Correlation between river substrate heterogeneity and benthic macroinvertebrate diversity

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Abstract: The characteristics of river substrate are closely related with the community diversity of river benthic macroinvertebrate. It is believed that river substrate heterogeneity is positively correlated with benthic macroinvertebrate diversity in rivers. In this paper, based on field data, we run quantitative analysis on the correlation between river substrate heterogeneity and benthic macroinvertebrate diversity. Taking a typical river of Oujiang in Zhejiang Province, China as an example, a coefficient of so-called non-uniformity index is used to characterize the river heterogeneity. The diversity of benthic macroinvertebrate is characterized by the Shannon-Wiener and Simpson index. Strong positive relationships between non-uniformity coefficient of river substrate and biodiversity index of benthic macroinvertebrate are observed. The results could be used to support decision-making tools in river restoration planning and management.

Keywords: river substrate, non- uniformity coefficient, benthic macroinvertebrate diversity, river restoration

1 Overview

Biological communities and physical habitat are closely linked in ecosystems. River stratum diversity, shoreline complexity, vertical meandering, riverbed sediment heterogeneity and other morphological characteristics create a rich diversity in river habitats and biological communities. River morphological diversity has laid an important foundation for maintaining the diversity of river biological communities [1].

Studies on 18 river reaches in the Lewis River and White River, Vermont, U.S.A, demonstrated that biological communities of benthic macroinvertebrates were directly affected by river meandering, river gradient and other geomorphological features, and that geomorphological factors could be used for effective river ecological assessment [2]. Assuming that water quantity and water quality remain unchanged, biological community diversity is positively correlated with habitat spatial heterogeneity [3]. Studies from 41 survey points of the Bega River, New South Wales, Australia, also showed that geomorphological features of different reaches were significantly positively correlated with large plants and benthic macroinvertebrates. The geomorphological conditions of the Bega River reaches were divided into good, moderate and poor condition, with the biomass in good reaches nearly twice as much as that in poor reaches [4]. Thus, the greater the morphological diversity of a river, the more microhabitats are available for species to coexist. In contrast, the unique morphology of a river will have a negative impact on biological community diversity, changing its nature, density, and proportion and resulting in ecosystem degradation to a certain degree. As one key representative of the river morphological diversity, river substrate heterogeneity plays an important role on the river ecosystem.

Through data analysis and on-site surveys, we explored riverbed sediment heterogeneity and biodiversity by quantitative analysis, and investigated typical Oujiang River reaches, riverbed sediments and the quality and conditions of benthic organisms, and discussed the relationship between riverbed sediment heterogeneity and benthic biodiversity.

2 Analysis of riverbed sediment heterogeneity and benthic biodiversity

2.1 Analytical method of riverbed sediment heterogeneity

Riverbed sediment components directly reflect riverbed sediment heterogeneity, are closely related to river channel roughness, and have great impact on flow rate, water depth and hydraulic characteristics of habitats. Riverbed sediments also provide the necessary microenvironment for survival for animals such as fish. For example, many fish lay eggs in specific sediment to ensure egg adhesion to the sediment surface [5]. Sediment pores also increase the oxygen levels in the water. At the same time, sediments can reflect the influence of the characteristics of the watershed on the habitat quality to some extent. Furthermore, forestry and agricultural activities can change the surface runoff and sediment transport rate, which can be reflected by riverbed sediment particle size.

Riverbed sediment components were analyzed in accordance with two industrial standards, "Technical standard for determination of sediment particle size in open channels (SL42-92)" and "Technical standard for measurements of bed load and bed material in open channels (SL43-92)" set by the Ministry of Water Resources, China. The analytical methods of sediment particles were determined by the type of samples, particle size range, and equipment conditions. River sediments were classified into cosmids, silts, sands, gravels, pebbles and boulders (Table 2-1).

Table 2-1 Classification of river sediments (Unit: mm)

Cosmids	Silts	Sands	Gravels	Pebbles	Boulders
<0.004	0.004~0.062	0.062~2.0	2.0~16.0	16.0~250.0	>250

To reflect the group combination characteristics of riverbed sediments, the distribution of sediment particles were analyzed and described with a grading curve and statistical characteristic values. The non-uniformity coefficient indicates the non-uniformity degree of the particle size distribution of riverbed sediments, and characterizes riverbed sediment diversity. The non-uniformity coefficient of hard riverbed in the extreme case can be considered as zero.

