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Effect of hydrological regime on the macroinvertebrate community in Three-Gorges Reservoir, China

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ABSTRACT

Dam construction resulting from river closure always leads to dramatic changes of the hydrological conditions and influences the aquatic ecosystems seriously. The response of the macroinvertebrate community during the 5 years (2 impoundment stages) after the impoundment of Three-Gorges Reservoir (TGR) was analyzed to illustrate the difference of the macroinvertebrate communities between the two stages after impoundment, indicating the hydrological effects on the aquatic ecosystem. The results showed that the total density of macroinvertebrates increased significantly, and displayed obvious seasonal patterns, after more than one year's ecosystem rebuilding. Density after the second impoundment did not show a significant difference compared to that of the two years before the second impoundment. The maximum value appeared in spring, with naididae dominating the community (relative abundance over 90%). Shannon-Wiener diversity index also displayed obvious seasonal fluctuations with the maximum value in winter and minimum in autumn. The NMS ordination to the macroinvertebrate community indicated the seasonal patterns have become relatively stable from 2005 in the first stage, except the autumn. After the second impoundment, the seasonal patterns became more stable, and even the macroinvertebrates in the autumn, when the impoundment plan was carried out, were also similar. The correlation analysis between the hydrological factors and the macroinvertebrate parameters showed that the effect of the hydrological regime began to be significant from 2005. The inflow discharge caused positive effects on tubificidae, but negative ones on naididae. Relatively high transparency was more beneficial to the survival of the naididae. Additionally, the water residence time appeared significant influence to the Shannon-Wiener diversity.

1. Introduction

Hydrological conditions, such as discharge and water disturbance, always play important roles in aquatic ecosystems (Wetzel, 2001; Alcocer and Filonov, 2007). The Yangtze River, with a length of 6400 km, is the third longest river in the world. It is located in the subtropical monsoon climate region, where precipitation is high in summer and low in winter (Jiang et al., 2006). The river discharge changes with the precipitation (Xu et al., 2008). High-discharge always causes dramatic changes in all environmental parameters such as water flow, thermal structure, oxygen conditions, light penetration, and nutrient gradients (Guézennec et al., 1999; Godlewska et al., 2003). All these changes could influence the organisms inhabiting in the reservoir ecosystem. The direct mechanistic effects are destruction of habitats as well as damage to the organisms themselves (Godlewska et al., 2003). The construction of the Three-Gorges Reservoir (TGR) by impounding the Yangtze River led to changes in the hydrological regime. In general, dam construction usually slows water velocity, prolongs water residence time (Friedl and Wüest, 2002), and finally influences the structure of the aquatic ecosystem (Wu et al., 2003; Jorcin and Nagueira, 2005).

TGR, in the upper reaches of the Yangtze River, will have a length of 600 km and a surface area of 1080 km^2 when completed (Wu et al., 2003; Chen et al., 2008). The whole impoundment plan was divided into three stages. In June 2003, the first stage was finished, and the water level in front of the dam reached 135 m above sea level. In October 2006, the second step was finished with the water level increasing to 156 m. When the project is completely finished, TGR will have three characteristic water levels: normal water level (175 m, with corresponding capacity 39.3 billion m^3), flood control limited level (145 m,

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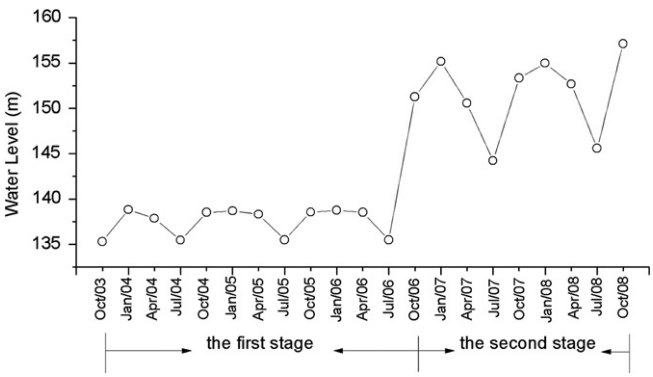

Fig. 1. Variations of the water level during the survey period.

22.2 billion m^3), and the lowest draw-off level in the dry season (155 m, 16.5 billion m^3)[2]. Variations of the water level during the survey were displayed in Fig. 1.

