Spatial scale determines how the morphological diversity relates with river biological diversity. Evidence from a mountain river in the central Chilean Andes.

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Key words: Fluvial geomorphology, morphological diversity, biodiversity, macroinvertebrates, fish, anurans, Chile.

ABSTRACT

Rivers shape the landscape and determine spatial connectivity for a variety of riverine and terrestrial organisms. Rivers impacted by human disturbances are often in need of restoration in order to increase their functionality and ecological diversity, and ultimately to improve the ecosystems services that they offer. Because it is usually assumed that physical diversity of river systems promotes biological diversity or riverine species, river restoration practices often tend to enhance simplified rivers by increasing structural morphological complexity of river reaches. However, the relationship between the variability of physical features and the biological communities in riverine environments is not necessarily straightforward to assume due to the high degree of complexity and feedback in the relationship. This work presents a case study with the application of a recent geomorphological method developed in Europe for the assessment and characterization of geomorphic conditions in combination with biological surveys, along a mountain river basin in Central Chile (Clarillo River). Although representing a single “snapshot” in the pulsating nature of a river system, our results suggest that availability of habitats provides the conditions to support different levels of biodiversity in a hierarchical way in terms of spatial scale. In particular, we found that abundance and diversity of macroinvertebrates are more related with
composition of geomorphic units, whereas the presence of fish is more related with the geomorphic nature of the reaches, and the presence of anurans is more related with the geomorphic nature of river segments.

1. Introduction

Rivers shape and determine the spatial connectivity of the landscape, providing a variety of resources and services (e.g. Brierley et al., 2013). However, rivers are often modified and impacted to the point that the environmental services they provide are severely affected (Wohl, 2014), and in need of restoration (Wohl et al., 2015). River restoration practices often tend to enhance simplified and ecologically poorly functional rivers by increasing structural morphological complexity of river reaches, with the aim to increase the potential availability of habitats and hence the presence of target organisms or communities (Wohl et al., 2015). The underlying ecological assumption is that physical environmental diversity would promote biological diversity (e.g., Frissell et al., 1986; Thorp et al., 2006). Although this assumption is reasonable and often demonstrated, several studies revealed that this is not always the case (e.g. Sullivan et al., 2004; Palmer et al., 2010; Eskew et al., 2012; Milner et al., 2015; Schumtz et al., 2016; Growns et al., 2017). Indeed, river biodiversity depends on a variety of drivers at small and large scales, such as fluvial processes, physico-chemical features, biological conditions (e.g., competition and predation) and land use (e.g. Friberg et al. 2009; Leps et al., 2015). Our knowledge on the ecological interactions between hydrological, geomorphological and biological processes is increasing and informing river restoration practices (Palmer & Ruhi, 2019). However, the relationships between physical and biological features in rivers remains poorly understood, mainly because surveys for physical habitat are not likely to coincide in a spatio-temporal scale to biological sampling (Rasmussen et al., 2011). A deep understanding of ecomorphological relationships between morphological and biological diversities in rivers is yet to be attained.

The morphological characteristics of a river system can be assessed using several protocols, and it is commonly quantified in order to support watershed managers in taking strategic decisions about river management and restoration priorities (Fryirs & Brierley, 2013; Rinaldi et al., 2015; Wheaton et al., 2015; Gurnell et al., 2016). Fluvial
geomorphological studies usually aim at understanding the river dynamics and processes at different spatio-temporal scales (Brierly & Fryirs, 2005; Rinaldi et al., 2015; 2017). In Europe, especially after the implementation of the EU Water Framework Directive 2000/60/EC, a variety of assessments, protocols and methodologies for river hydromorphological assessment have been developed (Belletti et al., 2015).

From the fluvial ecology perspective, the distribution of species occurs as a longitudinal transition depending on stream dimensions and type (Vannote et al., 1980), the regime of flow and flood pulse (Junk et al., 1989; Tockner et al., 2000), and the presence of single habitats. Furthermore, temporal and spatial scales of connectivity are currently considered as major drivers in the development of ecological functions in rivers (Poeppl et al., 2020). Ecological conditions and diversity in river systems depends on the degree of relations between the biotics and abiotic components, and within biotic communities, which are often assessed based on benthic macroinvertebrates (Thomson et al., 2004), although other groups such as diatoms, aquatic macrophytes, fish and terrestrial invertebrates should be taken into account as indicators for the overall river ecological and environmental conditions (Friberg et al., 2009; Golfieri et al., 2015; Kärnä et al., 2019).

The relationship between the variability of physical features and the biological communities in riverine environments have long been investigated (Frissell et al., 1986; Maddock, 1999), and it has been recognized that fluvial geomorphology is one of the main drivers for the fluvial biota (Kaller & Hartman, 2004; Poole et al., 2010). Attempts to test explicitly whether biotic communities are consistently different between different geomorphic units or different river styles suggest that geomorphic characteristics must be considered within the larger scale variables and processes that determine the presence and dynamics of such characteristics (e.g. Thomson et al., 2004; Chessman et al., 2006). Combining morphological indexes used in streams characterization systems with biotic indexes remains indeed a key issue for researchers, as the spatio-temporal differences in riverine communities will also depend on other variables, such as climate, water quality, and hydrological regimes amongst others (Golfieri et al., 2015; Palmer & Ruhi, 2019).

This makes difficult to verify and quantify the role of physical drivers on river ecosystem conditions and implies that field sampling and classification procedures
should be both biologically and geomorphologically meaningful (Brierley et al., 2013). Advances in this sense have been made since the River Styles Framework (RSF, Brierley & Fryirs, 2005; Fryirs & Brierley, 2013), which surveys at the basin scale the physical setting and morphology of rivers (i.e., the river character), the magnitude and dynamic of changes (i.e., the river behavior) and assess future evolutionary trajectories (see also the multi-scale hierarchical framework developed in Europe by Gurnell et al., 2016). Similarly, the Morphological Quality Index method (MQI; Rinaldi et al., 2015) and the Geomorphic Unit survey and classification System (GUS; Belletti et al., 2017) attempt at integrating information on the hydrology, fluvial geomorphology, riparian vegetation, and human pressures at a variety of scales, and provide a geomorphologically-sound template to study geomorphology-biology relationships.

