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Master Thesis

Barriers in Austrian river ecosystems: How fragmentation metrics help to explain impacts on fish assemblages

submitted by

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ABSTRACT

River fragmentation is seen as one of the key pressures on riverine ecosystems and is responsible for the decline of numerous migratory fish species. From a restoration perspective, it is necessary to prioritize river section where it is most beneficial for fish. For the first time, this thesis evaluates river fragmentation at two spatial scales, reach and segment and its impact on fish assemblages, in Austria. The intentions of this study were: (1) to adapt the method from Cooper et al. (2017) to the Austrian river network, (2) to analyze the extent of river fragmentation and how it differs between ecoregions, fish regions, and river sizes, (3) and to evaluate the effect of river fragmentation on fish assemblages in a multi stressor environment. The calculation of river fragmentation is based on a spatial analysis, considering 60 253 barriers and resulting in 19 fragmentation metrics (e.g. barrier density, barrier distance). The outcome showed that river fragmentation differs across ecoregions, fish regions, and river sizes. The highest barrier density was observed in the alpine region and along mainstem rivers. In particular, the ecoregion 'Dinaric Wester Balkan' showed a highly fragmented river network. Moreover, the results highlight a drastic decline in free-flowing river sections and catchment areas throughout Austria. Even though a shift in fish assemblages due to river fragmentation could not be observed, additional stressors induced by barriers showed an impact.

This study supports the application of a new method to calculate river fragmentation and assess the effect of river fragmentation on fish assemblages. Moreover, it helps to evaluate future barrier development and river restoration efforts.

ZUSAMMENFASSUNG

Die Fragmentierung von Flüssen gilt als eine der Hauptbelastungen für Flussökosysteme und verantwortlich für den Rückgang wandernder Fischarten. Aus der Perspektive der Wiederherstellung der Durchgängigkeit ist es notwendig Prioritäten zu setzen, dort wo es für Fische am vorteilhaftesten ist. In dieser Arbeit wird zum ersten Mal die Fragmentierung von Flüssen und ihre Auswirkungen auf Ebene der Flussabschnitte und -segmente auf die Fischbestände in Österreich untersucht. Die Intentionen dieser Studie waren: (1) die Methode von Cooper et al. (2017) auf das österreichische Flussnetzwerk zu adaptieren, (2) das Ausmaß der Flussfragmentierung zu analysieren und wie es sich zwischen Ökoregionen, Fischregionen und Flussgrößen unterscheidet, (3) und die Auswirkungen der Flussfragmentierung auf Fischgemeinschaften in einer mehrfach beeinträchtigten Umwelt zu bewerten. Die Berechnung der Flussfragmentierung basiert auf einer räumlichen Analyse, bei der 60 253 Barrieren analysiert wurden und die zu 19 Fragmentierungsmetriken führt (z. B. Dichte der Barrieren, Entfernung der Barrieren). Die Ergebnisse zeigen, dass die Flussfragmentierung je nach Ökoregion, Fischregion und Flussgröße unterschiedlich ist. Die höchste Barrieredichte wurde in der Alpenregion und entlang der Hauptflüsse beobachtet. Insbesondere die Ökoregion 'Dinarischer Westbalkan' wies ein stark fragmentiertes Flussnetz auf. Außerdem zeigen die Ergebnisse einen drastischen Rückgang der frei fließenden Flussabschnitte und Einzugsgebiete in ganz Österreich. Obwohl eine Veränderung der Fischbestände aufgrund der Flussfragmentierung nicht beobachtet werden konnte, zeigten zusätzliche Stressfaktoren von Barrieren, Auswirkungen.

Diese Studie unterstützt die Anwendung einer neuen Methode zur Berechnung der Flussfragmentierung und zur Bewertung der Auswirkungen der Flussfragmentierung auf die Fischbestände. Darüber hinaus hilft sie bei der Bewertung zukünftiger Entwicklung von Barrieren und Flussrenaturierungmaßnahmen.

1. INTRODUCTION

Freshwater ecosystems offer diverse habitats for numerous plants and animals (Jungwirth et al., 2002). Moreover, natural rivers are essential for various ecosystem services, including climate regulation, flood protection due to water retention, recharge and discharge of groundwater, and nutrient cycling (Lynch et al., 2023; Millennium Ecosystem Assessment (Program), 2005). However, rivers are also used for food supply, drinking water, irrigation for agricultural needs, energy and industrial production, and serve as transportation corridors (Haidvogl, 2018). The rising demand for energy, water supply and flood management require the expansion of dams, weirs, and other water infrastructure within rivers. To date, around 1.2 million barriers already exist in Europe and is potentially seen as the most fragmented landscape in the world (Belletti et al., 2020). As a consequence, over 200 000 km of river habitat is lost due to barriers (Parasiewicz et al., 2022). Dams are known to have various negative effects on river ecosystems, such as local changes in hydrology, river connectivity, water temperature, water chemistry, and sediment budget (Hauer et al., 2013, 2014; Schmutz et al., 2015; Ward and Stanford, 1983). Since rivers are a continuous ecosystem, local stressors can have impacts that span long distances and are cumulative in nature. Therefore, dams also disrupt rivers on landscape scale by reducing stream network connectivity, sediment transport and altering temperature regimes (Cooper et al., 2017; Nilsson et al., 2005).

