribution which was shown as a short arrow.

Most genera were at the circle near the center, which was probably because three environmental variables were

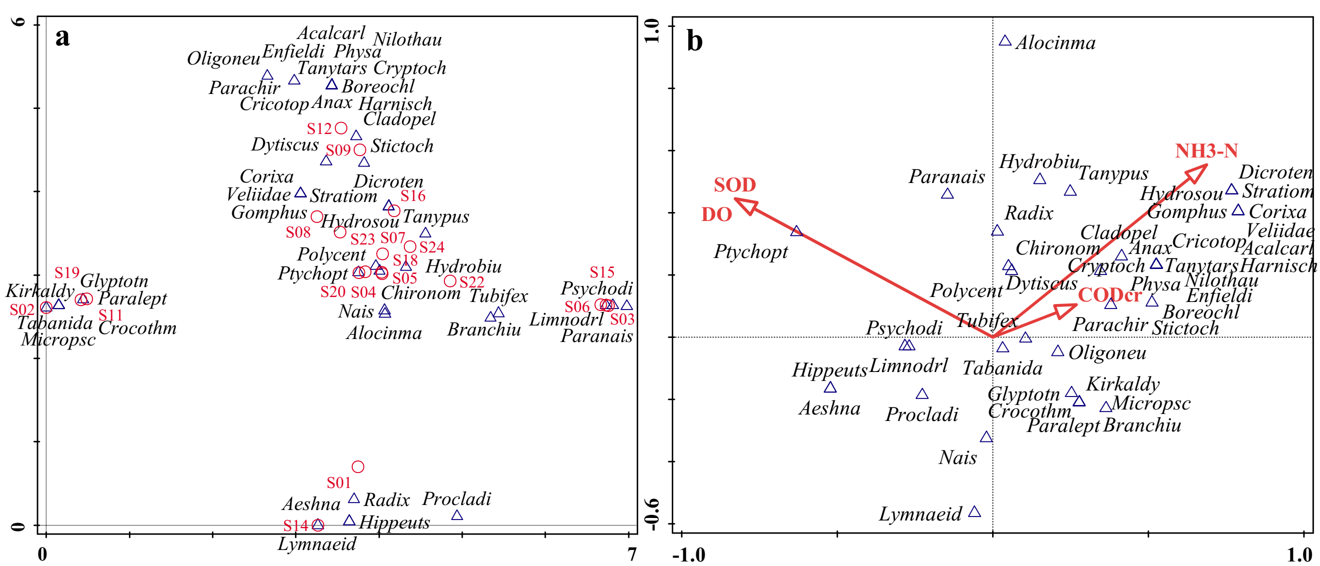

Fig. 4 DCA (**a**) and CCA (**b**) analysis of species-samples and species-environmental variables

conducive to oxygen consumption except DO, and they did not prefer anoxia. Nevertheless, there were taxa, such as *Alocinma* and *Lymnaeidae*, distributed far from the center and arrows of environmental variables, indicating that these taxa had a low frequency of occurrence and were indifferent to oxygen consumption. Many taxa distributed along the positive direction of the arrow of NH_4^+-N and were regarded as eutrophy lovers. These taxa included *Dicrotendipes*, *Corixa*, *Veliidae*, *Hydrosous*, *Gomphus*, *Hydrobius*, *Cricotopus*, *Tanytarsus*, *Cladopelma*, etc. There were minor groups of taxa distributed in the negative direction of the arrow of NH_4^+-N, including *Nais*, *Procladius*, *Psychodiae*, *Limnodrilus*, *Hippeutis*, etc. Most of the macroinvertebrates were distributed in the negative direction of the arrow of SOD, revealing a greater effect of SOD on benthic life (Fig. 4b).

Discussion

Although there may be multiple types of pollutants, DO depletion was a significant problem for the plain rivers in the ZRB. We determined the potential of DO consumption from the perspective of sediment and the overlying water synchronously. The study results showed that DO, SOD, and NH_4^+-N were the major factors contributing to the macroinvertebrate distribution and DO consumption. Liu et al. (2009) summarized sediment oxygen demand values in various systems from a literature review: river systems with substrate from clay loam to sandy loam had a 0–2 g m^{-2} day^{-1} (Liu et al. 2009). Based on our measurements, the sediment grain size of plain river in the ZRB was 10.21–60.07 μm (average 24.68 ± 12.12 μm), and the SOD was 0.41–2.60 g m^{-2} day^{-1} in summer and was 0.22–1.23 g m^{-2} day^{-1} in autumn. Compared with other studies, the river sediment had a high potential to consume DO in the plain area of ZRB.

According to the aquatic life water quality criteria of the US Environmental Protection Agency, aquatic organisms will fail to live if DO concentration was below 2.3 mg L^{-1}. The range and the average of DO concentration of water column in the Ziya plain rivers were separately 0.11 –4.03 mg L^{-1} and 1.35 ± 0.95 mg L^{-1}, indicating a low level. In this study, the range and the average of NH_4^+-N concentration were respectively 1.79–101.41 mg L^{-1} and 27.41 ± 14.45 mg L^{-1}, which far exceeded the class V guideline of NH_4^+-N (2.0 mg/l) according to the national quality standards for surface waters, China (GB3838-2002). Compared with other studies on nitrogen-polluted rivers, plain rivers were extremely polluted in the ZRB. For instance, NH_4^+-N concentration was 0.17–11.5 mg L^{-1} in the Haicheng River (China) (Bu et al. 2011), 0.003–0.285 mg L^{-1} in the Le′an River Catchment (China) (Gao et al. 2011), 0.07–2.67 mg L^{-1} in the Ebro River Basin (NE Spain) (Lassaletta et al. 2010), 0.097–0.157 mg L^{-1} in the Jadro River (Croatia) (Stambuk-Giljanovic 2006), and average 0.51 mg L^{-1} in the Qiantang river (China) (Wu et al. 2003).