This work presents a case study of the application of a geomorphological survey method for the assessment and characterization of geomorphic conditions (Rinaldi et al., 2017) in combination with biological surveys, along a mountain river basin in Central Chile (Clarillo River). The aim is to explore the relationships between geomorphic and biological diversity in a relatively low-impacted river, in order to contribute towards the understanding on how river communities such as amphibians, fish, and macroinvertebrates are influenced and distributed into the geomorphic complexity of the fluvial ecosystem, at different spatial scales. Specifically, we intend (i) to quantify differences in the communities between different spatial scales, i.e. segments, reaches, geomorphic (or geomorphological) units and microhabitats, characterized by homogeneous geomorphic conditions in a river with negligible human impacts; and (ii) to provide evidences of the link between biological and geomorphological diversity. The available knowledge on relationship between morphological and biological diversity in rivers is usually gathered in studies conducted in developed countries, with very scarce evidence available for rivers in developing countries. According to Andreoli et al. (2012), Chilean rivers show a high hydromorphological variability, and are poorly understood and generally ill-managed. Central Chile is an area of national concern, since it is where the water related issues re-emerged due to population growth and this is an hotspot area for biological conservation. In this sense, the case is paradigmatic for several countries with a fast-growing economy.
2. Methods

The study was carried out in the Clarillo basin, located in the central Chilean Andes (Figure 1). The Clarillo River basin drains an area of 367 km$^2$, and ranges in elevation from 609 to 3057 m a.s.l. The climate is typically Mediterranean, and the mean annual rainfall is around 300 mm. Approximately 63 percent of the basin is covered by xerophilic woods (below 1600 m a.s.l) and shrub lands (Alarcon et al., 2015). The upper part of the basin (131 km$^2$) is protected since 1982 as Reserve, managed by the Chilean National Forest Corporation (CONAF). The present study mainly focused on the main Clarillo River near the closing section of the Reserve (Figure 1), where the river is mostly alluvial, although confined by hillslopes and ancient terraces. The river features morphologies typical of high-gradient streams such as step-pool, cascade, and riffle-pool. In particular, the analysis focused on three segments (A, B, and C towards downstream direction), located near the entrance of the Reserve for a total length of approximately 9 km. On each segment, three reaches were selected (Figure 2), and all field surveys were conducted at this scale between September 2016 and May 2017, resulting in nine survey sites (reaches A1 to C3). The reaches were comparable in terms of length (on average 190 m), width (on average 9.4 m), and slope (on average 7%) and their main difference is the elevation (ranging from 814 to 1139 m a.s.l.).

2.1. Morphological surveys

In order to gain a general geomorphological understanding of the river system, the Morphological Quality Index (MQI; Rinaldi et al., 2015) was initially applied to the whole river network of the Clarillo basin. The MQI is a method to evaluate morphological conditions through a multiscale hierarchical framework based on a series of 28 indicators related to features such as functionality, artificiality, and recent channel adjustments. The MQI was applied at the basic spatial unit for the evaluation of morphological conditions which corresponds to a section of a few kilometers in length (named segment in this paper). We used this step to identify, through a geomorphologically-based procedure, the three segments on which perform the analyses described below. The method combines data from remote sensing (satellite images from Google Earth in this study), GIS analysis and field surveys.
At a smaller scale, three reaches were selected per each of the three segments (Figure 1 and 2; Table 1). At the scale of reach we applied the Geomorphic Units survey and classification System (GUS; Belletti et al., 2017) to characterize the geomorphological nature of the sites. The basic spatial unit at which the method classifies distinctive morphological characteristics is the geomorphic unit, which corresponds to the mesohabitat scale (i.e. about 10^0-10^2 m). Within a geomorphic unit, the sub-units correspond to the microhabitat scale, i.e. a characteristic patch within a unit (about 10^-1 - 10^1 m; Figure 2; Belletti et al., 2017).

In the Clarillo River, the GUS was applied at the scale of geomorphic units (Basic level; Belletti et al., 2017). The survey of geomorphic units mainly focused on the bankfull channel, given the absence of a continuous and extensive floodplain as the river is confined in its valley. The location, type, and number of each geomorphic unit was recorded in the field for each reach. Their identification was supported by remote-sensing analysis on the basis of high resolution vertical close-range photos obtained in the field using a Phantom 3 drone (DJI Technology Co., Ltd, USA) equipped with a FC300X camera (resolution of 4000x3000 and pixel size of 1.56x1.56 um, for a ground resolution of 7.55 mm/pixel). The flying altitude ranged between 12.6 and 63 m. A detailed orthophoto and elevation digital model of each reach were created using Structure-from-Motion (SfM) technique, using the Agisoft PhotoScan® professional software. The geomorphic units were then classified on the orthophotos by photo-interpretation and measured. Then we calculated the diversity and abundance of geomorphic units at three scales (segment, reach and geomorphic unit), adapting GUS metrics and indexes from Belletti et al. (2017). These indexes illustrate the presence, number, and spatial variability of the main geomorphic units found in the study site (cascade, pools, steps and riffles; Figure 3) at those different scales. We calculated the following:

- the abundance (N), proportion (%) and areal proportion (% area) of each submerged unit type (cascades, pools, steps and riffles);
- the richness of geomorphic units (GUs), as sum of types of GUs (\(\sum NT_{GU}\));
- the number of GUs (any type; \(\sum N_{GU}\));
- a modified Geomorphic Unit Richness within the bankfull channel (mGUSI-
R\textsubscript{BC}), as the sum of types of geomorphic units (GU) observed in a reach in comparison to the maximum number of possible unit types (submerged and emerged units within the bankfull; N=24);

- the Geomorphic Unit Density (GUSI-D) index, that is the sum of GUs (any type; in that case only for bankfull channel units) divided by the reach length;
- a modified Geomorphic Unit Density (mGUSI-D\textsubscript{A}) index where the sum of GUs (any type) is rated by reach area.

We also calculated sub-indexes differentiating between submerged and emerged units:
- a richness index of submerged units, the GUSI-R\textsubscript{C}, calculated as sum of types of submerged GUs observed in comparison to the maximum number of possible types of submerged units;
- the index of density of submerged units, the GUSI-D\textsubscript{C}, calculated as number of submerged GUs divided by the area of the submerged units;
- a modified sub-index of density of submerged units, the mGUSI-D\textsubscript{C}, where the number of submerged GUs is rated by the reach length;
- the sub-index of density of emerged units, the GUSI-D\textsubscript{E}, calculated as number of emerged GUs in comparison to area of these units.

