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Benthic Macroinvertebrate Diversity as Affected by the Construction of Inland Waterways along Montane Stretches of Two Rivers in China

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Abstract: Building inland waterways affects the natural structure, formation, and extent of the riverbed and riparian zone. It alters the hydrology and sediment deposition conditions and hence damages the aquatic ecosystem. To address the effects of the construction of inland waterways on the riverine biome, benthic macroinvertebrate communities were compared at different building stages of inland waterways along a gradient of shipping traffic density at two montane rivers in China. The Shannon–Wiener diversity index of the benthic macroinvertebrate communities ranged from 0.4 to 1.6; the lowest value was recorded in the completed inland waterway, while the highest value was recorded in the unaffected stretch. Principal component analysis and canonical correlation analysis showed the communities in the inland waterways to be distinct from those in the natural riparian habitats. Our results suggest that benthic macroinvertebrate communities can reflect the damage done by the hydromorphological modifications caused by building inland waterways. Benthic macroinvertebrate diversity and abundance should therefore be included when assessing the impact of building and operating inland waterways.

Keywords: benthic macroinvertebrate communities; waterway construction; riparian ecosystems; shipping traffic; Shannon–Wiener diversity

1. Introduction

Building inland waterways affects many components of river ecosystems [1,2] because of the inevitable anthropogenic interventions, such as regulating river channels, constructing dams, dredging channels, and building wharves [3–6]. Stream channels and riparian zones are affected by building and operating inland waterways [7,8], resulting in changes in dissolved and suspended nutrients, substrate composition, sediment deposition, and the abundance of aquatic organisms within specific stretches of the rivers [9,10]. Habitats within natural riparian zones are also heavily impacted when inland waterways are built in mountainous regions [11–14].

Natural riverbanks are land–water interfaces that affect the hydrological regime, river morphology, and fauna within rivers. In particular, benthic macroinvertebrates, which are typically larger than 0.5 mm or 1 mm and therefore visible to the naked eye, at the bottom of a water body in the riparian zone include the most ubiquitous species and perform many indispensable ecological functions in the riparian ecosystem [15–17]. Benthic macroinvertebrate species are found in the bottom sediment layer in rivers during spawning, reproduction, and feeding [18,19], and any disturbance to that bottom layer, inevitable during waterway construction and shipping, is bound to influence the abundance, composition, and diversity of those benthic macroinvertebrate assemblages [20].

Changes to hydrological conditions and the loss of riparian habitats caused by waterway construction significantly reduce the biomass (and therefore the abundance) and the diversity of aquatic organisms along the river [21,22], and ship traffic along inland waterways has been proposed as the key factor limiting the survival of benthic macroinvertebrate species [23,24]. Some characteristics of benthic macroinvertebrates can be used as bioindicators to evaluate the quality of riparian habitats [25–27], and benthic macroinvertebrate diversity and abundance can therefore be included in the criteria for assessing the likely environmental impact of building inland waterways before their construction is initiated.

The availability of habitats within a riparian zone is altered by the construction of river channels and the density of shipping traffic in ways that threaten the survival of a number of benthic macroinvertebrate species [28]. Additionally, the altered hydrologic regimes affect the structure of riparian habitats significantly, and the stability of a riverbank is affected by changes in the flow of discharge, the hydrological cycle, waves generated as a result of shipping traffic, and periods of inundation. Loss of suitable riparian habitats is a primary factor affecting the distribution of benthic macroinvertebrate species [29–31], and some studies have shown how benthic macroinvertebrates respond to the deterioration of riparian habitats [32,33] and how they are adversely affected by the construction and operation of river channels [34]. The species diversity and abundance of benthic macroinvertebrates decreased after inland waterways were built, especially following changes in riparian habitats [35,36]. Such changes may prevent benthic macroinvertebrates from colonizing specific stretches of a river and thus hasten the deterioration of benthic macroinvertebrate communities [37].

Earlier studies have only partly confirmed that construction of waterways and the subsequent traffic affect the composition of benthic macroinvertebrate communities significantly. Research on benthic macroinvertebrate diversity in riparian zones has focused on the relationship between benthic macroinvertebrate communities and environmental variables but ignored the different phases of inland waterway construction and the effects of traffic [38,39]. The effects of traffic and the presence of hydro-engineering structures in waterways could lead to permanent hydrological changes, resulting in loss of habitats, including riparian wetlands. Consequently, the riparian flora and fauna become less widely distributed. Furthermore, shipping traffic disturbs the deposition of sediment on the river bottom in the riparian zone, which may have even greater effects on the benthic macroinvertebrate communities than those caused by other environmental parameters. Once the construction of an inland waterway is complete, the ecosystem biodiversity begins its recovery, starting from sites in the riparian zone adjacent to the riverbed. Given a large stretch of diverse habitats, riparian benthic macroinvertebrate populations can survive the period of inland waterway construction and then recolonize the river ecosystem. Changes in streambed substratum habitats, improvement of the river water quality, regulation of the waterway operation intensity, and even optimization of the river's hydrological regime have been proposed as measures for the restoration of benthic macroinvertebrate populations, but the effectiveness of these measures is difficult to evaluate because there is little information addressing the mechanism of human disturbance of benthic macroinvertebrate communities [4]. More research is required into the dynamics of benthic macroinvertebrate populations as influenced by such construction and by shipping traffic in inland rivers.

The present study is an effort to address the influence of the construction of inland waterways on the benthic macroinvertebrate communities. We examined the differences in the response of benthic macroinvertebrate communities to construction at different building stages of inland waterways. Using the method of multivariate analysis, we tested the relationship between the diversity and the abundance of macroinvertebrate communities with the water quality factors and the density of traffic. We propose two hypotheses, namely: (1) benthic macroinvertebrate populations within a stretch of a river vary during different periods or phases of constructing a waterway along the river; and (2) once the waterway is operational, the density of traffic affects the abundance and the diversity of benthic macroinvertebrate populations in that ecosystem.