The non-uniformity coefficient of riverbed sediments was analyzed as follows:

(1) Samples were separated with a 64 mm-diameter sieve, and particles below and above the sieve were analyzed by sieve analysis and ruling method, respectively.

(2) Particles above the sieve were sorted according to particle size, and divided into several groups, with the maximum particle size as the first group.

(3) Three axes of the largest particle chosen from each group were measured with a steel ruler to obtain the geometric mean particle size, as follows:

$$D = \sqrt[3]{a \times b \times c}$$

Where, D represents the geometric mean particle size, mm; a represents the length of major particle axis, mm; b represents the maximum width of the particle perpendicular to direction a, mm; and c represents the maximum thickness of the particle perpendicular to directions a and b, mm.

(4) Particles of all groups were weighed and measurements recorded.

(5) Particles below the sieve were analyzed via sieve analysis.

(6) Circular coarse sieves were assembled upon their respective diameters of 32 mm, 16 mm, 8 mm and 4 mm.

(7) Square coarse sieves were assembled upon their respective diameters of 2 mm, 1 mm, 0.25 mm and 0.062 mm.

(8) Test samples were placed on the top of the sieves, and were shaken by hand gradually until no particles remained.

(9) Particles above the sieve were weighed and measurements recorded.

(10) The grading curve was drawn to obtain characteristic particle sizes d_{75} and d_{25}, and the non-uniformity coefficient was calculated by $\varphi = \sqrt{d_{75}/d_{25}}$. When the non-uniformity coefficient approaches 1, the sediment components are considered even. The larger the non-uniformity coefficient, the more uneven the characterized sediment components.

Through experiments, I have used a series of sieves separated by 1 phi intervals to obtain grain size distribution parameters.

2.2 Analytical method of benthic biodiversity

The benthic community is an aquatic animal population that spends all or most of its lifetime at the bottom of a water body. The benthos is an important component of freshwater ecosystems, with great theoretical significance for understanding ecosystem structure and function. Species composition and standing stock of benthos are significantly different in different water bodies and regions. Factors affecting the distribution and abundance of the benthos include physical factors like sediment, flow velocity and water depth, nutrient factors like total nitrogen, total phosphorus and organic matter, and aquatic density. Indexes of benthic bio-diversity and bio-communities increase with the increase in biological habitat diversity. The main influencing physical conditions, i.e., the biological habitat conditions for benthos, include riverbed sediment, water depth and flow rate, among which sediment has the greatest impact [6].

Biodiversity is a significant feature and core component of an ecosystem’s life-support system. It includes genetic diversity, species diversity, ecosystem diversity and landscape diversity [7], with ecosystem diversity referring to the diversity of habitats, biotic communities and ecological processes. Biotic community diversity refers to differences in biological communities related to composition, structure, kinetic energy and dynamics. Biotic community diversity can be measured as [8-10] biodiversity within communities or habitats (α), biodiversity among communities or habitats (β), and biodiversity of geographical regions (γ). Generally, α is used to calculate number of species within the communities and relative abundance among species, showing the coexistence of species within communities through competition for resources and utilization of the same habitat. Diversity α can also be divided into species richness index, species relative abundance index, the diversity indexes composed by species richness and relative abundance, and the species uniformity index. In particular, diversity indexes composed of species richness and relative abundance within communities are widely used, and include the Simpson Index and the Shannon-Wiener Index. However, no separate statistical indicators can properly describe biodiversity among communities, so several diversity indexes are used at the same time to achieve a more comprehensive description of the biodiversity objective. In this paper, both the number of species in the communities and the Simpson Index and the Shannon-Wiener Index of relative abundance of each species were used to measure benthic community diversity. The Simpson Index and the Shannon-Wiener Index formulas are as follows:

Shannon-Wiener Index (H): $H = -\sum_{i=1}^{s} P_i \ln P_i$;

Simpson Index (D): $D = 1 - \sum_{i=1}^{s} P_i^2$

Where: in the formula $P_i = {n_i}/{N}$, P_i represents the relative abundance of the i th species, n_i represents the individual number of the i th species, N represents the total individual number of all species in the community, and s represents the number of species.