2.2. Biological surveys and microhabitat scale characterization

Benthic macroinvertebrates, fish, and amphibians were surveyed at the scale of reach. A Surber sampler (mesh 500µm; Figure 4) was used for the benthic macroinvertebrates surveys. The sampler covered an area of 0.09 m\textsuperscript{2} (per sample) and was operated by manually rinsing sediments for five minutes within the sampling area before collecting the sample of macroinvertebrates. Eight samples were collected on each reach, at points randomly distributed across the different types of in stream geomorphic units (pools, riffles, and cascades), thus resulting in a total of 24 samples over 2.16 m\textsuperscript{2} per segment and 72 samples overall. Macroinvertebrate samples were conserved in alcohol 70% and taken into laboratory for identification to the taxonomic level of family, though a small part of the specimens were identified to the level of species.

The ichthyofauna within each reach was surveyed using the standard electrofishing method, using a backpacker Electrofishing Hatech Equipament (Haltech Aquatic Research Inc. Ontario, Canada; Figure 4). Two passes of approximately 40 min or one
pass of 60 min were conducted in each of the reaches, in the direction downstream-to-upstream. The collected fish were identified in the field to the level of species, and then measured and weighted, before releasing them back alive in the same sampling reach (Figure 4).

As to the amphibians, we used the Visual Encounter Survey and Time Constrained Search method. A systematic nocturnal survey of one hour was conducted in two transects covering the entire reach section, searching in potential habitats for the local species. When specimens were found, they were identified to the level of species, counted and released in the same reach in their respective potential refuge. The present investigation focused exclusively on adult individuals (Figure 4).

At the microhabitat scale, microhabitats conditions such as water depth (m) and flow velocity (m$^3$/s) were measured at the points of macroinvertebrate sampling using a tape and a propeller, respectively. At both the microhabitat scale and across the reaches, the grain size distribution was obtained using the traditional grid-by-number procedure at submerged and emerged units. Additionally, a multiparameter YSI (YSI Inc. Ohio, USA) sonde was used to measure conductivity, dissolved oxygen, pH, temperature, total dissolved solids on a random point at each reach.

2.3. Data analysis

The metrics used for the quantitative measurement of biodiversity were the richness (number of taxa; S) and abundance (number of specimens per each taxa, N). We also calculate the Shannon-wiener Index (H) which is accounting for the proportion of taxa abundances in comparison to the total number of taxa (calculated using natural logarithm). We also calculated the Simpson Index (1-D) as the proportion of taxa abundances relative to the total number of taxa and squared, and this indicates diversity through a relative dominance for each species. Furthermore, we calculated the Evenness (J) and the Margaleff index (D), which indicate the proportion of richness in comparison to abundance. Furthermore, for the macroinvertebrates we calculated the proportion of the orders Ephemeroptera, Plecoptera, and Trichoptera (EPT, broadly used as bioindicators), and the abundance of specimens from the family Chironomidae (a particularity tolerant family of macroinvertebrates). Also, an index of relative preference of habitats was adapted from Sullivan et al. (2004), which was calculated using the
number of individuals per taxa found in each type of unit in comparison to the total number of individuals. This was calculated exclusively for macroinvertebrates from each of the families identified, in order to associate directly the benthic macroinvertebrate community to geomorphic units. For fish, we calculated the capture per unit effort (CPUE), considering sampling length and time of field survey associated to abundance of specimens captured, their size and weight, which were considered as biological traits of life cycle.

We compared the biological indexes at the segment, reach and geomorphic unit (GU) scale by adopting an ANOVA test to find significant differences among the samples. To identify the relationships between the geomorphological (i.e. the indexes and sub-indexes of the GUS protocol) and the biological variables at three different scales (segment to GU), we used Pearson’s correlation. Further, multiple lineal regression analyses were used to quantify significant relationships. Spearman’s $r$ correlations were used for nonparametric data to explore for potential nonlinear relationships. All data was tested at the $\alpha = 0.05$ level. However, a cut value (i.e. $r > 0.5$) was used to verify correlation. All statistical analysis was performed using Statistica 7 software.

3. Results
3.1. Morphological Quality Index survey (MQI) at the scale of segments

The whole river network of the Clarillo basin was divided into 21 homogeneous segments. The MQI was assessed at the segment scale, and the values ranged from poor (0.47) to very good or high (0.97) (Table 2). Morphological values were higher in the upper part of the basin (located within the Reserve; segments 9 to 18) than in the lower part where there are water extraction points and other human activities and infrastructures within the riverine area (segments 1 to 3). The three selected segments investigated in this study (A, B, and C) are located within the natural Reserve and are mainly single-thread, straight, confined channels (Table 2). These segments were classified as very good ($0.8 \leq MQI < 1$) but did not reach the highest value because they lack potential sources of heterogeneity according to MQI characterization standards (e.g. large wood), and because of the presence of minor infrastructures (e.g. a small wooden bridge crossing one of the segments). The slope of these segments ranges from 0.02 to
and their length from 2.8 to 3.8 km. The selected segments feature mainly geomorphic units as cascades, riffles, steps, pools and bank-attached bars. Locally, small vegetated islands, mid-channel bars, and narrow floodplain pockets were also present.

3.2. Geomorphic Unit Survey (GUS) at the scale of reaches and segments

Figure 5 shows an example of the application of the GUS survey to reach C2. The reaches ranged from 130 to 230 m in length, from 7.8 to 11.12 m in width, and from 814 to 1139 m a.s.l. in terms of elevation (Table 1). Sediments sizes range from sand to boulders, although the dominant median grain size ($D_{50}$) was coarse gravel (Table 1). Overall, 242 submerged geomorphic units and 284 emerged units were identified within the bankfull channel across the nine surveyed reaches. The portion of reaches covered by submerged morphological units ranged between 67 to 91% of the bankfull area. The most abundant type of submerged unit was pool, followed by step, representing together the 76% of all submerged units (Table 3). The emerged unit types with the highest and lowest abundance were bank-attached high bar and small vegetated island, with 53 and 14%, respectively.

Steps were the most extended submerged morphological feature on reach A1 (38% of submerged units), followed by cascades (17%), riffles (12%) and pools (11%). In reach A2 and A3 the most extended submerged units were cascade and steps, accounting for 49 and 30% of the submerged areas, respectively (Table 3). In B1, the morphological unit cascade represented 47% of the submerged portion of the reach. Cascade was the most extensive morphological unit in B2 and B3 as well, with percentages of 53 and 47, respectively. In the reaches composing the segment C, cascade was again the morphological unit occupying most of the submerged portion of the river, accounting for 51, 47 and 42% of reaches C1, C2, and C3, respectively (Table 3).