2. Materials and Methods

2.1. Study Area

The study was carried out in the mountainous stretches of two rivers in southwest China, namely the Zhangjiang river and the Wuyang river, via repeated sampling in 2015 and 2016. Both the Zhangjiang river and the Wuyang river are part of the same hydrological catchment (Xijiang river basin), with similar hydrogeological conditions, including width, flow flux, and riverside substrate. There is very little vegetation in the bedrock or gravelly substrate of the riverside. An inland waterway project was under construction in the upper and middle reaches of the Zhangjiang river during the study period. The Wuyang river waterway had been in operation for nearly 3 years prior to the study. The total length of the Zhangjiang river is 100.6 km, and its average annual discharge is 28.8 m^3/s. The total length of the Wuyang river is 258.4 km, and its average annual discharge is 31.22 m^2/s. A total of 24 sampling sites were established (17 along the Zhangjiang river and 7 along the Wuyang river) (Figure 1). Discrete samples were collected (see Section 2.2 for details) from sites within similar niches (similar in terms of vegetation, land use, river width, and flow velocity). In September 2015 and 2016, the sampling sites were divided into three groups: Group A comprised seven sites (numbered A1 to A7) along a developed inland waterway in the Wuyang river; Group B comprised nine sites (B1–B9) representing an inland waterway under construction as part of the Zhangjiang river; and Group C comprised eight sites (C1–C8) representing a natural stretch of the Zhangjiang river (Figure 1). Traffic density along these stretches was estimated by observing and recording the number of ships passing a fixed point within a unit of time over ten consecutive days.
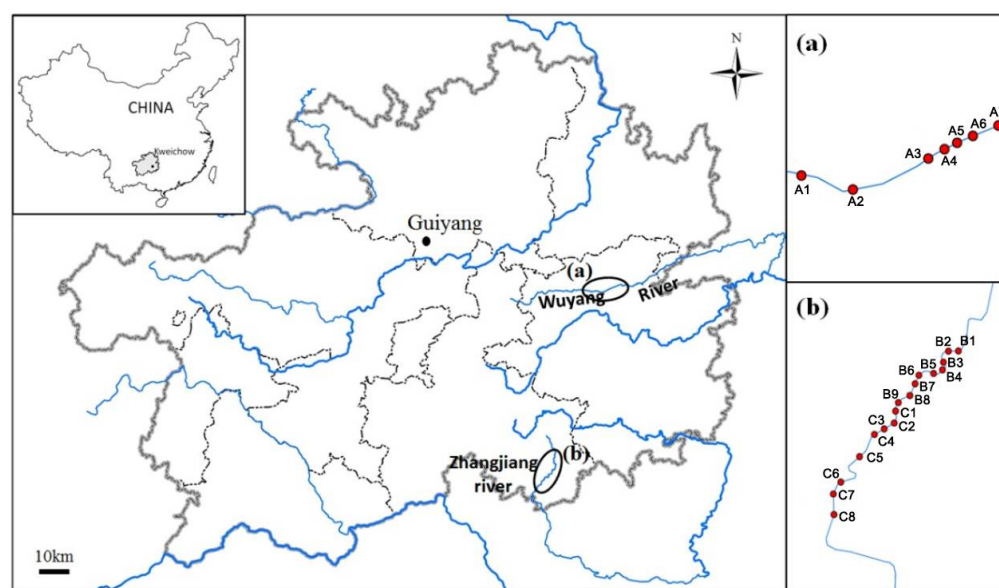

Figure 1. Sampling sites (red circles) along the Wuyang (**a**) and Zhangjiang (**b**) rivers in southwestern China. Sites A1 to A7 represent a developed inland waterway in the Wuyang river; sites B1 to B9 represent a stretch of inland waterway under construction along the Zhangjiang river; and sites C1 to C8 represent an undisturbed stretch of the Zhangjiang river.

2.2. Benthic Macroinvertebrate Sampling

Benthic macroinvertebrate populations were sampled from parts of the riverbank in contact with river water. From each sampling site in the riparian zone, three samples were collected as three replications using a Surber net (at a depth of 15 cm), each from an area 40 cm × 40 cm in size. The samples were filtered through a 2 mm sieve, and the residue was preserved in 5% (*v/v*) formaldehyde in plastic vials. The macroinvertebrates in the residue were handpicked using a dissection microscope at 10× magnification and preserved in 70% alcohol.

The subsequent classification and identification of the taxa or morphotaxa were conducted in the laboratory. The macroinvertebrates retained for identification were identified at the species level (few were identified at the family level), and the abundance of each species is expressed as the unit ind/m^2. The diversity of macroinvertebrates was calculated by the Shannon–Wiener diversity index *H'*.

$$H' = -\sum_{i=1}^{S} \frac{N_i}{N} \ln \frac{N_i}{N} \tag{1}$$

where *S* is the total number of species in a sample plot, N_i is the number of individual species *i*, and *N* is the number of all species in the sample plots.

2.3. Analyses of Environmental Factors

From each sampling site, we collected three water samples (10 L each). The physical and chemical properties of the water, including temperature (TEM), pH, dissolved oxygen (DO), total dissolved solids (TDS), and suspended solids (SS), were recorded using portable electrochemical meters (WTW Multi3320 multi-probes and WTW Turb 430T turbidity meter, Xylem Analytics Germany Sales GmbH & Co. KG., Weilheim, Germany). Water velocity (VEL) was measured using a portable flow meter (HD-DPF420 Doppler current meter, Haydn Technology Co., LTD, Chongqing, China). All the measuring devices were calibrated before use. Total nitrogen (TN), nitrate nitrogen (NO$_3$-N), total phosphorus (TP), chemical oxygen demand (COD), and ammonium nitrogen (NH$_4$-N) were measured in the laboratory according to the Chinese standard method for water quality monitoring (TN for Environmental Standard HJ636-2012; NO$_3$-N for Environmental Standard HJ84-2016; NH$_4$-N for Environmental Standard HJ535-2009; TP for Chinese National Standard GB11893-89; and COD for Environmental Standard HJ282-2017).

2.4. Statistical Analyses

To test the differences in environmental variables, macroinvertebrate abundance, and macroinvertebrate diversity between sampling sites, one-way analysis of variance (ANOVA) and Tukey's post-hoc multiple tests were used. Principal component analysis (PCA) was used to reduce the dimensionality of water quality datasets and provide an overview of how the environmental variables are grouped to form discrete environmental gradients. The data on environmental variables used for the PCA analysis were log(x + 1)-transformed to approximate a normal distribution for the physical parameters [40,41].

On the basis of taxa and environmental data, canonical correspondence analysis (CCA) was performed to reveal the most typical trends in the relationships between benthic macroinvertebrates and environmental variables. Besides water quality variables, building stages of an inland waterway (A, operational; B, under construction; and C, undeveloped river) and traffic density within the waterway were considered in the environmental variables. Any rare benthic macroinvertebrate taxa were removed, and only those that represented at least 1% of the abundance in each sample were retained. A total of 26 taxa were left out of a total of 39 taxa collected. Thus, 26 benthic macroinvertebrate taxa and significant environmental variables were subjected to CCA to identify the primary environmental factors affecting the benthic macroinvertebrate communities.

For an accurate interpretation of the relative importance of the building stage, traffic density, and water quality variables, variance partitioning was used to estimate the contribution of each variable group to the total variation in the benthic invertebrate assemblages [42–44]. Variance partitioning analysis determines the proportion of explained variation in the distribution of benthic macroinvertebrates for each environmental variable, interactions between two variables within a set of environmental variables, and interactions between all variables. During variance partitioning analyses, benthic macroinvertebrate abundances were natural-logarithm (ln)-transformed to guarantee the detection of any

non-constant error variance. All statistical analyses were performed using Canoco statistical software ver. 4.5 [45], Origin ver. 9.0, and SPSS ver. 22.0.