After impoundment, the TGR has been operated in the mode of "storing clear and releasing muddy", which caused a great difference between the water residence time within a year (Xu et al., 2009a). In flood seasons, low water level must be maintained to retain the capacity to prevent flood. The water residence time during the period is relatively short, and the ecosystem is more like a river ecosystem (Xu et al., 2009a). In non-flood seasons, however, the reservoir is mainly used to store water, so the water level is very high. The water velocity is accordingly slowed, and water residence time is prolonged. This kind of dramatic change in the hydrological conditions will cause an influence on the ecosystem of the reservoir. Many studies have been conducted in the reservoir region, including water chemistry (Ye et al., 2007; Xu et al., 2009a), phytoplankton (Zeng et al., 2006; Xu et al., 2009b), zooplankton (Yao et al., 2008), and others. Their studies indicated that, after the impoundment of the TGR, the dramatic change of the hydrological regime has caused many ecological problems, such as the increase of the nutrient concentration (Xu et al., 2009a) and the outbreak of some algal blooms (Ye et al., 2007; Xu et al., 2009b). These are all the reflections of aquatic ecosystem deterioration. However, they cannot reflect the long-time change trend of the ecosystem, because of their quick response to environment change (Geček and Legović, 2001; Kübar et al., 2005). Macroinvertebrates, as one important component of the aquatic ecosystem, living in the bottom of the water, have weak moving ability, and so have a relatively longer response time to environmental change (Berezina, 2000; Moreno and Callisto, 2006). So, taking macroinvertebrates as the indicator to reflect long-time change of the aquatic ecosystem is more appropriate. Shao et al. (2008a,b) have conducted research about the macroinvertebrates in the TGR region. For the mainstream of the TGR, they studied the first impoundment stage (October 2003–July 2006) (Shao et al., 2008b). They established the macroinvertebrate community successions after the first impoundment, and analyzed some factors influencing the dominant species.

In October 2006, the second stage of impoundment was finished, leading to the changes of some environmental factors. This paper analyzes 5 years' data of the macroinvertebrates during the two impoundment stages, in order to understand the macroinvertebrate community development after the second impoundment, and also discusses the effect of the hydrological regime on the community.

[2] http://www.ctgpc.com.cn/sxslsn/index.php?mClassId = 003000.

2. Materials and methods

Two transects (CJ01, CJ04) were set up in the Hubei part of TGR, with a distance of 30 km (Fig. 2). These are the routine sites in the long-time monitoring of the "Xiangxi River ecosystem monitoring station of Chinese Academy of Science/China Three Gorges Project Corporation". CJ01lies in the upstream of the dam, and CJ04 is located in the upper mouth of Xiangxi Bay. Three sites were set in each transect, located in the left, middle and right of each transect respectively. Site locations were measured using a geographical positioning system (GPS).

Twenty surveys were performed seasonally in autumn (October), winter (January), spring (April), and summer (July) from October 2003 to 2008. The survey of winter 2008 was delayed due to a heavy snowstorm. Macroinvertebrates were collected with a modified Petersen grab (area 0.0625 m^2) at each site. Samples were passed through a 200 μm mesh sieve, and materials maintained on the sieve were taken and preserved in 10% formaldehyde. Most taxa were identified to genus, and the densities were expressed as individuals/m^2 (ind/m^2). Simultaneously with the macroinvertebrate sampling, transparency was measured using a 20 cm diameter Secchi disk. Sampling methods referred to protocols for standard observation and measurement of the Chinese Ecosystem Research Network (CERN) (Huang et al., 2000; Cai, 2007).

The data of the inflow discharge and water level of the reservoir were provided by China Three Gorges Project Corporation. The storage capacity of the TGR at specific water level was estimated according to Huang et al. (2006). The residence time was calculated as (modified from George and Hurley, 2003):

$$\tau = \frac{V_T}{Q_T}$$

Where τ is the water residence time of the period T (day); V_T is the storage capacity (m^3); Q_T is the average inflow discharge (m^3/day). In this paper, V_T and Q_T were both the monthly mean values calculated by the day mean data.

Diversity of the community was described with Shannon-Wiener diversity index (H):

$$H = -\sum P_i \log_2 P_i$$

Where P_i is the relative abundance of the species i; $P_i = N_i/N$, N_i is the density of the species i, and N is the total density of the macroinvertebrates.

