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Article

Long-Term Changes in the Water Quality and Macroinvertebrate Communities of a Subtropical River in South China

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Abstract: Subtropical rivers support a highly diverse array of benthic macroinvertebrates. In this study, by combining historical data and new data, we identified specific changes in the Guanlan River, in South China, from 1981 to 2011, and evaluated the effectiveness of an ecological restoration project under highly polluted conditions. From 1981 to 2011, the water quality in the Guanlan River underwent three major stages. With the deterioration of water quality, there was an overall decrease in the species number of macroinvertebrates in the Guanlan River, an increase in macroinvertebrate density, and a reduction of the biodiversity, and a reduction of functional feeding groups. In 2011, after five years of comprehensive remediation, the Guanlan River was somewhat improved. Macroinvertebrate biodiversity in the middle reach of the Guanlan River, where a key ecological restoration engineering project was implemented, did not differ significantly from other sites. This finding indicates that the effectiveness of ecological restoration measures in highly polluted rivers, particularly at the reach-scale, is very limited and even ineffective.

Keywords: macroinvertebrates; high pollution; biodiversity; functional feeding groups; subtropical areas; developing country

1. Introduction

River ecosystems fulfil numerous functions for human populations, such as water supplies for industries, agriculture, transportation, power generation, and socio-economic development [1]. However, rapid population growth, industrialisation, and associated urbanisation exert pressure on water resources worldwide, particularly in developing countries [2,3]. This pressure on river ecosystems has become very evident in eastern and southern Asian areas, particularly in China, where the economy is rapidly developing [4]. The majority of studies on river ecosystems have focused on water quality (e.g., nitrogen and phosphorus), and most were conducted in developed countries with temperate climates (namely American and European catchments). Scientific analyses and assessments of human influences on regional river ecosystems are considerably lacking in subtropical areas, where ecosystems are more sensitive to urbanisation and biodiversity is at greater risk. There is an urgent need for sustainable management of subtropical river systems.

River ecosystems consist of biotic components and the abiotic environment; the biotic components play a greater role in the evolution of the river ecosystem [5]. Degradation and loss of aquatic organisms can lead to the reduction or even loss of the self-purification capacity of river ecosystems. Thus, biological indicators have been identified and widely applied in the assessment regime of river health [6,7].

Macroinvertebrates are the middle link of the food chain in river ecosystems. By playing a central role in energy flow and material cycling, macroinvertebrates directly influence the survival and reproduction of other taxa [6,8]. Different macroinvertebrate taxa have different sensitivities and tolerance capabilities to environmental conditions (e.g., organic matter, eutrophication, acidity and acidification) [9–11]. These taxa are very sensitive to environmental changes such as disturbance, deterioration, and improvement. Their life cycles are relatively long, but their migration ability is relatively weak. Therefore, macroinvertebrates can reflect the comparatively long-term temporal and spatial changes of river ecosystems and can predict future problems [12–16]. Macroinvertebrates are the most widely used bioindicators of river health status [6,13].

Rapid urbanisation and industrialisation and a lack of scientific management have significant adverse effects on river ecosystems. This study was conducted to understand the long-term changes in rivers in areas of rapid economic development in subtropical zones and assess the effect of ecological restoration measures in highly polluted rivers. The analysis used 30 years of hydrochemical and macroinvertebrate community data from the Guanlan River in the subtropical region of China. The objectives of the study were to (1) identify the specific events or changes in the Guanlan River that have triggered improvement or deterioration during the 30-year-period between 1981 and 2011; (2) evaluate the temporal relationships between the water quality regime and macroinvertebrate communities in the Guanlan River; and (3) evaluate the probability and efficiency of ecological restoration measures to improve the ecological status of the Guanlan River.

2. Materials and Methods

2.1. Study Area

The Guanlan River flows through the north-central area of Shenzhen City, then from south to north before passing through Longhua Township and Guanlan Township, and finally merges with the Dongjiang River (Figure 1). The Guanlan River is upstream of a first-order tributary, the Shima River of the Dongjiang River. The Dongjiang River is the third largest tributary of the Pearl River water system. The main stream length of the Guanlan River within Shenzhen City is 23.3 km, and its catchment area is 189.3 km^2. The river's mean longitudinal river slope is 2.18‰, and its width (water width) ranges from 8.5 to 38.0 m. The mean monitored flow velocity was 0.29 m/s in 2011. The substrates mostly consist of sandy materials and occasionally rough sands or gravels. The terrain of this catchment area can be characterised as a hilly gully area. The soil within this catchment area consists mainly of red earth, with a deep weathered horizon. The soils consist of as much as 70% sand. This area is located in a subtropical zone with a monsoon climate. The multi-year mean temperature is 22 °C and the multi-year mean rainfall is 1800 mm. Flood season is from April to September, which accounts for 85%–90% of the annual rainfall.

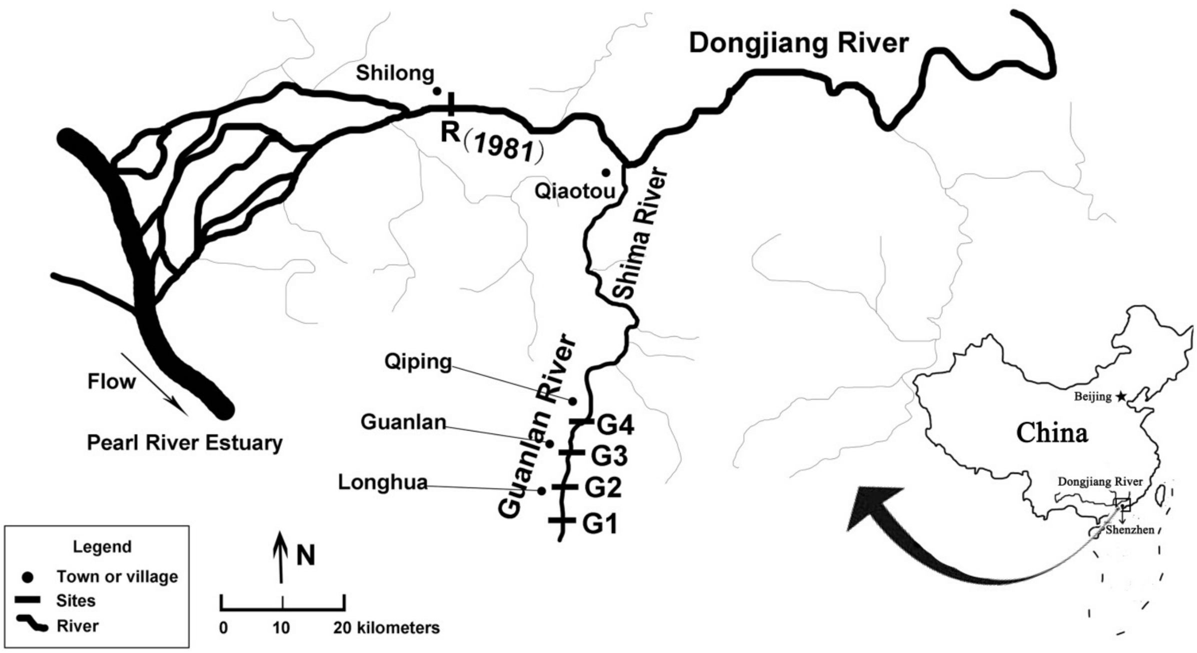

Figure 1. Study area and sampling sites. R was the sampling site (Shilong site) in 1981. G3 was the sampling site in 2006. G1, G2, G3 and G4 were the sampling sites in 2011. The G3 site was located at the Qinghu reach, where a key ecological restoration engineering project was implemented in 2007.

