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The Impact of Catastrophic Floods on Macroinvertebrate Communities in Low-Order Streams: A Study from the Apennines (Northwest Italy)

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Abstract: Floods are normal components of many river regimes and, as such, they exert a significant influence at the ecosystem level. In recent decades, however, climate change has increased the frequency and intensity of floods, with serious consequences for lotic biota, particularly benthic macroinvertebrates, due to their limited mobility and sensitivity to disturbance. The impact of floods varies according to different biological parameters including the characteristics of the macrobenthic communities (taxonomic composition, morphology, behaviour, and life history traits) on one hand and various nonbiological parameters such as flood intensity, artificialisation of the river bed, the presence of dams, and many other factors on the other. Understanding these dynamics is pivotal to improve the effective management and conservation of aquatic ecosystems in the context of current climate change. The aim of this short communication is to evaluate the impact of a catastrophic flood on the macroinvertebrate community of a low-order Appennine stream (NW Italy). This will provide data regarding the varying impacts on different taxa and the recovery pattern of this significant component of the ecosystem.

Keywords: hydrological disturbance; resilience; resistance; taxonomic diversity; stream ecosystems; functional feeding groups

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1. Introduction

Floods are intrinsic phenomena that play a vital role in shaping the structure and function of lotic ecosystems [1]. Naturally occurring flood events are fundamental to the ecological balance of rivers and streams, driving processes such as nutrient cycling, habitat formation, species diversity, and the dynamics of biological communities. These periodic inundations, depending on the river's hydrological regime, typically align with specific seasons—nival floods in spring due to snowmelt, pluvial floods in autumn driven by heavy rainfall, and glacial floods in summer as a result of glacial melt. However, in recent decades, the patterns and frequencies of these floods have been increasingly disrupted by global climate change. This has led to significant alterations in the hydrological regimes of rivers across various regions of the world. The effects of climate change have manifested in more frequent and intense flood events, which deviate from the historical norms and pose significant challenges to the stability of freshwater ecosystems. The increase in both the frequency and magnitude of these extreme flood events has profound implications for the resident biota and the overall health of aquatic ecosystems [2]. While seasonal floods are crucial for nutrient cycling, new habitat creation, species diversity, community dynamics [3] and overall ecosystem health, extreme and catastrophic flood events can have severe consequences for the resident biota [4]. These extreme events often lead to the homogenization of the affected river stretch. This homogenization process involves the simplification of habitat complexity, which is a key driver of biodiversity in aquatic systems. The loss of habitat heterogeneity can significantly reduce the capacity of the ecosystem to support a diverse range of species, leading to a decline in ecological resilience and slower recovery times following disturbances [5]. Among the most affected organisms are macroinvertebrates, due to their limited mobility, benthic habits [6], and sensitivity to disturbances [7]. The impact of extreme floods on macroinvertebrate communities can be severe, often leading to significant reductions in population densities and alterations in community composition. The physical disturbance of the substrate, coupled with the rapid changes in water quality and flow velocity, can displace these organisms, bury them under sediment, or even lead to their mortality. Additionally, the loss of habitat complexity due to substrate homogenization further exacerbates the decline in macroinvertebrate diversity, as many species are highly specialized and rely on specific microhabitats for survival.

Macroinvertebrate communities are composed of taxa with varying degrees of resistance and resilience to flood disturbance: resistant taxa can withstand the physical force of the flood and remain in their habitat, while resilient taxa can rapidly recolonize the area after disturbance. The degree of resistance and resilience of the macroinvertebrate community depends on its specific taxonomic, behavioural, and life-history trait composition [6]. For example, some taxa can burrow deeper into the sediment or attach to substrates to avoid being washed away, while others have rapid life cycles that allow quick recolonization [1]. The resistance and resilience of benthic macroinvertebrate communities to floods are also dependent on a variety of factors, including the intensity and timing of the event [8,9]. Macroinvertebrate community recovery after a flood event is a complex process influenced by the magnitude and duration of the disturbance, the ability of the community to recolonize, and the availability of undisturbed habitat patches [8,10]. The repercussions of these changes extend beyond the immediate aftermath of the flood event. The slow recovery of macroinvertebrate communities can have cascading effects throughout the food web, affecting species that depend on them for food and altering the overall functioning of the ecosystem. Furthermore, the repeated occurrence of extreme flood events can prevent these communities from fully recovering, leading to long-term shifts in community structure and function.