As to the GUS indexes at the reach scale (Table 3), the reach C3 featured the highest richness values ($\sum NT_{GU}=10$; GUSI-R=0.42), while reach C2 had the highest abundance of geomorphic units ($\sum N_{GU}=82$). As expected, richness indexes are quite homogeneous across the study area (Table 3). Linear density values are highest in reach B1 and lowest in reach B2 (GUSI-D=376.92 and 191.3 n/km, respectively). Areal density values are homogeneous across the study area, with lowest values for submerged and emerged units in reach C3 and C1, respectively (GUSI-D$_C=0.01$ n/km$^2$; GUSI-D$_E=0.021$ n/km$^2$).
Considering the GUS metrics averaged at the scale of entire segments, in general richness and density of geomorphic units slightly increased from A to C. The most important increment towards the downstream direction is recorded for overall linear density, where GUSI-D ranged from 304.5 to 341.22 n/km, and GUSI-D_E ranged from 0.06 to 0.21 n/km^2.

3.3. Benthic community at the scales of microhabitat, geomorphic units, reach and segment.

A total of 5274 specimens of macroinvertebrates were sampled in the field surveys. Representatives of 11 orders and 30 families were identified. At the order level, the dominant taxa were Dipterans (33%), Ephemeropterans (33%) and Trichopterans (22%), followed by Coleopterans (7%). At the family level, the dominant taxa were Leptophlaebidae, Baetidae, Chironomidae, Hydropsichidae, and Athericidae.

At the microhabitat scale, there was a positive and significant relationship between water depth and macroinvertebrates richness (r=0.67; r^2=0.45; p<0.05). Flow velocity was inversely and significantly related with several diversity metrics including the Shannon-Wiener (r=-0.76, r^2= 0.59, p<0.05), the Simpson (r= -0.8, r^2= 0.64, p<0.05) and the Evenness indexes (r=-0.9, r^2= 0.82, p<0.05), showing that less families are able to colonize and live in morphological units characterized by higher flow velocity.

At the scale of geomorphic units, none of the biological metrics showed statistically significant differences. For example, Figure 6 shows that the abundance and richness of macroinvertebrates is not significantly related with the type of submerged morphological unit (p>0.05). The relative preference index (see Sullivan et al., 2004) indicates that Hydrobiidae, Athericidae, Glossosomatidae, Ceratopogonidae, Elmidae and Hydroptilidae are more easily associated with pools, whereas Lumbriculidae, Chironomidae, Leptophlaebidae and Hydropsichidae are more likely found in riffles, and Gripopterygidae, Gomphidae, Tipulidae, Baetidae and Simulidae are more abundant in cascades.

At the reach scale, some of the indexes indicate significant differences. In particular, reaches differ in terms of Evenness indexes (p<0.05), EPT abundance (p<0.05) and percentage of Chironomidae (p<0.05) (Figure 7). At the reach scale but within each segment, reaches A1, A2, and A3 showed quite low variance in richness values.
Reach A3 featured the highest diversity values ($H=1.87$; $1-D=0.77$), being reaches A1 ($H=1.79$; $1-D=0.76$) and A2 ($H=1.86$; $1-D=0.74$) lower in terms of diversity indexes (Figure 7). Within segment B, the reaches B1, B2, B3 presented the highest richness among the study site, ranging between 18 and 22 families, and featuring among the higher values of abundance (between 1007 and 608 specimens). However, these reaches were dominated by the Ephemeropterans *Baetidae* and Dipterans *Tipulidae*, thus having the lowest values of diversity (especially in terms of $H$; Figure 7). Within segment C, the reach C1 had the highest abundance and richness (N=674; S=17), while C3 had the highest diversity index values ($H=2.2$; $1-D=0.87$), followed by C2 ($H=1.82$; $1-D=0.79$) and C1 ($H=1.72$; $1-D=0.72$) (Figure 7). At the scale of the three river segments, segment B had the highest value of abundance and richness of macroinvertebrates (N=2405; S= 25), followed by segment A (N=1601; S= 20) and C (N=1268; S=21). There are significant differences in terms of Shannon-Wiener, Simpson and Evenness index, and the EPT and Chironomidae (p<0.05), among the segments (Figure 8). The macroinvertebrates community in segment B was dominated by Ephemeropterans *Baetidae*, more precisely by *Andesiops torrens*. This resulted in lower biodiversity, represented by lower Shannon ($H=1.5$), Simpson (1-$D=0.66$) and Evenness indices ($J=0.25$) (Figure 8). In segment A, higher values of the Shannon-Wiener ($H=1.96$), Simpson (1-$D=0.78$) and Evenness indices ($J=0.42$) (Figure 8) showed a higher benthic macroinvertebrates diversity than in segment B. The highest diversity values were observed in segment C, where taxa displayed a more random distribution in terms of abundance and lower dominance, as showed by the Evenness ($J=0.52$) and Simpson indices (1-$D=0.84$). Further, a significant difference in the EPT representativeness between segments was observed, with lowest values for segment C (Figure 8).

### 3.4. Fish community at the scales of reach and segment.

Three fish species were identified in the Clarillo River, namely *Trichomycterus aerolatus* (Valenciennes, 1846), *Oncorhynchus mykiss* (Walbaum, 1792) and *Salmo trutta* (Linnaeus, 1758). The first is a Chilean species considered endemic, and widely distributed through central Chile (Habit *et al.*, 2006). It is typically found in habitats of cold flowing water and in sites with coarse sediments, although it can also be found
partially buried in fine sediments. *O. mykiss* and *S. trutta* are instead exotic introduced salmonid species (Habit et al., 2006). Overall, *T. aerolatus* was the most abundant species (n=347), followed by *O. mykiss* (n=201) and *S. trutta fario* (n=14).

At the reach scale the highest abundance of specimens was found in reaches B1, B2 and B3, although no statistically significant differences were found (p>0.05). *S. trutta* was found in small numbers but evenly distributed on the nine study reaches (Figure 9). *O. mykiss* was abundant in reaches B1, B2 and A3, and it was the dominant species in reaches A3, B1 and C2. *T. aerolatus* was abundant in reaches B1, B2, B3, C3, and it was the dominant species in reaches A2, B2, B3, C1 and C3 (Figure 9).

At the scale of segments, the abundance of fish varied, especially for *T. aerolatus* (Figure 9). In general, higher abundances were observed in segment B. Given the low number of species (S) observed, diversity indexes were not informative (data not showed).