During the period of 1981–2011, rapid urbanisation and industrialisation and a lack of scientific management led to the use of the Guanlan River as the primary channel for receiving sanitary sewage and industrial wastewater. The water quality of the Guanlan River continuously deteriorated, and water pollution has seriously limited further economic development. The municipal government of Shenzhen has consequently decided to restore the Guanlan River and improve its water quality. From 2006 to 2010, Shenzhen's municipal government invested a total of 1.32 billion RMB (211.33 million USD) to remediate the Guanlan River, including 634 million RMB (101.50 million USD) to establish two wastewater treatment plants along the river and 500 million RMB (80.05 million USD) to engineer translocation wastewater via box culverts. The ecosystem within 1.5 km of the middle stream of the Guanlan River (Figure 1, G3 site) was the focal point of the ecological restoration (186 million RMB, equivalent to 29.79 million USD). In 2007, a key ecological restoration engineering project was implemented in the middle stream of the Guanlan River. The major ecological restoration measures included the construction of an artificial wetland (35 million RMB, equivalent to 5.60 million USD) along the river for deep purification of tail water from the Longhua Waste Water Treatment Plant, ecological bank protection, and ecological landscape river renovation (e.g., the creation of an overflow dam, a waterfront leisure area and walking path, and a riparian forest and hygrophyte; 151 million RMB, equivalent to 24.18 million USD). However, only a box culvert project for channelling wastewater was implemented upstream (G1 site and G2 site in 2011) and downstream (G4 site in 2011) of the Guanlan River. The main purpose of the box culvert project was to directly control the water quality of the Guanlan River.

2.2. Data Collection Methods

Data were collected from the literature and the field. The 1981 macroinvertebrate data and the 2006 data were obtained from literature [17,18]. We collected the 2011 data from the sampling sites shown in Figure 1. From 1981 to 1982, Lai conducted a survey of the Pearl River water system in Guangdong province [17]. He conducted a survey on the macroinvertebrates at 16 sampling sites located upstream, midstream and downstream of the main branches of the Dongjiang River. The Shilong sampling site (Figure 1, R site, 23°6'20" N, 113°52'28" E) was located approximately 29 km downstream of the merging point with the Shima River (Guanlan River). The data acquired from this survey represented the survival status of macroinvertebrates in the Dongjiang River water system before the beginning of economic reform and rapid development. The data from the Shilong sampling site served as background data for the catchment area of the Guanlan-Shima River. In 2006, prior to the beginning of the key ecological restoration engineering project, the Shenzhen Water Planning and Design Institute conducted a survey of the aquatic ecology (Figure 1, G3 site at Qinghu reach). These macroinvertebrate data represent the ecological status of the Guanlan River catchment after more than 20 years of economic reform and development. In 2011, we conducted a survey of macroinvertebrates at four sampling sites located upstream, midstream and downstream of the Guanlan River (Figure 1, Table 1). The survey results comprehensively reflected the water's general ecological status within the Guanlan River after five years of comprehensive remediation. In 2011, macroinvertebrates were collected at four sites (Figure 1, Table 1; G1 site, G2 site, G3 site, G4 site) using quantitative Surber samplers (420 μm mesh, 30 cm × 30 cm). At each sampling site, samples were collected in February and September during the low water level period and flood period, respectively. Three replicates from each site were collected at each sampling period. The macroinvertebrate samples were fixed in 4% formaldehyde and brought to the laboratory for classification, identification, and weighing. Some macroinvertebates were identified at the species level, whereas others were identified at the genus level and distinguished as species.

Table 1. Sampling sites in 2011.

Sites	Longitude and Latitude	Comments
G1 site	22°38'22" N, 114°2'38" E	The upstream origin of the Guanlan River
G2 site	22°39'52" N, 114°2'19" E	The merging point of the Longhua River branch
G3 site	22°41'10" N, 114°2'25" E	The midstream site at Qinghu reach
G4 site	22°44'7" N, 114°3'32" E	The downstream site at Guihua Village

The water quality data from 1981 to 2006 were collected from the literature [18–23]. The water quality data in 2011 were collected in the field at the same time as the macroinvertebrate samples. Three water samples from each site were collected, mixed, and used to represent the water quality at that location. The water samples were brought to the laboratory and measured according to China's National Environmental Quality Standards for Surface Water (BOD_5: dilution and seeding method; COD: potassium dichromate method; NH_4-N: Nessler's reagent colourimetry; TN: alkaline potassium persulphate digestion-UV spectrophotometric method.) [24]. The analytical methods for water quality were the same in the 1981–1993 period, 2006, and 2011.

2.3. Metrics Selection and Calculation Methods

The hydrological process is a key element of river ecosystem maintenance. However, we did not include hydrological indices in this study because of a lack of historical monitoring data for hydrological conditions over time and a lack of significant differences in hydrological conditions (e.g., water flow rate and volume) among the upstream, midstream and downstream areas of the Guanlan River.

The water quality of the Guanlan River is mainly influenced by industrial wastewater and agricultural and sanitary sewage. The Guanlan River is representative of rivers polluted by oxygen-consuming organic substances and nutritional concentration [19,25]. Thus, in this study, four chemical indicators—BOD_5, COD, NH_4-N, and TN—were selected as the indicators to analyse the changes in environmental conditions in the Guanlan River.

Indices of macroinvertebrates, such as species diversity, density, biomass, tolerance value, and functional feeding groups, reflect changes in water quality and types of macroinvertebrate communities. Functional feeding groups reflect the nutritional structures of macroinvertebrate communities and can provide information about the functions and process of river ecosystems [26,27], water quality status [28] and river ecosystem integrity [29]. In our study, five indices—taxa richness, Shannon-Wiener diversity index, density, biomass, and functional feeding groups—were used as indicators to analyse the changes in macroinvertebrate communities. According to the methods of Merritt, Cummins and Duan *et al.*, macroinvertebrates were divided into five functional feeding groups: collector-filterer, collector-gatherer, scraper, shredder, and predator [6,30]. The Shannon-Wiener diversity index was calculated using Equation (1) [31]:

$$H = -\sum_{i=1}^{S} P_i \log_2 P_i \quad (1)$$

where H is the diversity index, S is the number of species, and P_i is the ratio of the individuals in the ith genus to total individuals.

The historical data were reabstracted, reclassified, and rearranged and uniformly analysed along with the new data obtained in 2011. Combined, these data reflect the changes in water quality and macroinvertebrate communities in the Guanlan River within Shenzhen City over a 30-year period.

2.4. Data Analysis

To examine the relationship between the Shannon-Wiener diversity index of macroinvertebrates and the number of species within the water quality indices, Pearson correlation analysis was conducted using Version 18.0 of SPSS. The results are expressed as Pearson correlation coefficients.

3. Results

3.1. Analyses of Water Pollution

The changes in the water quality of the Guanlan River between 1981 and 2011 are depicted in Figure 2. The results indicate that the water quality of the Guanlan River underwent three stages of change associated with economic development during the 30-year period (Figure 2). The first stage was a slow pollution period from 1981 to 1993. The second stage was a rapid pollution period from 1993 to 2006. In the third stage between 2006 and 2011, there was a gradual improvement in water quality.

