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Macroinvertebrate communities in the Big East Lake water network in relation to environmental factors

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Abstract – The Big East Lake water network (BELWN), located in Wuhan city, China, is mainly composed of six lakes and isolated from the Yangtze river. At the background of restoring the hydrological connectivity between rivers and lakes, four season investigations were conducted during 2014–2015 to study the spatial distribution and seasonal dynamics of macroinvertebrate communities, explore their relationships with environmental factors, and forecast the change trends in assemblages in a long period after restoration measures. A total of 40 species were recorded, oligochaetes and chironomids dominated the communities. Season variation in density and biomass were distinct and the community differences in lakes related to the degrees of organic pollution. In comparison with the historical data, the species richness of mollusks in Donghu lake sharply decreased due to water pollution and the loss of diverse habitat. Concerning on the whole BELWN, the whole taxa recorded in our study was slightly fewer than the previous study. A new recorded species polychaete *Nephtys* sp. was first collected with an important ecological interest. As an urban lake system dominated by eutrophication, the water nutrients significantly affected the distribution of macroinvertebrates. According to the GAM models, the dominant species responded to environmental gradients with different response curves. After restoring the hydrological connectivity between rivers and lakes, the macroinvertebrate communities would change and the biodiversity would steadily increase with time. Additionally, the new recorded species *Nephtys* sp. would spread into the whole BELWN in the foresee future.

Keywords: Big East Lake water network (BELWN) / macroinvertebrate communities / environmental factors / disconnected lake system / restoring hydrological connectivity

Résumé – Les communautés de macroinvertébrés dans le réseau du Grand lac Est, ses relations avec les facteurs environnementaux. Le réseau du Grand lac Est (BELWN), situé dans la ville de Wuhan, en Chine, est principalement composé de six lacs isolés du fleuve Yangtze. Dans le cadre du rétablissement de la connectivité hydrologique entre les rivières et les lacs, quatre études ont été menées pendant la période 2014-2015 pour étudier la répartition spatiale et la dynamique saisonnière des communautés de macroinvertébrés, explorer leurs relations avec les facteurs environnementaux et prévoir les tendances des changements dans les assemblages à long terme après les mesures de restauration. Un total de 40 espèces a été enregistré. Les oligochètes et les chironomides ont dominé les communautés. La variation saisonnière de la densité et de la biomasse était nette et les différences entre lacs dans les communautés étaient liées au degré de pollution organique. Par rapport aux données historiques, la richesse en espèces de mollusques du lac Donghu a fortement diminué en raison de la pollution de l'eau et de la perte de divers habitats. En ce qui concerne l'ensemble du BELWN, le total des taxons rencontrés dans notre étude était légèrement inférieur à celui de l'étude précédente. Une nouvelle espèce polychète *Nephtys* sp., d'un intérêt écologique important, a été échantillonnée. En tant que système lacustre urbain dominé par l'eutrophisation, les nutriments ont affecté de façon significative la répartition des macroinvertébrés. Selon les modèles GAM, les espèces dominantes ont répondu à des gradients environnementaux avec des courbes de réponse différentes. Après la restauration de la connectivité hydrologique entre les rivières et les lacs, les communautés de

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macroinvertébrés changeront et la biodiversité augmentera avec le temps. De plus, les nouvelles espèces comme *Nephtys* sp. se répandront dans tout le BELWN dans l'avenir.

Mots clés : réseau hydrographique du Grand lac Est (BELWN) / communautés de macroinvertébrés / facteurs environnementaux / système lacustre déconnecté / restauration de la connectivité hydrologique

1 Introduction

The Big East Lake water network (BELWN), as an urban lake system, is located at the south side of Yangtze river in Wuhan city, China (Dong and Mei, 2007). Historically, the BELWN was an open lake system connected to the Yangtze river before 1957. Due to the rapid urban development, the BELWN became a disconnected lake system and was isolated from the Yangtze river (Du, 1998; Yang *et al.*, 2009; Huang *et al.*, 2013). In 1950–1960s, the BELWN had abundant aquatic plants and clear water (Chen *et al.*, 1975; Wu *et al.*, 2003). Since the 1970s, with the rapid population growth, the rapid development of industry and agriculture, and the intensive fishery utilization, the amounts of nitrogen and phosphorus from huge domestic sewage and industrial wastewater that drain into the BELWN increased year by year (Liu and Huang, 1997), leading to the approaching extinction of aquatic plants, the frequent blooming of blue-green algae, and the deteriorating of water quality in several lakes (Lei and Jiang, 2012). In the BELWN, the species richness and biodiversity of aquatic organisms declined with water pollution. For instance, during 1992–2013, the species number of aquatic plants and fish decreased from 83 to 14 and 67 to 20 respectively, the species number of macroinvertebrates considerably reduced and the proportions of tolerant species remarkably increased, the communities of flora and fauna were unitary, and the rate of aquatic vegetation coverage was less than 2% (Li *et al.*, 2015). The pollutants sources in the BELWN are mainly from point source pollution, non-point source pollution, autogenous pollution and atmospheric dustfall (Yan and Li, 2010). With the implementation of sewage interception project in 2003, the amount of pollutants from point and non-point pollution into the BELWN greatly reduced (Yan and Li, 2010). In the past 20 years, the BELWN received more attention for its high recreational values (Du, 1998). The pollutants in sediments and surface water, including polycyclic aromatic hydrocarbons (PAHs) (Lin *et al.*, 2008; Yun *et al.*, 2016), organochlorine pesticides (OCPs) (Yang *et al.*, 2014; Yun *et al.*, 2014), and aquatic organisms were studied for various purposes (Kuang *et al.*, 1997; Gong, 2002; Tang *et al.*, 2008; Wang *et al.*, 2010, 2011; Wei *et al.*, 2011).

Macroinvertebrates play a critical role in the natural flow of energy and nutrients in aquatic system (Gong *et al.*, 2000; Ji *et al.*, 2011, 2015), and are ideal biological indicators to monitor and assess ecological status due to their relatively weak migration ability, long life cycles and different tolerance to stressors (Covich *et al.*, 1999; Beck and Hatch, 2009). The macroinvertebrates in the BELWN were frequently investigated, mainly focusing on community structure (Wang, 1996; Kuang *et al.*, 1997; Gong *et al.*, 2000; Gong, 2002; Wu *et al.*, 2005; Wang, 2009; Wang *et al.*, 2010; Cai *et al.*, 2013; Hu *et al.*, 2014). However, these surveys were basically limited to several lakes, not covering the whole BELWN, and the relationships with environmental variables in the water network were few explored. Since 2008 the government began to put into massive funds to implement the restoration of hydrological connectivity between the Yangtze river and lakes, for speeding up the water exchange and improving the ecological quality (Dong and Mei, 2007). For the foreseeable future, the status of macroinvertebrates in the water network would change with implementation of the project. The historical data on macroinvertebrates could not meet the requirements of comprehensive understanding the community status under new situations. In this paper, the principal objectives were to study the spatial distribution and seasonal dynamics of macroinvertebrate communities, explore their relationships with environmental factors, and forecast the change trends in assemblages in a long period after restoring the hydrological connectivity between the Yangtze river and lakes.

