Macroinvertebrate assemblages in relation to environments in the Dongting Lake, with implications for ecological management of river-connected lakes

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Macroinvertebrate Assemblages in Relation to Environments in the Dongting Lake, With Implications for Ecological Management of River-Connected Lakes Affected by Dam Construction

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The Dongting Lake, a river-connected lake, plays a vital role in people's living, agricultural production, and ecological security of the Yangtze River basin. A systematic investigation of macroinvertebrates was conducted in the Dongting Lake during May 2004 - January 2005. Altogether 65 taxa belonging to 27 families and 53 genera were identified. The annual average density and biomass of total macroinvertebrates were 265 ind/m^2 and 2.40 g dry mass/m^2, respectively. It is demonstrated that seasonal variation existed in environmental factors structuring macroinvertebrate assemblages of the Dongting Lake. Hydrological parameters (i.e., flow velocity, water depth) were the driving factors for macroinvertebrate assemblages in spring and summer, whereas the concentrations of water nutrients (i.e., phytoplankton chlorophyll a*, total dissolved phosphorus) played the leading role in governing macroinvertebrate assemblages in autumn and winter. After operation of the Three Gorges Dam in 2009, the Dongting Lake may be confronted with the threat of species diversity declining and assemblage structure changing. Thus, ecological restoration measures shall be put forward.* © 2016 American Institute of Chemical Engineers Environ Prog, 00: 000–000, 2016

Keywords: macroinvertebrates, environmental analyses, the Three Gorges Dam, the Dongting Lake

INTRODUCTION

The Dongting Lake is the second largest freshwater lake in China, and its inundation area shows great inter-annual variability. The Dongting Lake has several ecological service functions: (1) it is connected with the Yangtze River mainstream in the north of the lake, and connected with four tributaries (i.e., Xiang, Zi, Yuan, Li Rivers) in the south of the lake. The Dongting Lake is of great importance for flood storage and water sources in the midstream of the Yangtze River; (2) the lake can provide water for drinking and irrigation; (3) the lake is critical for maintaining the unique and diverse biota of the entire Yangtze ecosystem; (4) wetland ecosystem of the Dongting Lake has become an important tourism resource due to its natural landscape, unique biota, delightful climate, and beautiful scenery. Therefore, the Dongting Lake plays a key role in people's living and agricultural production.

In recent years, for the requirements of flood control and power generation, a series of cascade hydropower stations have been constructed in the mainstream and tributaries of the Yangtze River, among which the Three Gorges hydropower station is the largest one in the world. The operation of hydropower stations has changed the original processes of taking in - sending out water, as well as the original input and output mode of sediment and nutrient in the river-connected lakes [1,2]. After the operation of the Three Gorges Dam (TGD), replenishment ability of the Dongting Lake to the Yangtze River has been strengthened [3]. In the Dongting Lake, sediment deposition becomes slower due to reservoir intercepting sediment [4,5], and annual distribution of the runoff becomes more uniform, especially, low water period occurs ahead of time and prolongs [6,7]. The changing hydrological and sediment regimes break dynamic equilibrium of the relation between river and lake, and change the microhabitat conditions in local area, which leads to corresponding assemblages succession in the Dongting Lake. Therefore, it is necessary to select aquatic indicators for assessing the changing ecological status of the Dongting Lake.

In freshwater waterbodies, there are several assemblages such as phytoplankton, zooplankton, macroinvertebrates, fish, and macrophytes. Among these biota, macroinvertebrates are good indicators of long-term changes in environments because of their confinement to the bottom, long life cycles, and limited abilities to move [8–11]. So far, few