1.1 IMPORTANCE OF RIVER CONNECTIVITY

Generally, rivers are classified into temporal and spatial dimensions, the latter including longitudinal, lateral, and vertical components. The longitudinal aspect connects upstream and downstream river reaches. The lateral dimension links the riverine channel with the wetlands and floodplains, and the vertical dimension connects the surface water with groundwater (Standford & Ward, 1993; Ward, 1989). Longitudinal and lateral connectivity are responsible for the transport of organic and inorganic matter (Vörösmarty et al., 2003). Especially, longitudinal connectivity supports hydrological processes which are responsible for heterogeneous habitats and the resulting connectivity patterns (Bunn & Arthington, 2002; Connell, 1978; Diáz et al., 2019; Stanford & Ward, 1983). Moreover, it is crucial for the migration and dispersal of aquatic species (Cote et al., 2009; Fukushima et al., 2007) as well as for community composition and biodiversity in the river network (Altermatt, 2013). In particular, fish depend on an intact longitudinal river connectivity to access habitats critical for the completion of life cycle requirements. Fish migration depends on free-flowing rivers, water temperature, light, season, discharge, water quality and homing behavior (Baras & Lucas, 2001a). Migratory behavior is an essential characteristic of the life cycle of many fish species and is responsible for seasonal movements, protection from predation, enhances lifetime reproductive success, and allows for the recolonization of areas affected by disturbance (Benejam et al., 2016). This in turn supports fish growth, reproduction, genetic variation and survival of individuals, which are crucial for the health of the whole population or even community (Marshall & Frank, 1999). In observing fish population dynamics, it is important to not only consider longitudinal connectivity along river mainstems, but also longitudinal dendritic connectivity across the entire river network to understand population processes such as dispersion, growth and survival. River branches (i.e. tributaries) are frequently important determinants of fish species distributions by providing refugia, enhancing habitat heterogeneity and supporting habitat access for migratory fish (Campbell Grant et al., 2007).

Longitudinal connectivity is not only responsible for the distribution of fish, it determines the longitudinal zonation of riverine fish assemblages from headwaters to the river outlet. The so-called 'fish region concept', introduced by Illies (1961) and Huet (1949), indicates the presence of specific fish assemblages in predefined fish regions, i.e. trout, grayling, barbel and bream region and relates to biocoenotic regions (epirhithral, metarhithral, hyporhithral, epipotamal and metapotamal). A single biocoenosis differs in its composition of the river width, discharge, water temperature, oxygen content, slope, substrate, and turbidity (Illies, 1961).

Anyhow, longitudinal connectivity is seen as the most important connectivity dimension for riverine fish assemblages and therefore, in this thesis the focus is set on longitudinal connectivity; other dimensions are not addressed here. In this study longitudinal connectivity is defined as not only connectivity along river mainstems but also among tributaries, providing a view of longitudinal connectivity across entire river networks.

1.2 RESPONSE OF FISH ASSEMBLAGES TO RIVER FRAGMENTATION

The construction of barriers primarily interrupts fish migration corridors, but in addition hydropower barriers affect river ecosystems through hydro-morphological changes induced by water management and turbine operations (e.g. impoundment, water abstraction/residual flow, and hydropeaking) (Fuller et al., 2015). For example, impoundments alter upstream habitats through shifts from lotic to lentic conditions and lead to a displacement of fish species (Petts, 1984). Impoundments also act as a sediment trap and consequently affect the river downstream through bed siltation, clogging of interstitial space among substrates, and riverbed incision (Schmutz & Moog, 2018). Furthermore, impoundments block the upstream migration for spawning and act as an ecological trap for drifting eggs and juvenile fish (Pelicice & Agostinho, 2008). Since impoundments and residual flow alter hydraulics and sediment composition, this often leads to homogenization of habitats and subsequent changes in fish community composition and reduction in fish abundance (Poff & Zimmerman, 2010; Wiens, 2002). Moreover, hydropeaking changes the natural flow regime by causing short-term fluctuations of flow and water stage (Hayes et al., 2022). Due to the artificial sub-daily flow fluctuations, fish get injured, may relocate to less suitable habitats, or are even stranded on the shoreline (Hall et al., 2015). In general, these aspects lead to various impacts on fish populations such as a reduction in biomass and abundance, fish growth, survival rate, reproduction, and biotic integrity (Céréghino et al., 2002; Dahm et al., 2013; Finch et al., 2015; Parasiewicz et al., 1998; Schmutz et al., 2015a; Valentin et al., 1996). Moreover, the impact will depend on the response of different environmental guilds. Fish species belonging to the same guild, e.g., sharing the same requirements regarding reproduction (e.g., lithophil, phytophil, psammophil), habitat (e.g., rheophil, limnophil, indifferent) or migration pattern (e.g., diadromous, potamodromous) may likely respond similarly to river fragmentation (Jungwirth et al., 2003).

The shift from lotic to lentic environments in impounded sections particularly affects specialist species and those belonging to the lithophilic and rheophilic guild; generalist fish species may benefit from ecosystem changes (Cooper et al., 2017; Fukushima et al., 2007). Regarding fish migration, the diadromous guild, particularly long- and medium-distance migrants, are much more severely affected by barriers than their potamodromous counterparts, especially short-distance migratory species (Fukushima et al., 2007). Considering the location of barriers is crucial when assessing their impacts on fish migration. While barriers in close proximity to river mouths can have the greatest impact on river-run diadromous species, barriers in the middle section of rivers greatly influence potamodromous species (Cote et al., 2009).

Due to their sensitivity in terms of environmental changes, fish are an excellent bio-indicator for hydro-morphological alterations, including river fragmentation, and are, therefore, are one of the four Biological Quality Elements (BQEs) used for the status assessment of water bodies for the EU Water Framework Directive (WFD; European Commission, 2000). The WFD, a

European-wide instrument, was implemented to protect and restore water bodies. The goal of the WFD is to achieve a good ecological status/potential in all European water bodies and to prevent further deterioration by promoting sustainable water use. Different fish metrics can be considered as bio-indicators, including fish assemblage composition, guild affiliation or population parameters (BMLFUW, 2015). Fish are excellent indicators for river connectivity because they rely on the availability and accessibility of habitats along the river network (Jungwirth et al., 2003). The advantages of using fish as bio-indicators include their well-known taxonomy, ease of identification, life history, ecological requirements and their response to environmental stressors, as well as their wide dispersion in the river network. In addition, fish serve as a good representative for the ecological status of the riverine ecosystem as they gain broad attention from the public due to sport fishing and their importance for the food industry (EFI+ Consortium, 2009; Trautwein et al., 2013).