This scenario is further complicated by the fact that lotic systems are in general characterised by the massive presence of artificial structures. In particular, dams and other man-made barriers can have significant negative impacts on river ecosystems not only by altering the natural hydrological regime [11] but also by exacerbating the impacts of global climate change. This can have negative effects on the structure and function of macrobenthic communities that have adapted to specific hydrological regimes: for example, disrupting river connectivity, dams create physical barriers that prevent the migration and dispersal of macrobenthic species, isolating populations and reducing genetic diversity. This can make communities more vulnerable to the effects of extreme events such as catastrophic floods [12]. However, in the case of catastrophic floods, dams can have a positive effect, particularly by reducing the peak of the flood: dams can reduce the intensity of floods by storing some of the excess water upstream. This can reduce the destructive force of the current, protecting benthic habitats and the organisms that live there [13]. Catastrophic floods can also create refugia. Downstream of the dam, the water flow is generally more constant and less turbulent. These areas can act as refuges for the more fragile macrobenthic species, allowing them to survive during the flood event and then recolonise the upstream areas afterwards [14].

Overall, understanding the response of macroinvertebrate communities to catastrophic floods, as well as the time required for ecosystem recovery, is crucial for improving the effective management and conservation of lotic ecosystems in the face of increasing climate change [15]. The present study aims to analyse the impact of a catastrophic flood event on the macrobenthic community of a low-order Apennine stream, identify the most resilient organisms, and determine the recovery time of the macroinvertebrate community.

2. Materials and Methods

2.1. Area of Study

The Piota stream, a right tributary of the Orba stream (NW Italy), is a low-order Apennine lotic system about 30 km long. The Piota has an average flow of about 2.7 m^3/s and drains a catchment area of about 115 km2. In the study area, a hydroelectric plant established in 2017 modified the stream morphology. Three distinct elements are thus recognisable: a section upstream of the intake, a 1.8 km section underneath, and a section downstream of the restitution. We designed three sampling stations, one for each segment, that are designated as follows: "S1 UP" (N 44°38′55.0″–E 8°41′49.6″), which is upstream of the diversion for hydroelectric use, "S2 TAIL" (N 44°39′40.1″–E 8°41′04.4″), which is in the stretch subtended by the plant, and "S3 DOWN" (N 44°40′19.8″–E 8°40′38.7″), which is downstream of the restitution (Figure 1). From 2018 to 2022, we performed 12 sampling campaigns in the three stations, for a total of 360 Surber samples. During this period, a major flood event occurred in 2019 (with a peak of 800 m^3/s ca.; source: ARPA Piemonte), so our data can be of interest to analyse the impact of an extreme hydrological event in a highly manipulated stream reach.

