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Effects of the "Run-of-River" Hydro Scheme on Macroinvertebrate Communities and Habitat Conditions in a Mountain River of Northeastern China

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Abstract: The main objective of this study was to quantify the impacts of the run of river (ROR) scheme on the instream habitat and macroinvertebrate community. We sampled the macroinvertebrate assemblages and collected the habitat variables above and below an ROR hydropower plant: Aotou plant in the Hailang River, China. The effects of the ROR scheme on habitat conditions were examined using regulation-related variables, most of which, particularly the hydrological variables and substrate composition, presented spatial variations along the downstream direction, contributing to heterogeneous conditions between reaches. The macroinvertebrate richness, the density and the diversity metrics showed significant decreases in the "depleted" reach compared with the upper and lower reaches. Approximately 75% of reach-averaged densities and 50% of taxa richness suffered decreases in the "depleted" reach compared with the upper reach. Furthermore, functional feeding groups also showed distinct site differences along the channel. The relative abundance of both collector-gatherers and the scrapers reduced considerably at the "depleted" sites, particularly at the site immediately downstream of the weir. The total variance in the the functional feeding group (FFG) data explained by Canonical correlation analysis (CCA) was more than 81.4% and the high-loadings factors were depth, flow velocity, DO and substrate composition. We demonstrated that flow diversion at the 75% level and an in-channel barrier, due to the ROR scheme, are likely to lead to poor habitat conditions and decrease both the abundance and the diversity of macroinvertebrates in reaches influenced by water diversion.

Keywords: run of river hydropower; macroinvertebrate; river habitat; flow diversion; functional feeding group; the Hailang River

1. Introduction

Hydropower is the most common renewable source in the world and accounts for 16% of the total electricity production [1]. Because hydropower is commonly associated with river regulation, numerous studies have addressed the ecological impacts from flow manipulation and fragmentation [2–4]. Despite the broad recognition of the ecological consequences of hydropower, most studies focused on the impacts of large-scale hydropower on the habitats and behaviors of valuable fishes and relatively few studies paid attention to small-hydro [5–8].

Small-hydro is, in most cases, "run of river" (ROR). ROR schemes use in-stream flow and operate with little or no water storage. Channel obstructions include small dams, weirs and other barriers, which are associated with the secondary channel/tube to divert a proportion of flow to turbines in the powerhouse [1,9]. This small-hydro scheme is regarded as environmentally friendly, because it does not use significant d amming [9], but international studies and other reports are scarce to support this view. The manipulation of flow diversions alters the natural flow regime and will potentially change downstream habitat conditions, and both, in turn, may present threats to ecological processes and river organisms. Although relatively little attention has been given to the ecological impacts of the ROR scheme on river organisms, other relevant studies of water diversions and artificial drought, due to river regulations, revealed some potentially significant ecological impacts. For example, Dewson [10] used whole-channel flow manipulations to imitate real water abstractions and found that significant *Ephemeroptera*, *Plecoptera*, and *Trichioptera* (EPT) individuals decreased in response to reduced flows. Finn and Boulton [11] compared two Australian streams influenced with or without water extraction, and revealed that artificial drought resulted in declines in macroinvertebrate richness and density but increases in the representation by drought-tolerant groups. These studies provide useful perspectives and references for studying the impacts of an ROR scheme.

China deserves special attention toward the ecological impacts of hydropower. By the end of 2014, China has 27% of the hydropower-installed capacity and has installed a capacity of more than 300 million kW (National Energy Administration, China). Moreover, approximately 40% of small-hydro capacities exist in China, and most of them operate with the ROR scheme. However, the effects of the ROR scheme on river habitats and freshwater species are completely lacking in the rivers of China.

To access the regulation impacts of the ROR scheme on the river ecosystem and to reach a better and effective regulation management, more studies are needed on a case-by-case basis concerning indicator species and meso-habitats within rivers influenced by specific hydropower projects. The macroinvertebrate community is an important component of freshwater ecosystems, and it is widely used in environmental and ecological assessments in freshwater ecosystems [12]. By understanding the consequences of ROR operations on the alterations in the flows and habitat conditions, it may be possible to make inferences on the changes of macroinvertebrate communities associated with habitat variables. The perspective of species–habitat interaction compared with a single biological perspective should be more beneficial to the understanding of the ROR eco-impacts and potential regulation decisions.

The main objectives of this study were to understand the environmental and ecological impacts of ROR operations by comparing macroinvertebrate assemblages and habitat conditions above and below an ROR plant, the Aotou hydropower plant, situated in the Hailang River, northern China, from the middle of June to July 2014. Physico-chemical and biological data were gathered through field investigations and observations at designed sampling sites. The relationship between habitat environments and macroinvertebrate assemblages was also assessed. We hypothesized that flow diversions due to ROR operations could change habitat variables and then impact macroinvertebrate assemblages, which leads to reduced macroinvertebrate biodiversity and poor habitat quality in dewatering reaches. The present study will enrich the knowledge of river ecosystems in northern China.

2. Materials and Methods

2.1. Study Area

The field data were collected from the Hailang River. It is the largest tributary of the Mudan River in northern China, flowing approximately 210 km from the Changbai Mountain to the Mudan River. The Hailang River subcatchment drains 5225 square km of land, and has an annual precipitation of 800 mm. The river freezes from late November until early April. The highest flows in the Hailang River occur when the snow melts during the spring thaw.

As a mountain river, the Hailang River has a mean slope of 2.52‰. The elevation is from 773 m at the waterhead area to 243 m at the mouth. Due to the steep slope and high elevation range from the headwaters to the mouth, the Hailang River has abundant waterpower and a cascade of nine power plants is planned in the near future years. The Aotou Plant is a small ROR hydropower plant situated in a lower gradient reach of the Hailang River with a designed head of 5.5 m and a peak capacity of 1225 KW. The main channel is obstructed with an in-channel weir to regulate water levels, allowing a proportion of flow to be diverted down a "Left Bank" diversion channel to turbines before it is returned to the main channel, 3.7 km further downstream. The Aotou Plant operates without water storage but creates a 3.7 km-long depleted stretch from the main channel weir to return point. In the water-depleted reach, the natural flow regime reduced significantly, and little overflow and seepage are the main types of discharge. This phenomenon is particularly severe in the dry season.