1.3 DISTRIBUTION AND PATTERNS OF RIVER FRAGMENTATION

As previously described, the impact of barriers on fish species depends on their location in the river network. Fish migration is more sensitive to river fragmentation when barriers are located on river mainstem and major tributaries that disconnect the entire river network upstream rather than barriers high up in the head waters that disconnect smaller proportions of the upstream river network (Grill et al., 2014). Rivers in higher elevation landscapes are obstructed with barriers for flood protection, torrent control and hydropower production. Hydropower production is especially favored in regions where geology, topography, and climate as well as the storage capacity and river flow fulfil the requirements for hydropower potential. On the contrary, rivers in lowlands are mainly degraded by regulation and straightening to gain more land for agricultural use (Nõges et al., 2016). As a consequence, barriers are not evenly distributed among river network, and even across ecoregions differences in barrier density have been observed (Cooper et al., 2017; Lehner et al., 2005, 2011; Liermann et al., 2012). In addition, creeks are more likely to face localized influences (i.e. form individual barriers), whereas rivers farther downstream face cumulative impacts of dams (i.e. from all upstream barriers). Accordingly, particular ecoregions, fish regions and river size classes are more affected than others (Liermann et al., 2012).

1.4 STATUS QUO OF RIVER FRAGMENTATION IN AUSTRIA

The Austrian River Basin Management Plan (RBMP) is an implementation tool of the WFD, which includes an impact- and status assessment and give step-by step guidance on how to reach the WFD goals for Austria. The achievement of the goal was primarily set for the year 2015, but it couldn't be accomplished, and therefore the deadline got extended to the year 2021 (WFD; European Commission, 2000). To achieve a good ecological status according to the WFD, the physicochemical parameters, chemical parameters, biological parameters, and hydro-morphology need to be considered. In this thesis the focus is set on biological parameters, i.e. fish assemblages, and on hydro-morphology. For Austria, the national guideline for the assessment of hydro-morphology takes three main parameters into account: hydrology (residual flow, hydropeaking, and impoundment), barriers, and morphology (shoreline dynamics and river bed dynamics) (BMLFUW, 2015).

The assessment showed that 63% of all water bodies in Austria are at risk of failing the objectives of the WFD (high or good ecological status/ potential). The high risk of failing the objectives was mainly identified due to hydro-morphological pressures (BMLFUW, 2015). Overall, 53% of the water bodies are impacted by hydro-morphology alteration. Among others, this is caused by more than 33 000 non-passable barriers. About 60% of water bodies are disconnected, due to the existence of a barrier for nearly every kilometer in Austria.

River morphology assessment in Austria includes the consideration of shoreline structure and sediment transport. For these parameters, 29.2% of Austrian rivers (total river network length 32 201 km) are impacted, resulting in a total river length of 9 408 km. Barriers also interrupt the flow regime and result in 3 159 river stretches (with a total length of 4 415 km) which are impacted by residual flow, 1 448 river stretches are affected by impoundment sections (with a total length of 1 356 km) and 896 km of rivers are influenced by hydropeaking. Moreover, around 70% of water bodies are facing two or more stressors, whereas rivers impacted by more than two stressors increase to 80% as a function of increasing river size (>100 km²) (BMLFUW, 2015). These numbers underscore that river restoration efforts must be taken to improve the ecological status of water bodies and to reach the goals of the WFD.

Habitat fragmentation is considered one of the biggest source of local and regional species extinction in rivers. Hence, understanding the impact of fragmentation and restoring instream connectivity to conserve aquatic biota is a key focus of research and management globally (Abell et al., 2008; Fuller et al., 2015; Pringle, 2001; Zarfl et al., 2015). Various initiatives have been started to address this problem, such as the free-flowing initiative from World Wide Fund for Nature (WWF), and moreover the EU Biodiversity Strategy plan to reconnect 25 000 km of Europe's rivers by 2030 (Belletti et al., 2020). On the contrary, the upcoming guidelines for renewable energy for Austria, the so-called EAG (law for the expansion of renewable energy) implies that by 2030 100% of the power will be produced by renewable energy sources, regardless of the effects on river conditions (BKUEMIT, 2020). As such, guidelines like the EAG impede efforts to reconnect river networks. Therefore, the investigation of the impact of river fragmentation on fish assemblages is greatly needed in order to deliver data and support the mitigation of future pressures from barrier construction, assess restoration projects feasibility. For these reasons, this thesis focuses on the disruption on longitudinal connectivity by considering barriers along the whole river network, and its associated effects on fishes due to river barriers in Austria.

1.5 Study objectives

This thesis aims to assess the current status of river fragmentation in Austria by considering regional differences and how fragmentation affects riverine fish assemblages. It follows the study design of Cooper et al. (2017), who calculated various metrics of network fragmentation for rivers in the United States and evaluated the effect on fish assemblages. Compared to other studies, the methodology of Cooper et al. (2017) includes several fragmentation metrics, which are calculated and analyzed for different regions to allow a comprehensive conclusion about river fragmentation in Austria. These fragmentation metrics are then linked to fish assemblage metrics to facilitate analyses on the effects of river fragmentation on fish assemblages. The results of this thesis can support river management by providing a solid baseline for connectivity restoration measures. This thesis aims to answer the following research questions:

1. How fragmented are Austrian rivers?

a) Which fragmentation metrics identified by (Cooper et al., 2017) can be implemented in Austria, and how?

b) Does river fragmentation differ by fish region, ecoregion and/or river size classes?

2. How do fish assemblages respond to fragmentation and other (hydro-morphological) parameters in a multi-impacted environment?

2 MATERIALS & METHODS

All environmental data are derived from the RBMP (BMLFUW, 2015). The starting point for the spatial analysis is the Austrian river network considered in the RBMP. Therefore, the geodata of the so-called 'Route'-shapefile and the 'Typology'-shapefile were used for the analyses. In total, 8 065 streams (>10 km² catchment area) exist in Austria, resulting in a total river length of 32 201 km. (BMLFUW, 2015; RBMP-DB, 2015).

2.1 STUDY AREA

The study area of this thesis is the territory of Austria, located in Central Europe with humid continental conditions and consisting of temperate upland and temperate floodplain rivers, and wetlands (Abell et al., 2008; Kottek et al., 2006; Peel et al., 2007). The Austrian river network is part of the Danube, Rhine and Elbe river basins. Almost two-thirds of the country is covered by the European Alps (Alpine Convention, 2015). Generally, the river network extends over four ecoregions, i.e. relatively homogenous areas according to climate, hydrology, geology, landform, ground, vegetation and zoology (Moog et al., 2001; BMLFUW, 2015; RBMP-DB, 2015; Figure 1).