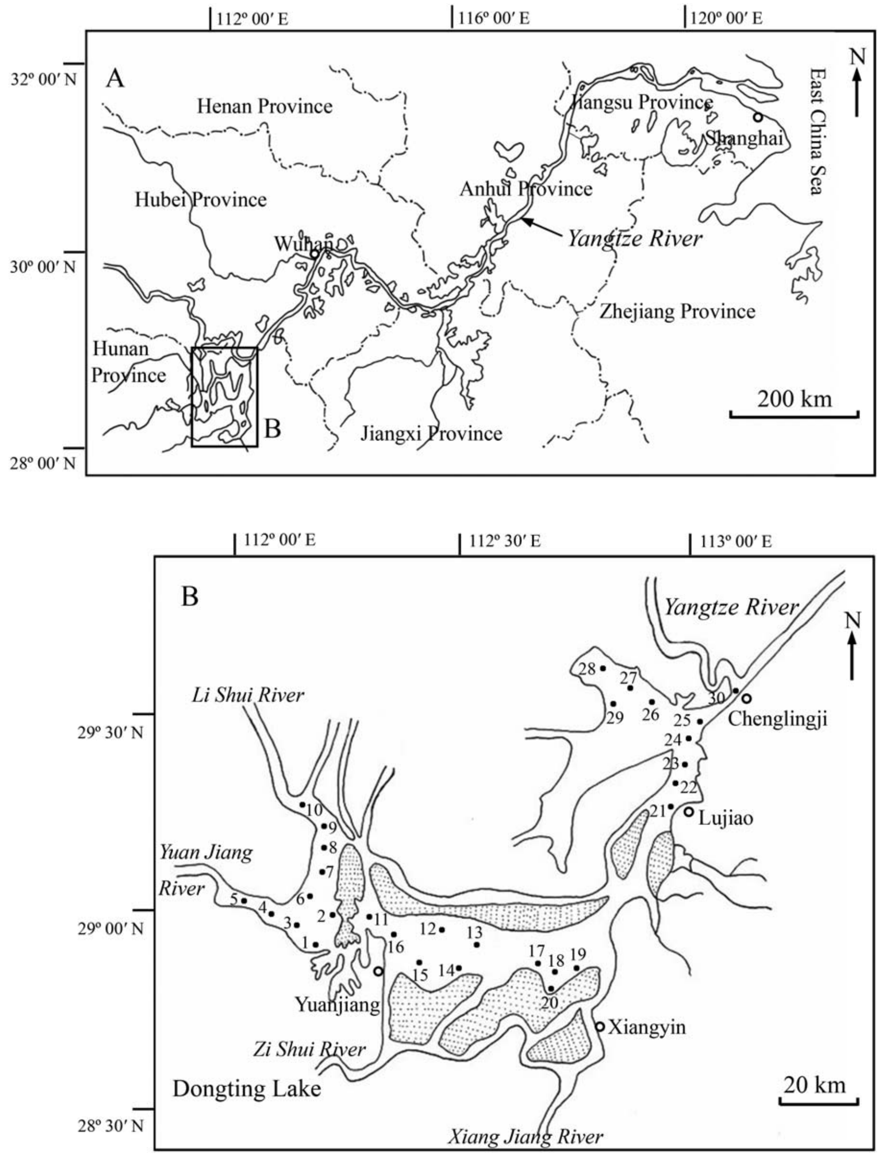

Figure 1. Locations of the study lake in the Yangtze basin (A) and sampling sites in the Dongting Lake (B).

studies on the benthic animals in Dongting Lake have been reported. Previous studies have been mostly restricted to water quality assessment using macroinvertebrates as indicators in special year [12], assemblage structure of macroinvertebrates in special lake region [13,14], and some biological groups of macroinvertebrates such as mollusks [15,16].

The construction of the TGD has three stages since 1990s. During the first construction stage, the damming of the Yangtze River happened in 1997. During the second construction stage, the TGD began to impound water and sediment discharge in 2003, when water level in the reservoir rose to 135 m. During the third construction stage, the whole dam was completed in 2009, when water level in the reservoir was raised to 175 m [17]. The Dongting Lake, as the first largest lake regulating runoff and sediment from the Yangtze River, is invariably bearing the brunt from the TGD's operation (Chang et al., 2010; Hu et al., 2013). When the TGD was under construction, ecological succession in the Dongting Lake was a gradual process. As far as we know, there was no scientific research on ecological assessment in the Dongting Lake during the period of the TGD construction, which impedes our understanding of the ecological succession process of the river-connected lake. Once we know the impacts of the TGD to the aquatic ecological status, some specific ecological restoration measures may be proposed for local governments, e.g., increasing incoming discharge in non-flood season, strictly control pollution sources, and connecting river network within the Dongting Lake basin.

Thus, our article reports the results of a systematic investigation of macroinvertebrates in the Dongting Lake completed in 2004–2005. The aim of our study was threefold: (1) to describe the overall characteristics of macroinvertebrate assemblages in the Dongting Lake; (2) to analyze the potential environmental factors influencing macroinvertebrate assemblages; (3) to put forward strategies of aquatic conservation and management for the river-connected lakes.