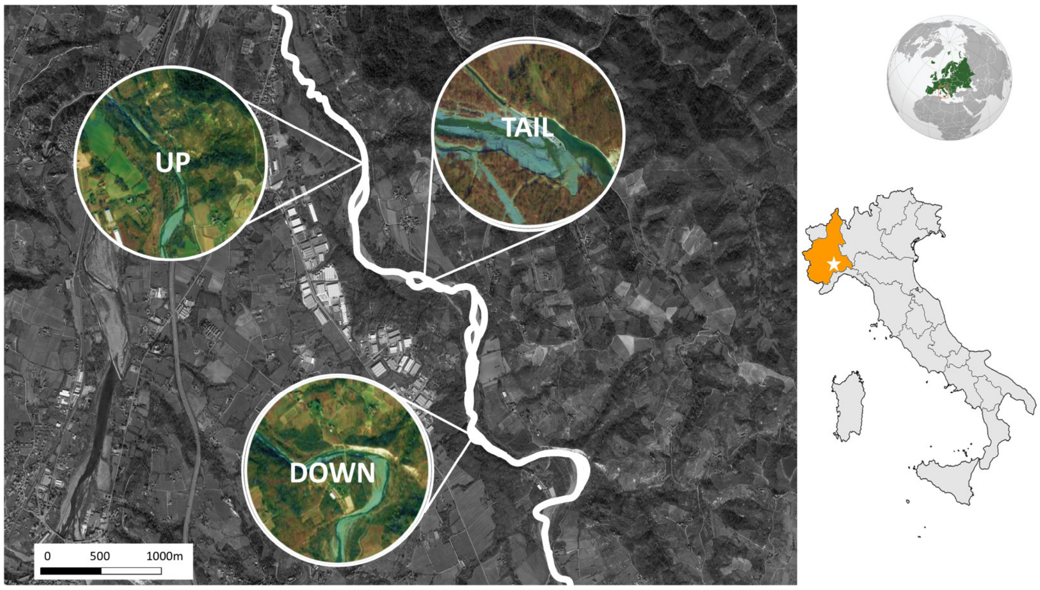

Figure 1. Map of the sites, with a focus on three different sampling stations relative to the dam: UP, TAIL, and DOWN.

2.2. Macroinvertebrate Sampling and Processing

In the study area, the substrate composition of the riverbed was estimated, considering both mineral components (mud, sand, gravel, and stones of various size classes) and biotic components (such as fallen leaves, macrophytes, and dead wood). According to the frequency of substrate categories, we collected ten quantitative samples in each sampling occasion and each station, thus applying a multi-habitat sampling. Quantitative samples of benthic macroinvertebrates were collected using a Surber sampler (20 × 20 cm, mesh = 255 μm) and then sorted, determined, and counted according to the STAR ICMi method [16]. A preliminary analysis of taxa accumulation curves showed that the sampling effort was largely adequate to obtain a representative characterisation of the diversity of macroinvertebrate communities at the three sites. Macroinvertebrates were counted and systematically identified at the family level, according to the dichotomous key available for the Italian benthic macroinvertebrate fauna [17,18]. The total number of taxa and the total number of individuals were then calculated for each sample.

2.3. Statistical Analyses

Compositional changes in macroinvertebrate communities before and after the flood and between stretches (up, tail, and down) were statistically tested using non-metric multidimensional scaling (NMDS) and permutational analysis of variance (PERMANOVA), respectively. To this end, all samples were used in this analysis, and the Bray–Curtis dissimilarity index was applied to macroinvertebrate abundances. To better understand the structure and dynamics of macrobenthic communities, nestedness and taxa turnover were calculated.

Analysis of variance (ANOVA) was used to assess total taxon richness, total abundance, abundance and taxonomic richness of Ephemeroptera, Plecoptera and Trichoptera (EPT), total number of taxa found in all groups, percentage of dominance of the top 3 three taxa (DOM-3: Chironomidae, Leuctridae, and Baetidae), and non-Chironomidae Oligochaeta richness (NCO). We also focused on possible differences in functional (i.e., feeding functional groups [19]) community metrics and beta diversity (nestedness and turnover) among sites and dates. Post hoc pairwise comparisons were performed with Tukey's test. Moreover, to analyse the response of macroinvertebrates to the flood, we conducted a Sankey flow plot and a Mann–Kendall analysis on the most abundant taxa to highlight the families with greater resilience and resistance.

All analyses were performed in the R statistical environment [20] using the basic functions and the following packages: vegan [21] for NMDS and PERMANOVA, betapar [22] for nestedness and turnover, and Kendal [23] for Mann–Kendall analysis. The significance threshold was set at $p < 0.05$.

3. Results

With the exception of the catastrophic flood, the main environmental characteristics of the river in the sections examined during the study period remained constant and homogeneous. We found no significant differences in the main physical and chemical characteristics between the sites: pH = 8.09 ± 0.02 (mean ± SD); conductivity (μS/cm) = 356 ± 17.9 (mean ± SD); BOD_5 (mg/L O_2) = 4.36 ± 1.67 (mean ± SD); total P (mg/L) = <0.001; NO_3 (mg/L) = 0.30 ± 0.16 (mean ± SD); and NH_4 (mg/L) = <0.003. Similarly, the estimated granulometric composition of the riverbed did not differ between sites (in general, 40% macrolithal, 40% mesolithal, 10% microlithal, and 10% gravel).