3. Results

3.1. Analysis of Environmental Variables

There was no significant difference in velocity between the two rivers (0.20 ± 0.02 m/s in the Wuyang river and 0.22 ± 0.03 m/s in the Zhangjiang river, $p = 0.688$, Figure 2a). There was an obvious gradient of shipping density in different construction stages (Figure 2b). The traffic density along the constructed waterway was more than twice that in the inland waterway under construction and the natural stretch. The water quality factors were different among the three groups (Figure 3). The total nitrogen, nitrate nitrogen, ammonium nitrogen, total phosphorus, and chemical oxygen demand in the developed inland waterway were much higher than in the inland waterway under construction and the natural stretch. The suspended solids were the highest in the inland waterway under construction. The temperature and pH of the three groups were close. The result of the PCA summarized the variation in the water quality factors and identified that the total nitrogen, nitrate nitrogen, and total phosphorus were the major environmental gradients (Table 1).
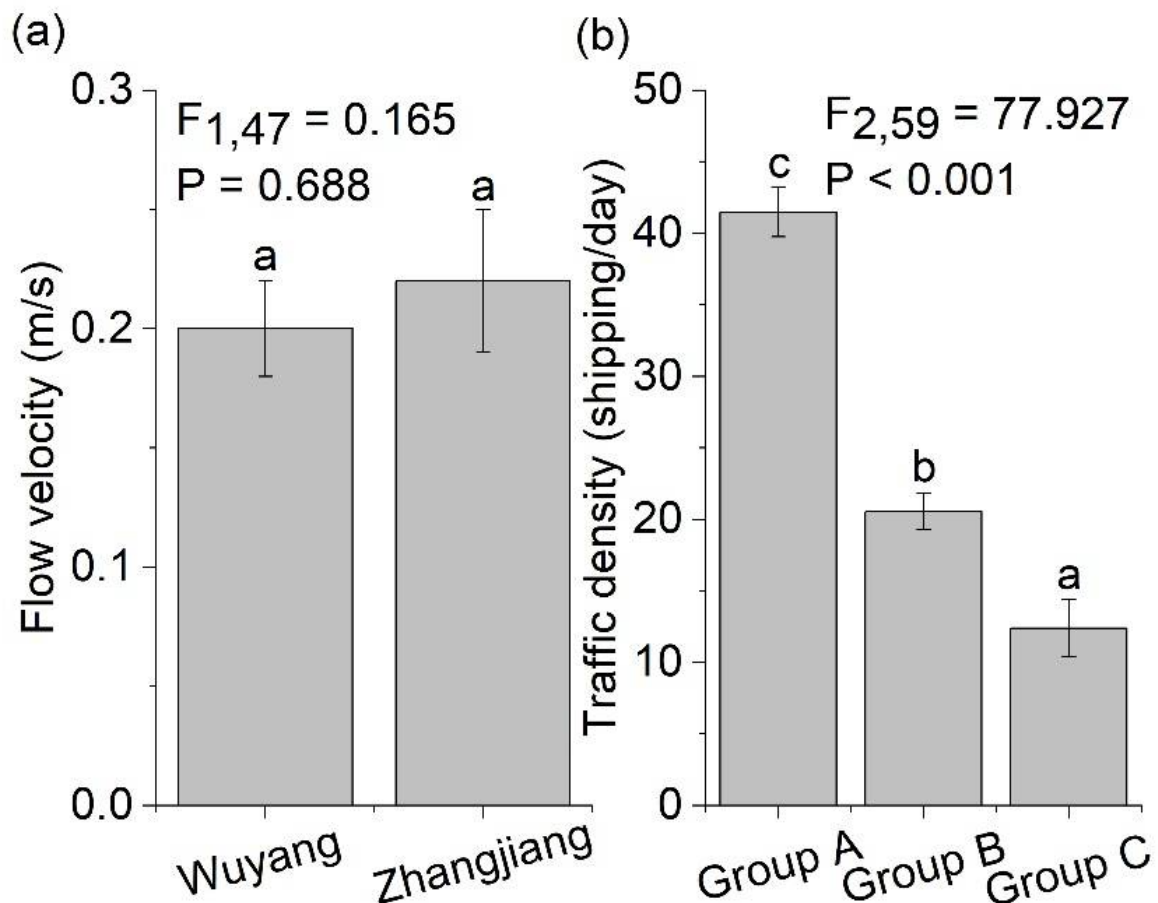

Figure 2. The environmental parameters in the study area, including (**a**) the flow velocity in the Wuyang river and the Zhangjiang river, and (**b**) the traffic density in the groups. Data are expressed as the mean $\pm$ SE and letters indicate significant differences based on Tukey's post hoc tests.
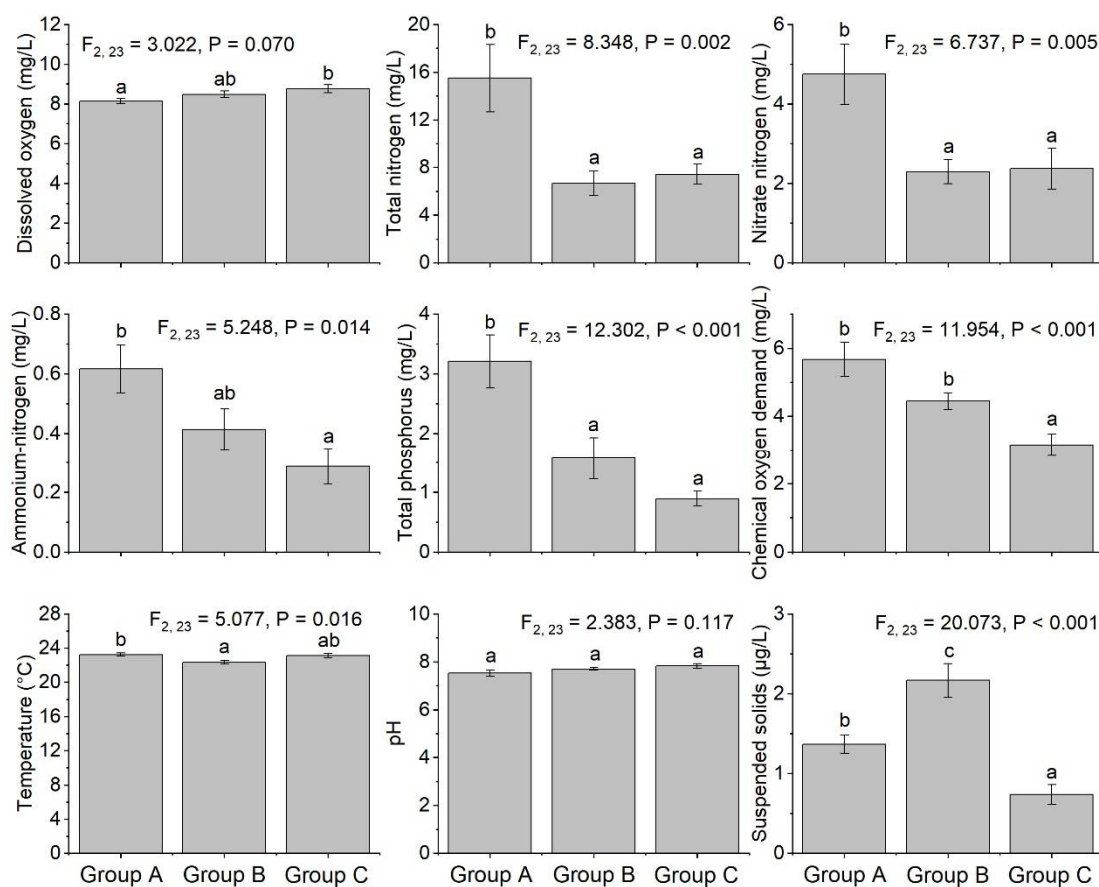
Figure 3. The differences in water quality variables among the three groups. Data are expressed as the mean ± SE and letters indicate significant differences based on post hoc tests.