Some sites were not sampled on occasion due to rip currents. The length-scale of the sampling (30 km) was negligible comparing to the total length of the reservoir (600 km). The spatial variation was neglected and the mean value of all sites was calculated for further analysis. Non-Metric Multidimensional Scaling ordination (NMS) was used for grouping all seasons. Then, Multi-Response Permutation Procedures (MRPP) were conducted to examine the specific similarity, which was expressed as A. $A > 0.3$ indicates that the similarity between two seasons is fairly high; $A = 1$ indicates all items within the groups must be identical (McCune and Mefford, 1999). In the analysis process, autumn 2003 and summer 2004 were rejected because the density is 0 in this sample. Analysis was performed with PC ORD 4.0.

One-way ANOVA was used to examine the differences of the hydrological factors among seasons and the density difference between the second impoundment stage and the latter two years of the first stage. In the analysis, the LSD method was used to perform the multiple comparisons within seasons, in SPSS 16.0. Correlation analysis between hydrological factors and biological parameters were also performed in SPSS 16.0.

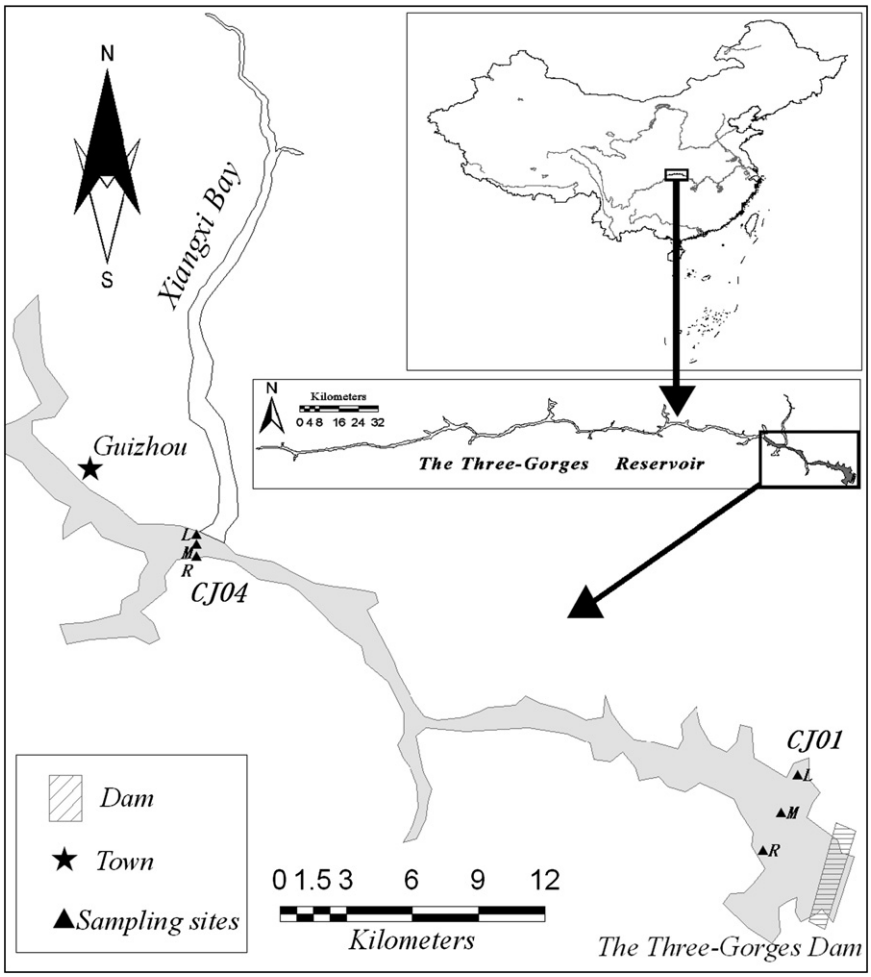

Fig. 2. Distribution of the sampling sites.