Benthic macroinvertebrate samples and environmental variables were collected along three reaches near the Aotou Plant in the Hailang River: (1) 6.3-km-long reach upstream of the weir; (2) 3.7-km-long "depleted" reach; and (3) 7.6-km-long reach below the flow returning point. Three sampling sites were selected over each sampling reach (Figure 1). Diversion channel was not included in the investigation due to the application of a rectangular reinforced concrete structure, which causes a steep slope and deep water levels, making only a small area available for sampling work.

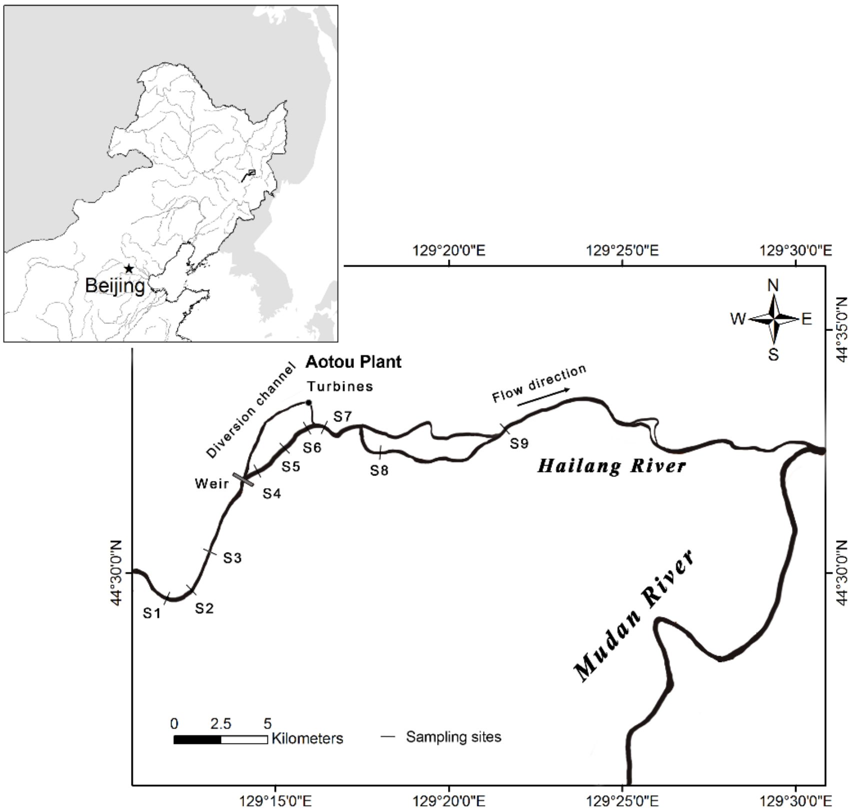

Figure 1. Locations of the study area and sites.

2.2. Sampling and Identification

At each sampling site, three replicates spaced at least 3 m apart were randomly selected from fast-flow habitats, such as riffles and runs. A modified kick-net (mesh size = 0.375 mm, area = 1 m^2), constructed out of a PVC frame and polyethylene net was used to collect benthic macroinvertebrate samples in areas with hard-bottomed substrate where the water depth was less than 0.7 m. Considering the reliability of the research results and sampling conditions, a sampling area of one square meter was chosen at each sampling location [13]. Additionally, the kicking intensity and duration were kept as similar as possible to ensure effectiveness and consistency. Each mixed sample of macroinvertebrates and debris was obtained from the net following a timed (1.5 min) disturbance of 0.2 m-depth of the substrate upstream from the kick-net. The debris and macroinvertebrates were rinsed through a sieve (mesh size = 0.50 mm) and subsequently moved into the labeled sample containers and preserved in a 5% formaldehyde solution.

All of the faunal samples were counted, sorted and identified in 70% alcohol under a stereoscopic microscope in the laboratory. Macroinvertebrates were identified to the lowest possible taxonomic classification, mostly species-level or genus-level. The sorted taxa were assigned to the functional feeding group (FFG) categories, proposed by Cummins [14,15], to describe feeding structure variations between the study sites. Five following groups were introduced: predators (prd), collector-gatherers (c-g), collector-filterers (c-f), scrapers (scr) and shredders (shr).

2.3. Physical Habitat Assessment

For each replicate, the sampling position was extended into a square cell, with a side length of 1.5 m. Each cell was considered to be a distinct habitat to allow a qualitative comparison of habitat types and quantitative assessments of physical and chemical variables. Hydraulic parameters, including water depth and flow velocity (at 0.6 of the depth by LS300, a portable flow meter), were measured and recorded *in situ* at each cell. The dissolved oxygen (DO) and water temperature (WT) were also detected *in situ* by a dissolved oxygen meter, YSI PRO-ODO. Qualitative records were also made in each cell in the presence or absence of hydrophyte, the coverage of riparian vegetation, the ratio of pool/riffle and the embeddedness of the substrate.

The water samples and substrata samples were collected at each site for further analysis. PH, chemical oxygen demand by the potassium permanganate method (COD_{Mn}), chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3-N), total phosphorus (TP) and total nitrogen (TN) were introduced for water-quality determination. All of these parameters were examined in the water quality analysis laboratory according to State Environmental Protection Administration of China (SEPA) standard methods. Substrata composition were measured and classified following the EPA standard in the laboratory. Four classes of particle sizes were introduced: CB Cobbles (>64 to 250 mm), CG Coarse Gravel (>16 to 64 mm), FG Fine Gravel (>2 to 16 mm) and SA Sand (>0.06 to 2 mm).