2 Material and methods

2.1 Study area and sampling sites

The BELWN is located at a subtropical monsoon climate zone, with an average annual temperature of 16.3 °C, an extreme maximum temperature of 40.5 °C and an extreme minimum temperature of –14.1 °C. The average frost-free duration and precipitation are 245 days and 1220 mm respectively. The water recharge is mainly derived from runoff and precipitation. The annual rainfall mainly concentrated in April to July (Editorial Committee of Encyclopedia of Rivers and Lakes in China, 2010). The BELWN is mainly made up of six lakes, with total water area of 62.5 km^2, including Donghu lake (DH) (with an area of 33 km^2, mean depth of 2.2 m), Shahu lake (SH) (2.8 km^2, 1.5 m), Yangchunhu lake (YCH) (0.2 km^2, 1.5 m), Yanxihu lake (YXH) (10.8 km^2, 2.5 m), Yandonghu lake (YDH) (7.5 km^2, 3.3 m) and Beihu lake (BH) (1.8 km^2, 2 m) (Appendix 1). Due to transportation and farming, the DH is divided into several lakelets, including Shuiguohu lake (SGH), Tanglinghu lake (TLH), Shaoqihu lake (SQH), Guozhenghu lake (GZH), Tuanhu lake (TH), Houhu lake (HH), Miaohu lake (MH) and Yujiahu lake (YJH). And the SH is divided into inner lake and outer lake (Wang *et al.*, 2010; Yan and Li, 2010; Ji *et al.*, 2011; Lei and Jiang, 2012) (Fig. 1).

In the hydrological connectivity restoration project, the water from the Yangtze river is pumped to the BELWN by two inflow canals from the sluices Qinshangang (QSG) and Zengjiaxiang and drained into the Yangtze river again by three outflow canals after sufficient water exchange, achieving seasonal connectivity between the lakes and the Yangtze river. Newly built and old canals are used to connect different lakes (Lei and Jiang, 2012). In our study, three sampling sites were set up in the QSG canal, and 26 sampling sites were set in the lakes. The sampling sites were mainly determined by the areas of the lakes and almost located at the waterways of exchange water fluxes between the lakes and the Yangtze river. According to the results of the Wuhan water environment bulletin from 2001 to 2007, the water quality of YDH was the

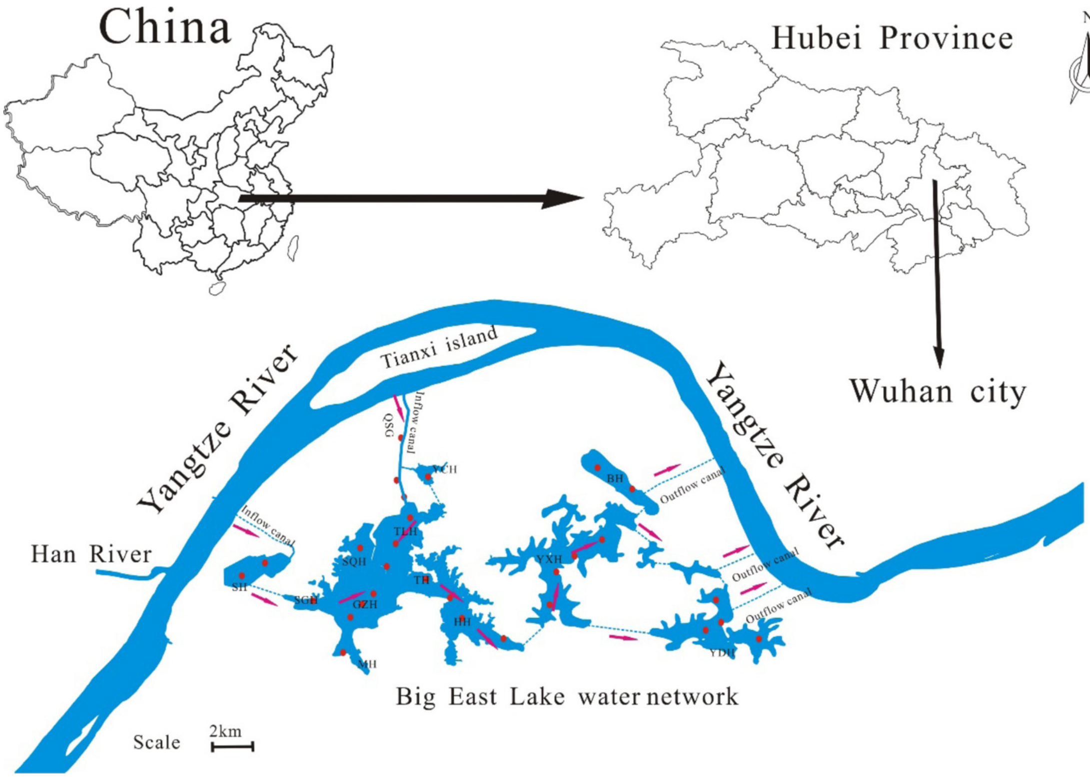


Fig. 1. Locations of sampling sites in the Big East Lake water network. *Note*: SH – Shahu lake; MH – Miaohu lake; SCH – Shuiguohu lake; GZH – Guozhenghu lake; SQH – Shaoqihu lake; TLH – Tanglinghu lake; TH – Tuanhu lake; HH – Houhu lake; YCH – Yangchunhu lake; BH – Beihu lake; YXH – Yanxihu lake; YDH – Yandonghu lake; QSQ – Qinshangang canal. Red points represent sampling sites; red arrows represent the direction of water flow.

best, followed by the DH, and other lakes suffered serious water pollution with worse than class V water quality. Among the lakes, The YDH and YXH had abundant aquatic macrophytes and the others had scare aquatic vegetation. The sediments of the lakes were mainly made up of silts (Appendix 1). The detail locations of sampling sites are in Figure 1. Four season investigations were carried out during 2014–2015 (April, August, October, 2014 and January, 2015).

2.2 Data collection and treatment

Macroinvertebrate samples with four grads were collected using a modified Peterson grad (area $0.0625\,m^2$) at each sampling site, and screened with 500 μm nylon net. The samples were preserved in 4% formalin with a 500 ml wide-mouth plastic bottle in the field. In the laboratory, aquatic insects, mollusks, crustaceans and leeches were identified using dissecting microscope, oligochaetes were sorted by dissecting microscope and identified by stereoscopic microscope. In the processing of identification, aquatic insects were identified to family or genus, oligochaetes to genus or species, mollusks to species, crustaceans and leeches to family. The identification keys were mainly based on the literatures of domestic experts (Liu *et al.*, 1979; Morse *et al.*, 1994; Wang, 2002).

A total of eleven water parameters were measured simultaneously with macroinvertebrate samples, including water temperature (WT), pH, conductivity (COND), transparency (TRANS), dissolved oxygen (DO), chemical oxygen demand (COD), total phosphorus (TP), soluble orthophosphate (SOP), total nitrogen (TN), ammonia nitrogen (AN) and nitrate nitrogen (NN). WT, pH, COND, TRANS and DO were measured *in situ* with a multi-parameter analyzer (YSI 6600) at each sampling site, and the other parameters were measured in laboratory according to the national standards (Chinese Environmental Protection Bureau, 2013). A correlation matrix-based principal component analysis (PCA) on water parameters was carried out to find out the main environmental gradients in different seasons (Parinet *et al.*, 2004).

In this paper, the dominant species was decided by Mcnaughton dominance index (Y). $Y = (Ni/N) * fi$, where Ni is the amount of species i in all samples, N is the total amount of all species in all samples, fi is the occurrence frequency of species i in all samples. If $Y > 0.02$, the dominant species is decided (Mcnaughton, 1967).

The eleven water parameters we measured were selected as environmental variables for multivariate analyses with software Canoco v5.0. Detrended correspondence analysis (DCA) on the macroinvertebrate data was done to judge the macroinvertebrate distribution pattern. If the gradient length of the first axis of DCA is greater than 3.0 SD, the macroinvertebrates were in unimodal rather than linear distribution and canonical correspondence analysis (CCA) is appropriate, or else redundancy analysis (RDA) is suitable (Glińska-Lewczuk *et al.*, 2016). To test the effect of explanatory variables which significantly accounted for the community variation, forward selection with 999 Monte Carlo permutations was used.