A total of 21,028 macroinvertebrates belonging to 59 taxa were collected. Among these, six taxa accounted for 56.27% of the whole community: Chironomidae (19.73%), Leuctridae (10.88%), Baetidae (9.59%), Hydropsychidae (7.77%), Ephemerellidae (4.84%), and Naididae (3.46%).

The occurrence of the 2019 flood had a significant impact on taxa richness (F1.141 = 0.047; $p < 0.001$), as shown in Figure 2a: this impact was general, and we detected no significant differences among stations/river stretches (F1.141 = 0.010; $p = 0.084$). The communities before and after the flood were diversified, but in 2022, we noticed that total beta diversity, in terms of percentage nestedness and turnover, returned to values comparable to the pre-flood period. In the year 2020, i.e., immediately after the flood, nestedness increased, although turnover constituted the largest portion of beta diversity for all sampling dates (Figure 2b).

The taxonomic metrics did not vary significantly across the different sites (Table 1); for this reason, the samples were grouped according to year for analysis. Considering macroinvertebrate total abundance (Figure 3a), we noticed a significant collapse in 2020 and 2021, followed by a return to values comparable to pre-flood values in 2022. This trend is rather similar in all other metrics such as richness, non-Chironomidae Oligochaeta richness (NCO) (Figure 3d), EPT abundance (Figure 3e), and EPT richness (Figure 3f), with the exception being DOM-3 (Figure 3c), for which we detected no real variation.

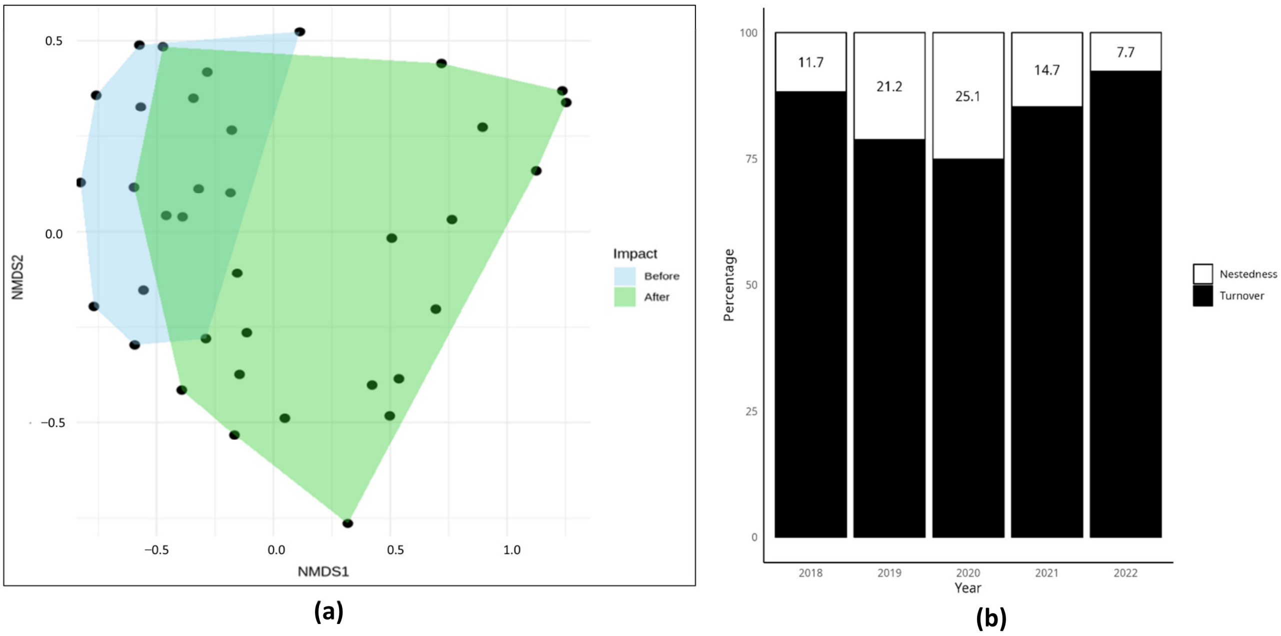

Figure 2. (**a**) NMDS ordination plot (stress = 0.143) considering samples collected before and after the flood event. (**b**) Barplot with the percentage contribution of nestedness (in white) and turnover (in black), representing the total beta diversity in the sampling period.