3 Case analysis

The main stream channels from the Yuxi Reservoir Tail Area to Kaitan Reservoir Head Area of Oujiang River and the local reaches of the main tributaries were used to investigate riverbed sediments and benthic organisms in January 2010 [11-12] at main stream, floodplain and tributary sample points, as shown in Table 3-1 and Fig.3-1.

Table 3-1 Distribution of sample points of target reaches

No.	Location	Sample points	North latitude	East longitude	Biological survey	Riverbed sediment survey
1	Main streams	Yuxi Reservoir Tail Area	28°14.641′	119°40.112′	*	
2		Yuxi Reservoir Middle Area	28°16.401′	119°41.745′	*	
3		Yuxi Reservoir Head Area	28°16.762′	119º42.172’	*	
4		Dagangtou	28°17.922′	119°43.726′	*	
5		Bihu Bridge	28°20.155′	119°47.146′	*	*
6		Toll station	28°22.543′	119°49.559′	*	
7		Upper reaches of Shuige	28°23.103′	119°49.489′	*	
8		Middle reaches of Shuige	28°23.566′	119°49.504′	*	
9		Lower reaches of Shuige	28°23.947′	119°49.815′	*	*
10	Tributaries	Songyin Stream	28°18.271′	119°43.800′	*	*
11		Xiaoan Stream	28°27.606′	119°50.971′	*	*
12	Floodplains	Nanshan Pond	28°20.595′	119°47.512′	*	

13		Pond confluence	28°20.722′	119°47.509′	*	*
14		Jiulong Wetland Stream	28°22.669′	119°49.135′	*	*

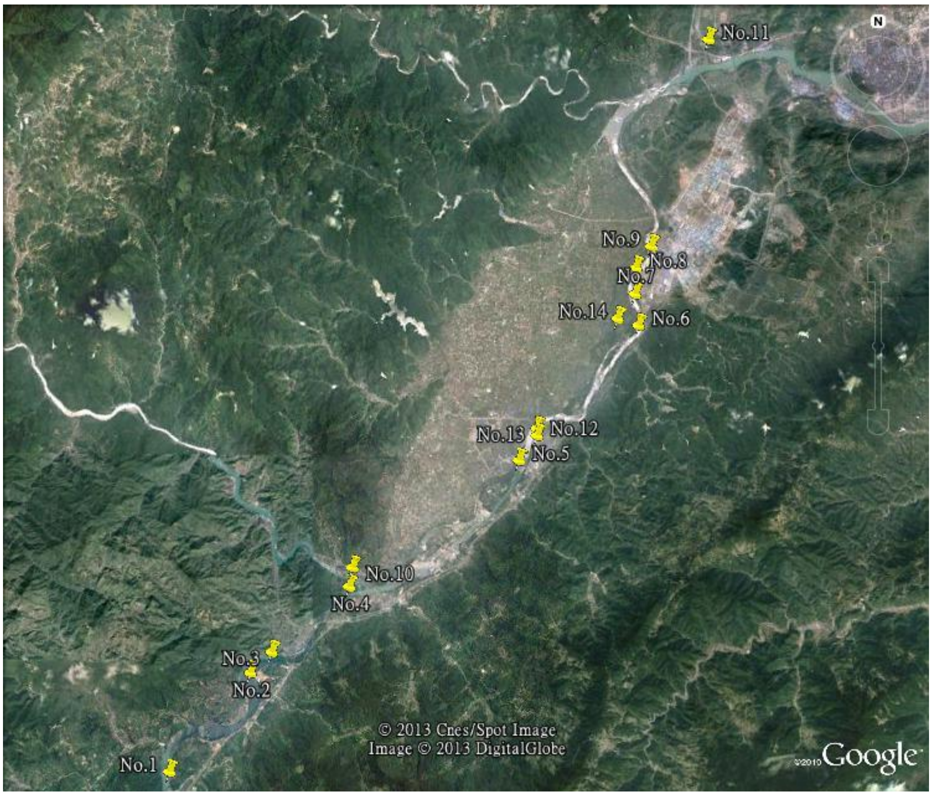

Fig. 3-1 Plan view of the survey sites(By Google Earch)