Table 1. Water physiochemical variables in four seasons (mean ± SD) *Note*: WT – water temperature; COND – conductivity; TRANS – transparency; DO – dissolved oxygen; COD – chemical oxygen demand; TP – total phosphorus; SOP – soluble orthophosphate; AN – ammonia nitrogen; TN – total nitrogen; NN – nitrate nitrogen.

Water parameters	Spring	Summer	Autumn	Winter
WT (°C)	19.26 ± 1.58	32.11 ± 2.81	17.62 ± 0.95	10.16 ± 1.06
pH	8.27 ± 0.5	9.56 ± 4.77	8.38 ± 0.03	8.14 ± 0.34
COND (μS/cm)	573.54 ± 135.64	466.67 ± 222.75	362.18 ± 95.11	459.43 ± 143.43
TRANS (cm)	60.27 ± 15.94	70.44 ± 95.25	38.54 ± 9.93	90.89 ± 43.17
DO (mg/L)	8.78 ± 2.44	10 ± 5.1	8.21 ± 2.95	9.27 ± 2.43
COD (mg/L)	13.96 ± 4	17.63 ± 5.64	14.29 ± 5.99	14.66 ± 5.14
TP (mg/L)	0.12 ± 0.17	1.41 ± 6.25	0.14 ± 0.11	0.19 ± 0.36
SOP (mg/L)	0.08 ± 0.16	0.11 ± 0.28	0.06 ± 0.08	0.11 ± 0.28
AN (mg/L)	0.4 ± 0.63	0.29 ± 0.69	0.74 ± 0.87	0.83 ± 1.71
TN (mg/L)	2.26 ± 2.12	1.37 ± 0.9	2.44 ± 2.87	2.99 ± 3.18
NN (mg/L)	1.33 ± 1.97	0.34 ± 0.69	0.82 ± 1.58	1.26 ± 2.23

The explanatory variables significant at $p < 0.05$ were included in the model. In order to explore the response patterns of species to environmental variables, the generalized additive models (GAM) using the Poisson distribution were undertaken (Ter Braak and Smilauer, 2012; Šmilauer and Leps, 2014). In the processing of multivariate analyses, macroinvertebrate data based on density were $\log(x+1)$ transformed and rare species were down-weighted.

3 Results

3.1 Physicochemical environmental conditions

In spring the values of COND and NN were the highest. In summer WT, pH, COD and TP had the highest values. In summer and winter, the concentrations of SOP were relatively high. In winter, the values of AN and TN were the highest (Tab. 1) According to the results of PCA, the eigenvalue of component 1 represented 51.97% of the total variance of spring data, and DO, TP, SOP, AN and NN were the main environmental gradients. In summer, the eigenvalue of component 1 represented 52.71% of total variance, and pH, TRANS, DO, TP, SOP and TN were the main environmental gradients. In autumn, the eigenvalue of component 1 represented 41.28% of total variance, and COND, AN and NN were the main environmental gradients. In winter, the eigenvalue of component 1 represented 50.26% of total variance, DO, TP, SOP and AN were the main environmental gradients (Tab. 2).

Table 2. The loadings of the principal component 1 in different seasons, brackets present explanation rates of the total variance, bold values represent high loadings with the absolute values higher than 0.80.

Water parameters	Spring (51.97%)	Summer (52.71%)	Autumn (41.28%)	Winter (50.26%)
WT	–0.471	0.129	0.721	0.586
pH	–0.739	**0.99**	–0.228	–0.78
COND	0.422	–0.422	**0.815**	0.558
TRANS	–0.27	**0.968**	0.038	–0.37
DO	**–0.903**	**0.836**	–0.475	**–0.898**
COD	0.36	–0.297	–0.377	0.232
TP	**0.949**	**0.992**	0.633	**0.83**
SOP	**0.916**	**0.953**	0.771	**0.838**
AN	**0.94**	–0.003	**0.912**	**0.928**
TN	0.633	**0.973**	0.603	0.792
NN	**0.853**	0.245	**0.863**	0.622

Table 3. The dominant species in the Big East Lake water network in different seasons (Y>0.02).

Dominant species	Spring	Summer	Autumn	Winter
Limnodrilus hoffmeisteri	0.498	0.036	0.132	0.187
Tanypus sp.	0.045	0.334	0.193	0.098
Chironomus sp.	0.027			
Limnodrilus claparedeianus	0.025			
Branchiura sowerbyi		0.043		
Bellamya aeruginosa		0.027		
Tokunagayusurika sp.			0.075	0.358

3.2 Macroinvertebrate communities

3.2.1 Taxonomic composition

A total of 40 taxa (14 aquatic insects, 12 oligochaetes, 9 mollusks, 2 crustaceans, 3 others) from 17 families were recorded in four season surveys (Appendix 2). In spring, 27 taxa were collected. The dominant taxa were *Limnodrilus hoffmeisteri* (Claperede, 1861), *Tanypus* sp., *Chironomus* sp. and *Limnodrilus claparedeianus* (Ratzel, 1868). In summer, 22 taxa were collected. The dominant were *Tanypus* sp., *Branchiura sowerbyi* (Beddard, 1892), *L. hoffmeisteri* and *Bellamya aeruginosa* (Reeve). Twenty-seven and twenty-one taxa were collected in autumn and winter respectively, and the dominant were *Tanypus* sp., *Tokunagayusurika* sp., and *L. hoffmeisteri* (Tab. 3). Overall, the macroinvertebrate communities in the whole BELWN were dominated by chironomids and oligochaetes, accounting for 46.4% and 47.7% respectively.

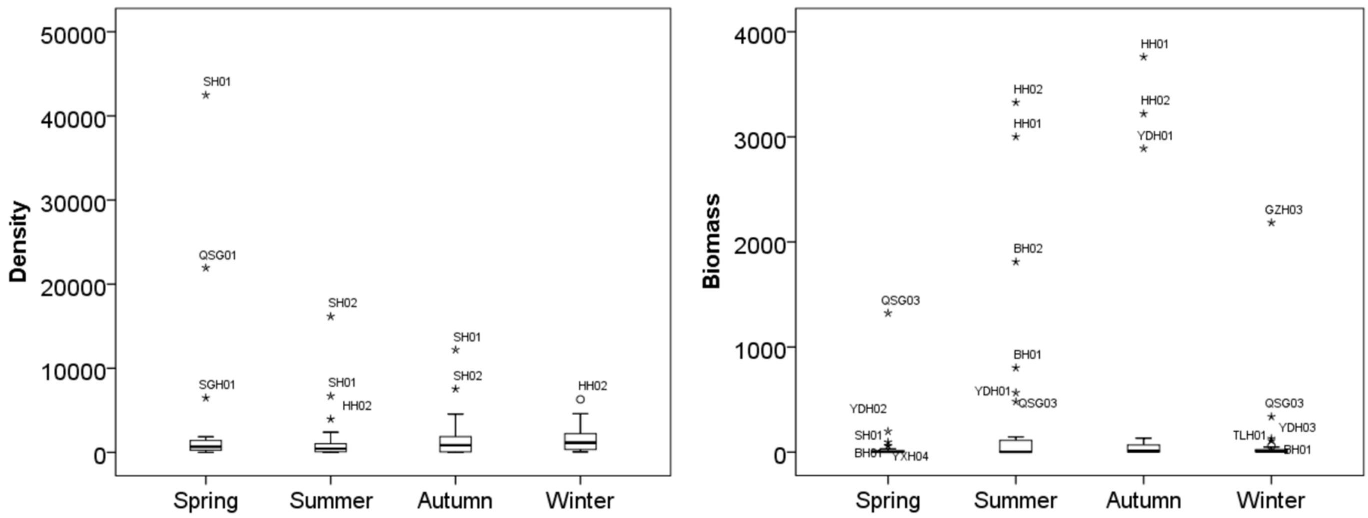


Fig. 2. The densities and biomass of macroinvertebrates in different seasons, density (ind./m^2), biomass (g/m^2).