Table 1. Results of nonsignificant ANOVA taxonomic metrics across different sites and sites by year.

Abundance	**F Value**	***p*-Value**
Sites	1.937	0.169
Site:Year	0.493	0.847
Richness	**F value**	***p*-value**
Sites	0.152	0.859
Site:Year	0.282	0.964
EPT_Abundance	**F value**	***p*-value**
Sites	1.567	0.232
Site:Year	0.482	0.854
EPT_Richness	**F value**	***p*-value**
Sites	0.109	0.896
Site:Year	0.340	0.940
DOM-3	**F value**	***p*-value**
Sites	0.006	0.994
Site:Year	0.327	0.724
NCO_Richness	**F value**	***p*-value**
Sites	0.077	0.926
Site:Year	0.340	0.714

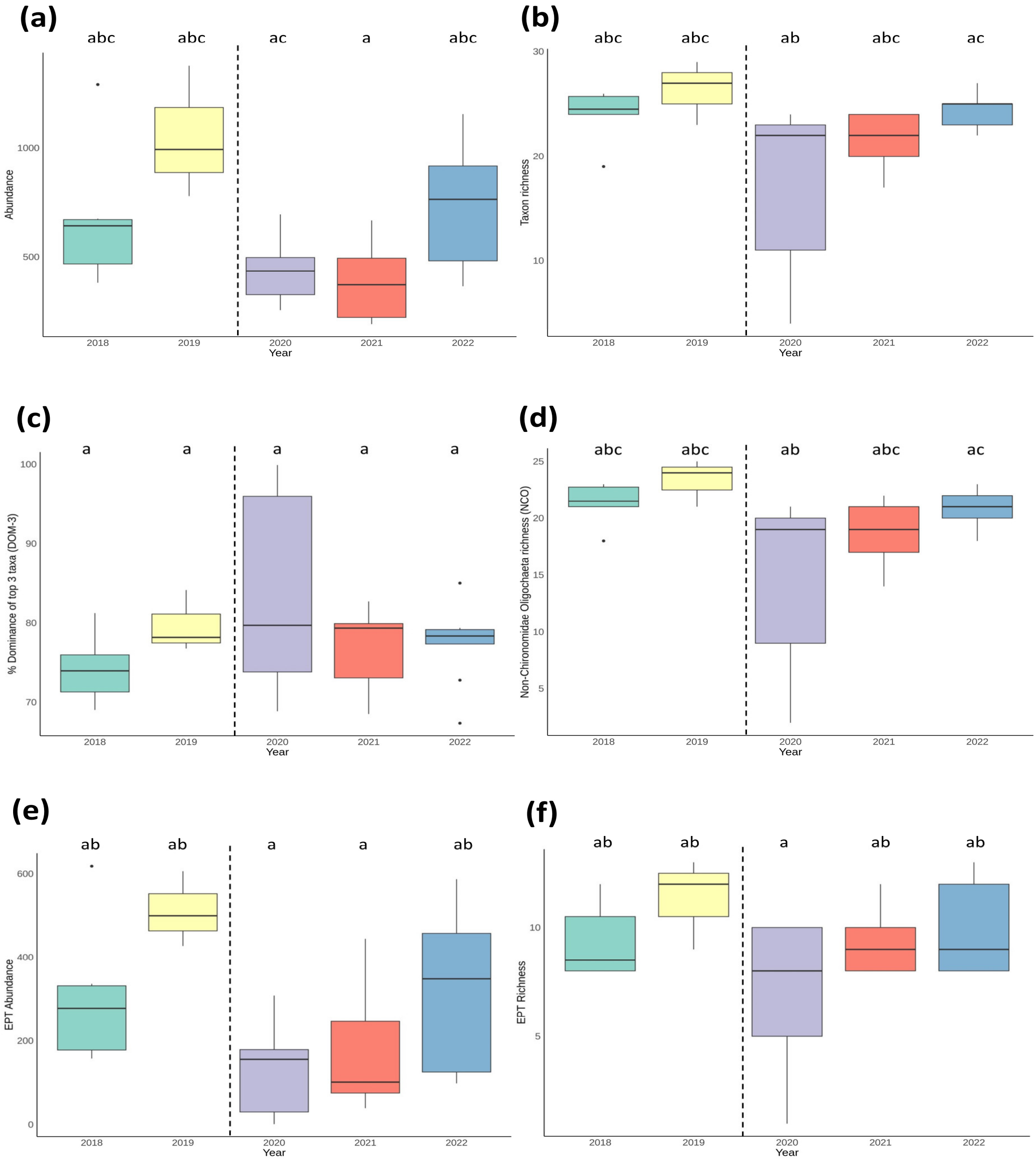

Figure 3. Boxplots illustrating the variation in the abundance (**a**), taxon richness (**b**), percentage of dominance of top 3 taxa (DOM-3) (**c**), non-Chironomidae Oligochaeta richness (NCO) (**d**), EPT abundance (**e**) and EPT richness (**f**) from 2018 to 2022. Horizontal black lines represent the median value, and the lower and upper edges of boxplots represent the 1° and 3° quartiles, respectively. Vertical lines above the boxplots