2.4. Methods of Analysis

Shannon-Wiener H', Pielou evenness J and Margalef richness d_M were used to evaluate the biodiversity of macroinvertebrate communities between the study sites. A one-way analysis of variance (ANOVA) was introduced to assess the reach differences in both habitat variables and macroinvertebrate data. A *posteriori* Tukey's HSD test was run when the difference was found.

Multivariate methods were used to determine the spatial and temporal patterns underlying abiotic and biotic data. Principal components analysis (PCA) of the physical and chemical habitat variables was used to summarize the total variation in the habitat data and identify major environmental gradients. Prior to the PCA, a Pearson correlation matrix of the environmental variables was introduced to determine the significantly correlated ones. The correlations of COD and COD_{Mn} (correlation coefficient is 0.987, $p < 0.01$), Coarse Gravel and Fine Gravel (correlation coefficient is 0.803, $p < 0.01$) were proved to be strong, so only COD and Fine Gravel were used in the analysis. BOD_5 was also excluded because of its constant value (2.00 mg/L). In total, 12 variables were included in the PCA. Canonical correlation analysis (CCA) was applied to examine the relative importance of environmental conditions in determining the differences in macroinvertebrates' FFG structure between the study sites. A direct gradient analysis using the coefficients for taxa and coefficients for environmental variables of habitats was used to maximize the species–environment correlation [16]. The data matrix of site environmental variables and the data matrix of site macroinvertebrate abundances in terms of FFG were used in the analysis. The significance of all primary CCA axes was determined by the Monte Carlo permutation testing (499 permutations) of the eigenvalues. Prior to the PCA or CCA, all of the data (habitat data in the PCA, habitat data and macroinvertebrate data in the CCA) were logarithmically transformed [$\log_{10}(x + 1)$] to standardize the scales.

3. Results

3.1. Physical and Chemical Variables

Our samplings were conducted from the middle of June to July 2014 (wet season) when the daily average flow ranged from 51.1 to 75.6 m^3/s, which was abundant enough to make the operation continuous. During the sampling period, the proportion of the total flow diverted from main channel to the turbines was approximately more than 75% which largely changed the hydrological regime in the reach below the weir. The average wetted area in the "depleted" reach obviously reduced compared with the upper reach and lower reach, particularly at S4 and S5.

The values of depth, velocity, DO and water temperature were averaged among the three replications at each site, whereas the water chemistry variables and substrata data were recorded once at each site. There were significant effects of the ROR scheme on both the reach-averaged hydraulic parameters water depth (ANOVA: $F = 21.246$, $p < 0.001$) and flow velocity ($F = 10.917$, $p < 0.001$). The water depth was significantly reduced in the "depleted" reach compared with the upper reach (*Tukey's HSD*, $p < 0.001$) and lower reach ($p < 0.05$) (Table 1), although there was no significant difference between the upper reach and lower reach, and the flow velocity was significantly reduced in the "depleted" reach ($p < 0.001$) and lower reach ($p < 0.001$) compared with the upper reach.

Table 1. Summary of habitat variables (SD) for all sites throughout the study period.

Variables	Units	Upper Sites			Depleted Sites			Lower Sites		
		S1	S2	S3	S4	S5	S6	S7	S8	S9
Depth	m	0.34 (0.03)	0.31 (0.06)	0.24 (0.03)	0.09 (0.02)	0.17 (0.04)	0.18 (0.03)	0.28 (0.04)	0.19 (0.04)	0.23 (0.02)
Velocity	m/s	0.56 (0.12)	0.53 (0.11)	0.56 (0.01)	0.21 (0.01)	0.24 (0.06)	0.27 (0.02)	0.34 (0.09)	0.21 (0.01)	0.37 (0.05)
DO	mg/L	10.13 (0.01)	10.38 (0.09)	10.20 (0.08)	9.22 (0.08)	9.29 (0.01)	9.57 (0.04)	9.27 (0.01)	9.19 (0.03)	9.11 (0.02)
Temp	°C	20.23 (0.03)	20.80 (0.31)	19.50 (0.20)	19.97 (0.12)	19.73 (0.03)	20.07 (0.17)	19.43 (0.03)	19.37 (0.03)	19.33 (0.03)
PH	–	7.69	7.36	7.30	7.27	7.23	7.19	7.25	7.27	7.25
COD_{Mn}	mg/L	5.70	4.60	4.70	4.50	4.80	4.80	4.60	4.50	4.40
COD	mg/L	19.50	16.10	16.10	15.40	16.30	16.50	15.90	15.40	14.60
BOD_5	mg/L	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
NH_3-N	mg/L	0.12	0.17	0.16	0.13	0.14	0.15	0.19	0.17	0.15
TP	mg/L	0.08	0.08	0.07	0.07	0.07	0.11	0.10	0.11	0.12
TN	mg/L	0.24	0.25	0.25	0.25	0.25	0.28	0.30	0.29	0.26
CB Cobble	%	60.00	37.00	42.40	22.89	32.92	28.32	30.73	34.61	27.92
GC Gravel	%	27.01	38.86	35.35	50.66	45.73	48.16	38.90	34.10	39.70
GF Gravel	%	7.80	15.69	13.23	21.94	17.20	19.90	20.90	16.20	20.70
SA Sand	%	4.00	8.10	9.02	4.20	3.70	3.10	9.10	14.50	11.10

The values of PH ($p < 0.001$) and DO ($p < 0.01$) were relatively higher in the upper reach than in either the "depleted" reach or the lower reach. Other water chemistry variables, including COD_{Mn}, COD, BOD_5, NH_3-N, TP, and TN, were not different between the upper reach and the "depleted" reach, however, these variables were significantly different between the upper reach and lower reach, with significantly higher values of COD_{Mn} ($p < 0.01$), COD ($p < 0.01$) in the upper reach and higher values of TP ($p < 0.001$), TN ($p < 0.001$) and NH_3-N ($p < 0.05$) in the lower reach.

The substrata percentage composition showed reach differences. The cobble percentage was significantly higher in the upper reach than the "depleted" reach ($p < 0.001$) and the lower reach

($p < 0.001$). However, the sand/silt percentage presented a significantly high value in the lower reach than the "depleted" reach ($p < 0.001$) and the upper reach ($p < 0.01$).