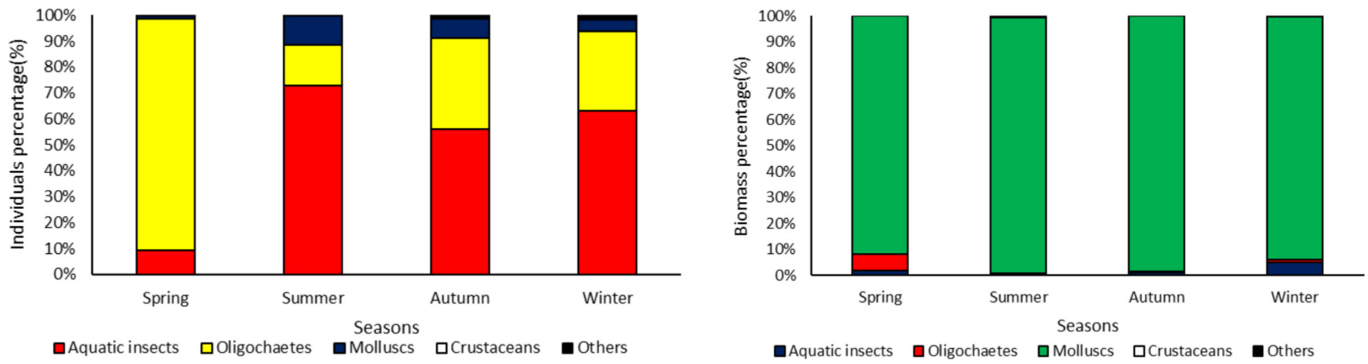


Fig. 3. The composition of macroinvertebrate communities in different seasons.

3.2.2 Seasonal variation in communities

Seasonal variation in densities and biomass of macroinvertebrates in the BELWN was not significant (Kruskal–Wallis test, for densities, $p = 0.158$; for biomass, $p = 0.196$). The densities in spring were very high (mean ± SD, 3144 ± 8600 ind./m^2), while the differences in densities in other seasons (summer, autumn and winter) were not distinct, the densities were 1453 ± 3168, 1646 ± 2601, 1599 ± 1545 ind./m^2 respectively. The biomass in summer and autumn were relatively high, with 368.31 ± 861.61 and 372.93 ± 1018.12 g/m^2 respectively, while the biomass in spring and winter were relatively low, with 65.70 ± 245.35 and 108.33 ± 404.98 g/m^2 respectively (Fig. 2).

In summer, autumn and winter, aquatic insects gave more contributions to abundances, the individual percentages were 72.98%, 55.90% and 63.18% respectively. While in spring, oligochaetes individuals were predominant (89.32%). Due to big bodies mollusks had important contributions to biomass in all seasons (Fig. 3).

In spring, macroinvertebrates in the BELWN had the highest biodiversity, and the Shannon–Wiener index was 1.21 ± 0.55. In autumn, the biodiversity decreased to the lowest, with the value of Shannon–Wiener index 0.80 ± 0.46. In total, the diversity indices in spring and winter were relatively higher than in summer and autumn (Fig. 4).

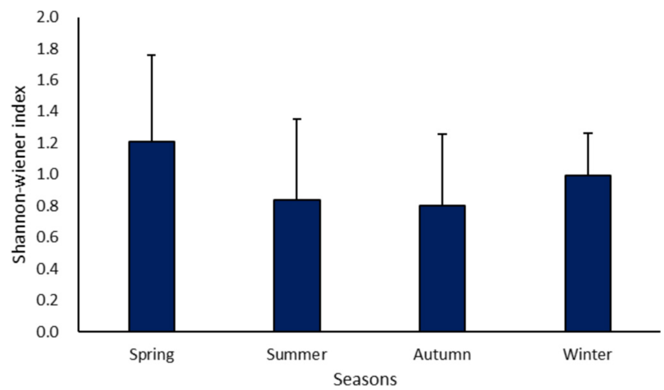


Fig. 4. The Shannon–Wiener index of macroinvertebrates in different seasons.

3.3 Comparison in communities of different lakes

The differences in densities and biomass among lakes were significant (Kruskal–Wallis test, for densities, $p < 0.001$; for biomass, $p = 0.013$). Among the lakes, the annual average density of SH was the highest, with 11,435 ± 6905 ind./m^2, followed by QSG, with 2129 ± 3341 ind./m^2. The annual average density of YDH was the lowest, with 195 ± 77 ind./m^2. While the annual average biomass of DH was the highest,

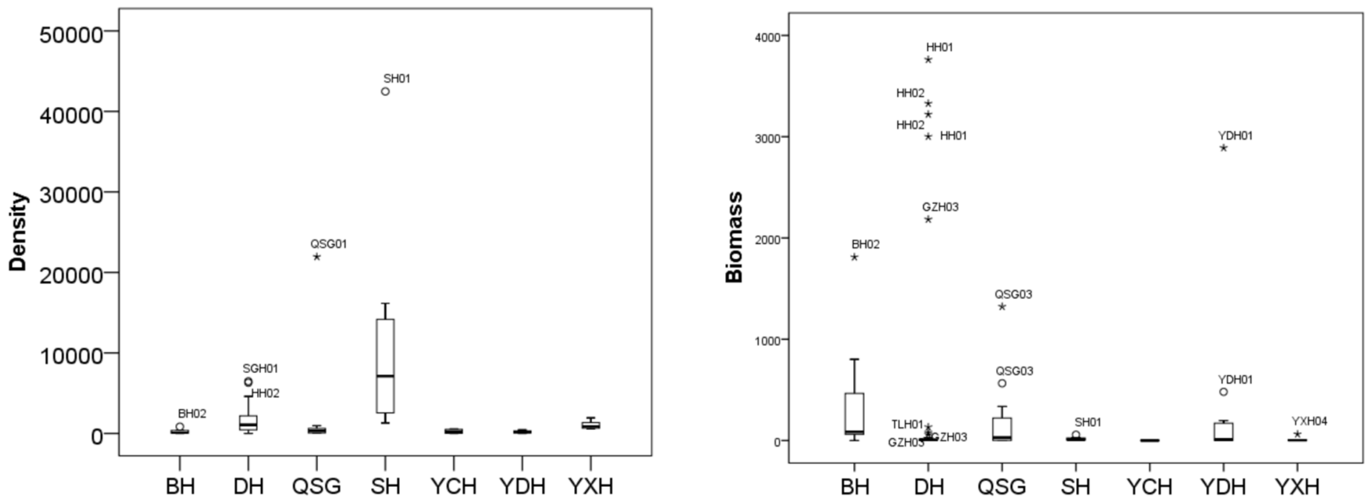


Fig. 5. The densities and biomass of macroinvertebrates in different lakes, density (ind./m^2), biomass (g/m^2). *Note*: BH – Beihu lake; DH – Donghu lake; QSQ – Qinshangang canal; SH – Shahu lake; YCH – Yangchunhu lake; YDH – Yandonghu lake; YXH – Yanxihu lake.