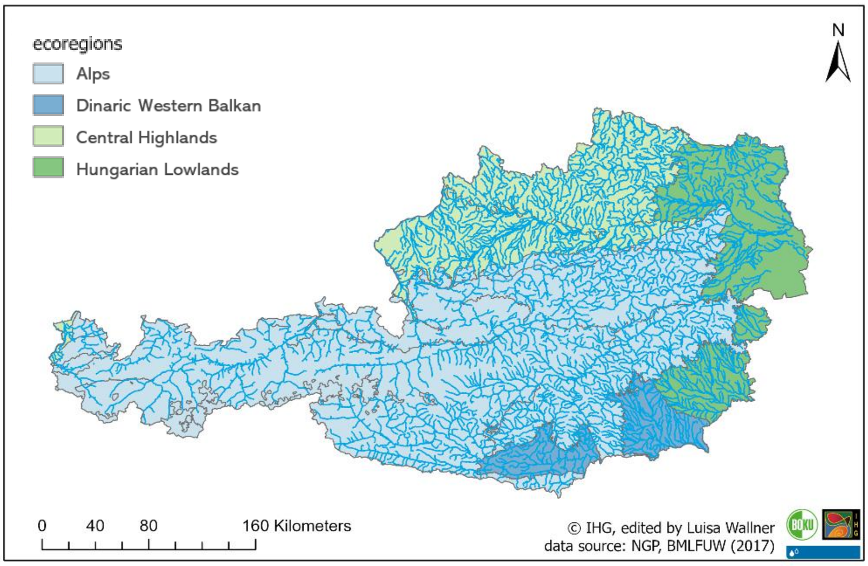

Figure 1: Austrian river network (limited by fish regions) within the four ecoregions according to RBMP, 2015.

2.2 RIVER NETWORK & FISH REGIONS

The area of interest were rivers located within the natural distribution range of fishes, as determined through fish regions (Figure 5). Hence, all streams outside of the distribution range of fishes (mostly high-altitude mountain streams) were excluded from the analyses. Fish regions are classified according to natural changes in the aquatic biocenosis along the longitudinal course of the river (Huet, 1959). Each biocenosis can be described by key parameters such as river width, discharge, water temperature, oxygen content, slope, substrate, and turbidity (Illies, 1961). The fish region classification used in Austria is the following: epirhithral, metarhithral, hyporhithral small/large, epipotamal small/medium/large, and metapotamal (BMLFUW, 2015). In this analysis, the fish regions were combined into the five main types: epirhithral, metarhithral, hyporhithral, epipotamal, and metapotamal (Figure 2/A; described below). Furthermore, rivers are classified into stream size classes according to their catchment area (<10 km², >10 km², >100 km², >500 km², >1 000 km², >4 000 km², and >10 000 km²) (Figure 2/B; BMLFUW, 2015; RBMP-DB, 2015).

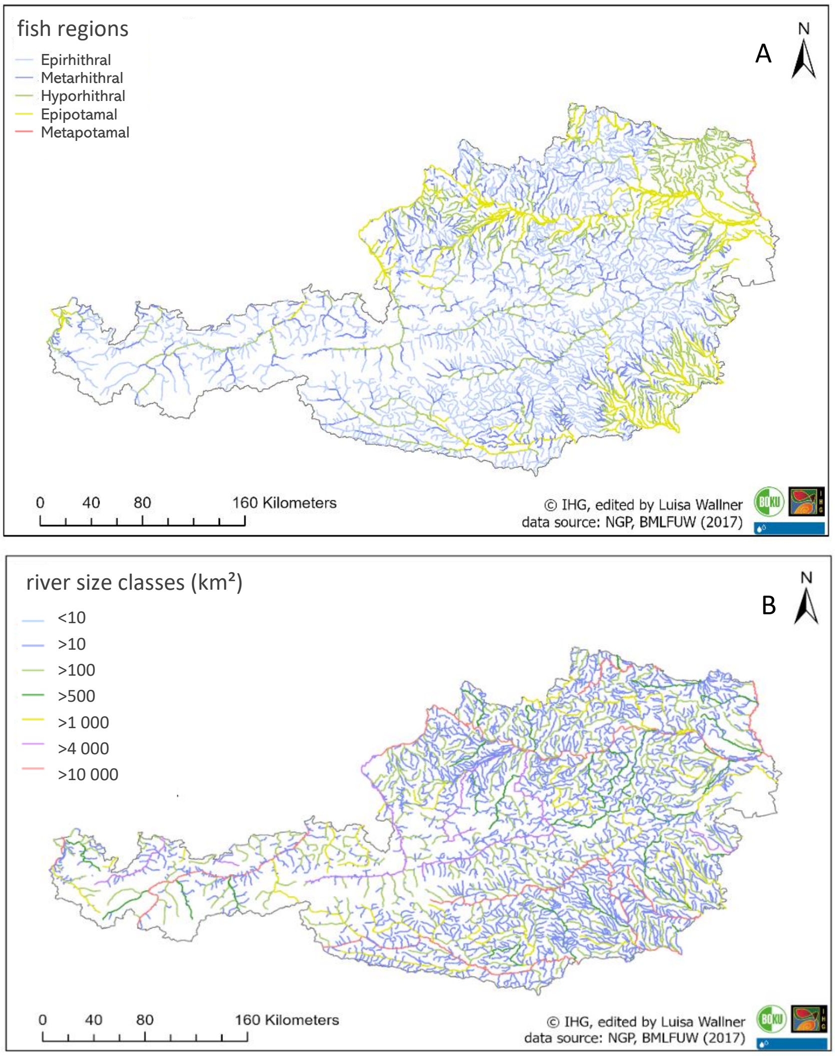

Figure 2: The Austrian river network classified by fish regions (A) and river size classes (B) according to the RBMP, 2015.