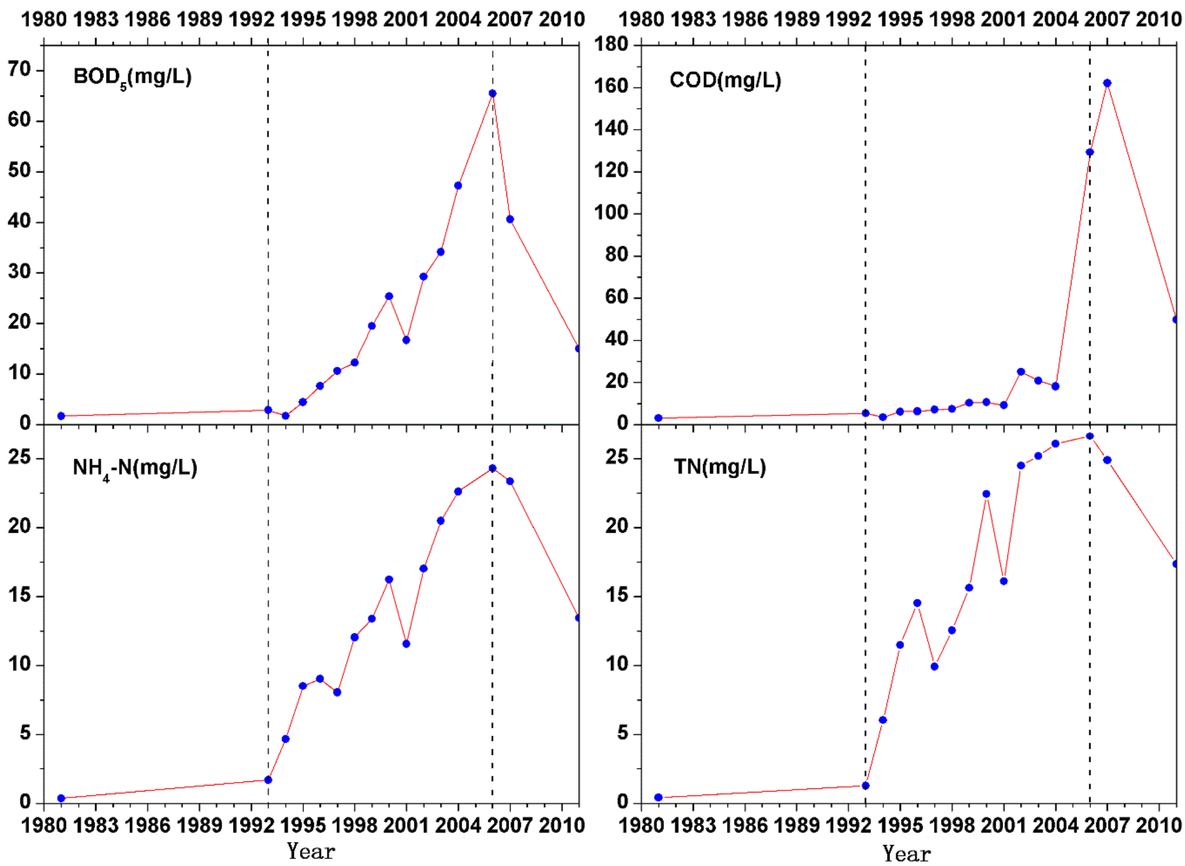

Figure 2. Thirty-year changes in water quality in the Guanlan River. The data from 1981 to 2006 were collected from the literature [18–23]. The 2011 data were obtained from the field.

The key periods of changes in water quality are outlined in Table 2. In 1981, the Guanlan River was generally in a non-polluted state. In 1993, the Guanlan River was moderately polluted. The BOD_5 index was in Grade I. The TN index most exceeded the norm level by the greatest amount and was in Grade V. Until 1999, the four indices were all in Grade V or lower. By 2006, the concentrations of these pollutants reached historical peak levels that were 38- to 67-fold higher than those in 1981 and exceeding Grade V by 3–13-fold. Thus, the Guanlan River was in an extremely polluted state. In 2011, after five years of comprehensive remediation, the concentrations of the four indices were reduced, but water quality still failed to exceed Grade V; in fact, the four indices were 1–8-fold higher than those of Grade V. The Guanlan River thus failed to meet the Grade III drinking water requirements because it was still in a highly polluted state.

Table 2. Water quality in the Guanlan River during the 30-year period between 1981 and 2011. Data for 1981–2006 were collected from the literature [18–23]. The 2011 data were obtained from the sampling sites.

Period of Change		BOD_5 (mg/L)	COD (mg/L)	NH_4-N (mg/L)	TN (mg/L)
Guanlan river	First period (1981–1993)	1.69–2.87 (I-I)	3.08–5.37 (II-III)	0.36–1.68 (II-V)	0.41–1.72 (II-V)
	Second period (1993–2006)	2.87–65.53 (I-V+)	5.37–129.30 (III-V+)	1.68–24.30 (V-V+)	1.72–26.64 (V-V+)
	Third period (2006–2011)	65.53–15.40 (V+-V+)	129.30–49.76 (V+-V+)	24.30–13.44 (V+-V+)	26.64–17.35 (V+-V+)
National environmental quality standards for surface water	I	≤3	≤2	≤0.15	≤0.2
	II	≤3	≤4	≤0.5	≤0.5
	III	≤4	≤6	≤1.0	≤1.0
	IV	≤6	≤10	≤1.5	≤1.5
	V	≤10	≤15	≤2.0	≤2.0

Notes: Grades I, II, III, IV and V in Table 2 are China's National Environmental Quality Standards for Surface Water. Grade I is the best, and Grade V is the worst. Poorer than Grade V is inferior V (V+).

3.2. Structural and Functional Changes in Macroinvertebrate Communities

3.2.1. Structural Changes in Macroinvertebrate Communities

The important years for the study of macroinvertebrate community status are indicated in Figure 3 and Table 3.

Figure 3a indicates that, in 1981, the macroinvertebrates collected at the R sampling site (Figure 1, Shilong site) included two phyla, 14 families, 21 genera, and 30 species These macroinvertebrates included molluscs and arthropods (*i.e.*, crustaceans and aquatic insects). In 2006, before restoration, only one species of macroinvertebrate was found in the Guanlan River. In 2011, after five years of comprehensive remediation, the macroinvertebrates collected in the Guanlan River included three phyla, eight families, 14 genera, and 14 species. The original 18 species of mollusc were replaced by four new species of mollusc. Five new pollution-tolerant species of Annelida (Oligochaeta) were identified in the samples collected in 2011.

Figure 3b shows that the Shannon-Wiener diversity index for the R sampling site (Shilong site) was 2.49 in 1981. The species and macroinvertebrate community compositions were relatively rich and uniform. In 2006, before restoration, the Shannon-Wiener diversity index was zero in the Guanlan River. In 2011, after five years of comprehensive remediation, the Shannon-Wiener diversity index was 1.61. During the 30-year period, the Shannon-Wiener diversity of the macroinvertebrates in the Guanlan River decreased by 35.48% overall. However, the comprehensive remediation engineering project increased the macroinvertebrate diversity in the Guanlan River.