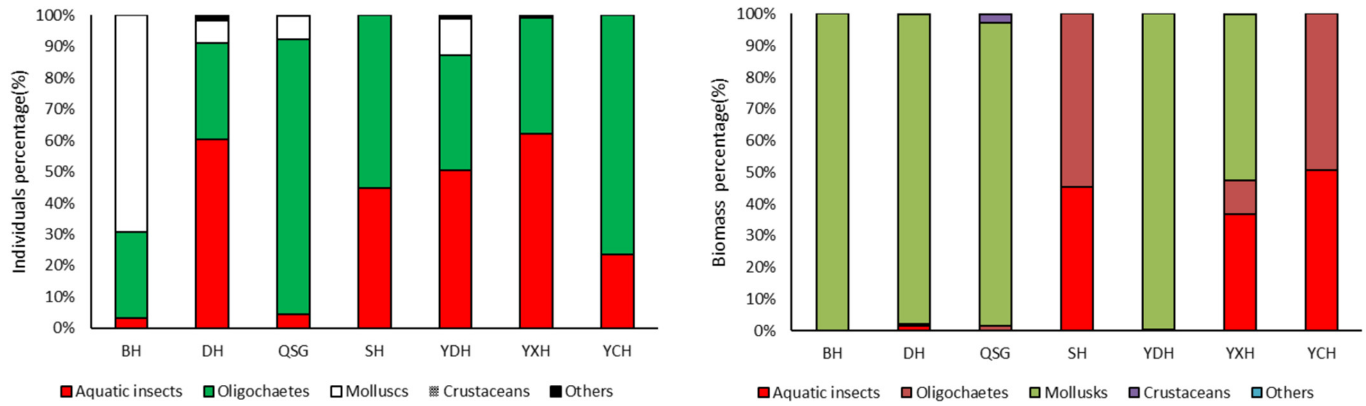


Fig. 6. The composition of macroinvertebrate communities in different lakes. *Note*: BH – Beihu lake; DH – Donghu lake; QSQ – Qinshangang canal; SH – Shahu lake; YCH – Yangchunhu lake; YDH – Yandonghu lake; YXH – Yanxihu lake.

with 4007.30 ± 2935.19 g/m^2, followed by YDH, with 962.13 ± 1131.22 g/m^2. The annual average biomass of YCH was the lowest, with 0.66 ± 0.74 g/m^2 (Fig. 5). Aquatic insects and oligochaetes were the predominant groups in most lakes except BH. In BH, mollusks occupied dominant position in individuals while aquatic insects and oligochaetes accounted for small proportions. In SH and YCH, no mollusks were found in four seasonal surveys (Fig. 6).

3.4 Relationships of communities with environmental factors

After data preprocessing, the macroinvertebrate density data from spring, summer, autumn and winter were proved to be suitable for CCA analysis, because the gradient lengths of axis 1 of DCA were all higher than 3.0 SD. In spring data, pH, TP and WT were selected and accounted for 23.4% of macroinvertebrate variation. The first four axes were statistically significant by global permutation test (pseudo-F = 1.5, p = 0.008), proving the results were reliable. In summer data, WT was selected and accounted for 7.3% of data variation. The first four axes were statistically significant by global permutation test (pseudo-F = 1.4, p = 0.036). In autumn data, pH and AN were selected and explained 18.3% of data variation. The first four axes were statistically significant by global permutation test (pseudo-F = 1.7, p = 0.006). In winter data, NN, WT, TRANS, COD and COND were selected and explained 36.0% of data variation (Tab. 4). The first four axes were statistically significant by global permutation test (pseudo-F = 1.9, p = 0.002) (Fig. 7).

According to the results of GAM models, among the dominant species in four seasons, oligochaetes *L. claparedeianus*, *L. hoffmeisteri* and chironomids *Chironomus* sp. in spring responded to TP, chironomids *Tanypus* sp. in summer responded to WT, oligochaetes *L. hoffmeisteri* in autumn responded to ammonia, chironomids *Tokunagayusurika* sp. in autumn and *Tanypus* sp. in spring responded to pH, all with unimodal curves. The response of chironomids *Chironomus* sp. in spring to pH displayed decreasing monotonic curve. With increasing WT, the abundance of *Chironomus* sp. in spring and *B. aeruginosa* increased after an initial decrease. The response of chironomids *Tanypus* sp. in spring to WT and oligochaetes *L. hoffmeisteri* in winter to COD both displayed

Table 4. The environmental variables influencing macroinvertebrate communities in the Big East Lake water network by multivariate tests.

Environmental variables	Explains (%)	Contribution (%)	Pseudo-F	*p*
Spring				
pH	11.2	20.7	3.0	0.002
TP	6.2	11.6	1.7	0.050
WT	6.1	11.2	1.7	0.046
Summer				
WT	7.3	13.6	1.8	0.024
Autumn				
pH	10.5	19.1	2.9	0.046
AN	7.8	14.3	2.3	0.048
Winter				
NN	11.7	20.6	3.4	0.004
WT	6.3	11.2	1.9	0.032
TRANS	6.9	12.2	2.2	0.014
COD	5.6	9.8	1.8	0.048
COND	5.5	9.7	1.9	0.036

increasing monotonic curves. With the increasing of WT, the abundance of chironomids *Tanypus* sp. in winter displayed a trend of first decline then up (Fig. 8).

4 Discussion

Among the major groups in macroinvertebrates, the mollusks attracted more people's attention for its high economic value. Due to water pollution and the loss of diverse habitat, the species richness of mollusks sharply decreased in the DH. For instance, 41 mollusks were found in 1960s (Chen *et al.*, 1975), 15 mollusks in 1970s (Chen and Liang, 1980), 3 mollusks in 1997–1999 (Gong *et al.*, 2000), 8 mollusks in 2008 (Wang *et al.*, 2010), 7 mollusks in 2009 (Ji *et al.*, 2011) and only 6 mollusks in our study. Focusing on the whole macroinvertebrates in the DH, based on the incomplete statistical results, the species richness decreased from 133 in 1960s to 67 in 1990s with sharply declining due to high anthropogenic pressure (Wang, 2005). With the improvement of water pollution in recent years, the species richness somewhat increased compared to the serious pollution period (Chen and Liang, 1980; Gong *et al.*, 2001; Wang *et al.*, 2010). Concerning on the BELWN, 50 species were found in 2008, while the species number recorded in our study was 40, slightly fewer than the previous study (Wang *et al.*, 2010), the differences in species richness possibly related to the differences in sampling sites.

Aquatic insects and oligochaetes were the main groups of macroinvertebrates in the BELWN in four seasons, and the species *L. hoffmeisteri* and *Tanypus* sp. dominated the communities in all seasons. In comparison with the historical data, the composition of dominant species in the BELWN almost unchanged, mainly including *L. hoffmeisteri*, *Tanypus* sp., *Chironomus* sp., *B. aeruginosa* and *B. sowerbyi* (Wang *et al.*, 2010; Ji *et al.*, 2011). At present stage, most of lakes in the BELWN have become phytoplankton-dominated lakes from macrophytic lakes. Studies showed diversity of macroinvertebrates decreased with eutrophication and macrophytic lakes had higher diversity than phytoplankton-dominated lakes (Gong *et al.*, 2001; Yan *et al.*, 2005; Pan *et al.*, 2015). Although DH did not massively outbreak algae bloom in recent years, the water quality was not good (Wang *et al.*, 2010), and it was also confirmed by the Shannon–Wiener index with average values lower than 1.5 across all seasons in this study. One study showed the seasonal changes of water pollution in DH was related to the precipitation and temperature changes, and the water pollution was usually serious in summer and autumn, and slight in winter and spring (Huang *et al.*, 2013), in our study the changes of Shannon–Wiener indices with seasons in the whole BELWN seemed to validate this rule.

In subtropical shallow lakes, the densities and biomass of macroinvertebrates usually show a distinct seasonal variation (Chen and Wang, 1982; Wu, 1989; Wang, 2005). The BELWN was no exception to have high seasonal variation in standing crops, it was related to the differences in growth rate of difference species in difference seasons (Cowell and Vodopich, 1981; Chen and Wang, 1982). Studies showed under normal conditions the dominant groups of macroinvertebrates in the urban lakes and eutrophic lakes were mainly composed of high-density oligochaetes and chironomids (Gong *et al.*, 2000; Ji *et al.*, 2011; Liu *et al.*, 2013). As an urban lake system, the BELWN conformed with the above-mentioned rules, with high percentages of chironomids in summer, autumn and winter (68.74%, 57.30%, 63.14%) and big percent of oligochaetes in spring (84.12%). The differences in densities and biomass among lakes were largely attributed to different degrees of water pollution, which was confirmed by the previous study (Wang *et al.*, 2010). Among the lakes, the SH was famous with its serious pollution, this study showed the macroinvertebrate communities were made up of chironomids and oligochaetes with the highest densities, and mollusks almost vanished in this lake.