represent ± 1.5 IQR (where IQR = interquartile distance). Observations beyond this range are illustrated using black dots. The vertical dashed line represents the flood event.

The percentage composition of the functional feeding groups showed a significant difference over time. In particular, collectors increased and prevailed in the year 2020 (Figure 4a) compared to a more balanced FFG distribution in the years before the flood event. After the flood, the ratio of scrapers/collectors plus shredders changed considerably (Figure 4b). This ratio decreased in 2019 and then increased in 2021 and 2022.

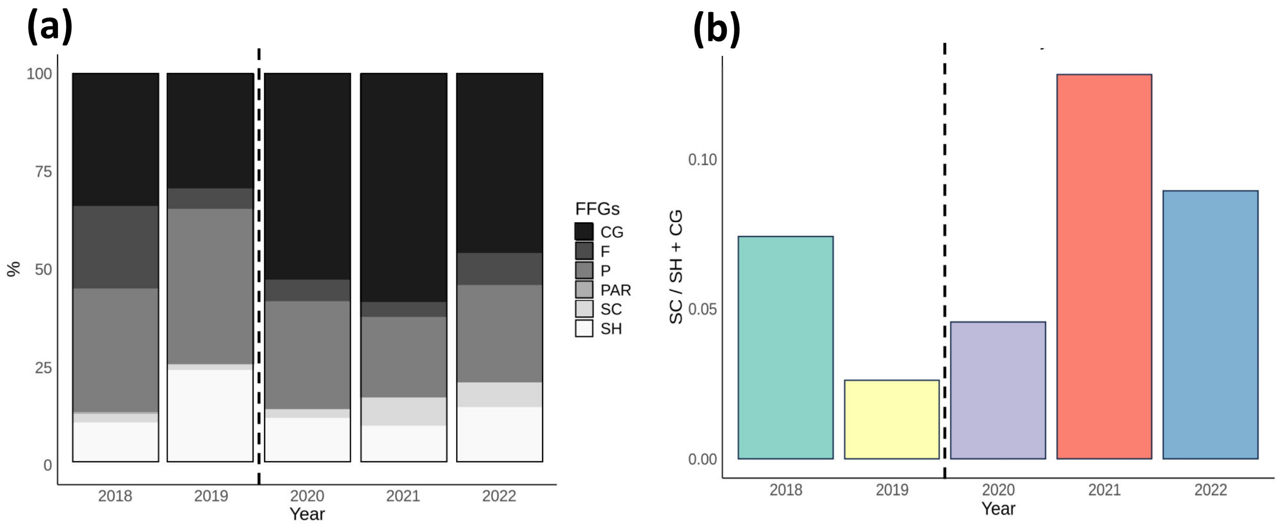

Figure 4. Stacked bars in panel (**a**) illustrate the average percentage of each feeding functional group (CG = collector–gatherers, F = filterers, P = predators, PAR = parasites, SC = scrapers, and SH = shredders) in the Piota River on sampling dates between 2018 and 2022. Bars in panel (**b**) represent the scrapers to shredders + total collectors ratio. The vertical dashed line represents the flood.