In addition, qualitative records suggested that the riparian and instream habitat conditions changed distinctly along the Hailang River (Figure 2). The habitat conditions, in terms of wetted area, vegetation coverage, pool/riffle ratio, embeddedness and riverbank stability, degraded sharply from the "optimal" in the upstream to "poor" in the immediate downstream of the weir, and upgraded gradually further downstream with flow returning, based on the criteria of the US EPA [17].

(**a**) (**b**) (**c**)

Figure 2. Sequential photographs showing the changing habitat character in a downstream direction in the Hailang River: (**a**) S2 at the upper reach; (**b**) S5 at the "depleted" reach; and (**c**) S7 at the lower reach.

An ordination by the PCA of the physical-chemical habitat variables (the 12 parameters mentioned above) explained 69.8% of the cumulative variance in the data by the first two principal component axes (Figure 3). The variance explained by axis1 was 49.5%. Significant loadings on axis1 showed a positive gradient of increasing water depth, flow velocity, DO, PH, COD, and cobble percentage. Significantly negative loadings exerted an increasing gradient of fine gravel percentage and TN. Axis 2 accounted for 20.3% of the data variance, and three variables, namely NH_3-N, TP and the sand percentage, represented significantly positive loadings on the axis.

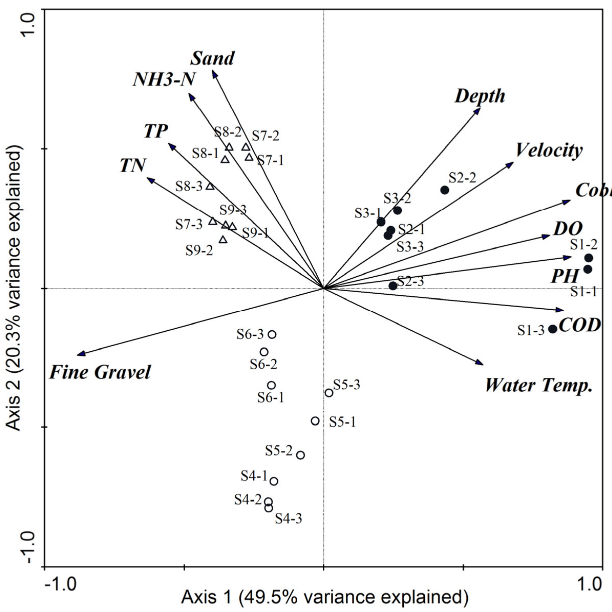

Figure 3. Plot of samples scores from the PCA of physical and chemical habitat variables along principal component axes 1 and 2. Cumulative variance in the data was explained 69.8% by two axes. Each *point* represents a different sampling location (replicate). *Closed circles* represent upper locations, *open circles* represent locations in the "depleted" reach, and *open triangles* represent lower locations.

The PCA of the physical-chemical variables' metrics indicated considerable site differences. The plot of sample scores demonstrated that the sampling locations of the upper reach, the "depleted" reach and the lower reach clustered into three groups. With respect to the axis1 scores, upper locations typically occupied further right positions compared to locations within the "depleted" reach and lower reach, characterizing the upper habitat conditions by higher velocity, water depth, DO and cobble percentage but lower TN and fine gravel percentage. With respect to the axis 2 scores, locations from the lower reach were located more towards the positive end of the axis than the others, characterizing the lower habitat conditions by higher concentrations of NH_3-N, TP and sand/silt percentage.

3.2. Assemblage Composition

In total, 25 taxa were recorded in the study area of the Hailang River, which belonged to 13 phyla, five classes, and 18 families (Table 2). *Insecta* was the dominant taxonomic group and accounted for 87.97% of the total captured individuals. *Ephemerellidae*, *Chironomidae* and *Heptageniidae* were the most abundant representative families, comprising 31.18%, 15.82% and 14.23% of the total fauna, respectively.

Great differences in the taxonomic composition of major communities presented within each reach (Figure 4). The relative abundance of *Ephemeroptera* was consistently high in the upper reach and lower reach, particularly in the upper reach, with a high proportion of 69.57%. *Diptera* had the second highest abundance followed by *Ephemeroptera* in the upper reach and lower reach, presenting 12.21% and 16.67%, respectively. In contrast, *Diptera* was the most numerous group in the "depleted" reach below the regulating weir, with a relatively high abundance of 34.32%. The percentage of *Ephemeroptera* presented a considerable reduction compared with that in other reaches, comprising only 23.78% of the total fauna. The relative abundance of all the other taxonomic groups, which primarily consisted of *Coleoptera*, *Trichoptera*, *Oodonata*, *Oligochaeta*, were consistently low in the reaches.

Table 2. Taxonomic composition (relative abundance) of macroinvertebrates between reaches in the Hailang River.

Class *Genus/Species*	Relative Abundances (%)		
	Upper Reach	**Depleted Reach**	**Lower Reach**
	Insecta		
Polypedilum sordens	0.79	6.49	2.19
Cryptochironomus defectus	3.95	14.32	4.50
Chironomus plumosus	5.89	9.19	7.30
Pocladius choreus	1.58	2.43	2.68
Cinygma sp1	4.58	–	–
Cinygma sp2	4.42	–	–
Epeorus uenoi	11.26	7.03	3.53
Drunella sp1	7.53	0.00	5.60
Drunella sp2	14.32	0.00	17.76
Ephemerella sp	14.47	3.24	8.52
Ephemera sp	10.53	7.84	10.22
Baetis sp	0.63	0.00	4.38
Potamanthus huoshanensis	1.84	5.68	2.07
Elmidae	2.16	–	0.73
Dytiscidae	0.11	2.97	–
Ieptoceridae	0.37	–	–
Hydropsychidae	4.32	2.16	9.85
Gomphidae	3.16	7.03	7.54
Muscidae	–	1.89	–
	Oligochaeta		
Tubificidae	2.47	8.11	1.82
	Clitellata		
Glossiphonia sp	1.42	–	2.43
Whitmania sp	1.95	–	0.61
	Gastropoda		
Radix ovata	1.00	5.41	2.92
Oncomelania	1.26	15.41	5.35
	Bivalvia		
Corbicula	–	0.81	–