In lake system, the environmental factors affecting the distribution of macroinvertebrates are numerous, including oxygen content at the sediment water interface, organic content of the sediments, substrate type, substrate particle size, macrophyte cover, water level, WT, pH, water depth, COND, salinity, DO, nutrients, etc. (Parrish and Wilhm, 1978; Takamura *et al.*, 2009; Cai *et al.*, 2010; Dalu *et al.*, 2012; Wang *et al.*, 2012; Meng *et al.*, 2015). In oligotrophic lakes, the key factors influencing the macroinvertebrate communities do not usually include the nutrient level, while in the phytoplankton-dominated lakes or eutrophic lakes, the nutrients are usually the important factors affecting the distribution of macroinvertebrates. For example, in the lakes and reservoirs in Taihu basin, the environmental variables including COND, TN, ammonium nitrogen, COD, TRANS, chlorophyll a, water depth and NN, were the important factors influencing the distribution of macroinvertebrates (Gao *et al.*, 2011). In Hongze lake, nitrate, TN and COD were the key factors determining the macroinvertebrate communities (Zhang *et al.*, 2012). In Erhai lake, TP could affect the macroinvertebrate communities (Zhang *et al.*, 2011), while in Gehu lake, nitrogen content was the important factor affecting the

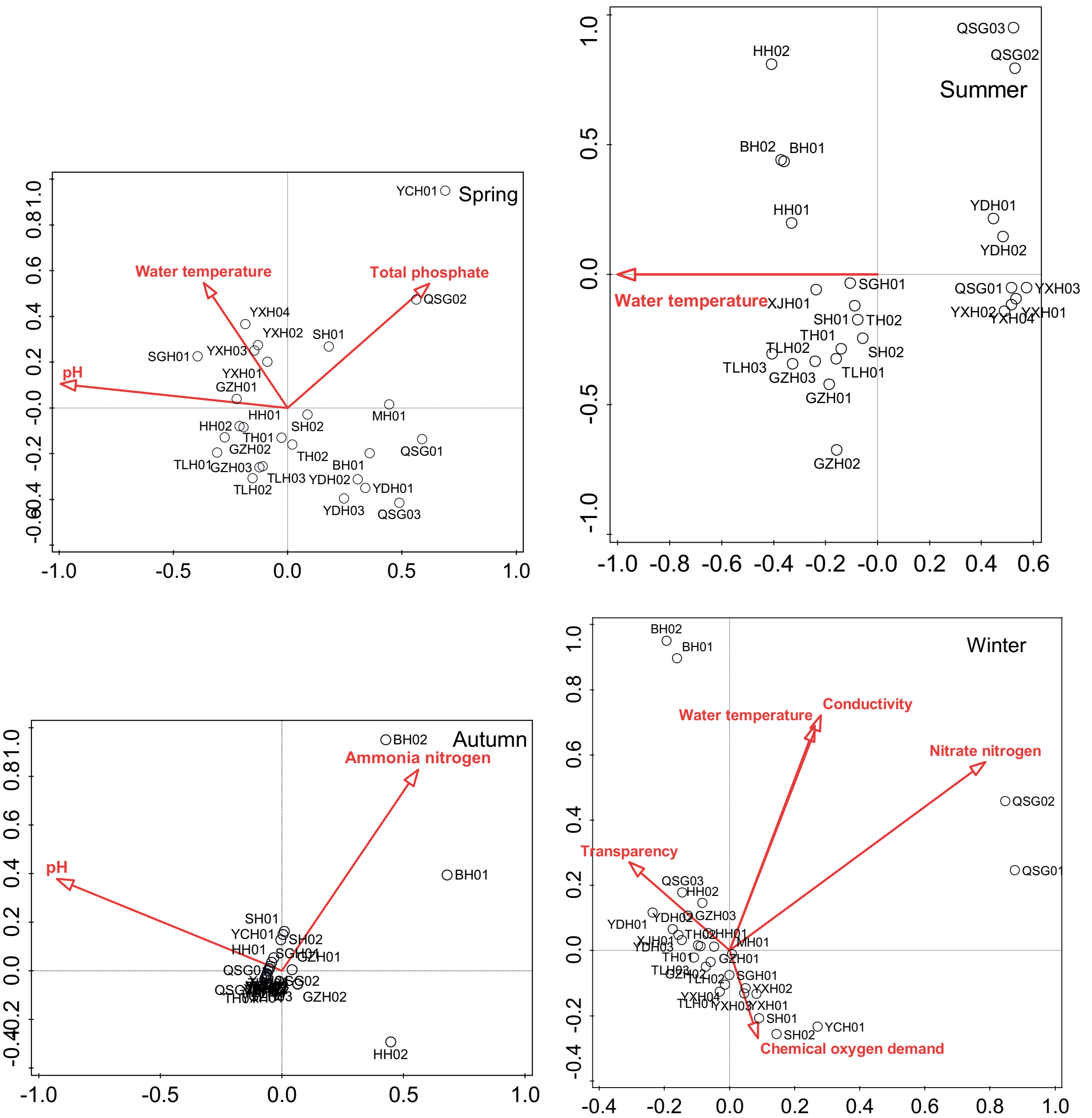
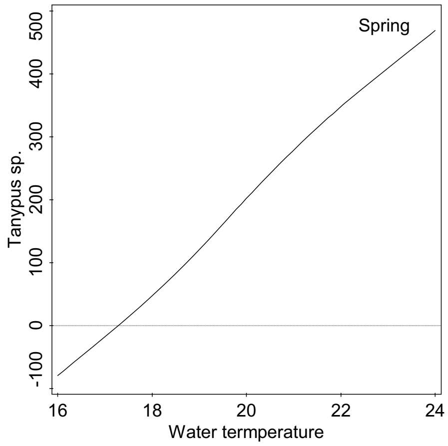


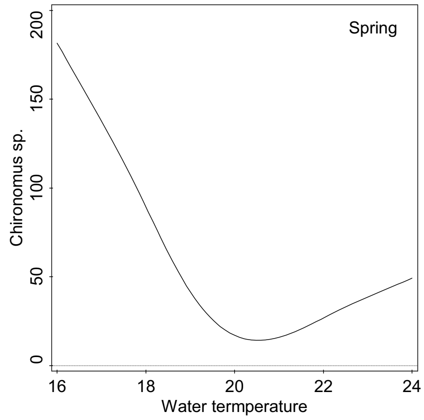
Fig. 7. The ordination plots of multivariate analysis based on macroinvertebrate data from the Big East Lake water network.

macroinvertebrate communities, meanwhile the dominant species were significantly negatively correlated to TN and nitrate (Chen *et al.*, 2016). In the BELWN, organic pollution was still the important stressor affecting the lake ecosystem, the nutrients in water were non-ignorable factors influencing the distribution of macroinvertebrates, which were confirmed by the multivariate analysis results and the above-mentioned studies.