Figure 3c,d show that the density of the macroinvertebrates in the R sampling site (Shilong site) in 1981 was 59.20 individual/m^2 and the biomass was 53.29 g/m^2. In 2006, before restoration, the density of the only species of macroinvertebrate (tubifex) reached 3600 ind./m^2, and the biomass was 5.44 g/m^2. The macroinvertebrate density in the Guanlan River was substantially higher in 2011, reaching as much as 4203.25 ind./m^2 with a biomass density of 74.67 g/m^2. In terms of species abundance, a few pollution-tolerant species dominated absolutely. After implementation of the comprehensive remediation engineering project, structural changes occurred in the macroinvertebrate communities, and biomass was gradually restored.

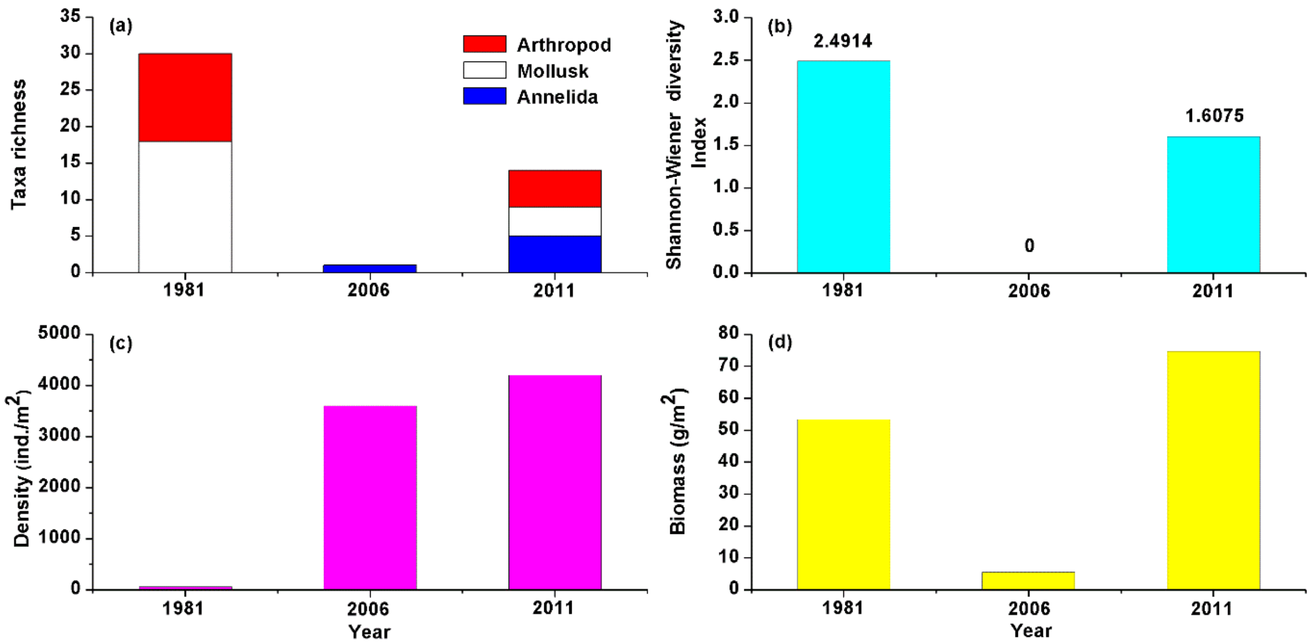

Figure 3. Changes in the composition of macroinvertebrate communities in the Guanlan River during the 30-year period from 1981 to 2011. (**a**) Taxa richness; (**b**) Shannon-Wiener diversity index; (**c**) Density; (**d**) Wet weight. The 1981 and 2006 data were obtained from the literature [17,18]. The 2011 data were collected from the field.

Table 3. The taxa list for the three sampling periods. The 1981 and 2006 data were collected from literature [17,18]. The 2011 data were obtained from the field.

1981	2006	2011
Cipangopaludina chinensis	*Tubifex* sp.	*Physa foncinalis*
Bellamya aeruginosa	-	*Bithynia fuchsiana*
Bellamya limnophila	-	*Semisulcospira libertina*
Bellamya purificata	-	*Hippeutis umbilicalis*
Angulyagra polyzonata	-	*Procladius choreus*
Melanoides tuberculata	-	*Pelopia* sp.
Radix auricularia	-	*Chironomus attenuatus*
Radix swinhoei	-	*Cricotopus trifasciatus*
Limnoperna lacustris	-	*Psychoda* sp.
Unio douglasiae	-	*Tubifex sinicus*
Lanceolaria grayana	-	*Limnodrilus hoffmeisteri*
Lamprotula leai	-	*Monopylephorus limosus*
Anodonta woodiana woodiana	-	*Branchiura sowerbyi*
Anodonta woodiana pacifica	-	*Nais variabilis*
Anodonta woodiana elliptica	-	-
Anodonta lucida	-	-
Corbicula fluminea	-	-
Corbicula nitens	-	-
Somanniathelphusa sinensis	-	-
Sesarma dehaani	-	-
Macrobrachium nipponensis	-	-
Macrobrachium sp.	-	-
Macrobrachium hainanense	-	-
Odonata sp.	-	-
Lethocerus indicus	-	-
Sphaerodema rustica	-	-
Enithares sinica	-	-
Notoerta montandoni	-	-
Cybister sp.	-	-
Chironomidae sp.	-	-

3.2.2. Structural Changes in the Compositions of the Functional Feeding Groups

As shown in Figure 4, in 1981 before water degradation, the species composition of macroinvertebrate functional feeding groups at the R sampling site in the Guanlan River was as follows: 33.33% collector-filterers, 26.67% scrapers, 20.00% predators, 16.67% shredders, and 3.33% collector-gatherers. The functional feeding groups were full, and the nutritional structures were complete. Before the Guanlan River was remediated in 2006, there was only one macroinvertebrate species of collector-gatherer that was pollution-tolerant, which accounted for 100% of all macroinvertebrates. In 2011, the composition of the macroinvertebrate functional feeding groups in the Guanlan River was as follows: 28.57% scrapers, 14.29% predators, and 57.14% collector-gatherers. The collector-filterers and the shredders, which are sensitive to pollution, were both absent. The nutritional structure of the macroinvertebrates in the Guanlan River underwent dramatic changes from 1981 to 2011; collector-gatherers increased by 1615.9%, and the important shredders disappeared.

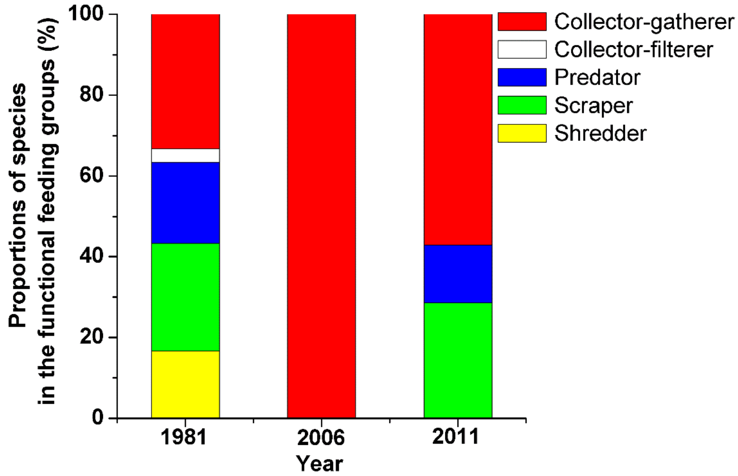

Figure 4. Changes in the composition of the functional feeding groups. The 1981 and 2006 data were collected from the literature [17,18]. The 2011 data were obtained from the field.