Table 1. Summary of eigenvalues between the axis and the variable produced by PCA using standardized values of nine environmental variables.

Environmental Variables	Total Eigenvalues	% Variance	Cumulative %
Total nitrogen (TN)	4.355	48.391	48.391
Nitrate nitrogen (NO$_3$-N)	1.528	16.973	65.364
Total phosphorus (TP)	1.006	11.112	76.476
Chemical oxygen demand (COD)	0.811	9.025	85.502
Suspended solids (SS)	0.509	5.652	91.154
Dissolved oxygen (DO)	0.462	5.135	96.289
Water velocity (VEL)	0.181	2.015	98.304
Temperature (TEM)	0.105	1.163	99.467
pH	0.048	0.501	99.968
Ammonium nitrogen (NH$_4$–N)	0.003	0.032	100.00

3.2. Characteristics of the Macroinvertebrate Community

We identified 26 macroinvertebrate taxa, the most dominant among them being *Oligochaeta*, represented by two taxa; *Gastropoda*, represented by eight taxa; and *Chironomidae*, represented by five taxa. *Bivalvia*, *Insecta*, *Malacostraca*, and *Hirudinea* also contributed several taxa each (Table 2). The abundance in the three river channels was significantly different ($F_{2,47} = 88.425$, $p < 0.001$). The highest macroinvertebrate abundance was observed in riparian habitats within the undeveloped stretch of the river (Figure 4a). The diversity of macroinvertebrate communities followed the same pattern as that of their abundance. The Shannon–Wiener diversity index within Group A was significantly lower than that in Groups B and C ($F_{2,47} = 13.652$, $p < 0.001$) (Figure 4b).

Table 2. Macroinvertebrate taxa and mean abundance (no. of individuals per square meter) at sampling sites along stretches of rivers representing three different phases of construction of inland waterways. Group A is the stretch of an operational inland waterway, Group B is the stretch of a waterway under construction, and Group C is the undisturbed stretch of the river. Data are expressed as means ± SE.

| Benthic Macroinvertebrate Taxa		Abbreviation	Group A	Group B	Group C
Oligochaeta	*Limnodrilus hoffmeisteri*	Lim	6.6 ± 0.7	6.4 ± 0.2	11.96 ± 0.1
	Branchiura sowerbyi	Bra sow	10.2 ± 2.2	11.2 ± 1.1	16.1 ±1.3
Hirudinea	*Glossiphonia* sp.	Glo		4 ± 0.5	2.76 ± 0.5
	Lithoglyphopsis sp.	Lith			12.88 ± 0.5
	Sinotaia aeruginosa	Sin			14.26 ± 0.9
	Bithynia sp.	Bith			9.66 ± 0.8
Gastropoda	*Radix swinhoei*	Rad		10.8 ± 0.5	20.56 ± 0.9
	Stenothyra glabra	Sten	12.6 ± 1.8	12.4 ± 0.4	6.44 ± 0.1
	Oncomelania sp.	Onc			10.58 ± 0.1
	Gyraulus convexiusculus	Gyr			2.76 ± 0.1
	Physa acuta	Phy		5.6 ± 0.2	
Bivalvia	*Corbicula fluminea*	Cor	7.8 ± 1.0	8.8 ± 0.6	8.28 ± 0.2
Crustacea	*Caridina* sp.	Car	5.4 ± 0.5	16.8 ± 1.8	5.98 ± 0.4
	Baetis sp.	Bae	7.2 ± 0.5		
	Caenis sp.	Cae	1.2 ± 0.1	1.2 ± 0.2	1.84 ± 0.2
	Hydropsychidae sp.	Hyd		1.6 ± 0.7	
	Gomphidae sp.	Gom	7.8 ± 0.7		2.76 ± 0.1
	Macromia sp.	Mac		6.0 ± 1.4	3.68 ± 0.1
	Corixidae sp.	Cor			1.84 ± 0.1
Isecta	*Elmidae* sp.	Elm			1.84 ± 0.1
	Psephenidae sp.	Pse		1.2 ± 0.2	
	Parapoynx sp.	Par		1.2 ± 0.4	
	Bezzia sp.	Bez			2.76 ± 0.1
	Tipulidae sp.	Tip		1.2 ± 0.9	
	Tabanidae sp.	Tab			1.84 ± 0.4
	Chironomus sp.	Chi	8.4 ± 0.4	4.8 ± 0.6	7.36 ± 0.3
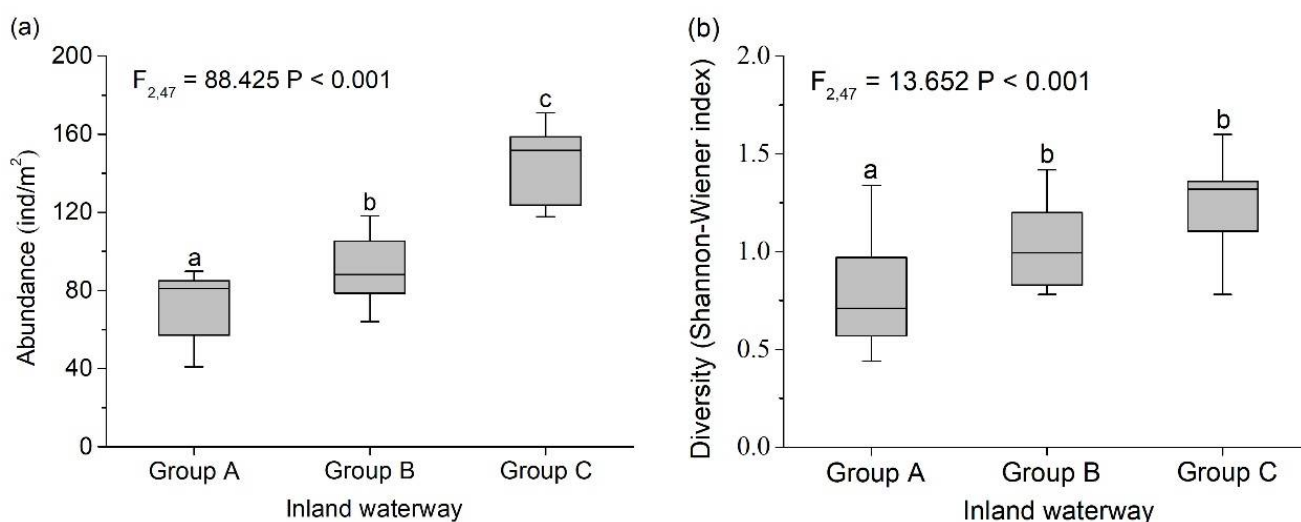
Figure 4. Box plots of (**a**) benthic macroinvertebrate abundance (no. of individuals per square meter) at sampling sites with different levels of traffic and at different stages of construction of the waterway and (**b**) benthic macroinvertebrate diversity (the Shannon–Wiener diversity index). Bars marked with the same lowercase letters were not significantly different according to Tukey's multiple comparison test. Vertical bars show standard errors.