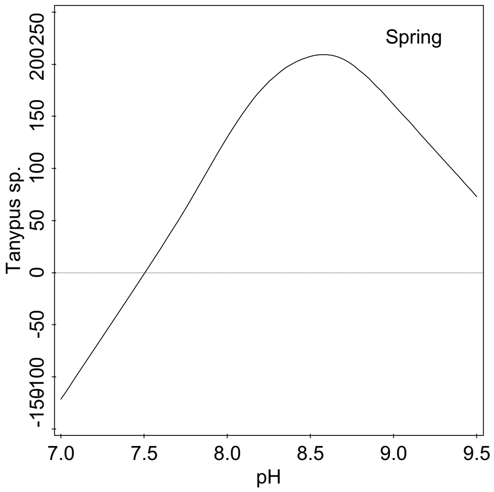
According to the GAM models, the oligochaetes *L. claparedeianus* and *L. hoffmeisteri* were good indicators for TP gradient, while the chironomids *Chironomus* sp., *Tanupus* sp. and *Tokunagayusurika* sp. were good indicators for pH and WT gradients. The mollusc *B. aeruginosa* was a good indicator for WT gradient. The oligochaetes *L. hoffmeisteri* was a good indicator for COD gradient. Studies showed abundant oligochaetes occurred in eutrophic waterbodies due to their high tolerance to hypoxic or anoxic conditions (Gong *et al.*, 2001; Volpers and Neumann, 2005; Wang *et al.*, 2014). In shallow lakes with serious eutrophication, the catabolism of organic matters spends lots of DO, and produces plenty of harmful matters such as hydrogen sulfide and ammonium nitrogen, seriously influencing the macroinvertebrate communities (Gong *et al.*, 2001). The densities of tubificids and chironomids were significantly positively related to the contents of nitrogen, phosphorus and chlorophyll of waterbodies, and the predication ability of tubificids density on nitrogen and phosphorus level was superior to chironomids density (Jiang *et al.*, 2011). Our study results showed the oligochaetes were suitable for detecting nitrogen and phosphorus gradients, while the chironomids were suitable for detecting pH and WT gradients. All these results would be useful for selecting and screening suitable bio-indicators in the future. Moreover, studies showed the soluble reactive phosphorus (SRP) excretion rates from sediments by the bioturbation of macroinvertebrate communities increased with WT, the maximum 70–90% and 33–90% of phosphorus flux in DH were released by the activity of chironomids and oligochaetes



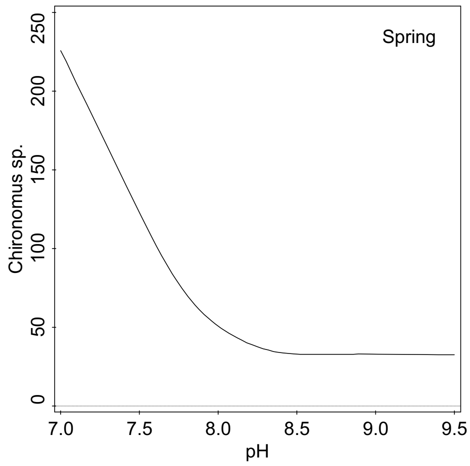
Model AIC 329.39
Model Test F = 12.2, p = 0.00024



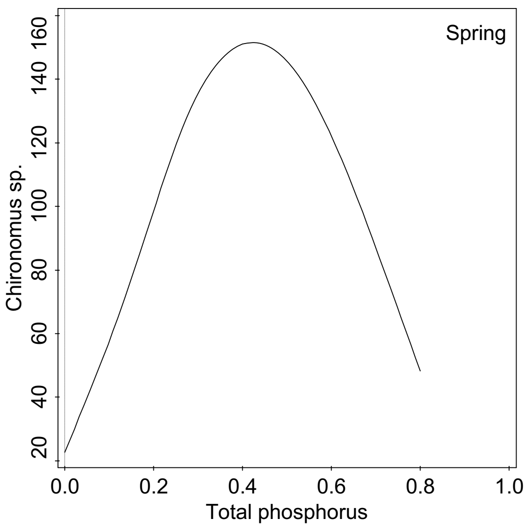
Model AIC 301.96
Model Test F = 4.1, p = 0.03017



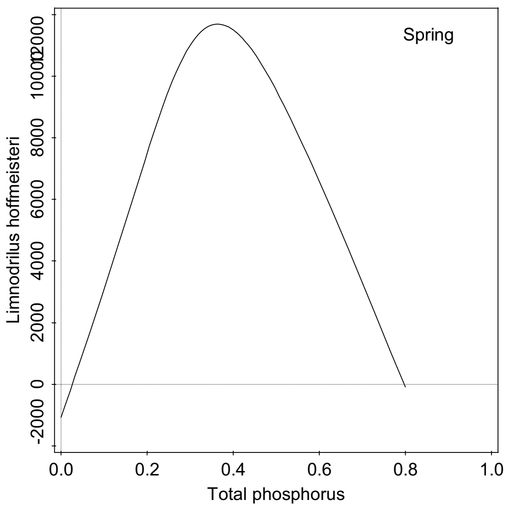
Model AIC 338.00
Model Test F = 5.5, p = 0.01099



Model AIC 301.37
Model Test F = 4.5, p = 0.02323



Model AIC 299.17



Model AIC 530.59

Fig. 8. The response curves of dominant species to different environmental variables in different seasons.

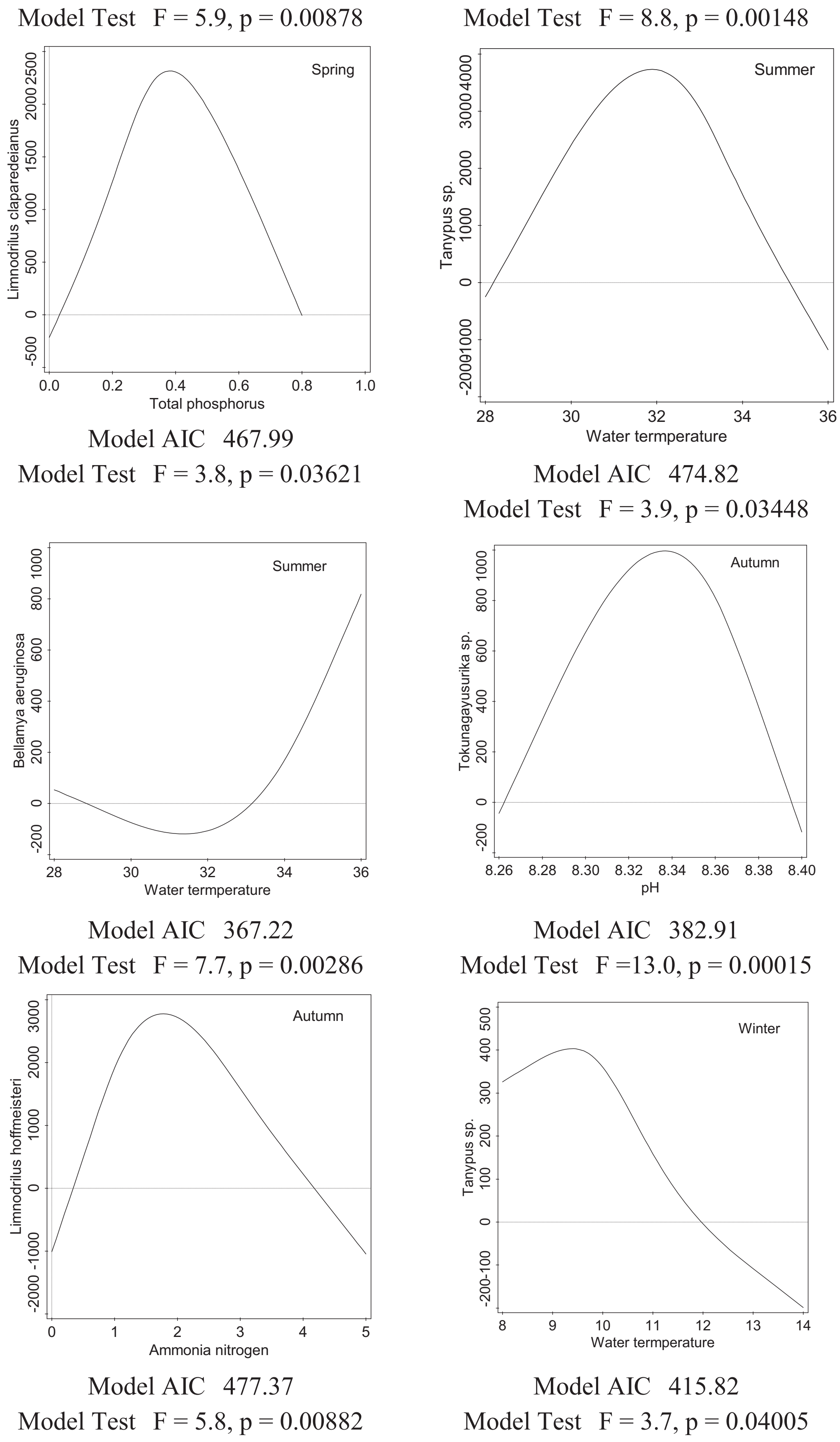
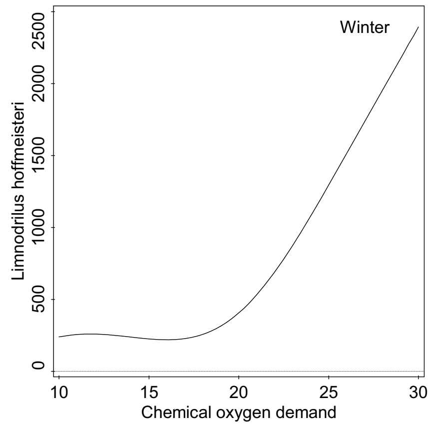