3.3. Responses of River Ecosystems to Water Pollution

Between 1981 and 2011, both water quality and macroinvertebrate communities in the Guanlan River underwent continuous change (Figure 5). Overall, the macroinvertebrate species diversity dramatically decreased as concentrations of oxygen-consuming organic pollutants and nutritional elements increased. In 2006, when water pollution was most severe, only one species of macroinvertebrate was identified in the Guanlan River. The Shannon-Wiener diversity index was zero. With comprehensive remediation of the Guanlan River, ecological restoration became evident; water quality was gradually restored, and concentrations of pollutants were reduced. Simultaneously, the species richness of the macroinvertebrate communities greatly increased.

Table 4 provides the correlations between the water quality index, taxa richness, density, macroinvertebrate biomass, and the Shannon-Wiener diversity index, calculated using the data from the four sites during February and September of 2011. The Shannon-Wiener diversity index revealed a significant negative correlation with the four indices of water quality, indicating that the deterioration of the water quality within the ecosystems in the Guanlan River was the key factor in species decline in the macroinvertebrate communities. The results of the Pearson correlation analysis (Table 4) are consistent with the correlation of macroinvertebrate diversity and water quality indices in Figure 5. However, in 2011, the macroinvertebrate species number at each site exhibited a highly significant positive correlation with the indices of water quality.

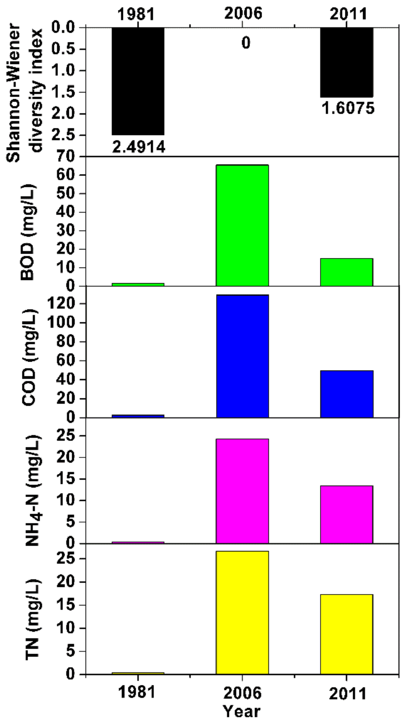

Figure 5. Relative changes in the macroinvertebrate diversity index and water quality indices.

Table 4. Correlations between macroinvertebrates indices of and water quality indices. The data are from February and September 2011.

Indices	BOD	COD	NH_4-N	TN
Taxa richness	0.552 **	0.559 **	0.606 **	0.542 **
Shannon-Wiener diversity index	−0.409 *	−0.477 *	−0.468 *	−0.454 *
Density	0.102	0.058	0.338	0.265
Biomass	0.044	0.132	0.237	0.263

Note: The data presented are Pearson correlation coefficients ($n = 6$). * indicates that these two indices were significantly correlated ($p < 0.01$). ** indicates that these two indices were extremely significantly correlated ($p < 0.001$).

3.4. Impacts of the Ecological Restoration

The distributions of the macroinvertebrate communities of the four sites upstream (G1 site, G2 site), midstream (G3 site) and downstream (G4 site) of the Guanlan River (Figure 1), after five years of comprehensive remediation, are shown in Figure 6. The Shannon-Wiener diversity index and biomass were highest at the G3 midstream site (Qinghu reach), where key ecological restoration has been conducted. The degree of improvement in macroinvertebrates was higher at the G3 site than the G1, G2, and G4 sites. While the taxa richness at the G1 site was greater than that at the G3 site, its degree of uniformity was lower. The ratio of the number of the most pollution-tolerant Oligochaeta species to the total number of species was higher at the G1 site than the G3 site, leading to an overall poorer situation than that at the G3 site. The restoration of macroinvertebrates in the reach of the middle stream of the Guanlan River (G3 site), where ecological restoration has been conducted, was superior to that of sites in the upper and lower stream reaches, where only sewage interception and pollution transport have been implemented.

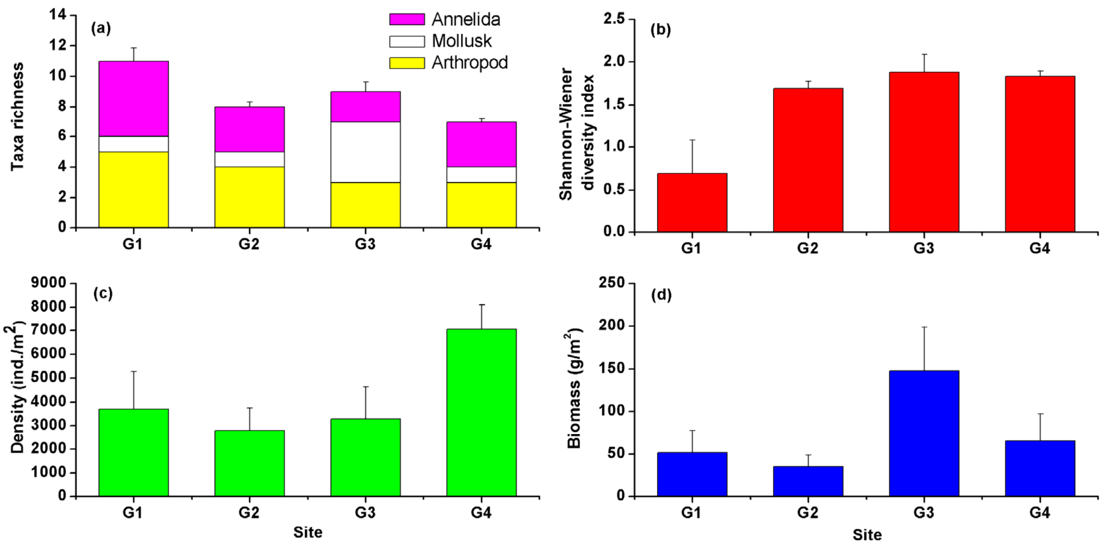

Figure 6. Spatial distributions of macroinvertebrates in the Guanlan River after five years of comprehensive remediation. Data are provided as a 2011 average, with SE error bars ($n = 6$). (**a**) Taxa richness; (**b**) Shannon-Wiener diversity index; (**c**) Density; (**d**) Wet weight.

4. Discussion

The changes in water quality in the Guanlan River have been synchronous with the speed of regional economic development. The dramatic economic and urban development over the last three decades has caused extensive ecological degradation of streams and rivers [32]. Shenzhen City is representative of the rapid economic development in China. The Guanlan River is one of five major rivers in Shenzhen City. Globally, serious pollution due to regional economic development has also been documented in the Rhine River. The Rhine River, a substantial contributor to European economic development, was in its most seriously polluted state in 1971 and completely lost its self-purification capability [33,34]. The Guanlan River was in its most seriously polluted state in 2006 (Figure 2, Table 2). The COD concentration in the Guanlan River in 2006 was comparable to that of the Rhine River in 1971, but the Guanlan River's BOD concentration was more than four times the poorest BOD concentration in the Rhine River. The Guanlan River's NH_4-N concentration was nearly 10 times that of the Rhine River in 1971. The extremely high concentrations of both BOD and NH_4-N indicate that the disorderly disposal of untreated sanitary sewage is the major cause of pollution. In contrast to developed countries, point-source pollution (particularly untreated organic pollution) remains the leading cause of river water quality degradation in developing countries [35]. Existing pollution legislation is generally not effectively enforced in developing countries such as China [36]. In addition to releasing incompletely treated industrial wastewater, the sewage resulted in a highly polluted status. Because of a partial or even complete lack of municipal facilities, sanitary sewage has become the major and permanent pollutant source in regional rivers. Degradable organic substances and nutritional salts are the major pollutants.