3.3. Influence of Environmental Variables on Benthic Macroinvertebrate Communities

Macroinvertebrate abundance in the riparian zone was negatively correlated to the stage of construction and the density of traffic. A clear relationship between benthic macroinvertebrate abundance and environmental variables was revealed by CCA ordination (Figure 5). The first and the second canonical axes accounted for 57.63% of the variation. The scores for Axis 2 (34.58% of the variance, eigenvalue = 0.13) sites were positively correlated with dissolved oxygen ($r = 0.61$, $p < 0.001$) and pH ($r = 0.56$, $p < 0.05$) but negatively correlated with total nitrogen ($r = -0.51$, $p < 0.05$), construction stage ($r = -0.54$, $p < 0.05$), total phosphorus ($r = -0.71$, $p < 0.001$), traffic density ($r = 0.57$, $p < 0.05$), and NH_3–N ($r = -0.68$, $p < 0.05$).
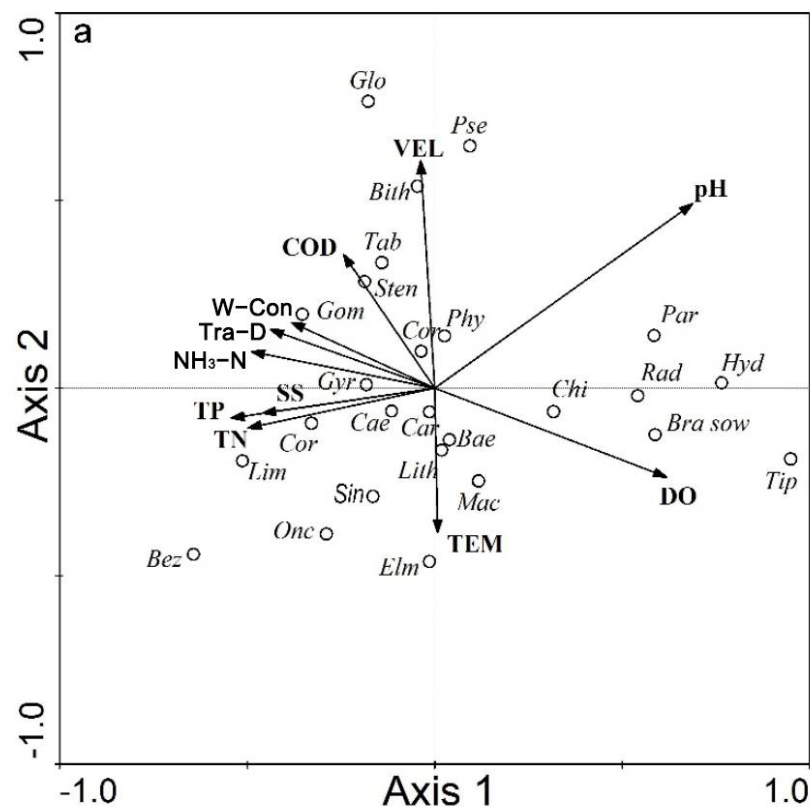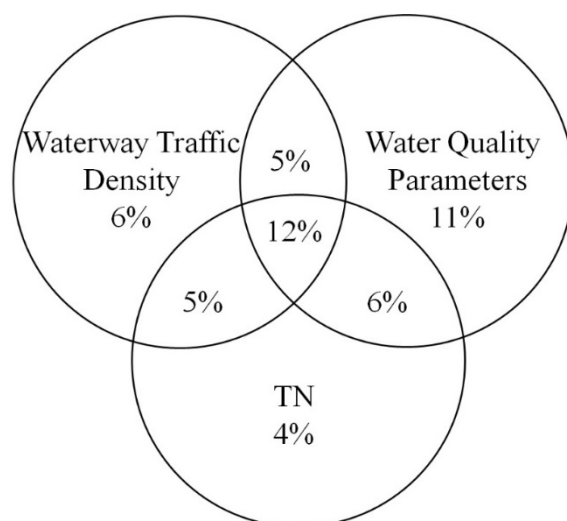

Figure 5. Ordination of macroinvertebrate abundance with environmental variables using canonical correspondence analysis. Significant environmental variables are represented by arrows. Abbreviations are spelled-out in Tables 1 and 2. Tra-D, traffic density; W-Con, construction phase; open circles, abundance of macroinvertebrates.

To determine the explanatory variance of benthic macroinvertebrate abundance, partial CCAs were conducted using reduced data sets. Single effects of water quality variables accounted for a large proportion of the variation but showed no significant difference between water quality and the density of shipping traffic. However, the effects of physical factors and the density were significantly different during the construction and operational phases. The shared variation among all three physical factors accounted for 12% of the variation (Figure 6), whereas 51% of the variation was unexplained. The taxa were clearly affected by water quality and by the phase of the waterway's construction. Nearly half of the variation in abundance was probably due to unknown and undetectable variables, such as individual behavior and interactions among taxa.

Unexplained variation: 51%

Figure 6. Variation partitioning of specific effects within the matrix of benthic macroinvertebrate abundances and the shared variation of each environmental parameter (total nitrogen and other water quality parameters).

4. Discussion

The different stages of waterway construction and different traffic densities were the major physical variables affecting the distribution of microhabitats suitable for macroinvertebrates. Two rivers with similar hydrogeological conditions were selected in our study, so there was no difference in the environmental background variables such as pH, temperature, and flow velocity. Building waterways can destroy riparian habitats by disturbing the water flow, the deposition of sediment, and nutrient concentrations. In the constructed inland waterway, the ship traffic brought about pollution. Therefore, the nitrogen, phosphorus, and organic pollutants in the constructed inland waterway were significantly higher than those in the waterway under construction and the natural stretch of river with a much lower traffic density. The results of this study support previous research showing that changes in some parameters of water quality can affect the composition of the macroinvertebrate community significantly [46–48]. Although the effect of flow rate was found to not be significant in this study, the influence of flow velocity on macroinvertebrate communities has been found to be very important in many cases [48,49]. In addition, riparian vegetation was not considered to be a factor affecting macroinvertebrate communities in this study because the study area is in a mountainous region and the bedrock or gritty substrate precludes the development of plant communities. The question of whether damage to riparian vegetation caused by inland waterway construction is an important factor affecting the macroinvertebrate community requires further study.