2.3 BARRIER DATA

Information for 60 253 barriers was derived from the geodataset 'Querelemente', with all barriers located in the fish regions mentioned above (including artificial and natural barriers, passable and impassible barriers; RBMP-DB, 2015). These barriers were used for the development of fragmentation metrics after Cooper et al. (2017) and included five different types of barriers (Table 1):

Table 1: Barrier types and their description in the guideline of the river hydro-morphology assessment for Austria (BMLFUW, 2015).

Type Nr.	Barrier type	Function
1	Weir	Stores water upstream
2	Barrier with other functions	Obstruction of the river under a bridge or a road; barriers for purposes other than hydropower (e.g. soil irrigation and regulation of water levels)
3	Barrier as a protective water engineer	Stabilize the river bottom (e.g. groundsills and bedload retention)
4	Natural barrier	Barriers > 1m high (e.g. waterfalls)
5	Chain of ramps	A series of a minimum of 5 barriers

2.4 ADDITIONAL STRESSORS

Type 1 barriers have different operation modes and consequently impact the hydro-morphology of a river. Accordingly, rivers are multi-impacted systems and additional stressors, as classified by the Austrian RBMP, were incorporated in the analyses including: residual flow (R), morphological alteration (M), connectivity disruption (B), impoundment (I), and hydropeaking (H). Also, chemical stressors and toxic substances as reported by the RBMP are included in the analyses, summarized as 'water quality' stress (C). Beside impacts of single stressors, this thesis also investigated a multi-stressor approach, in particular the number of stressors and the type of stressor combinations per water body (Schinegger et al., 2018). Stressors were assigned to different intensity classes ranging from A to D built on specific criteria, which are obtained from the Federal Inventory Assessment (BMLFUW, 2015) and classified according to Schinegger et al., (2018). The intensity classes 'A' and 'B' were classified as 'no stressor', so only classes 'C' and 'D' were incorporated into further analyses (BMLFUW, 2013); Schinegger et al., 2018; Table 2).

Table 2: Classification of stressor variables after the Federal Inventory Assessment (BMLFUW, 2015) and Schinegger et al. (2018).

Stressor intensity classes of the national impact assessment used in MARS Project			**A** **No or very low impact**	**B** **Low impact**	**C** **Possible significant impact**	**D** **Strong significant impact**
Stressors	**Impoundment (I)**	**River basin district <1 000km2**	No I	No I >500m & sum I <10% of surface water body (SWB)	Single I 500-1 000m or sum of multiple I cover 10-30% of SWB	Single I >1 000m or sum of multiple I cover >30% of SWB
		River basin district >1 000km2			Single I 500-2 000m or sum of multiple I cover 10-30% of SWB	Single I >2 000m or sum of multiple I cover >30% of SWB
	Hydropeaking (H)	**Small & medium rivers**	No H	<1:3 or designated as "no significant H-impact" [a]	1:3-1:5 or H amplitude unknown or designated as "significant H - present risk" [a]	>1:5 or designated as "significant H - present risk"
		large rivers		Very slight H or designated as "no significant H-impact" [a]	Designated as "significant H - present risk" [a]	>Each distinct flush or designated as "significant H - present risk" [a]
	Residual flow (R)		No abstraction or abstraction according to QOO Ecology [b]	Abstraction with dotation order during full year or during authorized abstraction period; according to QOO Ecology [b] 2 values are met or abstraction at facilities authorized 1990-2010 according to specifications of ecological functioning/good status	Abstraction with regulated dotation during the whole year or within authorized period; values according to QOO Ecology [b] 2" are not met [c] or abstracted dotation unknown	No or no dotation order during full year or no continuous dotation order during authorized abstraction period or water body sections, which fall dry due to insufficient dotation during the whole year or during certain periods.
	Connectivity disruption (B)	**Within fish habitat**	No B or passable without fish migration facility (e.g. ramp)	Limited passability of B or B [d] passable due to fish migration facility & no additional non-passable length elements	>=1 non-passable B	-
	Morphological alteration (M)		All 500m-sections within SWB = class 1 [e]	<30% class 3-5 [e]	30-70% class 3-5 & <30% class 4-5 [e]	>70% class 3-5 or > 30% class 4-5 [e]
	Water quality (C) [f]		1	2	3	-

[a] According to 'BOKU Hydropeakig-study' by (Schmutz et al., 2013)
[b] Quality objective ordinance ecology
[c] Abstractions with MQRW < MJNQTnat or NQTRW < NQTnat
[d] Barriers with functioning fish migration facilities and barriers with (possibly) limited passability
[e] Classes according to 'Guidance on hydromorphological state assessment' by (Mühlmann, 2013)
[f] Chemical status expressed in intensity classes 1-3 was selected instead of values proposed by impact assessment chemistry

2.5 FISH DATA

For analyses related to the response of fish assemblages to fragmentation and other stressors, the fish sampling database of the Austrian Federal Ministry of Agriculture, Regions and Tourism (BMLFUW) collected according to the decree on the water body state survey (Gewässerzustandsüberwachungsverordnung, GZÜV), and the Institute of Hydrobiology and Aquatic Ecosystem Management (IHG) were combined (Hayes et al., 2022; Schaufler, 2021). Combining data from these two sources resulted in 1761 fish assemblage survey sites.

The stressor-response of fish assemblages is described by the Fish Index Austria (FIA; Haunschmid et al., 2006). The FIA is an Index of Biotic Integrity (IBI), developed to assess the fish-ecological status in Austria and to achieve the objectives of the WFD. The FIA results from the information on dominant species, subdominant species, rare species, habitat guilds, reproductive guilds, fish region index, and population age structure. The assessment of the FIA results from the deviation between a predetermined reference condition ('Leitbildkatalog' (BAW IGF, 2015) and the actual state of the sampling site (Haunschmid et al., 2006). The reference conditions are predetermined for all river types and fish regions in Austria. The final FIA value is based on the weighted mean of summarized metrics, the status of fish species assemblages, fish zonation index, and age structure, ranging from 1 (high) to 5 (bad). The fish samples were collected following the standard sampling protocol of (Haunschmid et al., 2010).

For the analyses, fish samples collected within the time period of the 2. National River Basin Management Plan (from 2009 to 2018) were used in order to assure temporal conformity among stressor-responses of fish assemblages.