3.1 Survey of riverbed sediments

The Oujiang River riverbed is covered with thick pebbles and boulders, and the sediment particles are mainly pebbles with a particle size greater than 16 mm. Therefore, the riverbed was defined as a pebble bed, as shown in Figure 3-2.

a. Sediment conditions at Xiaoan Stream b. Sediment conditions at pond confluence c. Sediment conditions at Bihu Bridge

d. Sediment conditions at Songyin Stream e. Sediment conditions at Jiulong Stream

Fig. 3-2 Sediment conditions at different survey points

Because the riverbed is composed mainly of pebbles and gravel, the sediment samples were taken by the bucket-type sampler with surface sampling. The sampling depth of the pebble bed was about twice the median diameter of the riverbed particles. When the weight of the samples with a particle size above 2 mm was greater than 30% of the total weight of the samples, the weight of the samples taken was within the range of 2 kg and 20 kg. To reflect the general conditions of the riverbed sediments, representative sampling locations were selected. The sampling sites are shown in Figure 3-2.

Fig. 3-2 Field sampling of riverbed sediments

The grading curve of the particles at six survey points, that is, Xiaoan Stream, lower reaches of Shuige, pond confluence, Bihu Bridge, Songyin Stream and Jiulong Stream are shown in Fig. 3-3.

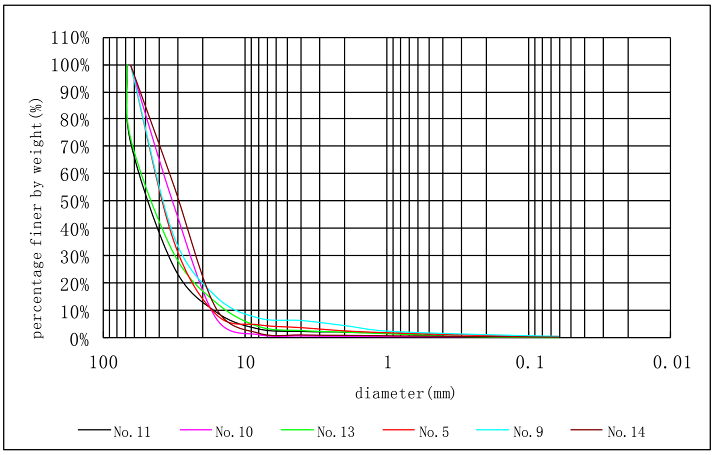

Fig. 3-3 Grading curve of the sediment particles at different survey points

The grading curve shows that the components on the riverbed surface were widely distributed from sands to gravels and pebbles, indicating their median diameter was within the range of 30~50 mm at all survey points. The median diameter of most particles was within the range of 10~60 mm, suggesting the substances on the riverbed surface were mainly pebbles and gravel, with some sand. The sand was rich in content at the lower reaches of the Shuige survey point due to ongoing engineering construction at the reaches resulting in an increase in fine particles in the riverbed sediment. According to the grading curve, the characteristic particle sizes of the riverbed sediments, d_{75} and d_{25}, were obtained at the different survey points, and the non-uniformity coefficient φ was derived, as shown in Table 3-2.

Table 3-2 Characteristic particle sizes and non-uniformity coefficient at different survey points

Survey points	Characteristic particle size d_{75} (mm)	Characteristic particle size d_{25} (mm)	Non-uniformity coefficient φ
Xiaoan Stream	69	31	1.4919
Lower reaches of Shuige	45	23	1.3988
Pond confluence	68	28	1.5584
Bihu Bridge	49	29	1.2999
Songyin Stream	49	26	1.3728
Jiulong Stream	43	20	1.4663

3.2 Survey of benthonic organisms of the target river reaches

The survey of the target river reaches included species spatial distribution, standing stock and community structure of the benthic organisms as well as the bio-diversity index.

(1) Species composition

There were 41 benthic species from 4 classes, 11 orders, 23 families, and 26 genera, mainly composed by aquatic insects and mollusks collected from the biological survey. Among them, 28 aquatic insects and 7 mollusks accounted for 68.3% and 17.1% of the total number of species, respectively. The most frequently seen species were *Corbicula fluminea*, *Macronemum zebratum*, *Leptophlebia* sp. and *Cricotopus* sp.