The abundance of fish was well correlated with environmental variables measured at the scale of microhabitat and averaged at the scale of reach, such as averaged flow velocity (r=0.69; p<0.05), conductivity (r=0.72; p<0.05) and total dissolved solids (TDS, r=0.75; p<0.05) at the reach scale. More specifically, the mean flow velocity at the reach scale is well correlated with the abundance of *T. aerolatus* (r=0.73; p<0.05), the dissolved oxygen is well correlated with the abundance of *S. trutta* (r=0.67; p<0.05), and the TDS is well correlated with the abundance *O. mykiss* (0.76; p<0.05).

3.4. Amphibian survey at the scales of reach and segment.

Two species were identified in the anuran group and a total of 54 specimens were found in the field. The most abundant species was *Pleuroderma thaul* (Lesson, 1826) (n=34) followed by *Rhinella aruncu* (Guichenot, 1848) (n=20), both being Chilean native species. Only *P. thaul* was observed in segment C, but both species were found in segments A and B, where *R. aruncu* was dominant (Figure 10). Segment C had the highest abundance (n=29), followed by segment B (n=14) and A (n=6) (p<0.05; Figure 10). Significant differences in abundance of anurans were observed at the scale of segment but not between reaches (p<0.002; Figure 10). At the reach scale, the mean elevation correlated negatively with abundance (r²=0.64, r=-0.8; p<0.05).

3.5. Relationships between the diversity of geomorphic units and the biological diversity.
The strongest positive relationships between biological and geomorphic diversity were found for the benthic macroinvertebrate group. In particular, the geomorphic unit density within the bankfull channel (GUSI-D) showed a significant positive relationship with Evenness diversity indexes ($r=0.37; r^2=0.14; p<0.03$) (Figure 11a). The abundance of geomorphic units relates mainly to the Evenness ($r=0.86; r^2=0.75; p<0.005$), Simpson ($r=0.61; r^2=0.37; p<0.05$) and Shannon-Wiener indexes ($r=0.55; r^2=0.31; p<0.05$) (Figure 11b and c). In addition, some specific geomorphic units tend to be associated with certain biological metrics. For instance, there was an inverse relation between the average area of pools (data not shown) and the Shannon-Weiner ($r=-0.55; r^2=0.3; p<0.05$), Simpson ($r=0.4; r^2=-0.63; p<0.05$), and Evenness indexes ($r=0.34; r^2=-0.59; p<0.05$). On the other hand, there was a positive relation between the number of cascades and Shannon ($r=0.64; r^2=0.41; p<0.05$) and Simpson ($r=0.55; r^2=0.3; p<0.05$) indexes (data not shown).

In terms of fish, the main relationship between geomorphic and biological diversity of the studied river site was found between the density index of submerged geomorphic units (mGUSI-D<sub>C</sub>) and the Margalef index D ($r=0.61; r^2=0.38; p=0.0006$). Also, there was a significant relationship between the number of pools and the Margaleff diversity index D ($r=0.65; r^2=0.42; p=0.0003$), and between the number of steps and the Shannon ($r=0.64; r^2=0.41; p<0.05$) and Simpson indexes ($r=0.50; r^2=0.25; p<0.007$) (Figure 12). Furthermore, a significant relationship was found between the number of riffles and the Shannon-Wiener index ($r=0.48; p<0.05$; data not shown). At the segment scale, we found a positive (although not significant) relationship between the density index for the submerged units and the Simpson diversity index and abundance of fish (except for S. trutta). In terms of single species, T. aerolatus biomass is significantly correlated to the average area of riffles ($r=0.78; r^2=0.62; p<0.05$) and cascades ($r=0.84; r^2=0.7; p<0.05$) (Figure 13). Besides, the biomass/SE of O. wykiss is significantly related to the mGUSI-D<sub>C</sub> index ($r=0.68, r^2=0.46; p<0.05$) (Figure 13), and the S. trutta is found in higher abundance in reaches with more cascades ($r^2=0.60; r=0.77, p=0.0137$).

Only few significant relationships were found between geomorphic diversity and biological metrics for the amphibians group. The number of cascades correlated negatively with the Shannon-Wiener and Simpson diversity indices ($p<0.05$). Only a
not-statistically significant relation was found between diversity indexes and the number of types of geomorphic units and the geomorphic index of richness at the scale of segments.

4. Discussion
In the Clarillo River, a permanent near-natural and confined system in the Central Chilean Andes, we found some significant relationships between the geomorphological nature of the study site and the local biological communities. The three biological groups observed (macroinvertebrates, fish and anurans) responded differently to the geomorphological scale under consideration, confirming that the spatial scale is crucial in understanding the relationship between the physical and biological nature of the riverine ecosystem.

4.1. Macroinvertebrates and the geomorphic units
Large scale environmental conditions such as land use and physiochemical parameters at the basin scale are recognized to influencing the presence, abundance, and diversity of macroinvertebrates of a certain river site (e.g. Kaller and Hartmann, 2004; Leps et al., 2015), but the local conditions also contribute to determine the composition of benthic macroinvertebrates communities (Harrison et al., 2007). Geomorphic diversity generally refers to the types and spatial distribution of geomorphic units in a certain area. However, the relationships between geomorphic and hydraulic units and the respective habitats for biota are very complex. Indeed, effects due to flow directionalities, zoogeomorphic footprint and ecological memory, add multiple levels of complexity to the relationship between morphological and biological diversity. Reid et al. (2010) reported that the heterogeneity of habitats influences macroinvertebrate communities in non-linear ways, and that habitat heterogeneity is likely to be related to greater diversity of macroinvertebrates. Our results show that, in the case of a near-natural confined system, the abundance of geomorphic units lead to a greater biological diversity of macroinvertebrates. The highest values of biological diversity metrics like the Shannon-Wiener (H), Simpson (1-D), and Evenness indices (J) were related to the reaches with highest abundance of geomorphic units. The latter is likely to support a greater habitat heterogeneity at micro-habitat scale, hence supporting greater diversity in
macroinvertebrate community.

The assemblages of species differed among geomorphic units with different depths and flow conditions. Overall, pools were the units with higher abundance and richness, resulting in higher diversity indexes. Through the relative habitat preference index (Sullivan et al., 2004), we observed an association between taxon at a geomorphic unit scale and within geomorphic unit types with slightly different hydraulic conditions (i.e., slow or rapid flow and shallow or deep water). For example, specific families of dipterans (Athericidae and Ceratopogonidae), ephemeropterans (Leptophlaebidae), megaloptera (Hidrobiidae), coleopterans (Elmidae) and trichopterans (Glossosomatidae), were more dominating in pools, usually with slow flows and deeper water. On the other hand, trichopterans (Hydropsichidae), dipterans (Chironomidae) and oligochaeta (Lumbricidae) were mostly found in riffles, with shallow water and moderate flow velocity. The plecopterans (Gripopterygidae) and Odonata (Gripopterygidae) in this case, were associated to cascades.