STUDY AREA AND METHODS

The Dongting Lake is situated in mid-to-lower Yangtze basin in the monsoon region of the East Asia subtropical zone. Limnological variables of the Dongting Lake are as follows: Area, 2432 km^2 (33.0 m asl); annual mean water-stage fluctuation, 5.9 m; annual mean precipitation, 1200–1450 mm; annual mean evaporation, 1174–1420 mm; retention time, 18.2 days; annual mean water sediment concentration, 127 g/m^3 [18], [19]. Locations and sampling sites

Table 1. Environmental variables (mean ± SE) of study sites in the Dongting Lake.

	Spring	Summer	Autumn	Winter	Average
T (°C)	23.4 ± 0.4	26.8 ± 0.3	16.1 ± 0.2	8.1 ± 0.2	18.6 ± 4.8
SS (kg/m^3)	0.0213 ± 0.0031	0.0277 ± 0.0024	0.0155 ± 0.0024	0.0142 ± 0.0025	0.0197 ± 0.0036
pH	7.6 ± 0.1	8.1 ± 0.1	7.7 ± 0.1	8.0 ± 0.1	7.9 ± 0.2
Z (m)	3.5 ± 0.4	4.9 ± 0.7	2.5 ± 0.2	2.3 ± 0.4	3.3 ± 0.7
Z_{SD} (m)	0.56 ± 0.03	0.55 ± 0.03	0.62 ± 0.11	0.75 ± 0.10	0.62 ± 0.05
U (m/s)	0.26 ± 0.03	0.31 ± 0.03	0.22 ± 0.04	0.17 ± 0.03	0.24 ± 0.03
TN (mg/m^3)	1564 ± 264	1656 ± 120	1147 ± 123	1588 ± 460	1489 ± 133
TDN (mg/m^3)	815 ± 47	1445 ± 122	895 ± 115	765 ± 225	780 ± 182
TP (mg/m^3)	213 ± 17	88 ± 10	96 ± 16	155 ± 18	138 ± 34
TDP (mg/m^3)	118 ± 11	45 ± 8	13 ± 4	77 ± 14	63 ± 26
Chl *a* (mg/m^3)	2.77 ± 0.48	2.73 ± 0.39	2.01 ± 0.27	1.66 ± 0.36	2.29 ± 0.32
B_{Mac} (g/m^2)	96 ± 68	155 ± 113	458 ± 330	0 ± 0	177 ± 114

Note: T, water temperature; SS, suspended solids; Z, water depth; Z_{SD}, water transparency; U, flow velocity; TN, total nitrogen concentration of water; TDN, total dissolved nitrogen concentration of water; TP, total phosphorus concentration of water; TDP, total dissolved phosphorus concentration of water; Chl *a*, phytoplankton chlorophyll *a* concentration; B_{Mac}, wet biomass of macrophytes.

of studied lake are given in Figure 1. Field investigations were conducted in May 2004 (spring), July 2004 (summer), September 2004 (autumn), and January 2005 (winter) in the Dongting Lake.

Samples of bed sediment were taken and analyzed by Laser Diffraction Particle Size Analyzer (MS-2000), and sediment sizes were determined by Wentworth scale. Water temperature (T) was measured with a thermometer. Suspended solids (SS) was analyzed according to APHA [20]. Water depth (Z) and Secchi depth (Z_{SD}) were measured with a sounding lead and a Secchi Disc, respectively. Flow velocity (U) was measured with a propeller type current meter (Model LS 1206B) manufactured by Nanjing Automation Institute of Water Conservancy and Hydrology, Chinese Ministry of Water Resources. Water samples were taken near the surface and at the bottom, and combined for laboratory analyses. pH was measured with a portable pH meter (Model PT-20). Total nitrogen (TN) was analyzed by the alkaline potassium persulfate digestion-UV spectrophotometric method. Total phosphorus (TP) was analyzed by the ammonium molybdate method. Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) were analyzed according to Standard Methods for Water and Wastewater Monitoring and Analysis [21]. Phytoplankton chlorophyll *a* concentration (Chl *a*) was measured after acetone extractions by reading absorbance at 665 nm and 750 nm using a spectrophotometer (Unico UV-2000, Shanghai, China). In the same habitat adjacent to benthic sampling site, macrophytes were sampled with a scythe (0.2 m^2), two to four times at each site, then cleaned, removed superfluous water and weighed for wet weight (B_{Mac}). Environmental variables of study sites in the Dongting Lake are given in Table 1.