The deterioration of water quality in the Guanlan River has inflicted serious damage on macroinvertebrate communities. Analyses of the 2011 surveyed data revealed that macroinvertebrate diversity was significantly negative correlated with water quality (Table 4). Degradation of water quality is a serious threat to the diversity of freshwater organisms, and organic pollutants have a significant impact on community compositions and the structures and functions of river macroinvertebrates [37–42].

Water quality deterioration is the underlying cause of extensive damage to macroinvertebrate communities. Degradable organic substances and nutritional salts decrease dissolved oxygen, resulting in the disappearance of intolerant groups of macroinvertebrates. The rate of macroinvertebrate disappearance in the Guanlan River is 6.4-fold higher than that of the Rhine River [34]. Although the number of macroinvertebrate species increased to 14 after comprehensive remediation in 2011, the compositions and structures of the macroinvertebrate communities changed greatly. The density sharply increased from 59.20 ind./m^2 in 1981 to 4203.25 ind./m^2, an increase of more than 70-fold. Furthermore, pollution-tolerant species (*i.e.*, those species with a pollution-tolerance value of 7–10 [43]) accounted for 93.7% of the total species and included mainly Oligochaeta, Gastropoda, and Chironomidae. The presence of these macroinvertebrate taxa also indicates that the river was in a state of organic pollution [44]. The number of macroinvertebrate species has been shown to decrease under conditions of pollution and shift to pollution-tolerant species (e.g., tubificid worms and Chironomidae) [45–48], consistent with the results of this study. The dominance of a few pollution-tolerant species induces instability in macroinvertebrate communities and reduces the ability of the communities to resist external forces (such as flooding) and their restoration ability. Furthermore, the reduction of species diversity and changes in species compositions influence the processes within ecosystems [49] and reduce the effectiveness of ecosystem services [50].

During the 30-year period from 1981 to 2011, the macroinvertebrate communities in the Guanlan River underwent structural simplification of functional feeding groups and the loss of key functional feeding groups. Although the proportion of scrapers in the functional feeding groups in 2011 was comparable to that in 1981, shredders completely disappeared. Shredders are very sensitive to environmental changes [51], indicating serious degradation in the water quality of the Guanlan River due to pollution. Merritt and Cummins have suggested that the ratio of collector-filterers to collector-gatherers in rivers that have not been polluted should be greater than 0.5, while the ratio of shredders to collectors should be greater than 0.25 [30]. In 1981, the macroinvertebrates in the Guanlan River followed these ratios, but the values of these indices decreased to zero by 2011. The deterioration of water quality in the Guanlan River led to a decrease in macroinvertebrate species diversity, greatly simplifying the macroinvertebrate community structure, which led, in turn, to inefficient utilisation of primary producers (floating algae and benthic algae) within the river ecosystems and increased the potential for algal bloom outbreaks. In addition, this simple macroinvertebrate community cannot provide sufficient food for higher-level feeders, such as fish, further increasing ecosystem degradation in the Guanlan River.

Over the last several decades, various river restoration projects have been implemented throughout the world. These efforts have been directed at a variety of types of damaged rivers and had different restoration goals [52]. Restoration technologies in China are still in the preliminary and exploratory stage, and they are mainly focused on water quality restoration. However, the restoration of the Rhine River, a successful example of "pollution first and then restoration," focused on its catchment area and employed an ecosystem-level approach [34]. Although the pollution of rivers in China is relatively recent, this pollution is more serious and occurred more rapidly. Developing appropriate schemes for restoring of China's polluted rivers remains challenging.

In its highly polluted state, the implementation of ecological measures to restore the Guanlan River ecosystem improved water quality and macroinvertebrate communities, although with low efficiency, slow speed and high cost. The water quality in the Guanlan River was poorest in 2006. Between 2006 and 2010, Shenzhen City implemented a comprehensive remediation engineering project in the Guanlan

River. A key ecological restoration project was implemented in Qinghu reach (G3 site) midstream in the Guanlan River. As a result, the overall water quality of the Guanlan River was significantly higher in 2011 than in 2006. The water quality in the key ecological restoration reach (the G3 site) did not still achieve the water quality standards of Grade III. The macroinvertebrate survey results indicate that the status of macroinvertebrates was better in 2011 than in 2006. Furthermore, the diversity and biomass of the macroinvertebrates at the G3 site were greater than those at upstream or downstream sites in the Guanlan River, where ecological measures for ecosystem restoration were not implemented. However, the differences in diversity and biomass were not statistically significant. Correlation analysis indicated that there were significant negative correlations between water quality and macroinvertebrate species diversity. However, the Pearson correlation coefficient was only 0.4–0.5, which indicates that, in addition to water quality, other factors (such as environmental media) are also responsible for the macroinvertebrate decline in the Guanlan River. A study of North American rivers by Allan and Flecker indicated that water pollution accounted for only 38% of the changes in macroinvertebrates [53]. This result suggests that ecological restoration measures should also consider improving other environmental conditions. The Guanlan River basin underwent rapid urbanisation and industrialization during the period of 1981–2011. Besides hydrological and geomorphological modification, urban streams elevate nutrient and contaminant concentrations [54]. Urbanisation poses an increasing threat to the biodiversity and services provided by aquatic ecosystems world-wide [55]. Efforts to restore biodiversity and ecological function in streams and rivers degraded by substantial land use change or by human activities such as urbanisation, development, and channelization have proved to be much more difficult [56,57]. In America, there has been widespread improvement in the water quality and biota of many urban waterways since the implementation of the Clean Water Act in the 1970s [58]. While investigating the effects of stream rehabilitation on several large rivers in the United Kingdom, Harrisonet *et al.*, also saw modest improvement of macroinvertebrate abundance and diversity [59]. Mueller *et al.*, suggested that although instream restoration measures could contribute to freshwater biodiversity conservation, reproductive success of species depending on long-term improvement of interstitial water quality cannot be achieved without considering catchment effects and natural substratum dynamics [60]. For every measured reach- and patch-scale attribute, Violin *et al.*, found that restored streams were indistinguishable from their degraded urban stream counterparts. Their study suggests that reach-scale restoration is not successfully mitigating for the factors causing physical and biological degradation [54]. The effects of reach-scale restoration engineering on the ecological restoration of an entire catchment area are inherently limited [52,54], as confirmed by our study.

5. Conclusions

In summary, the results of this study indicate that the water quality of the Guanlan River underwent three major periods from 1981 to 2011. The changes in the macroinvertebrate community were synchronous with changes in water quality in the Guanlan River. The recovery rate of macroinvertebrate communities has lagged behind the improvement of water quality in the Guanlan River. Ecological restoration, particularly at the river-reach scale, is very limited and even ineffective under highly polluted conditions. These results represents a case study for better understanding long-term changes in subtropical rivers and provide a scientific basis for the identification of sustainable water policy options and management strategies for the Guanlan River and similar rivers in subtropical areas.