There were simple macroinvertebrate communities under the condition of extreme DO depletion in both sediment and the overlying water. First, there were low biomass and density. Other similar researches were compared with our results. For instance, for a tributary to the Rio Grande in the upper Paraná basin, a human-impacted tropical river, density ranged from 0 to 7467 ind m^{-2}, and biomass ranged from 0 to 1515 mg m^{-2} during the rainy season (Aguiar et al. 2015). Huo et al. surveyed macroinvertebrate community in Songhua River of different seasons, and density and biomass were respectively 48. 63 and 23.12 g m^{-2} (Huo et al. 2012). A tributary of the Yellow river, which was heavily polluted with total nitrogen, had a density and biomass of 1173.5 and 5430.1 mg m^{-2}, respectively (Fu et al. 2010). Macroinvertebrate assemblages were investigated in the river system which was with heavy organic pollution in plain area of Shanghai city. The results showed that density declined from the city (8776.3 ind m^{-2}) to the countryside (690.3 ind m^{-2}) (Chen et al. 2013). The Haiyinqiao reach of Zhujiang river, which received large amounts of industrial discharge, had the maximum of density (305,280 ind m^{-2}) and biomass (664.72 ind m^{-2}) (Jiang et al. 2011). The results of our research showed that the biomass ranged from 0.0009 to 2.57 g m^{-2}, and the density from 11.11 to 3022.22 ind m^{-2}, indicating a low level compared with other similar studies.

Second, the dominant taxa were principally Chironomidae and Tubificidae, and most of them were tolerant to pollution and anoxia. Justus's et al. (2014) research showed that those extremely tolerant taxa had a competitive advantage and would be successful when DO minima were <2 mg L^{-1}; *Glyptotendipes* had a higher tolerance than *Chironomus* to anoxia (Justus et al. 2014). Irving et al. (2004) conducted a 10-day toxicity testing with *Chironomus tentans* larvae, showing that exposure to 1.2 ± 0.1 mg L^{-1} DO for 10 days did not affect *C. tentans*' survival or growth and significant behavioral changes at 2.0 ± 0.1 mg L^{-1} DO or less (Irving et al. 2004). When oxygen content was decreased to 0.3–0.5 mg L^{-1}, combined with sulfidic conditions, *Tubifex* showed much lower mortality and even better growth than *L. hoffmeisteri* did (Volpers and Neumann 2005). These studies provided assisted proofs for explaining the abnormal macroinvertebrate assemblages in our study area; under the condition of extreme DO depletion, there were few genera that survived, and high tolerance taxa dominated, such as *Limnodrilus*, *Tubifex*, *Chironomus*, *Glyptotendipes*.

Indeed, macroinvertebrate has been applied broadly in assessment of ecological status of aquatic ecosystems, such as Benthic Index of Biotic Integrity (B-IBI) in the USA (Kerans and Karr 1994), River Invertebrate Prediction and Classification System (RIVPACS) in the UK (Wright 1995), Australian River Assessment System (AUSRIVAS) in

Australia (Coysh et al. 2000), and the Development and Testing of an Integrated Assessment System for the Ecological Quality of Streams and Rivers throughout Europe using Benthic Macroinvertebrates (AQEM) in the EU (Hering et al. 2004). Thus, abnormal community structure of macroinvertebrate indicated a poor ecological status. It is advisable to improve DO condition and macroinvertebrate diversity in river harnessing and management in the plain areas of the ZRB.

Conclusions

This study evaluated the impact of hypoxia environment on macroinvertebrate community structure, and the results showed the following:

1. There was an all-around hypoxia environment and a high potential of DO consumption in the plain rivers of the ZRB. The value ranges of DO, SOD, COD_{Cr}, NH_4^+-N were separately 0.11–4.03 mg L^{-1}, 0.41–2.60 g m^{-2} day^{-1}, 27.50–410.00 mg L^{-1}, and 1.79–101.41 mg L^{-1}.
2. Three macroinvertebrate classes, Insecta, Gastropoda, and Oligochaeta, appeared in the plain rivers of the ZRB. These classes included 9 orders, 30 families, and 54 genera. Aquatic insects were the overwhelming majority of taxa. There was a low biodiversity, with Shannon-Wiener index of 0.00–1.72.
3. SOD and NH_4^+-N had major impact on macroinvertebrate community, and the former had negative effect on most taxa, for instance, *Nais, Branchiura*, *Paraleptophlebia*, etc. These taxa were sensitive or had a moderate-high tolerance to pollution. NH_4^+-N had both positive and negative impacts on benthic animals, for instance, *Dicrotendipes*, *Gomphus*, *Cricotopu*s, etc., for the former and *Procladius*, *Limnodrilus*, *Hippeutis*, etc., for the latter. These taxa had a moderate-high tolerance to pollution.

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