Quantitative samples of macroinvertebrates were taken from the hyporheic zones with a weighted Petersen grab (0.0625 m^2 × 0.15 m) and then passed through a 420-mm sieve. Specimens were manually sorted out from sediment on a white porcelain plate and preserved in 10% formalin. Benthic animals were identified to the lowest feasible taxonomic level according to the relevant references 22–27 and counted. Wet weight of animals was determined with an electronic balance after being blotted, and then dry weight (mollusks without shells) was calculated according to the ratios of dry-wet weight and tissue-shell weight reported by Yan and Liang [28]. All taxa were assigned to functional feeding groups (shredders, collector-gatherers, collector-filterers, scrapers, and predators) according to related materials [22,29]. When a taxon had several possible feeding activities, its functional designations were equally proportioned, e.g., that if a taxon can be both collector-gatherer and scraper, the abundance of it is divided 50:50 into these groups.

CANOCO 4.53 (Microcomputer Power, Ithaca, New York) was used for Detrended Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA). DCA indicated that a normal model (gradient lengths > 2.0 standard units) would best fit the data, and CCA was used to analyze the relation between animal assemblages and environments. In CCA, analyses of forward selection and Monte Carlo permutation test were used to obtain important environmental factors influencing abundance and distribution of macroinvertebrates. Altogether 17 environmental variables (12 quantitative variables including T, SS, pH, Z, Z_{SD}, U, TN, TDN, TP, TDP, Chl *a*, B_{Mac}; five qualitative variables including clay, silt, fine sand, medium sand, coarse sand) and 65 macroinvertebrate taxa were used for CCA. During analysis, 1 or 0 was used to indicate appearance or absence of these types of substrates. Before statistical analyses, data were $x^{0.5}$ transformed to reduce heterogeneity of variances.

RESULTS

Taxa Composition of Macroinvertebrates

Altogether 65 taxa of macroinvertebrates from quantitative samples belonging to 27 families and 53 genera were identified. Among them were 9 oligochaetes, 24 mollusks, 26 arthropods, and six other animal (Table 2). With regard to taxonomic groups, Chironomidae was the predominant group, being 24.6% of the total taxa. With regard to assignment of functional feeding groups, 32.8%, 31.2% and 22.5% of the identified taxa belonged to collector-gatherers, scrapers and predators, respectively.

Density and Biomass of Macroinvertebrates

The density and biomass of each taxonomic group and each functional feeding group of macroinvertebrates are given in Tables 3 and 4. The annual average density and biomass of total macroinvertebrates in the Dongting Lake were 265 ind/m^2 and 2.40 g dry mass/m^2, respectively. The variations of standing crops of macroinvertebrates existed among different seasons. The density and biomass of total macroinvertebrates peaked in summer, when collector-filterers

Table 2. List of macroinvertebrates taxa in the Dongting Lake.