3. Results and discussion

3.1. Hydrological factors

Fig. 3 displays the seasonal variations of the inflow discharge and the water residence time. Inflow discharge was high in summer and autumn, low in winter and spring, mainly due to the subtropical monsoon climate (Jiang et al., 2006). The water residence time could respond to the mixing degree of the water-body. According to Straskraba and Tundisi (1999), a reservoir with water residence time less than 20 days is an A-type reservoir, having riverine characteristics. Where the residence time ranges from 20

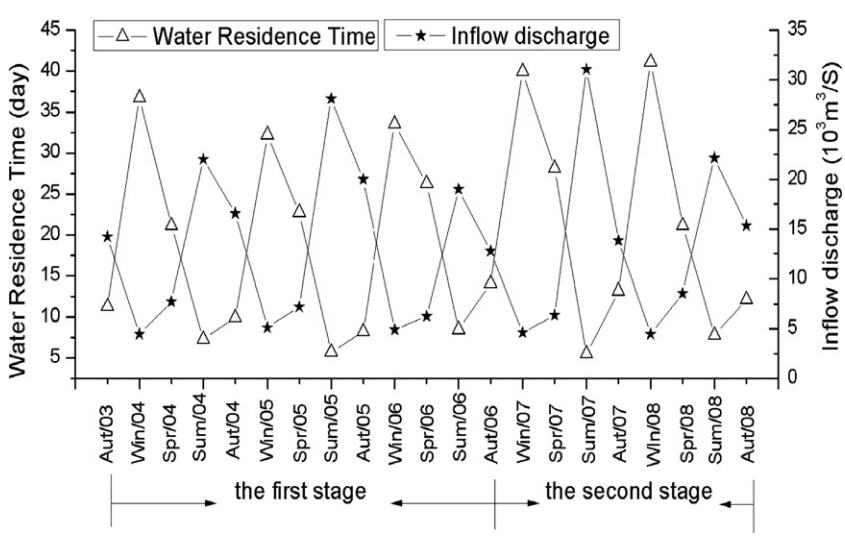

Fig. 3. Variations of some hydrological parameters during the study period.

Table 1
Significance of the multiple comparison difference among seasons.

Seasons compared		Inflow discharge	Water residence time
Spring	Summer	0.000[b]	0.000[b]
	Autumn	0.000[b]	0.000[b]
	Winter	0.178	0.030[a]
Summer	Autumn	0.000[b]	0.000[b]
	Winter	0.000[b]	0.000[b]
Autumn	Winter	0.000[b]	0.000[b]

[a] Difference is significant at 0.05 level.
[b] Difference is significant at 0.01 level.

to 300 days, the reservoir is considered as B-type. If the residence time is longer than 300 days, it belongs to C-type, as a lake. As displayed in Fig. 3, in the survey period, the residence time in winter and spring ranged from 20 to 45 days. At that time, the reservoir was a B-type, "semi-river and semi- lake". In summer and autumn, the residence time fluctuated between 5 and 15 days. Then, the reservoir was an A-type, as a river. By comparing the two stages, the residence time in the second stage was a little longer than in the first stage generally, but the type of the reservoir in each season did not change.

A one-way ANOVA was performed between all seasons. The results are displayed in Table 1. For inflow discharge, there was no significant difference between spring and winter, while differences between other seasons were fairly significant. For water residence time, differences between all seasons were significant, but the significance level between spring and winter was relatively higher ($p = 0.030$) than that between other seasons ($p < 0.001$).

3.2. Community structure of the macroinvertebrates

A total of 45 taxa were collected during the survey period (Appendix 1), including 33 in the first stage, 22 in the second stage, and 15 species in common. The macroinvertebrates mainly consisted of three main groups: tubificidae, naididae, and chironomidae. In the survey period, the occurrence frequency of the *Polypedilum scalaenum* group was the highest (75%). *Procladius* sp., *Limnodrilus hoffmeisteri*, and *Branchiura sowerbyi* also had relatively high occurrence frequencies of 55%, 55%, and 45% respectively. There were 19 taxa appearing only at one time. The occurrence frequency of *L. hoffmeisteri* decreased in the second stage. For the three main groups, the occurrence frequencies were: frequency (Chironomidae) > frequency (Tubificidae) > frequency (Naididae).