Milner et al. (2015) stressed that the mosaic of different geomorphic types supports the “pool of species” and that a river composed of several geomorphic unit types provides more species than a river dominated by a single type. Interestingly, at the reach scale we observed that benthic diversity is well related with the number and density of geomorphic units rather than exclusively the different types of geomorphic units, suggesting that the complexity of the mosaic of geomorphic units to support biodiversity can also be determined by its patchiness (i.e. for a same number of types, a higher number of smaller units supports better biodiversity than few larger units). Indeed, given that the Clarillo River featured approximately the same geomorphic units in all study reaches, their relative abundance appears to be the main modulator of macroinvertebrate communities.

Pools are the smallest among the most abundant submerged geomorphic unit types, and were mainly related to abundance and richness of taxa. On the other hand, there were fewer riffles and cascades, but they were wider, longer and were also associated with abundance of macroinvertebrates. This suggests that also the relative size of specific geomorphic units is important for determining the range of macroinvertebrates. This relative size is likely associated with a ratio between the mean size of the unit and the
channel width, or as a ratio between the mean size of the unit and the grain size of sediments (Belletti et al., 2017), and deserves further attention. In any case, it must be stressed that the abundance and richness of geomorphic units must be interpreted with care, as these units are not independent of each other from a morphological point of view, and also depend on the overall boundary conditions (Wheaton et al., 2015; Belletti et al., 2017). Similarly, the macroinvertebrate communities found on specific morphological units are not independent of communities found on surrounding morphological units or of upstream conditions (Frisell et al., 1986).

At the larger scale of river segment, the Clarillo River showed significant differences in terms of macroinvertebrate diversity, although a longitudinal trend does not clearly emerge, as previously demonstrated by Thorp et al. (2006). Abundance and richness were higher in segment B, located in the middle segment of the studied river. In this segment, a taxonomic dominance is also occurring, leading to lower values of biodiversity indexes.

4.2. Fish community and the morphological diversity at the reach scale

The fish community in the Clarillo River is composed of a small number of species and individuals. This was expected, since it is a small river and the fish community in Chile is limited to 44 native and a few exotic species (Habit et al., 2006). The most abundant species in the Clarillo River was T. aerolatus, classified as an endemic species which overall indicates a good habitat status for the river ecosystem. The presence and abundance of O.mykiss and S trutta is not necessarily a good indicator of excellent ecological conditions as both species are invasive.

Fish are key indicators of hydromorphological conditions due to their high mobility, physiology and ecological traits (e.g., Brey and Sullivan, 2015). Indeed, we could not determine a clear direct relationship between fish species and a preferred geomorphic unit. Also, it is unlikely that a single geomorphic unit could be preferred by a certain fish species for the entire life cycle (see also Schmutz et al., 2014; Wolter et al., 2016), as fish life-cycle depends on a shifting range of habitat mosaic at different spatial scales (Brennan et al., 2019).

As for the diversity indexes of fish, the Margalef index was significantly correlated with the density index of submerged geomorphic units. Interestingly, some single species
were found in higher abundance on reaches with more specific morphological units (e.g.\textit{S. trutta} and cascades). At this scale, the hydraulic nature of specific sites can determine the presence of different species (Eskew et al., 2012, Wolter \textit{et al.} 2016; Growns \textit{et al.}, 2017). For instance, Bernardo et al. (2003) showed that native species in rivers in Spain preferred shallow riffles whereas exotic species would prefer pools. In our study, reaches with larger numbers of morphological units with high velocity flows such as rapids and cascades featured higher abundance of fish, especially \textit{T. aerolatus}. Instead, \textit{O. mykis} and \textit{S. trutta} were found in reaches irrespective of their geomorphic units composition. This is likely due to the fact that geomorphic units have to be considered in the framework of how they are assembled with the surrounding units in complex patterns. It is also worth stressing that, to the best of our knowledge, there are virtually no studies which were able to determine the morphological preferences of native versus exotic freshwater species in Chile, and Chilean rivers are severely affected by presence of exotic species that are strongly affecting local endemic species (Rojas \textit{et al.}, 2019).

The morphological complexity due to the spatial composition and density of geomorphic units also determines the diversity of fish. In our study, we found more fish on reaches with more riffles and cascades. However, in reaches with higher number of pools we found higher diversity. The fish diversity is better correlated with morphological diversity at an intermediate spatial size which is the reach scale, although fish abundance clearly depends on the habitats available in the whole hydrographic network (Schmutz \textit{et al.}, 2014; Brey and Sullivan, 2015; Wolter \textit{et al.}, 2016).

4.3. \textit{Amphibian community and the morphological diversity at the segment scale}

Anurans rely on both submerged and exposed geomorphic units at different stages of their life-cycle, and usually prefer habitats such as ephemeral ponds and nearshore channels sites. In the Clarillo River we could find no evidence of conclusive association between certain geomorphic units or river reaches, and biological characteristics or indexes for this small anuran community. However, we preferentially observed more anurans on reaches with more diverse morphological units in the small an elongated floodplain pockets (which were not surveyed using the GUS), as showed in previous studies (e.g., Reilly \textit{et al.}, 2015). A more detailed morphological survey on the floodplain could shed further light on the morphological characteristics of the
floodplains that these anurans tend to prefer. Also, more frequent field surveys could provide further evidence of abundance, since *P. thaul* is one of the most broadly distributed anurans in Chile (Diaz-Páez and Ortiz, 2003) and *R. aruncu* is the most abundant species in the Reserve and is considered a common species.

The Simpson index diversity was higher if calculated at the scale of segment, indicating that this is the spatial scale that is more likely to determine differences in the abundance of anurans. As argued by Tockner et al. (2006), amphibians are more strongly associated with the floodplain than with the main channel. In the island braided Tagliamento River (Italy), the active floodplains were found to be highly important habitats for amphibian distribution. In the study site, which is a confined river, direct observations suggest that anurans are more likely to be found in small pools along the gravel bars or in portions of the active channel with low flow velocity.

4.4. Relationships between geomorphic and biological diversity

The three groups of organisms studied in the current investigation are considered good indicators of environmental conditions. Fish are indicators for aquatic habitats conditions, such as the rheophilic fish species which have a significant response to river changes (Eskew et al., 2012; Schmutz et al., 2014). Amphibians and macroinvertebrates are indicators of both aquatic and fluvial terrestrial environments, as they occupy different types of habitats over the entire fluvial corridor during their life cycles.