2.6 CALCULATION OF FRAGMENTATION METRICS

The fragmentation metric calculation procedure was adopted from Cooper et al. (2017) who established several metrics of river network fragmentation for the conterminous USA on river reach and segment level. River reaches are described as confluence-to-confluence stream sections, with confluences appearing at stream junctions (Figure 3). River segments are defined as the fragmented subdivision of the stream network and its corresponding catchment (Wang et al.,2011). In this study, both river reaches and segments were subdivided at barrier locations (Figure 3 & Figure 6).

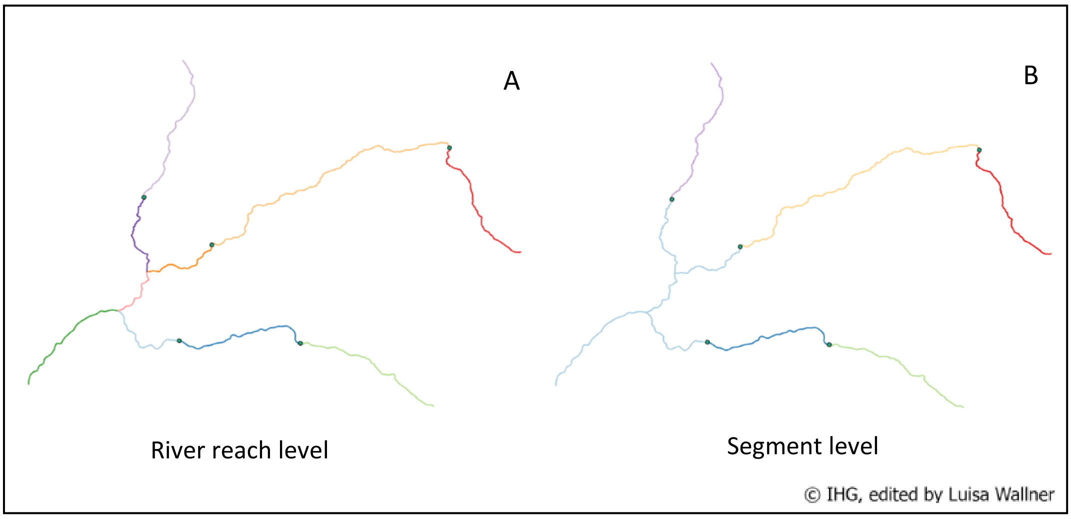

Figure 3: River network represented by individual river reaches (3A) defined by stream junctions and/or barriers (points) and river segments (3B) defined using barriers only.

ArcGIS Pro (2.9.0) was used for the calculation of river fragmentation metrics, a software product established by the Environmental Systems Research Institute (ESRI, 2021). It allows for the creation of geographical maps and facilitates spatial and temporal analyses.

The following tools were used for the generation of fragmentation metrics and shapefiles:

'Selection': Extract features with a specific attribute from an input feature. With the selection a new layer representing features with a special condition can be selected out of an original layer.

'Clip': The 'Clip' tool is comparable to a cookie cutter, which cuts the input layer at the border of the clip feature. The information of the input table remains. Only the geometry of the layer gets modified.

'Flip': It reverses the orientation of a selected line feature, respectively it changes the from-to-direction of a line feature.

'Planarize lines': A line feature gets split up at junctions and turns into multiple line features. It helps to ensure that streams are properly connected by enforcing junctions.

'Assign Hydro ID': Develops a unique hydro ID for individual stream reaches.

'Generate From/To Nodes for Lines': Every end node of a line feature gets a continuous ID for both starting node ('From' node) and ending node ('To' node), illustrating the orientation of a line.

'Features Vertices to Points': Point features emerge from the starting and end node of a line feature.

'Spatial Join': Merge data from one feature layer's attribute to another based on the spatial relationship between both layers.

'Add Join': Joins a layer to another based on common fields within attribute tables.

'Field Calculator': Calculates selected records for string, number, and date fields.

The fragmentation metric calculation procedure was separated into three main parts: pre-processing, metric calculations and post-processing. The whole procedure was executed two times, once for reach level and then for segment level to calculate all intended fragmentation metrics (Figure 4). The calculations on segment level was executed to get two additional ecological relevant fragmentation metrics (segment length and segment catchment area).