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Author Contributions

Kun Li and Haijun Yang planned the research. Kun Li, Zhenxing Zhang, and Hongyong Xiang gathered empirical data. Kun Li performed analysis. Kun Li wrote the first draft of the manuscript. All authors contributed substantially to revisions.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Jackson, R.B.; Carpenter, S.R.; Dahm, C.N.; McKnight, D.M.; Naiman, R.J.; Postel, S.L.; Running, S.W. Water in a changing world. *Ecol. Appl.* **2001**, *11*, 1027–1045.
2. Al-Shami, S.A.; Md Rawi, C.S.; Ahmad, A.H.; Abdul Hamid, S.; Mohd Nor, S.A. Influence of agricultural, industrial, and anthropogenic stresses on the distribution and diversity of macroinvertebrates in Juru River Basin, Penang, Malaysia. *Ecotox. Environ. Safe* **2011**, *74*, 1195–1202.
3. Friberg, N.; Bonada, N.; Bradley, D.C.; Dunbar, M.J.; Edwards, F.K.; Grey, J.; Hayes, R.B.; Hildrew, A.G.; Lamouroux, N.; Trimmer, M. Biomonitoring of human impacts in freshwater ecosystems: The good, the bad and the ugly. *Adv. Ecol. Res.* **2011**, *44*, 1–68.
4. Zhang, Y.; Dudgeon, D.; Cheng, D.; Thoe, W.; Fok, L.; Wang, Z.; Lee, J.H.W. Impacts of land use and water quality on macroinvertebrate communities in the Pearl River drainage basin, China. *Hydrobiologia* **2010**, *652*, 71–88.
5. Niu, C.J.; Lou, A.R.; Sun, R.Y.; Li, Q.F. *Basic Ecology*, 2nd ed.; Higher Education Press: Beijing, China, 2007. (In Chinese)
6. Duan, X.H.; Wang, Z.Y.; Xu, M.Z. *Benthic Macroinvertebrate and Application in the Assessment of Stream Ecology*; Tsinghua University Press: Beijing, China, 2010. (In Chinese)
7. Norris, R.H.; Thoms, M.C. What is river health? *Freshwater Biol.* **1999**, *41*, 197–209.
8. Bao, Y.X.; Ge, B.M.; Zheng, X.; Cheng, H.Y. Spatial distribution and seasonal variation of the macrobenthic community on tidal flats of Tianhe, Wenzhou Bay. *Acta Zool. Sin.* **2006**, *52*, 45–52. (In Chinese)
9. De Pauw, N.; Gabriels, W.; Goethals, P.L. River monitoring and assessment methods based on macroinvertebrates. In *Biological Monitoring of Rivers*; Ziglio, G., Flaim, G., Siligardi, M., Eds.; John Wiley & Sons: Chichester, UK, 2006; pp. 113–134.

10. Murphy, J.F.; Winterbottom, J.H.; Orton, S.; Simpson, G.L.; Shilland, E.M.; Hildrew, A.G. Evidence of recovery from acidification in the macroinvertebrate assemblages of UK fresh waters: A 20-year time series. *Ecol. Indic.* **2014**, *37*, 330–340.
11. Nguyen, H.H.; Everaert, G.; Gabriels, W.; Hoang, T.H.; Goethals, P.L.M. A multimetric macroinvertebrate index for assessing the water quality of the Cau river basin in Vietnam. *Limnologica* **2014**, *45*, 16–23.
12. Dos Santos, D.; Molineri, C.; Reynaga, M.; Basualdo, C. Which index is the best to assess stream health? *Ecol. Indic.* **2011**, *11*, 582–589.
13. Karr, J.R. Defining and measuring river health. *Freshwater Biol.* **1999**, *41*, 221–234.
14. Shao M.L.; Xie, Z.C.; Ye, L.; Cai, Q.H. Monthly change of community structure of zoobenthos in Xiangxi Bay after impoundment of three gorges reservoir. *Acta Hydrob. Sin.* **2006**, *30*, 64–69. (In Chinese)
15. Smith, M.; Kay, W.; Edward, D.; Papas, P.; Richardson, K.S.J.; Simpson, J.; Pinder, A.; Cale, D.; Horwitz, P.; Davis, J. AusRivAS: Using macroinvertebrates to assess ecological condition of rivers in Western Australia. *Freshwater Biol.* **1999**, *41*, 269–282.
16. Wang, B.X.;Yang, L.F. A study on tolerance values of benthic macroinvertebrate taxa in eastern China. *Acta Ecol. Sin.* **2004**, *24*, 2768–2775. (In Chinese)
17. Lai, Z.X. Survey on benthic macroinvertebrate in Dongjiang River water system in Guangdong province. *Freshw. Fish* **1988**, *21*, 28–34. (In Chinese)
18. Fu, G.P.; Zhu, W.B.; Li, C.F.; Huang, Y.L. Research on the ecological restoration project of the qinghu channel, the Guanlan River in Shenzhen. *China Rural Water Hydropower* **2008**, *34*, 57–61. (In Chinese)
19. Wu, H.R.; Li, L.L. The changing trend in water quality pollution in Baoan Disrict section of Guanlan River in Shenzhen City and the strategy for prevention and treament. *Guangzhou Environ.* **2000**, *15*, 42–44. (In Chinese)
20. Dongguan City Sanitation and Antiepidemic Station. Survey on the reform of rural drinking water in Dongguan City. *Guangdong Heal. Epidemic Prev. Inform.* **1979**, *5*, 31–37. (In Chinese)
21. Li, W.B. Pollution scenarios in Pearl River water system. *Pearl River* **1982**, *3*, 29–32. (In Chinese)
22. Chen, Q.D. Water resources of Shenzhen. *Trop. Geogr.* **1986**, *6*, 51–62. (In Chinese)
23. Yue, J.; Wang, Y.L.; Li, Z.G.; Zhang, Y.; Bu, X.G. Spatial-temporal trends of water quality and its influence by land use: A case study of the main rivers in Shenzhen. *Adv. Water Sci.* **2006**, *17*, 359–364. (In Chinese)
24. Chinese Research Academy of Environmental Sciences. *Environmental Quality Standards for Surface Water*; China Environmental Science Press: Beijing, China, 2003. (In Chinese)
25. Huang, Y.L.; Wang, Y.L. River water quality degredation in Shenzhen City and its influencing mechanisms. *China Rural Water Hydropower* **2007**, *33*, 10–13. (In Chinese)
26. Simberloff, D.; Dayan, T. The guild concept and the structure of ecological communities. *Annu. Rev. Ecol. Syst.* **1991**, *22*, 115–143.
27. Vannote, R.L.; Minshall, G.W.; Cummins, K.W.; Sedell, J.R.; Cushing, C.E. The river continuum concept. *Can. J. Fish. Aquat. Sci.* **1980**, *37*, 130–137.