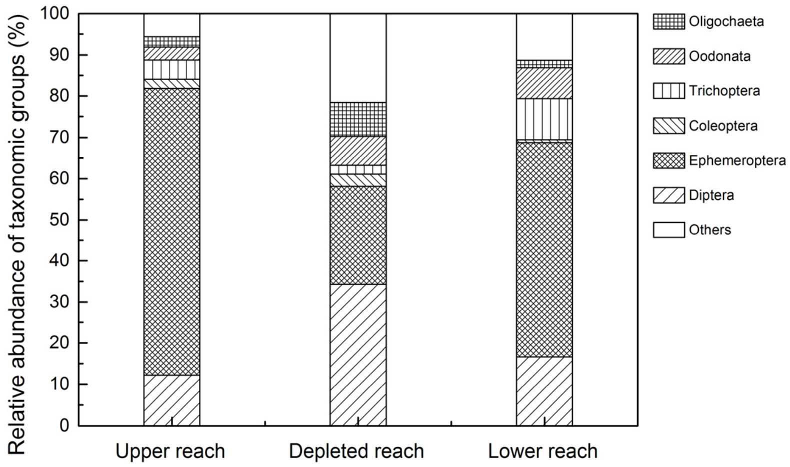

Figure 4. Relative abundance of major taxonomic groups between reaches. Percentage values are for the abundance pooled across the nine samples collected from each reach.

The ROR scheme impacted the distribution of fauna, and the effects could be reflected by density, taxon richness, EPT richness and other common biodiversity indices (Figure 5). For all of the patterns of site density, richness and derived biodiversity indices, the ANOVA indicated significant differences between reaches (density $F = 98.712$, $p < 0.001$; taxon richness $F = 64.012$, $p < 0.001$; EPT richness $F = 78.301$, $p < 0.001$; d_M $F = 23.515$, $p < 0.001$; $H'F = 18.363$, $p < 0.001$; and $JF = 9.284$, $p < 0.001$).

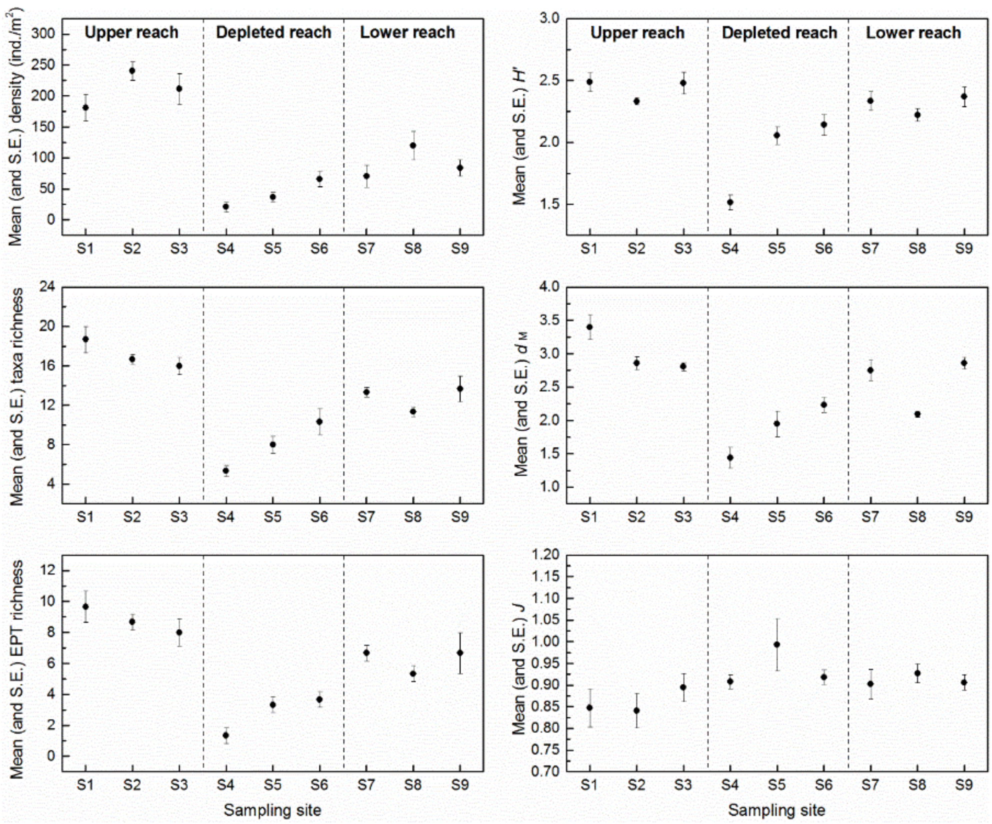

Figure 5. Macroinvertebrate abundance, taxon richness, EPT richness and other indices of diversity from each sampling site in the Hailang River. Mean (±1 SE) are given for samples collected from nine sites on three reaches.

In terms of density, taxon richness, EPT richness, Shannon-Wiener index H' and Margalef richness d_M, there were significant reductions in the "depleted" reach compared with the upper reach (*Tukey's HSD*, for all indices, $p < 0.001$), particularly at S4, where all of the indices were consistently the lowest compared with other sites. Compared to the upper reach, the indexes reduced significantly in the lower reach (density, taxon richness, EPT richness $p < 0.001$; d_M $p < 0.05$) with the exception of Shannon-Wiener index, which showed no significant difference. From S4 to S9, with flow returning, the levels of these indexes increased gradually in the downstream direction and were significantly higher in the lower reach than the "depleted" reach (for all indices, $p < 0.001$). For Pielou evenness J, significantly higher values were found in the "depleted" reach ($p < 0.001$) and the lower reach ($p < 0.05$) than in the upper reach, although there was no significant difference between the "depleted" reach and lower reach.