The diversity of taxa is the most effective indicator of the health of a river [50]. Both the diversity and abundance of the macroinvertebrate community decreased as a result of construction because such construction destroyed many natural riparian microhabitats, thereby upsetting the balance within the riverine ecosystem and the diversity of benthic invertebrates. Undeveloped rivers or undeveloped stretches of rivers can serve as natural floodwater reservoirs, wildlife habitats, and water purifiers. Inland waterway construction often focuses on the efficiency of construction and operation, at the cost of riparian habitats, water quality, biodiversity, and hydrology. The present research has shown that benthic invertebrates were sensitive to changes in their habitats, and constructing inland waterways damaged the components of benthic macroinvertebrate communities, damage that may prove irreversible [51,52]. The diversity and abundance of macroinvertebrate communities are lower in mountainous rivers compared with rivers on plains or agricultural irrigated areas [4,21,29]. Benthic macroinvertebrate communities in mountain rivers were found

to be more responsive to the waterway construction activities. If habitats are suitable, populations of benthic macroinvertebrate fauna can survive periods of intense external disturbance to the riparian ecosystem [51]. Essentially, reducing the damage to river channels associated with inland waterway construction could maintain both the diversity and abundance of macroinvertebrates in undeveloped rivers. During construction and operation, the inland waterways were found to be unable to sustain high levels of abundance and biodiversity. Therefore, inland waterway projects should not focus on economic benefits alone; if necessary, waterway construction must be modified to minimize the negative effects of construction and traffic on the river ecosystem.

The results of this study show that river stretches during the construction and operation of inland waterways are poor habitats for macroinvertebrates and the deterioration of these habitats (owing to channel regulation and dams, for example) may reduce benthic invertebrate diversity severely. Although benthic invertebrate communities are affected by external disturbances, such adverse impacts can be mitigated if waterway projects adopt strategies to protect the river ecology [53–55]. We therefore recommend that biological conservation, environmental protection, and habitat restoration be considered during the planning and construction of waterways. Any waterway project should seek to minimize disturbances to the river ecosystem and provide suitable habitats for benthic macroinvertebrate communities. The influence of different phases of waterway construction on macroinvertebrate communities emphasizes the importance of matching inland waterway construction to the properties of local habitats. It may not always be necessary to develop waterways along the entire length of a river. The authorities responsible for waterway construction should establish appropriate waterway management systems that facilitate the conservation of aquatic fauna and the restoration of their habitats to derive greater ecological benefits during the construction of inland waterways.

One part of understanding inland waterway ecosystems is studying the fluctuations in macroinvertebrate populations over extended periods. Benthic invertebrates are sensitive to external changes such as those resulting from construction, and those organisms can be reliable indicators of water quality and of the health of the inland waterway ecosystem [56]. In particular, restoration of the riparian zone should focus on protecting specific benthic invertebrates, and the conservation of aquatic fauna should be coupled with the restoration of habitat quality to facilitate the survival of taxa on a regional scale. The effects of an anthropogenic intervention on undeveloped rivers can be investigated using the abundance and the diversity of benthic invertebrates as indicators. The strategies for conservation and restoration of inland waterways should ensure that once a waterway construction project is complete, the habitats become suitable once again for recolonization [57]. A reduction in diversity, for example, is a typical detrimental effect of construction on ecosystems in the riparian zone, and appropriate ways to restore the diversity to its former level should be part of the restoration strategy. However, this requires detailed field studies on macroinvertebrates as well as on water quality and habitat quality carried out before (to serve as baselines), during, and after the completion of any project of waterway construction.

5. Conclusions

Both the diversity and abundance of benthic invertebrates decreased markedly during the construction of inland waterways, and the subsequent shipping along the completed waterway continued to lower the quality of their habitat. Such operations as dredging, building dams and wharves, and regulating waterway channels had adverse impacts on natural ecological processes. The likely density of traffic along a stretch of the waterway should also guide waterway construction. Conserved or restored habitats that will sustain the diversity and abundance of benthic macroinvertebrate communities must be established along the inland waterways. The findings of the present research quantify the influence of waterway construction and operation on benthic invertebrates in the riparian zone and will help in devising appropriate strategies to protect the fauna or to minimize the adverse impacts of construction on benthic communities. Further research is also necessary to

explore how the changes in the environment that result from constructing inland waterways influence the riparian benthic macroinvertebrate communities within the waterways.

Intensive research must be carried out to investigate the influence of ship waves on the riparian benthic invertebrate assemblages and to identify the best strategies for establishing alternative habitats for macroinvertebrates. Further research should also be conducted to understand the dynamics and functions of benthic invertebrate communities in inland waterways and to examine the effects of shipping traffic on local benthic assemblages. More data are required on the diversity and abundance of aquatic organisms within inland waterways. The findings of such research will help in managing both the construction and the operation of inland waterways in ways that avoid or minimize the detrimental impacts of waterways on their ecology.