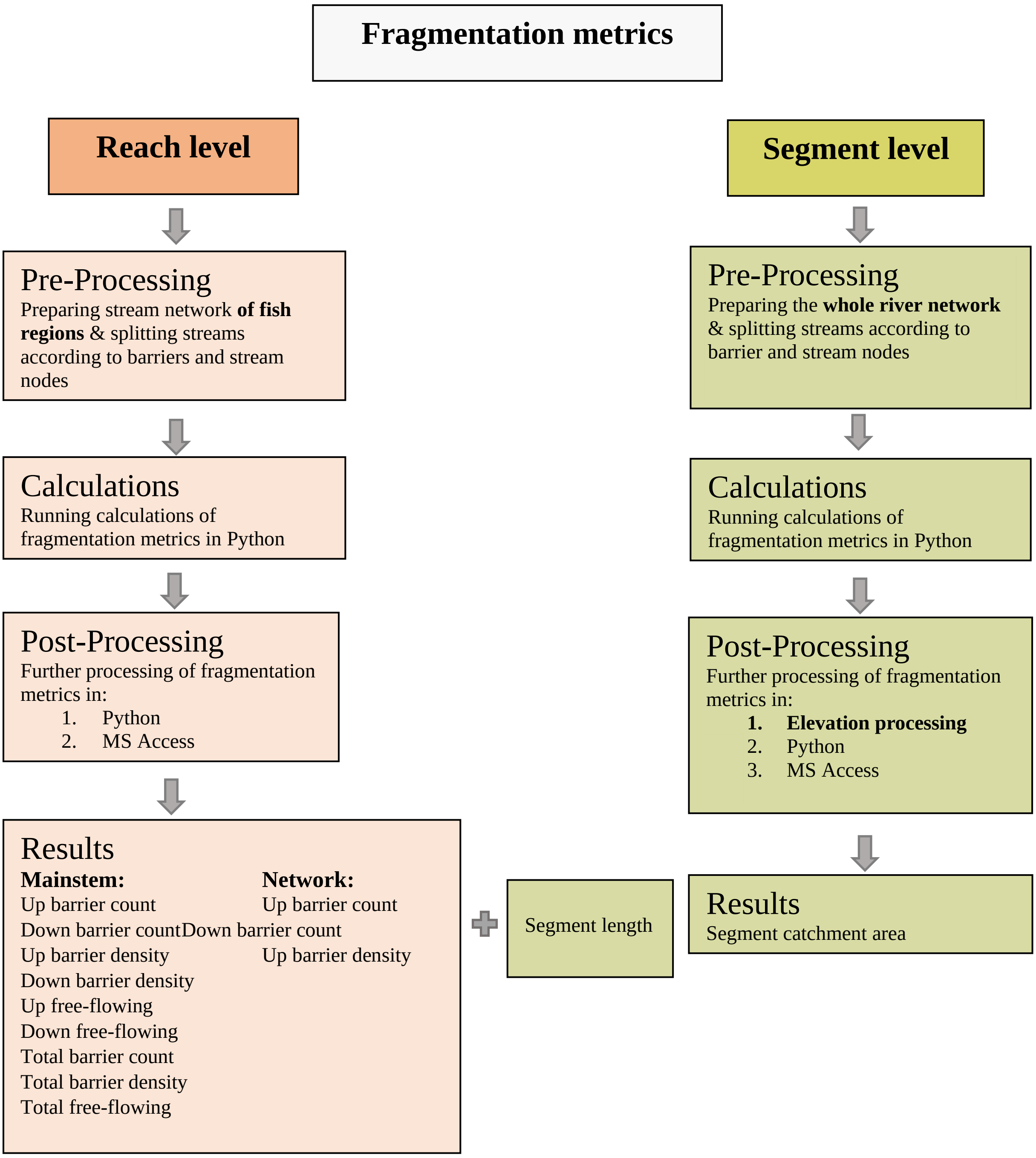

Figure 4: Conceptual model for the calculations of fragmentation metrics for both reach and segment levels. 'Up' = upstream, 'Down' = downstream and 'Total' = 'Up' & 'Down' combined.

2.6.1 Reach level analyses

The Austrian river network and barriers, derived from the RBMP-DB (2015), are the main geodata used for the analyses.

Pre-processing

The main goal of this thesis was to analyze the impact of river fragmentation on fish assemblages. Therefore, the river network and the barriers were pre-processed to only select those sections and barriers located within the natural distribution area of fish in Austria.

The GIS-layer 'Typology' represents the river network of Austria, considered in the RBMP and includes information on fish regions. Therefore, the 'Typology'-shapefile was restricted to fish regions by applying the 'Selection' tool in ArcGIS Pro (Figure 5). The data on fish regions was sometimes incomplete and showed gaps within the river network. Hence, the gaps were manually closed, and the missing data were completed by adapting the upstream fish region.

To include information on flow direction, the 'Routen'-shapefile was used as the basis layer for calculations. The 'Routen'-shapefile represents the Austrian river network, which goes beyond the Austrian border and includes rivers with a catchment area <10 km² (Figure 5). To only incorporate rivers >10 km² in Austria and a river network restricted to fish regions, the 'Clip' tool was executed to align the 'Routen'-shapefile to the adapted 'Typology'-shapefile. The 'Routen'- and 'Typology-shapefiles differ in their geometry, and therefore a tolerance of 0.5 m was set, and the remaining gaps within the river network were corrected.

In addition, the river stretches of Inn, Danube and Thaya, which cross the Austrian border to other countries, were added manually to the river network in order to have a continuous route file. This adaptation was necessary for the proximate calculation of up- and downstream barrier counts. The final river network was a continuous network restricted to fish regions with information on flow direction.

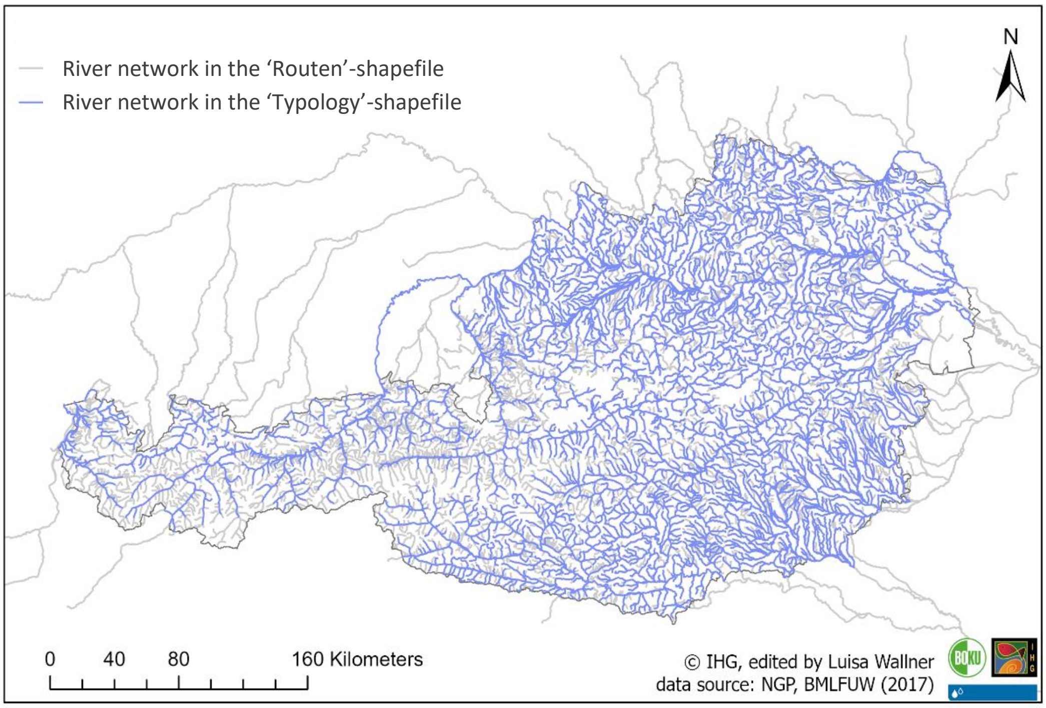

Figure 5: The blue line ('Typology'-shapefile) shows the river network restricted to fish regions, including adapted river stretches of Inn, Danube and Thaya rivers, which either border Austria and/or flow from other countries into Austria. The grey lines ('Routen'-shapefile) represent the river network beyond the Austrian border and outside of the river network considered in the RBMP dataset.