Fig. 8. (Continued)



Model AIC 438.21
Model Test F =10.6, p = 0.00048

Fig. 8. (Continued)

respectively (Ji *et al.*, 2011), the nutrient flux in Taihu lake was greatly affected by the dominant species *L. hoffmeisteri* (Ji *et al.*, 2015), and the results of the GAM models in this study seemed to support the above-mentioned findings indirectly.

It was important to note that a new recorded species polychaete *Nephtys* sp. was first collected in the BELWN. The species was collected in the site QSQ in autumn. Although it is an occasional species only sampled one time, the appearance of this species has very important ecological interest. Many studies showed the upper limit of distribution of this species only reached to the Poyang lake and its surrounding lakes located in the lower reaches of Yangtze river (Wang *et al.*, 2007; Ouyang *et al.*, 2009; Cai *et al.*, 2013, 2014; Chi *et al.*, 2016). As an estuarine and marine species, the species *Nephtys* sp. was never collected and recorded in the lakes located in the middle reaches of Yangtze river based on the published literatures. The interpretation that these inland lakes historically had connected with marine fauna seemed to be untenable (Wang *et al.*, 2007; Cai *et al.*, 2014). Studies showed increasing hydrological connectivity level could promote species diversity and introduction of alien species after restoration measures (Gallardo *et al.*, 2008; Amael *et al.*, 2009; Paillex *et al.*, 2009). At present stage, the BELWN had connected to the Yangtze river by the artificial ditch QSQ. So, the discovery of the species *Nephtys* sp. in the site QSQ could be regarded as the consequences of connectivity between the Yangtze river and lakes. According to the study results from the disconnected lakes and connected lakes in the middle-lower reaches of Yangtze river, mussels usually occupy dominant position in densities and biomass in river-connected lakes (Wang *et al.*, 2007). Moreover, many studies reported that α-diversity of macroinvertebrates in floodplain waterbodies reached a maximum at an intermediate level of connectivity (Obrdlik and Fuchs, 1991; Tockner *et al.*, 1999; Ward *et al.*, 1999; Amoros and Bornette, 2002). Compared to disconnected floodplain lakes, river-connected lakes were characterized by maxima biodiversity, biomass and production of macroinvertebrates, so linking disconnected lakes freely with the mainstream are crucial (Pan *et al.*, 2014). According to the above-mentioned experiences, when the BELWN became an open aquatic system again after restoring the hydrological connectivity between the Yangtze river and lakes, the macroinvertebrate communities would change with time, and some typical riverine species such as *Corbicula fluminea* or rheophilic mussels would dominate the communities in foresee future. The diversity of macroinvertebrates would steadily increase with time. Moreover, the species *Nephtys* sp. would possibly spread into the whole water network from the Yangtze river. Of course, the predication should be tested in subsequent monitoring programs in the future.

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Appendices

Appendix 1. The limnological characteristics of the six lakes in the Big East Lake water network, the nutrient data on water quality are from Wuhan water environment bulletin (2001–2007). *Note*: YDH – Yandonghu lake; YXH – Yanxihu lake; SH – Shahu lake; DH – Donghu lake; YCH – Yangchunhu lake; BH – Beihu lake.

Lakes	Average water area (km^2)	Average depth (m)	COD (mg/L)	TN (mg/L)	TP (mg/L)	Water quality grade	Aquatic macrophytes	Substratum type	Number of sampling sites
YDH	7.5	3.3	13.76	0.88	0.0361	Class III	Abundant	Silt	4
YXH	10.8	2.5	41.33	3.76	0.1124	Worse than class V	Abundant	Silt	4
SH	2.8	1.5	57.8	8.28	0.2423	Worse than class V	Scarce	Silt	2
DH	33	2.2	30.06	2.23	0.3309	Class IV worse than class V	Scarce	Silt	13
YCH	0.2	1.5	28.04	1.53	0.1082	Worse than class V	Scarce	Silt	1
BH	1.8	2	26.28	2.8	0.1313	Worse than class V	Scarce	Silt	2

Appendix 2. List of macroinvertebrates in the Big East Lake water network.

Species	Spring	Summer	Autumn	Winter
Aquatic insects				
Tanypus sp.	+	+	+	+
Procladius sp.	+	+	+	+
Clinotanypus sp.	+	+	+	+
Chironomus sp.	+	+	+	+
Microchironomus sp.	+	+	+	+
Tanytarsus sp.	+			
Einfeldia sp.			+	
Dicrotendipes sp.	+	+		
Tokunagayusurika sp.	+	+	+	+
Cladopelma sp.	+			
Chironomidae pupa	+	+	+	
Ceratopogonidae sp.	+		+	+
Culicidae sp.	+			
Libelludidae sp.	+	+	+	
Oligochaetes				
Branchiura sowerbyi (Beddard, 1892)	+	+	+	+
Limnodrilus hoffmeisteri (Claperede, 1861)	+	+	+	+
Limnodrilus grandisetosus (Nomura, 1932)	+	+	+	+
Limnodrilus udekemianus (Claparède, 1862)	+			
Limnodrilus claparedeianus (Ratzel, 1868)	+	+	+	+
Teneridrilus mastix (Brinkhurst, 1978)				+
Aulodrilus pluriseta (Piguet, 1906)		+	+	+
Aulodrilus pigueti (Kowalewski, 1914)		+		
Aulodrilus sp.				+
Rhyacodrilus sinicus (Chen, 1940)	+	+	+	+
Nais communis (Piguet, 1906)			+	
Slavina appendiculata (Udekem, 1855)	+			
Mollusks				
Gyraulus convexiusculus (Hütton)			+	
Bellamya aeruginosa (Reeve)	+	+	+	+
Bellamya purificata (Heude)	+			
Parafossarulus striatalus (Benson)	+	+	+	+
Corbicula fluminea (Müller)		+		
Sphaerium lacustre (Muller)	+		+	+
Anodonta woodiana (Lea)		+		
Anodonta woodia pacifica (Heude)			+	
Unionidae sp.	+		+	
Crustaceans				
Procambarus clarkii (Girard)		+		
Gammarus sp.			+	+
Others				
Glossiphoniidae sp.	+	+	+	+
Nematoda sp.	+		+	+
Nephtys sp.			+	

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