After analysing the most abundant macroinvertebrate taxa, Chironomidae (Tau = 0.5317, *p*-value = 0.02729) (Figure 5a) increased significantly in the year after the flood at each site, while Baetidae (Figure 5a) (Tau = 0.5151, *p*-value = 0. 0236) and Limoniidae (Figure 5b) (Tau = 0.5954, *p*-value = 0.009) increased significantly in 2021, and the abundance of Hydropsychidae and Leuctridae (Figure 5a) returned in 2022, although not significantly. Caenidae (Tau = −0.5200, *p*-value = 0.0261) and Elmidae (Tau = −0.5918, *p*-value = 0.0148) decreased significantly after the flood event (Figure 5b).

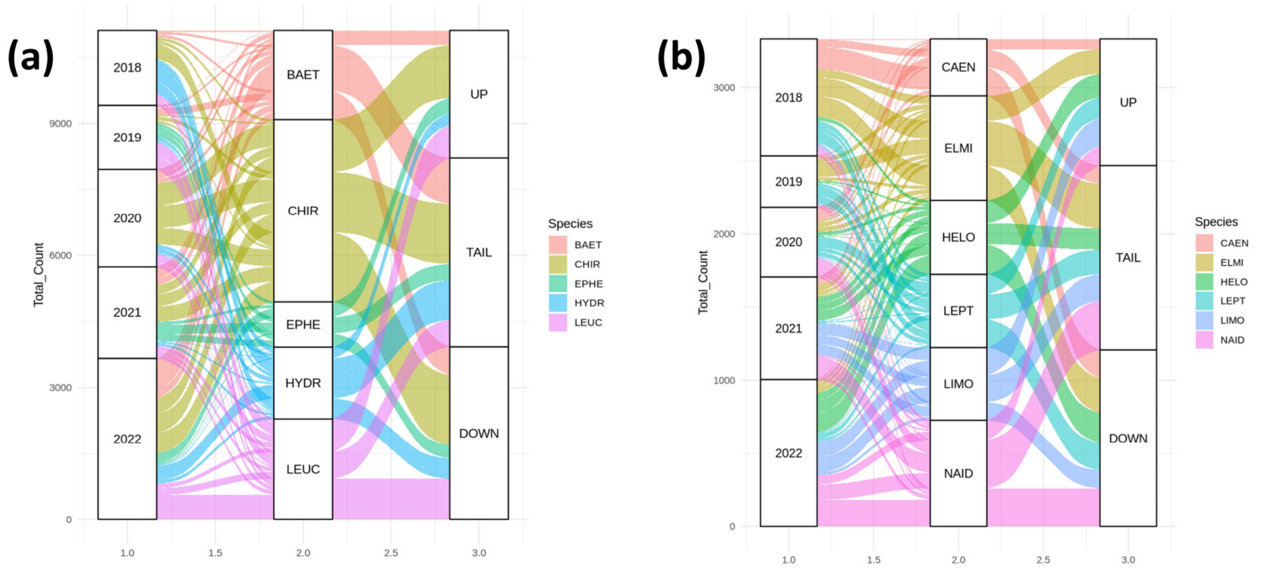

Figure 5. Comparative analysis of the annual variation in the total count of different families of macroinvertebrates across different years and stretches. The chart in panel (**a**) presents the families Baetidae (BAET), Chironomidae (CHIR), Ephemerellidae (EPHE), Hydropsychidae (HYDR), and Leuctridae (LEUC), and the chart in panel (**b**) shows the families Caenidae (CAEN), Elmidae (ELMI), Helodidae (HELO), Leptophlebiidae (LEPT), Limoniidae (LIMO), and Naididae (NAID). Each family is represented with a specific color to highlight trends across different years and stretches.