Oligochaeta
Tubificidae
(1) *Aulodrilus japonicus* Yamaguchi
(2) *Aulodrilus pluriseta* (Piguet)
(3) *Branchiura sowerbyi* Beddard
(4) *Limnodrilus claparedeianus* Ratzel
(5) *Limnodrilus grandisetosus* Nomura
(6) *Limnodrilus hoffmeisteri* Claparede
(7) *Limnodrilus* sp.
(8) *Spirosperma nikolskyi* (Lastockin et Sokolskaya)
(9) *Rhyacodrilus sinicus* (Chen)
Mollusca
Gastropoda
Viviparidae
(10) *Angulyagra polyzonata* (Frauenfeld)
(11) *Bellamya aeruginosa* (Reeve)
(12) *Bellamya purificata* (Heude)
(13) *Cipangopaludina chinensis* (Gray)
(14) *Rivularia auriculata* (Martens)
(15) *Rivularia bicarinata* Kobelt
(16) *Rivularia ovum* Heude
Pilaidae
(17) *Pila gigas* Spix
Pomatiopsidae
(18) *Oncomelania hupensis hupensis* Gredler
Bithyniidae
(19) *Alocinma longicornis* (Benson)
(20) *Parafossarulus eximius* (Frauenfeld)
(21) *Parafossarulus sinensis* (Neumayr)
(22) *Parafossarulus striatulus* (Benson)
(23) *Stenothyra glabra* (A. Adams)
Pleuroseridae
(24) *Semisulcospira amurensis* (Gerstfeldt)
(25) *Semisulcospira cancellata* (Benson)
(26) *Semisulcospira gredleri* (Boettger)
Lymnaeidae
(27) *Radix swinhoei* (H. Adams)
Planorbidae
(28) *Hippeutis cantori* (Benson)
(29) *Gyraulus compressus* (Hütton)
Bivalvia
Mytilidae
(30) *Limnoperna lacustris* (Martens)
Corbiculidae
(31) *Corbicula fluminea* (Müller)
(32) *Corbicula largillierti* (Philippi)
Sphaeriidae
(33) *Sphaerium lacustre* (Müller)
Insecta
Ephemeroptera
(34) Ephemeridae
Trichoptera
(35) Hydropsychidae
(36) Polycentropodidae
Odonata
(37) *Dromogomphus* sp.
(38) Gomphidae
Coleoptera
(39) Dytiscidae
(40) *Peltodytes* sp.
Diptera
(41) Ceratopogonidae
(42) Psychodidae
(43) Stratiomyidae
(44) *Axarus* sp.
(45) *Chironomus* sp.
(46) *Clinotanypus* sp.
(47) *Cryptochironomus* sp.
(48) *Demicryptochironomus* sp.
(49) *Dicrotendipes* sp.
(50) *Einfeldia* sp.
(51) *Gillotia* sp.
(52) *Microchironomus* sp.
(53) *Nanocladius* sp.
(54) *Paracladopelma* sp.
(55) *Polypedilum* sp.
(56) *Procladius* sp.
(57) *Stictochironomus* sp.
(58) *Tanypus* sp.
(59) *Xenochironomus* sp.
Others
(60) Amphipoda
(61) *Barbronia* sp.
(62) Cirolanidae
(63) Erpobdellidae
(64) Glossiphoniidae
(65) Nematoda

(mainly bivalves) and scrapers (mainly gastropods) were the predominant groups.

Environmental Factors Structuring Macroinvertebrate Assemblages

As shown in Figure 2, analyses of forward selection and Monte Carlo permutation test revealed that the key environmental factors influencing macroinvertebrate abundance in spring were flow velocity (*U*), water depth (*Z*), water temperature (*T*), and wet biomass of macrophytes (B_{Mac}). In summer, the important environmental factors structuring macroinvertebrate assemblage were *U*, pH, B_{Mac}, and *Z*. In autumn, the primary regulating factors were phytoplankton chlorophyll *a* concentration (Chl *a*), total dissolved phosphorus concentration of water (TDP), B_{Mac} and water transparency (Z_{SD}). In winter, the primary regulating factors were Chl *a*, TDP, *T*, and pH.

DISCUSSION

The river-connected lakes are a kind of special water with inter-annual exchange. At the temporal scale, they are lakes in the flood period, while they are like rivers in the low-water-stage period. At the spatial scale, there are some lotic lake regions, while other lake regions are lentic. Correspondingly, with regard to composition of macroinvertebrates, there were some potamophilic taxa and other taxa fond of still water. Similar features also have been found in European river-connected lakes [30,31]. With regard to seasonal fluctuation of benthic animal assemblages, higher taxa numbers appeared in spring and summer, and they were twice higher than that in winter. Density and biomass of macroinvertebrates reached the maxima in summer, when the assemblage was dominated by collector-filterers (i.e., bivalves) and scrapers (i.e., scrapers).

It is demonstrated that seasonal variation existed in environmental factors structuring macroinvertebrate assemblages of the Dongting Lake (cf. Figure 2). In spring and summer, hydrological parameters (i.e., flow discharge, water depth) were the driving factors for macroinvertebrate assemblages, whereas in autumn and winter, the concentrations of water nutrients (i.e., phytoplankton chlorophyll *a*, total dissolved phosphorus) played the leading role in governing macroinvertebrate assemblages. In spring and summer, water stage rises and flow velocity increases accordingly, thus, benthic animals are flushed directly by flow. Moreover, flow determines

Table 3. Mean (± SE) density (D; ind/m^2) and biomass (B; g dry mass/m^2; mollusks without shells) of each taxonomic group of macroinvertebrates in the Dongting Lake. Numbers in parentheses are percentages (relative abundance).