3.3. FFG Variations

In total, scrapers, collector-gatherers and predators were the first three predominant functional feeding groups in benthic samples, comprising 41.46%, 35.22% and 15.62% of the macroinvertebrate assemblage, respectively. Collector-filterers and shredders were relatively uncommon and only consisting of 5.63% and 2.07% of the total fauna, respectively. Collector-filterers were primarily at lower sites and appeared to be poor at other sites. Shredders were distributed unevenly and appeared to be present at "depleted" sites and absent at most other sites.

On a reach-scale, the spatial variations of the FFG composition observed at the "depleted" sites (S4–S6) were more distinct than either the upper sites (S1–S3) or the lower sites (S7–S9). The relative abundance of predators decreased from 49.18% at S4 to 22.73% at S6; however, both scrapers and collector-gatherers had a two-fold increase from S4 to S6. The relative abundances of FFG were relatively stable both at the upper sites and the lower sites (Figure 6).

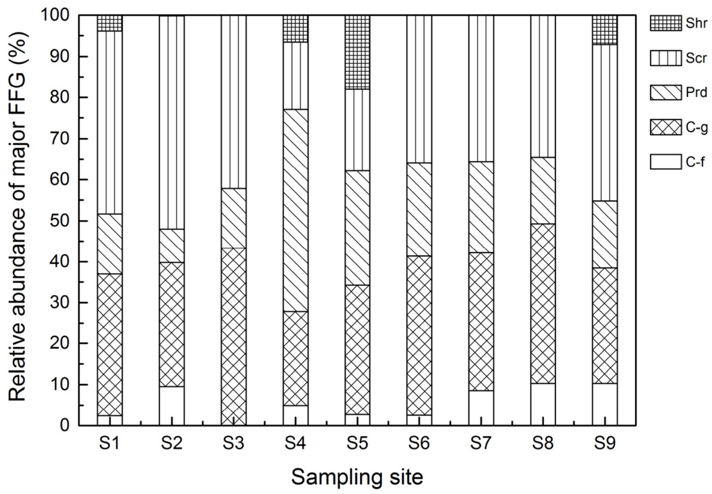

Figure 6. Relative abundance of functional feeding groups between sites. Percentage values are for the abundance pooled across the three samples collected from each site.

Macroinvertebrates' abundances classified according to the FFG were included in multivariate analyses (Figure 7). A CCA of the physical-chemical habitat data with macroinvertebrate data based on FFG abundance explained 81.4% of the total variance in the first two canonical variables. The first canonical variable captured 57.2% of the variance and the strong positive loadings were from hydraulic variables depth, flow velocity, DO and NH_3-N. The second canonical variable accounted for 24.2% of the total variance. For canonical variable 2, COD_{Mn}, sand proportion and cobble proportion presented the highest positive loadings, whereas water temperature and TP presented the highest negative loadings. The bi-plot of the macroinvertebrate data with the physical-chemical habitat data revealed that scrapers and collector-gatherers were situated to the positive end of variable 1 and appeared to be positively associated with hydraulic variables and DO. In contrast, predators and shredders appeared to be negatively associated with hydraulic variables and DO, especially for shredders, which exerted the highest negative loading. Partial correlations of FFG with each strongly correlated physical-chemical variable revealed a significantly positive correlation between velocity, DO, cobble proportion with scrapers and collector-gatherers. Shredders were negatively correlated with NH_3-N. Collector-filterers were positively correlated with water temperature, NH_3-N and the sand proportion. Predators were also positively correlated with the coarse gravel proportion (Table 3).

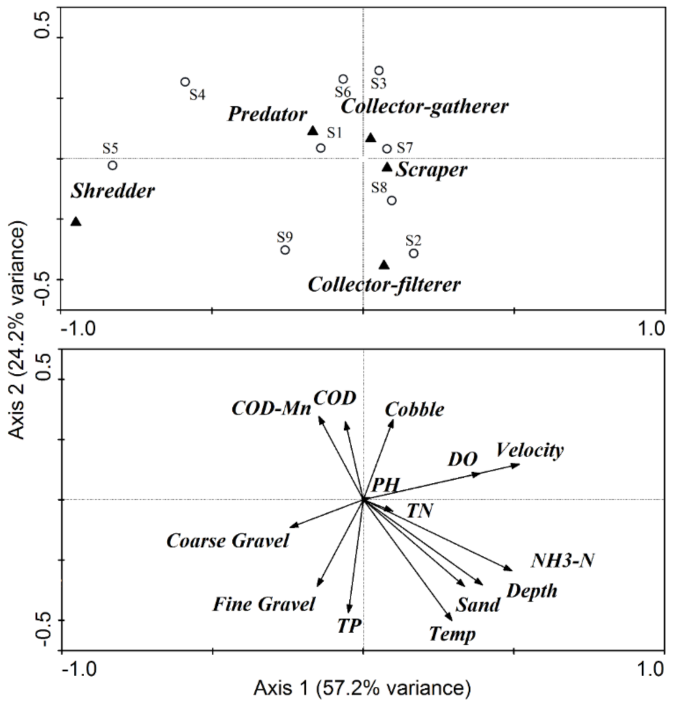

Figure 7. Biplot of FFG data with habitat variables by the CCA along principal component axes 1 and 2. Data from all of the sites were included and the two axes explained 73.9% of the cumulative variance in the data. Test of significance: axis1: $p < 0.005$; all canonical axes: $p < 0.005$.

Table 3. Partial correlations between FFG and the physical and chemical habitat variables measured in the study from the CCA. Variables with absolute correlation coefficients greater than 0.3 are listed.

Group	Positive Correlation Coefficients	Negative Correlation Coefficients
Scr	Velocity * (0.453) DO ** (0.783) Cobble * (0.408)	TN † (−0.321) Fine Gravel † (−0.346)
Shr	–	NH_3-N * (−0.373)
Prd	Coarse Gravel * (0.377)	–
C-g	Velocity * (0.452) DO ** (0.646) Cobble * (0.434)	Fine Gravel * (−0.370)
C-f	Water Temp.** (0.770) NH_3-N * (0.138) Sand ** (0.694)	–

† Correlation is significant at the 0.1 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed); and ** Correlation is significant at the 0.01 level (2-tailed).