4. Discussion

The flood event that occurred in the Piota stream in 2019 had a significant impact on the structural and functional composition of the macroinvertebrate community. Immediately after the flood, there was a drastic decline in both the abundance and richness of the macroinvertebrates in all stretches. Moreover, the pattern of beta diversity reflected the dynamic nature of the macroinvertebrate community's response to a catastrophic flood, highlighting its capacity for resilience and reorganization over time [24]. The increase in nestedness observed in 2020 indicates a gradual recovery of the community, with the reestablishment of some of the taxa that were present before the flood. However, the continued dominance of turnover suggests that the community has not yet fully returned to its pre-flood state, with new species replacing those that were lost during the event.

In general, the macroinvertebrate community showed signs of resilience after the flood, with a gradual recovery of taxonomic diversity and abundance over the following years. Some taxa, such as Chironomidae and Baetidae, were able to rapidly recolonize the river system after the disturbance, as previously reported [25,26]. These taxa show a combination of resistance and resilience capacity due to their propensity to drift, their morphological/behavioural adaptations, and the use of refugia during high flows [27,28]. By contrast, other taxa such as Caenidae and Elminthidae were more sensitive to the flood and showed a longer-term decline in their populations [29]. In particular, Chironomidae tend to enter the drift mainly in a passive way and are carried by the current without active control, often due to disturbances like floods. However, they can also enter the drift actively in response to environmental changes. They prefer gravel or sandy substrates that offer refuges during floods. Some species build silk tubes in the substrates, which can provide protection during floods. They can actively seek refuge in protected microhabitats, such as under rocks or among aquatic vegetation, to avoid being swept away by the current. Baetidae exhibit a combination of active and passive drift, with a greater propensity for active drift. They are good swimmers and can use this ability to avoid being carried away by the current. They can enter the drift actively, especially at night to avoid predators. This behavior allows them to colonize new areas and escape adverse conditions. Baetidae can also be passively transported by the current, but they tend to have better control over their movement compared to Chironomidae. They prefer gravel or sandy substrates, similar to Chironomidae, which offer refuges during floods, and they can actively seek refuge in protected microhabitats, such as under rocks or among aquatic vegetation, to avoid being swept away by the current (e.g., Dagnino et al., 2008 [28]). Baetidae have slender, hydrodynamic bodies that reduce resistance to the current.

The functional composition of the macroinvertebrate community also underwent shifts after the flood, with an initial increase in the proportion of collector–gatherers, reflecting the predominance of fine particulate organic matter over coarse organic matter and periphyton grazing [30,31]. Over time, the functional composition gradually returned to a more balanced state, with a recovery of scraper and shredder abundance [32].

The recovery of the macroinvertebrate community in the Piota River following the 2019 flood event was relatively rapid, with the community structure and diversity returning to levels comparable to pre-flood conditions within 2–3 years This confirms that macroinvertebrate communities in low-order river systems have a high resilience to flood disturbances [29,33].

It is interesting to note that the recovery may not be uniform across all taxa, and some sensitive or rare species may require more time to reestablish their populations. Additionally, the long-term impacts of such flood events on the ecosystem services provided by the macroinvertebrate community, such as nutrient cycling, organic matter processing, and food web support, are still less known and need further investigation [34]. Finally, this study highlights the importance of understanding the response of macroinvertebrate communities to catastrophic floods in order to better manage and protect these critical components of aquatic ecosystems [35,36]. Even though this is a single event in a single stream, we believe that such events are likely to be more and more diffuse and recurrent because of the increasing effects of global climate change [37], and our data provide information that can be used in the context of broader studies that consider multiple cases of this type.

Author Contributions: Conceptualization, T.B.; methodology, T.B.; formal analysis, A.M.; writing—original draft preparation, T.B., A.M. and S.F.; writing—review and editing, T.B., A.M. and S.F.; supervision, T.B. and S.F.; funding acquisition, T.B. and S.F. All authors have read and agreed to the published version of the manuscript.

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