		Spring	Summer	Autumn	Winter	Average
Total	D	291 ± 58 (100)	533 ± 181 (100)	92 ± 22 (100)	144 ± 44 (100)	265 ± 114 (100)
	B	2.22 ± 0.74 (100)	3.38 ± 1.18 (100)	1.58 ± 0.85 (100)	2.42 ± 1.10 (100)	2.40 ± 0.43 (100)
Oligochaeta	D	42 ± 21 (14.5)	54 ± 28 (10.0)	13 ± 5 (13.7)	34 ± 16 (23.5)	35 ± 10 (13.4)
	B	0.04 ± 0.02 (1.8)	0.07 ± 0.06 (2.0)	0.02 ± 0.01 (1.0)	0.04 ± 0.02 (1.8)	0.04 ± 0.01 (1.7)
Gastropoda	D	51 ± 18 (17.5)	159 ± 86 (29.9)	39 ± 17 (42.2)	20 ± 13 (14.2)	67 ± 36 (25.4)
	B	1.08 ± 0.40 (48.6)	2.52 ± 1.18 (74.6)	1.21 ± 0.71 (76.2)	1.20 ± 1.00 (49.8)	1.50 ± 0.39 (62.6)
Bivalvia	D	54 ± 23 (18.5)	250 ± 128 (46.9)	11 ± 5 (12.4)	27 ± 16 (18.5)	85 ± 64 (32.3)
	B	0.94 ± 0.55 (42.4)	0.71 ± 0.27 (21.1)	0.33 ± 0.22 (21.2)	1.14 ± 0.58 (47.3)	0.78 ± 0.20 (32.7)
Insecta	D	136 ± 40 (46.8)	45 ± 10 (8.4)	17 ± 5 (18.6)	20 ± 7 (13.6)	54 ± 32 (20.5)
	B	0.16 ± 0.07 (7.1)	0.04 ± 0.01 (1.1)	0.02 ± 0.01 (1.3)	0.006 ± 0.004 (0.3)	0.05 ± 0.03 (2.3)
Others	D	8 ± 4 (2.7)	25 ± 8 (4.8)	12 ± 6 (13.1)	43 ± 27 (30.2)	22 ± 9 (8.4)
	B	0.003 ± 0.001 (0.1)	0.04 ± 0.02 (1.3)	0.005 ± 0.003 (0.3)	0.02 ± 0.01 (0.8)	0.02 ± 0.01 (0.7)

Table 4. Mean (± SE) density (D; ind/m^2) and biomass (B; g dry mass/m^2; mollusks without shells) of each functional feeding group of macroinvertebrates in the Dongting Lake. Numbers in parentheses are percentages (relative abundance).

		Spring	Summer	Autumn	Winter	Average
Shredders	D	24 ± 12 (8.1)	19 ± 8 (3.7)	9 ± 5 (10.2)	45 ± 27 (31.1)	24 ± 9 (9.2)
	B	0.01 ± 0.01 (0.6)	0.03 ± 0.02 (0.7)	0.003 ± 0.002 (0.2)	0.02 ± 0.01 (0.8)	0.02 ± 0.01 (0.6)
Collector-filterers	D	54 ± 23 (18.7)	262 ± 131 (49.1)	12 ± 5 (13.3)	27 ± 16 (18.9)	89 ± 67 (33.6)
	B	0.94 ± 0.55 (42.4)	0.72 ± 0.27 (21.4)	0.34 ± 0.22 (21.2)	1.14 ± 0.58 (47.4)	0.79 ± 0.20 (32.8)
Collector-gatherers	D	114 ± 33 (39.2)	64 ± 28 (12.0)	21 ± 6 (23.1)	38 ± 16 (26.5)	59 ± 23 (22.4)
	B	0.08 ± 0.03 (3.5)	0.08 ± 0.06 (2.5)	0.02 ± 0.01 (1.6)	0.05 ± 0.02 (1.9)	0.06 ± 0.02 (2.4)
Scrapers	D	51 ± 18 (17.7)	161 ± 86 (30.2)	39 ± 17 (42.8)	20 ± 13 (14.2)	68 ± 36 (25.7)
	B	1.08 ± 0.40 (48.6)	2.52 ± 1.18 (74.5)	1.21 ± 0.71 (76.4)	1.20 ± 1.00 (49.8)	1.50 ± 0.39 (62.6)
Predators	D	47 ± 14 (16.3)	27 ± 6 (5.0)	10 ± 3 (10.6)	13 ± 6 (9.3)	24 ± 10 (9.1)
	B	0.11 ± 0.07 (4.9)	0.03 ± 0.02 (0.9)	0.01 ± 0.01 (0.6)	0.002 ± 0.001 (0.1)	0.04 ± 0.03 (1.6)