28. Orendt, C.; Wolfram, G.; Adámek, Z.; Jurajda, P.; Schmitt-Jansen, M. The response of macroinvertebrate community taxa and functional groups to pollution along a heavily impacted river in Central Europe (Bílina River, Czech Republic). *Biologia* **2012**, *67*, 180–199.
29. Friberg, N.; Dybkjær, J.B.; Olafsson, J.S.; Gislason, G.M.; Larsen, S.E.; Lauridsen, T.L. Relationships between structure and function in streams contrasting in temperature. *Freshwater Biol.* **2009**, *54*, 2051–2068.
30. Merritt, R.; Cummins, K. Trophic relations of macroinvertebrates. In *Methods in Stream Ecology*; Hauer, F.R., Lamberti, G.A., Eds.; Academic Press: San Diego, CA, USA, 2007; pp. 585–610.
31. Shannon, C.E.; Weaver, W.J. *The Mathematical Theory of Communication*; University of Illinois Press: Urbana, IL, USA, 1949.
32. Che, Y.; Yang, K.; Wu, E.; Shang, Z.; Xiang, W. Assessing the health of an urban stream: A case study of Suzhou Creek in Shanghai, China. *Environ. Monit. Assess.* **2012**, *184*, 7425–7438.
33. Liu, H.Z.; Lu, X.Y. Comparison of water pollution control between rivers in China and abroad. *World Environ.* **2001**, *19*, 27–30. (In Chinese)
34. Wilken, R.D. The Recovered Rhine and Its History. In *The Rhine*; Knepper, T., Ed.; Springer: Berlin, Germany, 2006; pp. 47–87.
35. Thorne, R.; Williams, P. The response of benthic macroinvertebrates to pollution in developing countries: A multimetric system of bioassessment. *Freshwater Biol.* **1997**, *37*, 671–686.
36. Beyene, A.; Legesse, W.; Triest, L.; Kloos, H. Urban impact on ecological integrity of nearby rivers in developing countries: The Borkena River in highland Ethiopia. *Environ. Monit. Assess.* **2009**, *153*, 461–476.
37. Dudgeon, D. The impacts of human disturbance on stream benthic invertebrates and their drift in North Sulawesi, Indonesia. *Freshwater Biol.* **2006**, *51*, 1710–1729.
38. Allan, J.D.; Castillo, M.M. *Stream Ecology: Structure and Function of Running Waters*; Springer: Berlin, Germany, 2007.
39. Álvarez-Cabria, M.; Barquín, J.; Juanes, J.A. Microdistribution patterns of macroinvertebrate communities upstream and downstream of organic effluents. *Water Res.* **2011**, *45*, 1501–1511.
40. Arimoro, F.O.; Ikomi, R.B.; Iwegbue, C. Water quality changes in relation to Diptera community patterns and diversity measured at an organic effluent impacted stream in the Niger Delta, Nigeria. *Ecol. Indic.* **2007**, *7*, 541–552.
41. Dudgeon, D. Responses of benthic macroinvertebrate communities to altitude and geology in tributaries of the Sepik River (Papua New Guinea): The influence of taxonomic resolution on the detection of environmental gradients. *Freshwater Biol.* **2012**, *57*, 1794–1812.
42. McCabe, D.J.; Hayes-Pontius, E.M.; Canepa, A.; Berry, K.S.; Levine, B.C. Measuring standardized effect size improves interpretation of biomonitoring studies and facilitates meta-analysis. *Freshwater Sci.* **2012**, *31*, 800–812.
43. Maxted, J.; Barbour, M.; Gerritsen, J.; Poretti, V.; Primrose, N.; Silvia, A.; Penrose, D.; Renfrow, R. Assessment framework for mid-Atlantic coastal plain streams using benthic macroinvertebrates. *J. N. Am. Benthol. Soc.* **2000**, *19*, 128–144.
44. Nadushan, R.M.; Ramezani, M. Bioassessment of Kordan Stream (Iran) Water Quality Using Macro-Zoobenthos Indices. *Int. J. Biol.* **2011**, *3*, 127–134.

45. Cao, Y.; Bark, A.W.; Williams, W.P. Measuring the responses of macroinvertebrate communities to water pollution: A comparison of multivariate approaches, biotic and diversity indices. *Hydrobiologia* **1996**, *341*, 1–19.
46. Dyer, S.D.; Wang, X. A comparison of stream biological responses to discharge from wastewater treatment plants in high and low population density areas. *Environ. Toxicol. Chem.* **2002**, *21*, 1065–1075.
47. Ortiz, J.; Puig, M. Point source effects on density, biomass and diversity of benthic macroinvertebrates in a Mediterranean stream. *River Res. Appl.* **2007**, *23*, 155–170.
48. Xu, M.; Wang, Z.; Duan, X.; Pan, B. Effects of pollution on macroinvertebrates and water quality bio-assessment. *Hydrobiologia* **2014**, *729*, 247–259.
49. Loreau, M.; Naeem, S.; Inchausti, P.; Bengtsson, J.; Grime, J.; Hector, A.; Hooper, D.; Huston, M.; Raffaelli, D.; Schmid, B. Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science* **2001**, *294*, 804–808.
50. Sandin, L.; Solimini, A.G. Freshwater ecosystem structure-function relationships: From theory to application. *Freshwater Biol.* **2009**, *54*, 2017–2024.
51. Duan, X.H.; Wang, Z.Y.; Xu, M.Z. Effects of fluvial processes and human activities on stream macro-invertebrates. *Int. J. Sediment Res.* **2011**, *26*, 416–430.
52. Bernhardt, E.S.; Palmer, M.A. River restoration: The fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecol. Appl.* **2011**, *21*, 1926–1931.
53. Allan, J.D.; Flecker, A.S. Biodiversity conservation in running waters. *BioScience* **1993**, *43*, 32–43.
54. Violin, C.R.; Cada, P.; Sudduth, E.B.; Hassett, B.A.; Penrose, D.L.; Bernhardt, E.S. Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. *Ecol. Appl.* **2011**, *21*, 1932–1949.
55. Kemp, S. The potential and limitations of linking biological monitoring data and restoration needs of urbanized waterways: A case study. *Environ. Monit. Assess.* **2014**, *186*, 3859–3873.
56. Bernhardt, E.S.; Likens, G.E.; Hall, R.O.; Buso, D.C.; Fisher, S.G.; Burton, T.M.; Meyer, J.L.; McDowell, W.H.; Mayer, M.S.; Bowden, W.B.; *et al.* Can't See the Forest for the Stream? In-stream Processing and Terrestrial Nitrogen Exports. *BioScience* **2005**, *55*, 219–230.
57. Palmer, M.A.; Bernhardt, E.S.; Allan, J.D.; Lake, P.S.; Alexander, G.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C.N.; Follstad Shah, J.; *et al.* Standards for ecologically successful river restoration. *J. Appl. Ecol.* **2005**, *42*, 208–217.
58. Lyon, G.; Stein, E. How effective has the Clean Water Act been at reducing pollutant mass emissions to the Southern California Bight over the past 35 years? *Environ. Monit. Assess.* **2009**, *154*, 413–426.
59. Harrison, S.S.C.; Pretty, J.L.; Shepherd, D.; Hildrew, A.G.; Smith, C.; Hey, R.D. The effect of instream rehabilitation structures on macroinvertebrates in lowland rivers. *J. Appl. Ecol.* **2004**, *41*, 1140–1154.
60. Mueller, M.; Pander, J.; Geist, J. The ecological value of stream restoration measures: An evaluation on ecosystem and target species scales. *Ecol. Eng.* **2014**, *62*, 129–139.