4. Discussion

4.1. The Effects of ROR Scheme on Spatial Variations in Habitat Conditions

The most critical process affecting downstream habitats within the "depleted" reach of Aotou plant was the flow reduction. In general, natural rivers have relatively stable flow regimes, mostly running at base flow levels [18,19]. However, the operations of the ROR scheme disturb the natural flow regime through in-channel barriers associated with flow diversion by secondary diversion channels. The collected data in the study showed that over the entire sampling period (June to July, 2014), the diverted flow was estimated at 70%–80%, which meant that only 20%–30% of the total flow fed the downstream channel of the weir. Flow regimes are regarded as playing a fundamental role in determining river habitat availability and ecological integrity [20–22]. The direct consequences of flow variations are the alterations of hydrological habitat factors, generally including flow velocity, water depth and wetted widths, which were commonly recognized as key physical habitat factors in river ecosystems. At depleted sites, particularly site S4, the recorded hydrological variables declined dramatically compared with the upper sites due to flow reductions. The mean flow velocities and water depths in riffles located at the "depleted" sites were 3–4 times lower than the upper ones, and the wetted channel widths of these dewatered sites also experienced a reduction of 30%–60%. Decreased flow created a large proportion of lentic or slow-flow habitats in the "depleted" reach, which was largely inconsistent with upper ones that featured riffles and runs. This declining trend is consistent with the results of other case studies [23,24]. With flow return, water depths and flow velocities tended to increase gradually at lower sites, although the magnitudes of increases were heavily dependent on the channel morphology, and the habitat conditions at the lower reach upgraded significantly from the "depleted" reach.

The results from the present study identified spatial variations in DO concentrations, with levels that were significantly higher in the upper reach. The DO concentration in rivers is influenced by many biological, chemical, and physical interactions, and in terms of the physical process, it is heavily controlled by water temperature, water pressure and flow velocity [25,26]. In this case, with little water temperature difference, the lower velocities and induced relatively weak disturbances in downstream reaches are likely to decrease oxygen aeration and, hence, reduce DO levels. Other chemical water chemistry variables (including COD_{Mn}, COD, BOD_5, NH_3-N, TP, and TN) showed no significant differences between the upper reach and the "depleted" reach. These results suggest that the ROR scheme contributed little to level variations of nutrients and organic contaminants. Increasing levels of nutrients (TN, TP and NH_3-N) were found in the lower reach, mainly due to agriculture practices along both the diversion channel and the downstream channel, which contributed to more nutrient loadings to the receiving water.

In addition to changing the flow regime, in-channel barriers are effective sediment traps and are known to have an important effect on the downstream channel [27]. The longitudinal characteristics of substrate compositions were remarkable in the study. Large-diameter sediments, such as cobbles and coarse gravel, were the dominant compositions in the upper reach and were accompanied by great embeddedness. In contrast, cobble compositions significantly decreased in the lower reach, but sand compositions increased. We are unsure as to what extent these changes depended on the ROR plant; therefore, more studies are needed to further explain the shifting mechanisms. Unstable riverbanks with poor riparian vegetation were detected in the "depleted" reach, particularly at sites immediately downstream of the weir. The volume flux of overflow and the resulted sediment composition may be the best explanation for the poor condition. The flow over regulating weir was low in the load of suspended sediment, and such flow can easily lead to erosion and channel incision [27,28]. With respect to the riverbank condition, the duration of periods with no surface flow controls vegetation structure along the "depleted" channel [29]. In the "depleted" reach, the surface flow is intermittent, groundwater levels along the riverbank show strong declines, and these hydraulic conditions are less available to the riparian vegetation. Flow reductions are usually associated with decreases in the riparian water table at higher elevations and losing riparian vegetation due to drought stress [30,31]. Riverbank collapse occurs when the driving forces exceed the resisting forces. Poor vegetation is widely believed to weaken the resisting force, thus decreasing the stability of riverbanks [32]. The interaction of both processes of vegetation loss and erosion acceleration leads to degradation of riparian habitats and exerts impacts on the riverine ecology.

Comparisons of habitat conditions, in terms of physical and chemical variables between reaches, demonstrate that the ROR scheme of the Aotou plant could exert impacts on river habitats in the "depleted" reach and further downstream in terms of three aspects: changing the hydrological regime through flow diversion and return; degrading the riparian condition (poor vegetation and rich bank erosion) in the "depleted" reach; and shifting levels of some water chemistry variables, such as PH and DO. The results of the PCA showed that the key factors, such as flow velocity, cobble composition, DO, and COD, were mainly responsible for the variations obtained in the habitat conditions. The results show that no one factor exerts a supreme influence on habitat conditions, whereas combinations and interactions of these variables appear to fully account for the characteristic differences between reaches.