References

1. Dębska, K.; Rutkowska, B.; Szulc, W. Influence of the catchment area use on the water quality in the Utrata River. Environmental Monitoring and Assessment. *Environ. Monit. Assess.* **2022**, *194*, 165. [CrossRef] [PubMed]
2. Arbaciauskas, K.; Semenchenk, V.; Grabowski, M. Assessment of biological contamination of benthic macroinvertebrate communities in European inland waterways. *Aquatic Invasions* **2018**, *3*, 211–230. [CrossRef]
3. Paarlberg, A.J.; Guerrero, M.; Huthoff, F. Optimizing Dredge-and-Dump Activities for River Navigability Using a Hydro-Morphodynamic Model. *Water* **2015**, *7*, 3943–3962. [CrossRef]
4. Li, K.; Zhang, Z.X.; Yang, H.J.; Bian, H.F.; Jiang, H.B.; Sheng, L.X.; He, C.G. Effects of instream restoration measures on the physical habitats and benthic macroinvertebrates in an agricultural headwater stream. *Ecol. Eng.* **2018**, *122*, 252–262. [CrossRef]
5. Fraser, M.A.; Baldwin, D.S.; Rees, G.N.; Silvester, E.J.; Whitworth, K.L. Rehabilitation options for inland waterways impacted by sulfidic sediments-Field trials in a south-eastern Australian wetland. *J. Environ. Manag.* **2012**, *102*, 71–78. [CrossRef] [PubMed]
6. La Guardia, M.J.; Hale, R.C.; Newman, B. Brominated Flame-Retardants in Sub-Saharan Africa: Burdens in Inland and Coastal Sediments in the eThekwini Metropolitan Municipality, South Africa. *Environ. Sci. Technol.* **2013**, *47*, 9643–9650. [CrossRef]
7. Lorenz, S.; Pusch, M.T. Filtration activity of invasive mussel species under wave disturbance conditions. *Biol. Invasions* **2013**, *15*, 2681–2690. [CrossRef]
8. Conder, J.M.; Fuchsman, P.C.; Grover, M.M.; Magar, V.S.; Henning, M.H. Critical review of mercury sediment quality values for the protection of benthic invertebrates. *Environ. Toxicol. Chem.* **2014**, *34*, 6–21. [CrossRef]
9. Hanafiah, M.M.; Leuven, R.S.E.W.; Sommerwerk, N.; Tockner, K.; Huijbregts, M.A.J. Including the introduction of exotic species in life cycle impact assessment: The case of inland shipping. *Environ. Sci. Technol.* **2013**, *47*, 13924–13940. [CrossRef]
10. Whitfield, A.K.; Becker, A. Impacts of recreational motorboats on fishes: A review. *Mar. Pollut. Bull.* **2014**, *83*, 24–31. [CrossRef]
11. Weber, A.; Wolter, C. Habitat rehabilitation for juvenile fish in urban waterways: A case study from Berlin, Germany. *J. Appl. Ichthyol.* **2016**, *33*, 136–143. [CrossRef]
12. Deng, X.; Xu, Y.P.; Han, L.F.; Yu, Z.H.; Yang, M.N.; Pan, G.B. Assessment of river health based on an improved entropy-based fuzzy matter-element model in the Taihu Plain, China. *Ecol. Indic.* **2015**, *57*, 85–95. [CrossRef]
13. Adkins, J.K.; Barton, C.D.; Grubbs, S.; Stringer, J.W.; Kolka, R.K. Assessment of Streamside Management Zones for Conserving Benthic Macroinvertebrate Communities Following Timber Harvest in Eastern Kentucky Headwater Catchments. *Water* **2016**, *8*, 261. [CrossRef]
14. Gabel, F.; Garcia, X.F.; Schnauder, I.; Pusch, M.T. Effects of ship-induced waves on littoral benthic Invertebrates. *Freshw. Biol.* **2012**, *57*, 2425–2435. [CrossRef]
15. Weber, A.; Zhang, J.; Nardin, A.; Sukhodolova, T.; Wolter, C. Modelling the Influence of Aquatic Vegetation on the Hydrodynamics of an Alternative Bank Protection Measure in a Navigable Waterway. *River Res. Appl.* **2016**, *32*, 2071–2080. [CrossRef]
16. Feiler, U.; Höss, S.; Ahlf, W.; Gilberg, D.; Hammers-Wirtz, M.; Hollert, H.; Heininger, P. Sediment contact tests as a tool for the assessment of sediment quality in German waters. *Environ. Toxicol.* **2012**, *32*, 144–155. [CrossRef] [PubMed]

17. Tricarico, E.; Junqueira, A.O.R.; Dudgeon, D. Alien species in aquatic environments: A selective comparison of coastal and inland waters in tropical and temperate latitudes. *Aquat. Conserv.-Mar. Freshw. Ecosyst.* **2016**, *26*, 872–891. [CrossRef]

18. Sukhodolova, T.; Weber, A.; Zhang, J.X.; Wolter, C. Effects of macrophyte development on the oxygen metabolism of an urban river rehabilitation structure. *Sci. Total Environ.* **2017**, *574*, 1125–1130. [CrossRef]

19. Verbrugge, L.N.H.; Schipper, A.M.; Huijbregts, M.A.J.; Velde, G.V.; Leuven, R.S.E.W. Sensitivity of native and non-native mollusc species to changing river water temperature and salinity. *Biol. Invasions* **2012**, *14*, 1187–1199. [CrossRef]

20. Aufdenkampe, A.K.; Mayorga, E.; Raymond, P.A.; Melack, J.M.; Doney, S.C.; Alin, S.R.; Aalto, R.E.; Yoo, K. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Front. Ecol. Environ.* **2011**, *9*, 53–60. [CrossRef]

21. Meng, X.L.; Jiang, X.M.; Li, Z.F.; Wang, J.; Cooper, K.M.; Xie, Z.C. Responses of macroinvertebrates and local environment to short-term commercial sand dredging practices in a flood-plain lake. *Sci. Total Environ.* **2018**, *631–632*, 1350–1359. [CrossRef] [PubMed]

22. Dilts, T.E.; Weisberg, P.J.; Leitner, P.; Matocq, M.D.; Inman, R.D.; Nussear, K.E.; Esque, T.C. Multiscale connectivity and graph theory highlight critical areas for conservation under climate change. *Ecol. Appl.* **2016**, *26*, 1223–1237. [CrossRef] [PubMed]

23. Rahman, M.A.; Jaumann, L.; Lerche, N.; Renatus, F.; Buchs, A.K.; Gade, R.; Geldermann, J.; Sauter, M. Selection of the Best Inland Waterway Structure: A Multicriteria Decision Analysis Approach. *Water Resour. Manag.* **2015**, *29*, 2733–2749. [CrossRef]

24. Leitner, P.; Borgwardt, F.; Birk, S.; Graf, W. Multiple stressor effects on benthic macroinvertebrates in very large European rivers –A typology-based evaluation of faunal responses as a basis for future bioassessment. *Sci. Total Environ.* **2021**, *756*, 143472. [CrossRef]

25. Gergs, R.; Koester, M.; Schulz, R.S. Potential alteration of cross-ecosystem resource subsidies by an invasive aquatic macroinvertebrate: Implications for the terrestrial food web. *Freshw. Biol.* **2014**, *59*, 2645–2655. [CrossRef]

26. Rico, A.; Van den Brink, P.J.; Graf, W.; Focks, A. Relative influence of chemical and non-chemical stressors on invertebrate communities: A case study in the Danube River. *Sci. Total Environ.* **2016**, *571*, 1370–1382. [CrossRef]

27. Hawkins, C.P.; Yuan, L.L. Multitaxon distribution models reveal severe alteration in the regional biodiversity of freshwater invertebrates. *Freshw. Sci.* **2016**, *35*, 1365–1376. [CrossRef]

28. Lintott, P.R.; Bunnefeld, N.; Park, K.J. Opportunities for improving the foraging potential of urban waterways for bats. *Biol. Conserv.* **2015**, *191*, 224–233. [CrossRef]

29. 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. [CrossRef]

30. Weber, A.; Lautenbach, S.; Wolter, C. Improvement of aquatic vegetation in urban waterways using protected artificial shallows. *Ecol. Eng.* **2012**, *42*, 160–167. [CrossRef]

31. Liedermann, M.; Tritthart, M.; Gmeiner, P.; Hinterleitner, M.; Schludermann, E.; Keckeis, H.; Habersack, H. Typification of vessel-induced waves and their interaction with different bank types, including management implications for river restoration projects. *Hydrobiologia* **2014**, *729*, 17–31. [CrossRef]

32. Kupilas, B.; McKie, B.G.; Januschke, K.; Friberg, N.; Hering, D. Stable isotope analysis indicates positive effects of river restoration on aquatic-terrestrial linkages. *Ecol. Indic.* **2020**, *113*, 106242. [CrossRef]