Fig. 4 displays the total density of the macroinvertebrates (expressed by the density of the three main groups), and the Shannon-Wiener diversity index. The total density of the macroinvertebrates began to increase from 2005, especially in spring. The density of the second impoundment stage showed no significant difference from that of the latter two years, from Jan. 2005 to Jul. 2006 in the first stage (one-way ANOVA, $p > 0.05$). The highest values for each year all occurred in spring. Naididae was absolutely dominant, with the relative abundances over 90%. In those seasons with low density, the community was mainly composed of tubificidae and chironomidae. The trend of the Shannon-Wiener diversity, however, displayed a different trend, with the maximum value

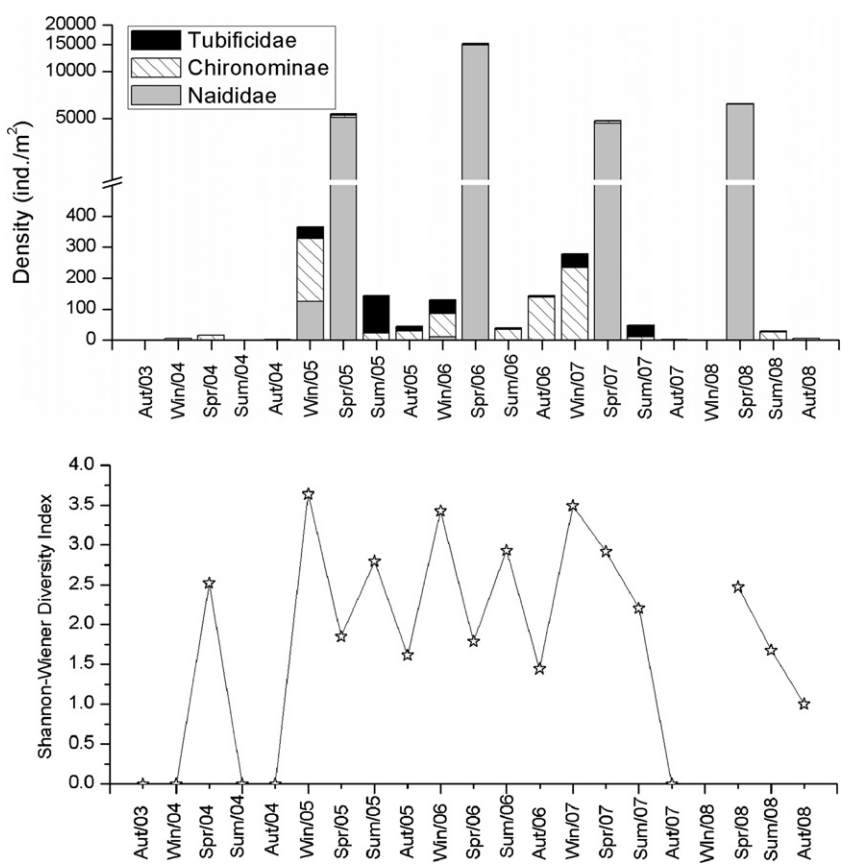

Fig. 4. Density of the macroinvertebrates and the diversity index.

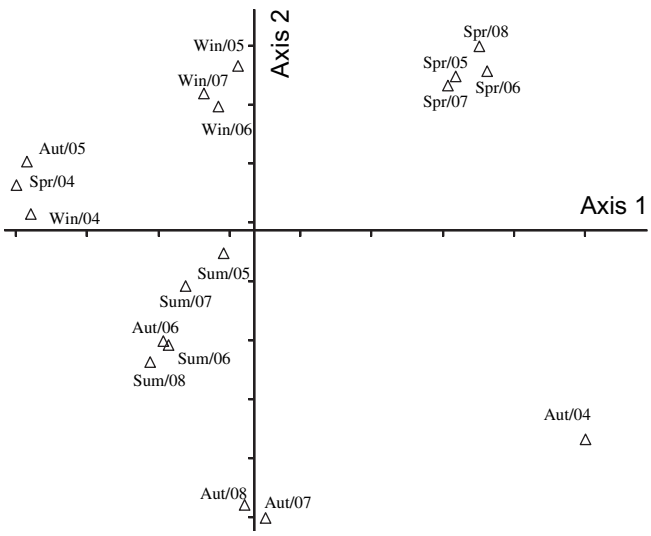

Fig. 5. Results of NMS ordination (Spr: Spring; Sum: Summer; Aut: Autumn; Win: Winter. Ordination stress, final instability, and number of iterations were 13.8, 0.13931, and 100 respectively).

in winter, and the minimum in autumn. Especially in autumn 2007, there was only one species appearing in all sites, so the diversity index was 0. Compared to some results of the observations by other researchers before the dam construction (Borutsky et al., 1959; Liang, 1987; Xie et al., 1999), the density and diversity have increased dramatically in the mainstream of the Yangtze River, which also verified the prediction that, "construction of the TGR will benefit the macroinvertebrate community" by Borutsky et al. (1959).