substrate properties [32,33], and inhibits growth of phytoplankton and aquatic plants [34,35]. Therefore, it is concluded that water flow affects food source and habitat quality of macroinvertebrates. In addition, the change of water depth reflects the fluctuation of water stage. Water stage falls in autumn and winter, when water nutrients prevailed over flow effects on macroinvertebrate assemblages (cf. Figure 2). In comparison with river-disconnected lakes, nutrient concentrations of water played the critical role in structuring benthic assemblages in every season [29,36]. The difference of influencing factors of the benthic fauna in different waterbodies was attributed to variation of seasonal fluctuation of hydrological regime.

Along with operation of the TGD, natural hydrological regime of the Dongting Lake was disturbed, and this has some potential impacts on aquatic ecology. Firstly, after dam operation, the peak flood discharge reduced and flow process is flattened in the Dongting Lake. Amoros and Bornette [37] demonstrated that natural hydrological regime is the critical driving force for maintaining high biodiversity. Macroinvertebrates diversity in the Dongting Lake may decline due to the gradual loss of natural hydrological regime. Secondly, retention time of the Three Gorges Reservoir is prolonged, and the water exchange capacity decreases in the Dongting Lake because the water stage of the Yangtze River mainstream is too low to flow into the lake. Previous studies revealed that moderate hydrological disturbance resulted in the highest biological diversity [38,39]. Hydrological disturbance of the Yangtze River to the Dongting Lake is weakening, thus, biodiversity of the lake may reduce, and especially potamophilic taxa would be decreased. Thirdly, the period of low water stage occurs ahead of time and prolongs after the TGD impoundment in September [6,7]. In the low water period, water self-purification capacity weakens, islets in the lake are exposed, water quality deteriorates, and biological community structure would change accordingly.

After operation of the TGD, sediment from upstream Yangtze River to the Dongting Lake reduces due to a major of sediment trapping by dam. The reduced water sediment weakens the inhibitory effect of sand on algae growth. High concentrations of sediment results in light limitation on algal growth, moreover, sand pellets carried may spoil cell walls of phytoplankton [33,40]. Since impoundment of the Three Gorges Reservoir, sediment deposition in the Dongting Lake decreased significantly as well as the decreasing flow discharge into the lake, and the average scour depth of lake bottom was about 10.9 cm [41]. Sediment size in the eroded lake bottom becomes coarsened, and the loss of fine particulate matters leads to decline in the proportion of benthic collector-gatherers.

The above analyses indicate that construction and operation of the TGD have some adverse effects on the aquatic ecosystem of the Dongting Lake. The diversity of benthic animals would fall, the assemblage structure of macroinvertebrates would be changed, and some potamophilic species would disappear. To restore the river-connected lakes back to a healthy status, it is essential to reestablish the natural hydrological regime, e.g., the TGD increasing flow discharge to downstream in non-flood season, and dredging the Songzi River, Hudu River, Ouchi River that increase the discharge to the Dongting Lake in the flood season. Furthermore, ecological peak flood made by reservoir ecological operation may improve biodiversity. During the low water period, water from the Yangtze River mainstream can be used to supplement water amount of the Dongting Lake through sluice construction in Chenglingji (final outlet of the lake) and dredging in three river-lake exchange mouths (i.e., Songzi, Taiping, Ouchi). Thus, water exchange capacity and water environmental self-purification capacity of the Dongting Lake can be increased, and ecological status of the Dongting Lake may be improved in the future.