In the Clarillo River, the abundance and diversity of macroinvertebrates were more closely related with the abundance and density of geomorphic units, whereas the abundance of fish related to a higher degree with the reach and segment scales, and the amphibians were more broadly related to the nature of the river segments. This reinforces the idea that geomorphic influence is part of a larger chain of events in a hierarchical spatio-temporal scale that sustains such environmental complexity (Frissel et al., 1986; Amoros & Petts, 1993; Friberg et al., 2009; Belletti et al., 2017; Leps et al. 2015). The results of this study stress that both biological and geomorphic diversity and their interactions need to be considered at a variety of scales, and that the degree to which they relate depends on what is measured. Indeed, as pointed out by Fryirs & Brierley (2009), promoting geomorphic diversity at the reach scale (which is usually the scale at which river restoration projects are implemented) is not necessarily appropriate.
for each site and may not result in higher diversity of the targeted biota. Also, as pointed out by Brennan *et al.* (2019) the habitat mosaics supporting biota should be considered dynamic in time (i.e., shifting due to interactions with geomorphological processes and biological responses) and at the scale of the entire watershed. Furthermore, the hydrological regime and the geological characteristics of the basin should be taken into account to understand how biology interact with fluvial geomorphology (Castro & Thorne, 2019). Additionally, we did not consider biological interactions between biota at different levels in the riverine environment (i.e., competition and predation) that could also affect considerably the outcomes of this investigation.

The current study compared a considerable group of environmental and biological variables at multiple spatial scales. However, only a few very significant statistical differences were observed, probably because the reaches belong to similar river sections, which have very comparable intrinsic morphological conditions and negligible human pressures. Though, the present study expands our knowledge of the current eco-hydromorphology for the upper part of the Clarillo River. The extensive field survey provided a “snapshot” about the geomorphic and biological nature of the studied river section. Further efforts in this direction should focus on exploring fluvial processes (e.g. flow and sediment regimes and channel changes) rather than only forms, and to monitor seasonal changes of aquatic communities in order to include a temporal component in the analysis, and to allow for future habitat modeling efforts in relating geomorphic and biological diversity (e.g. Vezza *et al.*, 2014). Indeed, natural fluvial process triggered by floods can increase geomorphic diversity (Williams *et al.*, 2020), and this can affect the diversity of biota in different ways depending on the magnitude and seasonality of the events, and on the recovery of the system within the long-term evolutionary trajectory of the river system (Brierley & Fryirs, 2005), which is worth exploring as a whole.

4.5. Potential implications

Chilean rivers are particularly sensitive systems, given their peculiar natural condition of isolation in South America (i.e., basins are constrained by the Andes and the Pacific Ocean, and are generally short and steep), which sustains a low level of biodiversity, when compared to rivers in other countries of the continent. However, the same conditions contribute to a high level of endemism (Rojas *et al.*, 2019). For instance,
among the different bioclimatic regions (i.e. arid to humid), the Mediterranean zone is a hotspot for biodiversity, sustaining an important part of Chilean fauna (i.e. higher values of richness for fish species). Unfortunately, the Mediterranean zone hosts large urban areas, intensive agriculture and mining sites, all of which is threatening the functioning and biodiversity of Chilean rivers (i.e., water overexploitation, intense gravel mining, decrease of water quality). In particular, unfortunate management choices and excessive exploitation of river services are leading to a very threatening context (Andreoli et al., 2012). Although there are increasing more studies concerning river management in Chile, there are still no examples of river restoration being implemented. The current study highlights the importance of considering biodiversity-geodiversity interactions at the right scale for different purposes. Furthermore, as recently pointed out by Johnson et al. (2020), in case of river restoration the biota should also be recognized as an active factor that can determine fluvial forms and processes. Our work can help selecting the right scale for sampling and monitoring in Environmental Impact Assessment of river-related projects in Chile, which are currently under-standard in Chile, especially for fish (Lacy et al. 2017). In this sense, wider and proactive sampling and monitoring programs carried out at the regional/national scale would represent a critical baseline to appraise the conditions of Chilean rivers and understand natural and anthropogenic controls upon future trajectories of change. More specifically, being a protected site, the dataset collected in the Clarillo River could allow future assessments of the ecological consequences of evolutionary trajectories of the river morphological and biological adaptations to climate change, that in the area is characterized by a decade-long period of precipitation deficit (e.g., Alvarez-Garreton et al., 2020).

5. Final remarks
Our study highlights the relationship between geomorphological and biological diversity, where the availability and diversity of morphological units is the key driver for biodiversity. Our results suggest that availability of habitats provides the conditions to support different levels of biodiversity in a hierarchical way. In particular, we found that abundance and diversity of macroinvertebrates are more related to the abundance of geomorphic units, whereas the presence of fish is more related to the geomorphic nature
of the reaches, and the presence of anurans is more related to the nature of river segments.

This study reinforces the need to expand the field survey protocols and assessments to a broader scale, as suggested by others (i.e., Wolter et al., 2016). The MQI and the GUS protocols adapted in this study are termed multiscale since their approaches range from basins to geomorphic unit scales (Rinaldi et al., 2015; 2017). The approach of including topographic data in research focusing the geo-biological relationship is not very common and it can be crucial for the ecological riverine studies in a near future (Kärnä et al., 2019). Here we combined these protocols (MQI and GUS) with biological surveys as an attempt to incorporate geomorphological conditions at different scales and biological composition, for the first time in Latin America. The use of the hierarchical approach ranging from the basin to the geomorphic unit scales should be taken as a necessary input to improve the existing assessment tools and to support future management or conservations plans from the local to the regional scale in the Chilean territory.

Acknowledgements

This work was supported by the project Fondecyt Regular 1170657. Ricardo Carillo, Juan Ernesto Izquierdo, Enzo Montenegro, Fernando Ugalde are thanked for their help in the field. We are grateful to the Chilean National Park Service (CONAF) for providing access to the sample locations and on-site support of our research.

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### Table 1. The surveyed reaches on the Clarillo River.

<table>
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<tr>
<th>Reach</th>
<th>Length (m)</th>
<th>Basin area (Km²)</th>
<th>Max. elevation (m a.s.l.)</th>
<th>Min. elevation (m a.s.l.)</th>
<th>Slope (m/m)</th>
<th>Mean bankfull width (m)</th>
<th>$D_{50}$ (mm)</th>
<th>Dominant morphology</th>
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### Table 2. Characteristics and MQI values of the Clarillo River segments along the entire network. The detailed morphological and ecological surveys were conducted on segment 8 (A), 7 (B), and 4 (C).