(2) Species spatial distribution

The changed number of benthic species was between 0 and 23 species. The stratum with the largest number of species was Xiaoan Stream of the Yuxi Reservoir Tail Area. The stratum with largest number of species (9) in the main stream samples was at Bihu Bridge. There was a relatively small number of species (less than 4) in the remaining strata. There were 10 species in Songyin Stream, 20 species in the floodplain pond confluence, and 4 species in the other two strata (Table 3-3).

Table 3-3 Distribution of benthic species along the river

Sample points	Main streams									Tributaries		Floodplains		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of species	/	4	1	1	9	4	2	2	4	10	23	4	20	4

(3) Standing stock and spatial distribution of benthos

The density of benthos ranged between zero and and 755. 6 ind./m^2, with a mean density of 195.2 ind./m^2. The stratum with the highest density was Xiaoan Stream, followed by Songyin Stream. The biomass of benthos ranged between zero and 165.4 g/m^2, with a mean biomass of 18.8 g/m^2. The stratum with the highest biomass was Yuxi Reservoir Middle Area, followed by Jiulong Stream with a biomass of 25.3792 g/m^2. Generally, benthic density was low in the main stream and floodplain samples, but high in the tributaries, and biomass was high in the Jiulong Wetland of the floodplains and Yuxi Reservoir Middle Area in the main stream samples due to the large weight proportion of mollusks, but lower in the remaining strata than in the tributaries (Table

3-4).

Table 3-4 Standing stock of benthos (density: ind./m^2, biomass: g/m^2)

Sample points	Main streams									Tributaries		Floodplains		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Density	/	256.0	16.0	3.2	141.8	57.1	/	12.7	15.9	596.8	755.6	304.8	127.0	56.00
Biomass	/	165.4	2.3	0.2	6.0	0.1	/	0.2	0.5	11.2	12.3	0.4	2.2	25.4

(4) Diversity index

The Shannon-Wiener Index ranged between zero and 3.77, with a mean of 1.52. The stratum with the highest Shannon-Wiener Index was the floodplain pond confluence, followed by Xiaoan Stream with a Shannon-Wiener Index of 3.73. The Shannon-Wiener Index was 0 in the Yuxi Reservoir Head Area and Dagangtou, less than 1 in the upper and middle reaches of Shuige, and 1-2 in the other strata. The Simpson Index ranged between zero and 0.90, with a mean of 0.49. The stratum with the highest Simpson Index was Xiaoan Stream, followed by the pond confluence with a Simpson Index of 0.89. Generally, the diversity index was high in the lower reaches of Shuige in the main stream samples, but low in the remaining strata. The diversity index was higher in Xiaoan Stream than in Songyin Stream, and higher in Jiulong Stream than in Nanshan Pond (Fig. 3-4 and Table 3-5).

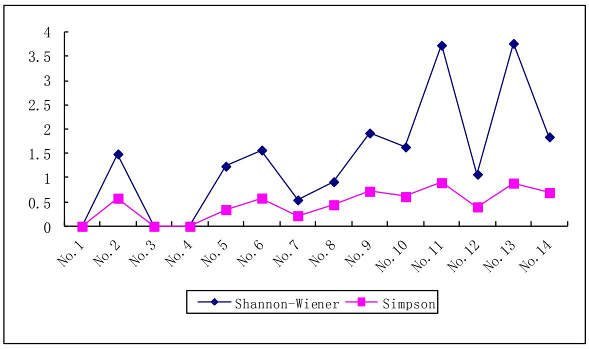

Fig. 3-4 Diversity index change in benthos along the river

Table 3-5 Diversity index of benthos

Sample points	Main streams									Tributaries		Floodplains		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Shannon-Wiener	/	1.491	0	0	1.237	1.571	0.543	0.918	1.921	1.634	3.731	1.071	3.768	1.842
Simpson	/	0.578	0	0	0.343	0.580	0.218	0.444	0.720	0.611	0.899	0.400	0.889	0.693

3.3 Correlation analysis between non-uniformity coefficient of sediments and benthic organisms

The correlation between the non-uniformity coefficient of riverbed sediments and the Shannon-Wiener and Simpson Indexes of benthic organisms at the six survey points, that is, Xiaoan Stream, lower reaches of Shuige, pond confluence, Bihu Bridge, Songyin Stream and Jiulong Stream, are shown in Fig. 3-5 and Fig. 3-6.