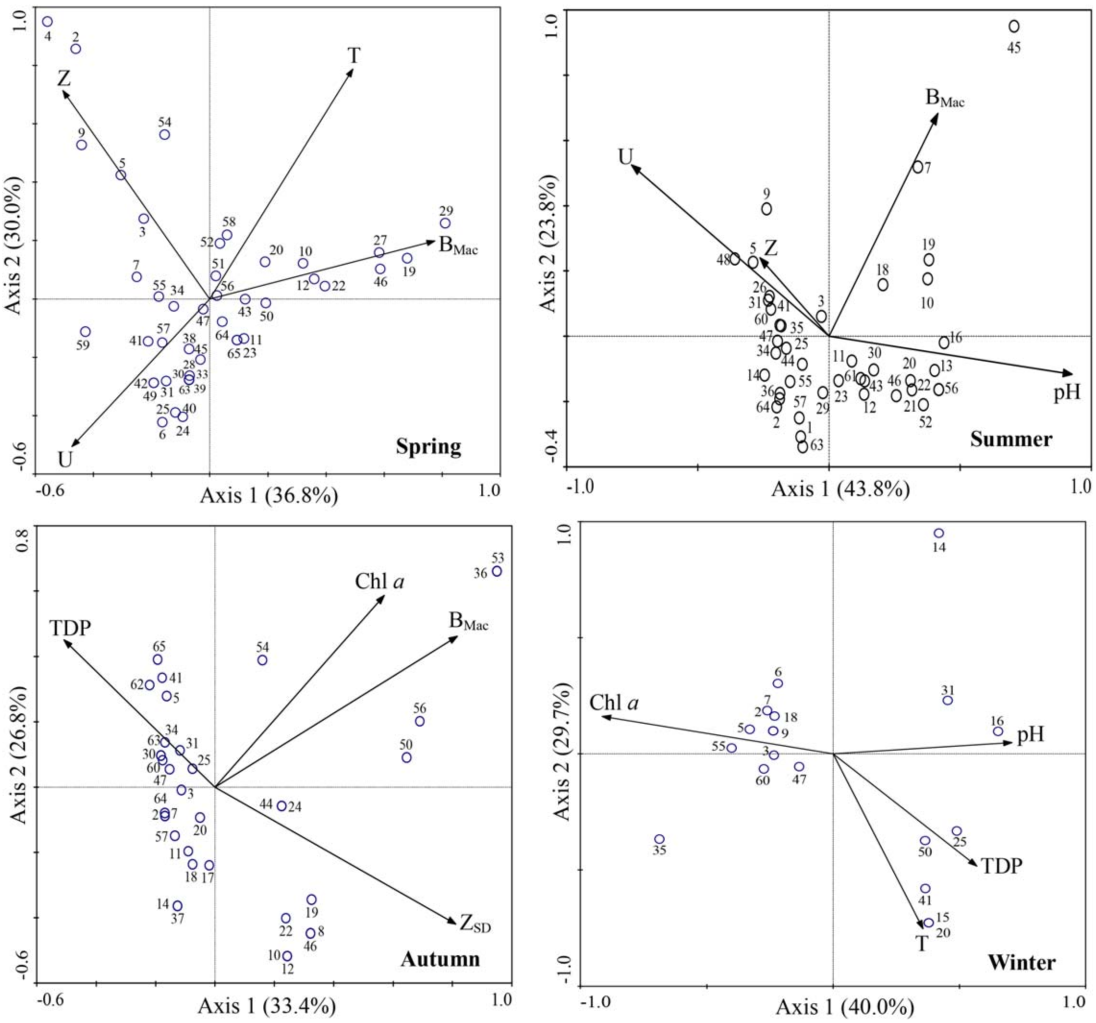

Figure 2. CCA biplots of environmental variables influencing macroinvertebrates density in each season. The species number is referred to Table 2. T, water temperature; Z, water depth; Z_{SD}, water transparency; U, flow velocity; TDP, total dissolved phosphorus concentration of water; Chl *a*, phytoplankton chlorophyll *a* concentration; B_{Mac}, wet biomass of macrophytes. [Color figure can be viewed at **wileyonlinelibrary.com**]

CONCLUSIONS

Macroinvertebrate assemblages of the Dongting Lake, a Yangtze River-connected lake, are characterized by high diversity and mollusks dominant in standing crops. Seasonal variation existed in environmental factors structuring macroinvertebrate assemblages of the Dongting Lake. Under the effects of the TGD, the diversity of benthic animals may fall, and the assemblage structure of macroinvertebrates would be changed, especially, some potamophilic species would disappear. Therefore, it is suggested that reservoir ecological operation and increasing water diversion from the Yangtze River to the Dongting Lake may improve ecological status of the river-connected lake.

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ABBREVIATIONS

CCA Canonical Correspondence Analysis
DCA Detrended Correspondence Analysis
TDN Total dissolved nitrogen
TDP Total dissolved phosphorus
TGD Three Gorges Dam
TP Total phosphorus

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