<table>
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<tr>
<th>Segments</th>
<th>Length (km)</th>
<th>Max. elevation (m a.s.l.)</th>
<th>Min. elevation (m a.s.l.)</th>
<th>Slope (m/ml-h)</th>
<th>Mean bankfull width (m)</th>
<th>Confinement index</th>
<th>Sinuosity index</th>
<th>MQI index</th>
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**Table 3.** Results of the application of GUS at the scale of reach. $\Sigma N_{\text{GU}}$: number of types of geomorphic units; $\Sigma N_{\text{GUs}}$: number of geomorphic units; NSteps: number of steps; NPools: number of pools; NRiffles: number of riffles; NCascade: number of cascades; NSubm: number of submerged units; %Steps: proportion of steps as submerged morphological units; %Pools: proportion of pools as submerged morphological units; %Riffles: proportion of riffles as submerged morphological units; %Cascade: proportion of cascades as submerged morphological units; Steps: area represented by steps within the bankfull (%); Pools: area represented by pool within the bankfull (%); Riffles: area represented by riffles within the bankfull (%); Cascade: area represented by cascades within the bankfull (%); Submerged area: area represented by submerged morphological units within the bankfull (%); Emerged areas: area represented by emerged morphological units within the bankfull (%); mGUSI-R_{BC}: modified index of geomorphic unit richness for bankfull channel units; GUSI-D: linear density index of geomorphic units (n/km); mGUSI-D_{A}: modified density index of geomorphic units (areal density); GUSI-R_{C}: a richness index for submerged units; mGUSI-D_{C}: modified sub-index of density of submerged units (number of submerged GU/reach length: m); GUSI-D_{E}: density index of emerging geomorphic units (n/km^2).

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**FIGURE CAPTION**

**Figure 1.** Location and map of the Clarillo River basin, and the boundaries of the Natural Reserve of Clarillo River (in green). The segments of the river network are colored reflecting their hydromorphological condition assessed using the MQI method proposed by Rinaldi *et al.* (2015) (blue: high; yellow: good; orange: moderate). The yellow lines indicate the study segments, corresponding to A, B and C (from upstream to downstream).

**Figure 2.** Synthetic representation of the range of spatial scales at which morphological and biological samplings and analysis were performed.

**Figure 3.** Pictures of the most common geomorphic units in the Clarillo River: a) riffle; b) cascade; c) step; and d) pool.

**Figure 4.** Pictures of the biological field samplings: a) macroinvertebrate sampling using a Surber sampler; b) fish capture using the electrofishing technique; c) a specimen of *O. mykiss* being measured; and d) a specimen of *R. aruncu* being captured during night visual encounter surveys.

**Figure 5.** Example of the application of the GUS (Belletti *et al.*, 2017) for the survey and evaluation of meso-habitats for the reach C2 (close-range drone photo on the left
and GUS application on the right. The geomorphic units showed here are: F: Riparian Zone; LB: Lateral bar; MCB: Mid-channel bar; RS: rock step; P: pool; I: island, R: riffle, and C: cascade.

**Figure 6.** Differences in abundance N (a) and richness s (b) of benthic macroinvertebrates at the scale of geomorphic unit. The solid line indicates the range between the 25\(^{th}\) and 75\(^{th}\) percentiles, the square indicates the median, the whiskers indicate the maximum and minimum non-outlier values. Solid circles indicate outliers and diamonds indicate extreme values. Difference was evaluated using an ANOVA test.

**Figure 7.** Differences in Shannon-Wiener (H) and Simpson diversity index (1-D) (a), Evenness (J) and Margaleff index (D) (b) and indexes of Ephemeroptera Trichoptera Plecoptera (ETP) and Chironomids indicators (c) for benthic macroinvertebrates at the reach scale (A1 to C3). The solid line indicates the range between the 25\(^{th}\) and 75\(^{th}\) percentiles, the square indicates the median, the whiskers indicate the maximum and minimum non-outlier values, the solid circles indicate outliers and the diamonds indicate extreme values. Difference was evaluated using an ANOVA test.

**Figure 8.** Differences in Shannon-Wiener (H) and Simpson diversity index (1-D) (a), Evenness (J) and Margaleff index (M) (b) and representability of Ephemeroptera Trichoptera Plecoptera (ETP) and Chironomid indicators (c) for benthic macroinvertebrates at the segment scale (A, B, C). The solid line indicates the range between the 25\(^{th}\) and 75\(^{th}\) percentiles, the square indicates the median, the whiskers indicate the maximum and minimum non-outlier values, the solid circles indicate outliers and the diamonds indicate extreme values. Difference was evaluated using an ANOVA test.

**Figure 9.** Differences in fish abundance (a) and values of capture per unit of effort (b) at the reach scale (A1 to C3) and differences of fish abundance at the segment scale (c). The solid dark line indicates the species *T. aerolatus*, the solid blue line indicates the *O.mykiss* and the dashed line indicates *S.trutta*. Difference was evaluated using an ANOVA test and Kruskal-Wallis test.

**Figure 10.** Differences in anuran abundance at the reach (a) and segment (b) scales. The solid dark line indicates the species *P thaul*, the solid grey line indicates the *R. aruncu*. Difference was evaluated using an ANOVA test and Kruskal-Wallis test.
Figure 11: Correlations between geomorphic units index or values and ecological indexes for the macroinvertebrate community: a) GUSI-D density index vs. Evenness (J); b) Number of Geomorphic Units vs. Evenness index; c) Number of Geomorphic Units vs Shannon-Wiener (H) and Simpson diversity index (1-D). The correlation analysis was performed using the Pearson correlation at p<0.05).

Figure 12. Correlations between geomorphic units index or values and ecological indexes for the fish community: a) mGUSI-D_{BC} vs. Margalef diversity index vs. Shannon-Wiener and Simpson diversity indexes; b) Number of pools vs Shannon-Wiener and Simpson diversity indexes; c) number of steps vs Shannon-Wiener and Simpson diversity indexes. The correlation analysis was performed using the Pearson correlation at p<0.05).

Figure 13. Correlations between geomorphic units index or values and ecological indexes for the anuran community: abundance of *T. aerolatus* vs areal extension of riffles and pools (a and b); abundance of *O.mykiss* vs mGUSI-D_{C} (c); and abundance of *O.mykiss* vs number of cascades (d). The correlation analysis was performed using the Pearson correlation at p<0.05.
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