33. Habersack, H.; Hein, T.; Stanica, A.; Liska, L.; Mair, R.; Jager, E.; Hauer, C.; Bradley, C. Challenges of river basin management: Current status of, and prospects for, the River Danube from a river engineering perspective. *Sci. Total Environ.* **2016**, *543*, 828–845. [CrossRef]

34. Cron, N.; Quick, I.; Zumbroich, T. Assessing and predicting the hydromorphological and ecological quality of federal waterways in Germany: Development of a methodological framework. *Hydrobiologia* **2018**, *814*, 75–87. [CrossRef]

35. Navarro-Llacer, C.; Baeza, D.; de las Heras, J. Assessment of regulated rivers with indices based on macroinvertebrates, fish and riparian forest in the southeast of Spain. *Ecol. Indic.* **2010**, *10*, 935–942. [CrossRef]

36. Vries, J.; Kraak, M.H.S.; Verdonschot, R.C.M.; Verdonschot, P.F.M. Quantifying cumulative stress acting on macroinvertebrate assemblages in lowland streams. *Sci. Total Environ.* **2019**, *694*, 133630. [CrossRef]

37. Paganelli, D.; Kamburska, L.; Zaupa, S.; Garzoli, L.; Boggero, A. Impacts Analysis of Alien Macroinvertebrate Species in the Hydrographic System of a Subalpine Lake on the Italian–Swiss Border. *Water* **2021**, *13*, 3146. [CrossRef]

38. Theodoropoulos, C.; Stamou, A.; Vardakas, L.; Papadaki, C.; Dimitriou, E.; Skoulikidis, N.; Kalogianni, E. River restoration is prone to failure unless pre-optimized within a mechanistic ecological framework | Insights from a model-based case study. *Water Res.* **2020**, *173*, 115550. [CrossRef]

39. Kosnicki, E.; Sefick, S.A.; Paller, M.H.; Jerrell, M.S.; Prusha, B.A.; Sterrett, S.C. A Stream Multimetric Macroinvertebrate Index (MMI) for the Sand Hills Ecoregion of the Southeastern Plains, USA. *Environ. Manag.* **2016**, *58*, 741–751. [CrossRef]

40. Feld, C.K.; Bello, F.; Doledec, S. Biodiversity of traits and species both show weak responses to hydromorphological alteration in lowland river macroinvertebrates. *Freshw. Biol.* **2014**, *59*, 233–248. [CrossRef]

41. Mantyka-Pringle, C.S.; Martin, T.G.; Moffatt, D.B.; Linke, S.; Rhodes, J.R. Understanding and Predicting the Combined Effects of Climate Change and Land-Use Change on Freshwater Macroinvertebrates and Fish. *J. Appl. Ecol.* **2014**, *51*, 572–581. [CrossRef]

42. Legendre, P.; Caceres, M. Beta diversity as the variance of community data: Dissimilarity coefficients and partitioning. *Ecol. Lett.* **2013**, *16*, 951–963. [CrossRef] [PubMed]

43. Soininen, J. A quantitative analysis of species sorting across organisms and ecosystems. *Ecology* **2014**, *95*, 3284–3292. [CrossRef]

44. Pinto, U.; Maheshwari, B.L. River health assessment in peri-urban landscapes: An application of multivariate analysis to identify the key variables. *Water Res.* **2011**, *45*, 3915–3924. [CrossRef]
45. ter Braak, C.J.F.; Smilauer, P. *CANOCO Reference Manual and CanoDraw for Windows User's Guide, Software for Canonical Community Ordination*; Version 4.5; Microcomputer Power: Ithaca, NY, USA, 2002.
46. Halabowski, D.; Lewin, I. Triggers for the Impoverishment of the Macroinvertebrate Communities in the Human-Impacted Rivers of Two Central European Ecoregions. *Water Air Soil Pollut.* **2021**, *232*, 55. [CrossRef]
47. Martel, N.; Rodriguez, M.A.; Bérubé, P. Multi-scale analysis of responses of stream benthic macroinvertebrate to forestry activities and environmental context. *Freshw. Biol.* **2007**, *52*, 85–97. [CrossRef]
48. Stewart, B.A. An assessment of the impacts of timber plantations on water quality and biodiversity values of Marbellup Brook, Western Australia. *Environ. Monit. Assess.* **2011**, *173*, 941–953. [CrossRef]
49. Bunn, S.E.; Abal, E.G.; Smith, M.J.; Choy, S.C.; Fellows, C.S.; Harch, B.D. Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation. *Freshw. Biol.* **2010**, *55*, 223–240. [CrossRef]
50. Norris, R.H.; Linke, S.; Prosser, I.; Young, W.J.; Liston, P.; Bauer, N. Very-broad-scale assessment of human impacts on river condition. *Freshw. Biol.* **2007**, *52*, 959–976. [CrossRef]
51. Langston, W.J.; O'Hara, S.; Pope, N.D.; Davey, M.; Shortidge, E.; Imamura, M. Bioaccumulation surveillance in Milford Haven Waterway. *Environ. Monit. Assess.* **2012**, *184*, 289–311. [CrossRef]
52. Launois, L.; Veslot, J.; Irz, P. Development of a fish-based index (FBI) of biotic integrity for French lakes using the hindcasting approach. *Ecol. Indic.* **2011**, *11*, 1572–1583. [CrossRef]
53. Holmes, R.W.; Anderson, B.S.; Phillips, B.M.; Hunt, J.W.; Crane, D.B.; Mekebri, A.; Connor, V. Statewide Investigation of the Role of Pyrethroid Pesticides in Sediment Toxicity in California's Urban Waterways. *Environ. Sci. Technol.* **2008**, *42*, 7003–7009. [CrossRef] [PubMed]
54. Nishijima, W.; Nakano, Y.; Nakai, S.; Okuda, T.; Imai, T.; Okada, M. Macrobenthic succession and characteristics of a man-made intertidal sandflat constructed in the diversion channel of the Ohta River Estuary. *Mar. Pollut. Bull.* **2014**, *82*, 101–108. [CrossRef]
55. Sang, L.Z.; Wall, A.; Mao, Z.; Yan, X.P.; Wang, J. A novel method for restoring the trajectory of the inland waterway ship by using AIS data. *Ocean Eng.* **2015**, *110*, 183–194. [CrossRef]
56. Saxena, G.; Marzinelli, E.M.; Naing, N.N.; He, Z.L.; Liang, Y.T.; Tom, L. Metagenomics Reveals the Influence of Land Use and Rain on the Benthic Microbial Communities in a Tropical Urban Waterway. *Msystems* **2018**, *3*, e00136-17. [CrossRef] [PubMed]
57. Hein, T.; Schwarz, U.; Habersack, H.; Nichersu, I.; Preiner, S.; Willby, N.; Weigelhofer, G. Current status and restoration options for floodplains along the Danube River. *Sci. Total Environ.* **2016**, *543*, 778–790. [CrossRef]