The NMS results (Fig. 5) based on the density of each taxon revealed that, in the first year after the first impoundment (October 2003–2004), the seasonal distribution was a little disordered. From 2005, the distribution in the same seasons began to be aggregated, but autumn was an exception. Because autumn was the period when impoundment was carried out, the impoundment process in autumn caused some effect on the habitat of the macroinvertebrates during that period. After the second impoundment (Oct. 2006), the seasonal pattern of the macroinvetebrates became more stable than that in the first stage. Even with the impoundment in autumn of 2007 and 2008, the influence to the macroinvertebrate community seemed not to be very obvious. From this point, with the increasing of the water level, the effect of the impoundment process on the macroinvertebrates became more and more gentle.

MRPP analysis examined the community similarity among all seasons. The results showed that relatively higher similarity of the community structure appeared between spring and winter ($A = 0.4$, $p < 0.05$), and the hydrological factors between the two seasons also had the same trend. This indicated that the relatively similar hydrological conditions in spring and winter made contributions to the similar community structure.

3.3. Factors affecting the macroinvertebrate community

To explore the influence of the hydrological conditions on macroinvertebrates, the correlations between environmental factors and the biological parameters according to different stages were analyzed (Table 2). Firstly, from the results based on all data of the 5 years, the discharge had significant influences on both the abundances of tubificidae (negative effect) and naididae (positive effect). Transparency also significantly influenced the total density, Shannon-Wiener diversity and the relative abundance of the naididae, and all correlations are positive. No significant correlations appeared between the water residence time and the biological parameters. When correlation analysis was performed with the data of the first and the second impoundment stage respectively, no any significant correlation was found. However, the result of the analysis of the latter 4 years' data (Jan. 2005–Oct. 2008) showed that the inflow discharge, the transparency and the water residence time all had significant effects, and even the relationships between the biological parameters and inflow discharge and transparency were greatly improved. This indicated that the hydrological factor effects began to be relatively significant from 2005. Additionally, from the analysis, chironomidae were not influenced significantly by the hydrological regime in any stage of the impoundment analyzed.

In the three main groups analyzed above, naididae usually selected diatoms, detritus, bacteria and even activated sludge (Bowker et al., 1983; Ratsak et al., 1993; Lölein, 1996) as food. When the inflow discharge increased and the water residence time was reduced, the water might be strongly disturbed, which could influence the sedimentation of the suspended matter (Maritin and Neely, 2001; Peeters et al., 2004) and finally influence the density of naididae. The high density of the naididae mainly appeared in the low-discharge spring. In summer and autumn, because of the high inflow discharge and the low transparency, the density of the naididae was accordingly reduced. The reduction of the density in spring 2007 and 2008, compared to that in 2006, was mainly due to the increase of the inflow discharge. Tubificidae can tolerate relatively higher environmental stress (Milbrink, 1994; Wetzel, 2001). In poor environment conditions, they would dominate the community because of the reduction of other species. That was why their densities were relatively high in high-discharge and low-transparency seasons. Chironomidae often emerge prior to or at the beginning of flooding (Dudgeon, 2000; Gresens et al., 2007), so dramatic changes of the hydrological conditions had little effect on them. The different responses of the three main groups could also be used to explain the difference of their occurrence frequencies in the five years after the impoundment of the TGR.

Table 2
The correlation coefficient between environmental factors and the macroinvertebrate parameters.