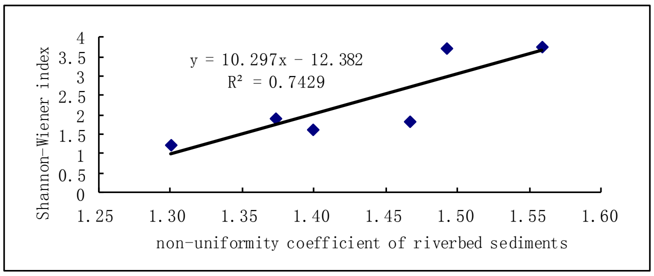

Fig. 3-5 Correlation between non-uniformity coefficient of riverbed sediments and Shannon-Wiener Index of benthic organisms

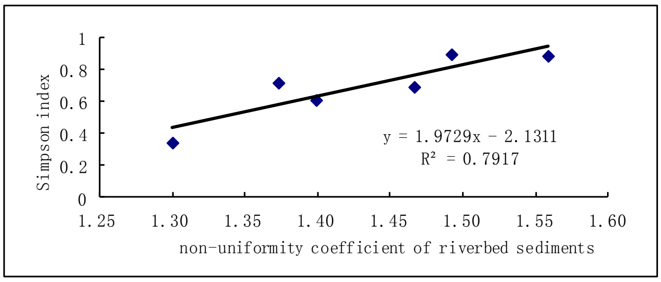

Fig. 3-6 Correlation between non-uniformity coefficient of riverbed sediments and Simpson Index of benthic organisms

Figures 3.5 and 3.6 show that the non-uniformity coefficient of riverbed sediments was significantly positively correlated with the Shannon-Wiener Index and the Simpson Index of benthic organisms, with correlation coefficients of 0.86 and 0.89, respectively.

4 Conclusion

The analysis of riverbed sediment heterogeneity and benthic community diversity as well as the case study show that the representation methods of riverbed sediment heterogeneity by non-uniformity coefficient and benthic community diversity by the Shannon-Wiener and the Simpson Indexes were simple, practical and easily applied. The non-uniformity coefficient of riverbed sediments reflected riverbed sediment heterogeneity. The large non-uniformity coefficient of sediments indicated the rich components of riverbed sediments and the coexistence of both large and small particles, resulting in diversified flow patterns and stable sediment conditions. The pores between large particles (boulders, pebbles, gravel) were enclosed and covered by fine sand, silt and clay, which created a micro-habitat environment rich in nutrients. Thus, characterizing riverbed sediment components may be of practical use by providing design reference for river restoration projects. Species diversity is not only an important community characteristic, but also a composite indicator of number of species in the community, the number of individuals and uniformity indicators. Species diversity not only reflects species richness and changes or uniformity in communities or habitats, but also reflects the relationship between different natural geographical conditions and communities. Under normal circumstances, community species diversity is strongly associated with community stability and succession. The Shannon-Wiener Index is a measure of diversity, which mostly reflects species richness. The Simpson Index, also known as the dominance index, measures the opposite side of diversity, that is, concentration. Both indexes are widely used in the statistical analysis of biological diversity.

Highly positive correlation between the non-uniformity coefficient of the riverbed sediments and benthic community diversity from the studied river reaches showed that the conditions of the riverbed sediments with high non-uniformity coefficient were more conducive to the survival of benthic organisms, and could improve benthic community diversity as well as provide the basis for developing river restoration measures like improving riverbed sediment diversity where high non-uniformity coefficient more easily achieved, e.g. the area of river confluence. However, because the non-uniformity coefficient only reflected riverbed sediment heterogeneity from the aspect of riverbed sediment composition, other heterogeneity characteristics, e.g. riverbed morphology, should be further analyzed with observations or physical experiments. At the same time, the correlative data between substrate heterogeneity and biodiversity should be collected in more time series and sampling points to obtain more detailed and comprehensive results.

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