4.2. Response of Macroinvertebrate Structure and Biodiversity to ROR Scheme

In total, 25 macroinvertebrate taxa were recorded from the nine sampling sites during the survey. The dominance feature of *Insecta* group is similar to the other studies conducted in the Hailang River [33,34]. Tangbin Huo [33] recorded about 51 taxa throughout the whole river during August 2011 and found that 75.44% of them belonged to *Insecta*. Teng Fei [34] record 36 taxa in summer 2010 and *Insecta* accounted for 65.5% of the fauna. The mean density of total macroinvertebrates in the "depleted" reach and lower reach were significantly reduced compared with the upper reach. Total macroinvertebrates density in the "depleted" reach was only 25% of the upper one, despite the increased percentage in the lower reach, which was 43%. This decreasing trend was not consistent with some previous studies concerning the impacts of water diversion and artificially reduced flow regime on stream macroinvertebrates [35,36]. Their cases revealed that the density of macroinvertebrates showed no significant decreases, or even increases under reduced flow. However, the decreasing trend was found in other studies. McIntosh & Benbow [37] found that the mean density of total macroinvertebrates above the diversion was 46% greater than below the diversion, while Cazaubon & Giudicelli [38] found macroinvertebrates in regulated sites had lower densities and diversity compared with natural ones in the same district. Similarly, some previous studies also found taxa richness reductions in low flow conditions. McKay & King [36] compared reaches above and below a diversion and found a low family richness in the 'diverted' treatment reach. In this study, the total taxa richness, EPT richness and d_M were introduced to access the richness from multiple perspectives. These indices also consistently suffered sharp reductions in the "depleted" reach. Chemical variables were considered to make little contribution to the EPT richness differences, because they varied within a limited range and satisfied the same quality standard, given to measure the surface water quality of China. The levels of total taxa richness, EPT richness and d_M increased further in the lower reach, but still remained at relatively lower levels compared the upper reach. Comparisons of density and richness between reaches suggested that both the density and richness (total taxa and EPT taxa) may change in response to the flow variations resulting from the ROR scheme, and reduced flows were prone to decrease both indices.

In general, losses of macroinvertebrate density and richness in the downstream reaches appear to be attributed to two major causes. First, the physical barrier represented by the weir may disturb the river connectivity and may restrict macroinvertebrate drifts from the upstream reach to the downstream reach. This physical isolation and restricted movement may contribute to the insufficient recolonization of macroinvertebrates downstream of the weir and then bring about poor density and richness. Second, intra-species and inter-species competitions are likely to become more intense in the low-flow area due to the limited habitat area and food resources [18,37,39]. Competition may influence the community structure and combine the fauna into fewer species that dominant the confined area.

Additionally, the downstream reaches were always accompanied by low macroinvertebrate diversity, which could be explained by the degradation of habitat diversity. River habitat primarily depends on the channel morphology and hydrological conditions and flow decreases can reduce habitat diversity. In the "depleted" reach, extreme low-flow conditions facilitate the replacement of lotic habitats with lentic ones, which is not suitable for the taxa preferring fast-flow conditions. We assume poor habitat diversity to be a primary factor contributing to the low richness and low diversity.

On the reach-scale, the macroinvertebrate community structure found in the "depleted" reach was distinct from those in other reaches. *Diptera* was the dominant group in the "depleted" reach mainly because of the contributions of *Chironomidae*, which were wildly distributed and abundant. Other taxa with low-flowing preferences (e.g., *Oligochaeta* and *Coleoptera*) also increased in relative abundance in the "depleted" reach. However, the relative abundance of EPT taxa associated with higher flow velocities and heterogeneous instream habitats, such as *Ephemeroptera* and *Trichoptera*, decreased dramatically. The result clearly suggests that macroinvertebrate distribution and community structure are sensitive to flow alterations, and heavily depend on habitat conditions.

In biomonitoring, the environmental quality of a given site is judged from its species assemblages [40]. Further analyses of community composition alterations between sites according to the functional feeding group were made. Functional feeding group classification was helpful for ecological assessments about the river habitat conditions and widely used in previous studies regarding the ecological impacts of water diversion or river regulation [37,41].

A CCA of the physical-chemical habitat data with the macroinvertebrate data based on the FFG abundance explained 81.4% of the total variance in the first two canonical axes. The strong association of macroinvertebrate data with habitat conditions suggests that habitat changes due to the ROR scheme could exert large impacts on the distributions of major functional feeding groups of macroinvertebrates. Partial correlations between habitat variables and functional feeding groups provide a perspective to find the main factors that determine the distribution of the specific group. Different functional feeding groups have different habitat preferences [42]. In upper sites, where flow velocity was the highest and the cobble composition and DO were also higher, the collector-gatherer species and the scraper species were most common. This result is consistent with previous studies [42,43]. For example, Quinn [42] found that filter-feeding species had strong preferences for habitats with high velocity and seston. As for scraper species, Heino [43] found that their composition showed a strong positive relationship with the habitat heterogeneity and water depth. In contrast, the relative abundance of both collector-gatherers and the scrapers reduced at the "depleted" sites, particularly at the site immediately downstream of the weir. Although these reductions were predictable and similar to a previous study [44], predators at these sites were prone to be the dominant group. Due to extremely low density and diversity at these sites, the predators' dominance could not be attributed to either the adaptation ability of some predatory taxa (e.g., *Chironomidae*) or the high competition advantages, due to uncertainty. In the lower reach, the habitat diversity tended to be higher with flow increase, and the compositions of FFG, particularly collector-gatherers and scrapers, tended to be similar to the upper reach. This trend suggests the functional feeding group structure and composition downstream of the diversion reach were resilient to flow alterations. Another feature found in the lower reach was the relatively higher proportion of collector-gatherers, which was positively associated with the sand composition. This may be partially explained by the study of Likens [45], who studied the invertebrate community composition in sand or silt habitats and found that collector-gatherers (e.g., *Chironomids*) were the primary residents in sand habitats. In general, DO, velocity and substrate compositions seem to be the key factors that are positively correlated with FFG groups.

The habitat preferences of macroinvertebrates depend on the balance of various requirements of macroinvertebrates, including the lentic or lotic area preferences, food resources, thermal condition, oxygen acquisition of maintaining position, water quality, substrate and biotic interactions [19,42,46–49]. The ROR scheme changed the natural flow regime and river connectivity through a weir and flow-diversion channel, resulting in distinct habitat conditions between reaches, with particularly low habitat diversity and poor habitat quality in the "depleted" reach.

The changes in the habitat conditions exerted pronounced effects on macroinvertebrate density, richness, diversity and composition structure. The comparisons between reaches can provide insight in order to assess the ecological impacts of the ROR scheme. This study also clearly indicates that macroinvertebrate distribution and community structure are largely affected by habitat variables; thus, they can fulfill a role as indicators for habitat conditions. A series of new ROR plants will be constructed in the near future. The cumulative impacts of hydroelectric development and longitudinal habitat fragmentations on macroinvertebrate communities along the regulated river should be considered in future studies.

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