	The whole 5 years ($n = 20$)			The 1st stage ($n = 12$)			The 2nd stage ($n = 8$)			The last 4 years ($n = 15$)		
	D	T	WRT	D	T	WRT	D	T	WRT	D	T	WRT
TD	−0.369	0.477[a]	0.272	−0.333	0.416	0.250	−0.332	0.694	0.688	−0.420	0.458	0.312
H	−0.215	0.510[a]	0.394	0.054	0.446	0.256	−0.486	0.629	0.370	−0.046	0.492	0.546[a]
%N	−0.463[a]	0.553[a]	0.358	−0.427	0.553	0.365	−0.483	0.604	0.367	−0.525[a]	0.561[a]	0.419
%T	0.481[a]	−0.350	−0.339	0.509	−0.374	−0.405	0.676	−0.314	−0.210	0.601[a]	−0.336	−0.325
%C	−0.137	−0.016	0.148	−0.342	0.201	0.407	−0.010	−0.327	−0.134	0.044	−0.300	−0.150

D: discharge (10^3 m^3/s); T: transparency (cm); WRT: water residence time (day); TD: total density of the macroinvertebrates (ind./m^2); H: Shannon-Wiener diversity index; %N: relative abundance of Naididae; %C: relative abundance of Chironomidae; %T: relative abundance of Tubificidae.

[a] Correlation is significant at the 0.05 level (2-tailed).

4. Conclusions

Through one year's rebuilding of the ecosystem, the macroinvertebrates have adjusted themselves to the new environment. The density increased dramatically from 2005, and also the biological diversity. After the second impoundment, the density of the macroinvertebrates showed no significant difference.

The seasonal patterns began to be gradually stable from 2005, and after the second impoundment, the community became more stable. Although the water level increased about 20 m after the second impoundment, the community was only influenced during the impoundment process. A possible hypothesis is: the deeper the water, the lesser the effect to the bottom environment caused by the water disturbance.

The hydrological effect on the macroinvertebrate community began to appear immediately after the first impoundment of the TGR. A relatively stable environment promoted macroinvertebrate development. However, the effect on the seasonal pattern began to be gradually significant from 2005. Both the inflow discharge and transparency had influence on the abundance of naididae. Low discharge and high transparency would be beneficial to their survival. As naididae is absolutely dominant in spring, the total density of the macroinvertebrates in spring could be accordingly influenced by inflow discharge and transparency. In contrast, the high-discharge would be helpful to increase the dominant position of the tubificidae by reducing the competitive power of their competitors. For chironomidae, because of their special life history, there was little relation with the hydrological regime.

Acknowledgements

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Appendix 1. Taxa found in Three-Gorges Reservoir

Taxon	2003	2004				2005				2006				2007				2008		
	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Apr	Jul	Oct
Nematoda							+								+	+		+		
Oligochaeta																				
Limnodrilus hoffmeisteri						+	+	+	+	+	+	+	+	+	+			+		
*L.*sp1																+				
*L.*sp2														+						
Teneritrilus mastix						+	+	+	+	+	+				+			+		
Branchiura sowerbyi						+		+	+		+	+		+	+	+		+		
B. sp.								+	+	+										
Brothrioneurum vejdovskyanum						+								+						
Aulodrilus limnobius						+	+													
Tubifex tubifex											+				+				+	
Tubificidae sp1.					+															
Tubificidae sp2.														+						
Tubificidae sp.								+		+	+					+				
Nais inflata						+	+			+	+				+			+		
N. variabilis											+				+			+		
N. communis											+									
N. sp.															+			+		
Paranais frici							+				+				+			+		
Pristina sp.						+					+									
Pristinella sp.																		+		
Chironomidae																				
Procladius sp.							+	+			+	+	+	+	+	+	+		+	+
Polypedilum scalaenum group		+	+			+	+	+	+	+	+	+	+	+	+	+		+	+	
P. halterale gr.											+				+			+		
P. braseniae															+					
P. tritum														+						
P. sp1.											+			+	+					
P. aviceps															+					
Dicrotendipes sp.											+									
Orthocladiinae sp.							+				+									
Harnischia sp.						+	+			+	+									
Demicryptochironomus sp.											+									
Stictochironomus sp.						+	+			+	+	+								
Cladotarnysus sp.						+														
Tanytasus sp.							+				+									
Chironomus plumosus							+													
Cryptochironomus sp.							+	+		+	+	+								
Cryptotendipes sp.												+								
Chironomidae sp1.														+	+			+		
Chironomidae sp2.													+							
Chironomidae sp5.							+	+												
Padonominae sp.													+							
Goeldchirinomus sp.														+						
Gomphidae sp.			+																	
Endotribelos sp.			+																	
Ceratopogonidae sp.						+	+													

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