The same procedure was executed for the available barriers by clipping them according to the adapted 'Typology'-shapefile. When applying the 'Clip' tool, the input shapefiles were reviewed for alignment and the output shapefiles regarding completeness.

Before executing the calculations, additional adaptations at the river network shapefile were necessary, e.g., applying the 'Planarize lines' tool to remove any overlapping line segments to ensure the presence of correct stream junctions. Also, the flow direction of the Austrian river network had to be adapted, because the river flow indicated the reverse direction. Therefore, the 'Flip Line' tool was executed to turn the from-to direction of line features.

The barrier locations were used to split streams by applying a tool in the programming language Python (established by A. Cooper). The outcomes is a set of individual river reaches determined by a combination of hydrologic junctions (i.e. confluences) and barriers (Figure 3).

Additional information on unique IDs, up- and downstream barriers, and river length were added to each generated river reach. The unique IDs were generated with the 'Assign Hydro ID' tool available in the 'ArcHydro' extension. Information on barrier locations up- or downstream of river reaches was incorporated by first executing the 'ArcHydro' tool 'Generate From/To nodes for lines' to establish river reach typology. Afterwards, the tool 'Feature vertices to points' was applied to convert flowline vertices to upstream and downstream node points. The upstream and downstream node points were added to the barrier shapefile through a 'Spatial Join'. A 'Tabular Join' combined the information of overlapping upstream and downstream nodes with barriers. With the aid of the field calculator, additional fields were added to the attribute table, giving information on the existence of barriers upstream and downstream (i.e. 'yes' or 'no' for each river reach).

In the end, the length of the Inn, Danube, and Thaya River stretches, flowing through Germany and the Czech Republic were subtracted from the Austrian river network to derive correct results.

Calculation of fragmentation metrics

After information on the single river reaches and the location of barriers was added, a Python script (provided by A. Cooper) was executed and generated fragmentation metrics according to the presence of barriers after Cooper et al. (2017) for both the reach level and segment level.

Table 3: Output fields from the calculations with Python, representing fragmentation metrics on the reach level and segment level, after Cooper et al. (2017).

Shortcut	Description
ID	Unique river reach identifier
nUpAlongMain	Number of dams upstream along the mainstem
nUpAnyWay	Total number of dams upstream along all paths
dUpMain2Dam (km)	Distance upstream along the mainstem to the first dam. If a barrier is located on the river reach upstream node, the distance is zero
dUpMain2Head (km)	Distance upstream along the mainstem to the headwaters
nDownAlongMain	Number of dams downstream along the mainstem
dDownMain2Dam (km)	Distance downstream along the mainstem to the first dam. If a barrier is located on the river reach downstream node, the distance is zero
nDownAnyWay	Total number of dams downstream along all paths
dToCoast (km)	The distance from the river reach to the coastline (i.e. the last river reach of a stream network flowing out of Austria)
bFlowsToCoast	Does this arc flow downstream to a 'coastline' stream arc? One if yes, zero if no
Seg ID	Unique segment identifier of a patch associated with this arc

The output field 'bFlowsToCoast' (Table 3) was used to examine if all streams are connected. A filtering process helped to detect and correct cases where streams were disconnected, e.g., due to the wrong flow direction (wrong order of up- and downstream nodes).

Post-processing

In addition to the fragmentation metrics as described above (Table 3), post-processing of the fragmentation calculations resulted in metrics quantifying barrier densities and the river openness along the mainstem and for the entire river network.

To calculate barrier density and river openness along the river network, total river length along the river network was established. With the existing information on flow direction, the IDs, and the length of the single river reaches, another Python script (provided by A. Cooper) was applied which calculated the total upstream river length along the river network.

Finally, fragmentation metrics developed in the previous step (Table 3) and the calculated river length of the river network were used to generate barrier density and river openness along the mainstem and the river network. This was done in MS Access 2016 with the aid of query expressions in Table 4, provided by A. Cooper.

The information on the environmental regions (fish regions, ecoregions and river size classes) for the single river reaches was added to the river network in GIS with the 'Spatial Join' tool, resulting in a database of individual river reaches with the information on fragmentation metrics and environmental regions.

2.6.2 Segment level analyses

The results of the fragmentation metrics at reach level were used to calculate the total stream length at the segment level. Therefore, river reaches with the same Seg ID (Table 3) were merged and accordingly the total segment length was calculated to represent free-flowing river stretches.

Pre-processing

The pre-processing for the segment catchment area was similar to the calculations at reach level, however differed in that the whole river network, not only the parts inhabited by fish species, was incorporated (Figure 5). This adaptation was necessary to generate the correct catchment area even for portions of the river network restricted to the fish regions. Therefore, the 'Routen'-shapefile was adapted to the original 'Typology'-shapefile, to only consider rivers with catchment area >10 km². All barriers, even those upstream of fish regions, were included in the calculations.

Calculation of fragmentation metrics

The segment level calculations follow the same calculation procedure as those at the reach level (see chapter (2.6.1).

Post-processing

Austria's digital elevation model (DEM) was used to generate local catchments. A Python script was executed (provided by A. Cooper) which follows the 'AGREE' elevation processing method (Hellweger & Maidment, 1997; Moore et al., 2019). In this processing method, the elevation grid is aligned with and assigned to the stream network with a series of steps that culminates in the delineation of local catchments.

The catchments were initially generated at reach level, but were merged to segment catchment level using the Seg ID information (Table 3) of individual catchments. Hence, each segment catchment is limited by the existence of barriers (Figure 6). For each catchment, the total area was calculated.

To compare the segment length and area between the environmental regions, a 'Spatial-Join' was executed to combine the information of the regions and the river segment metrics.

The entire procedure described above was repeated without barriers to calculate catchment size in the absence of barriers.

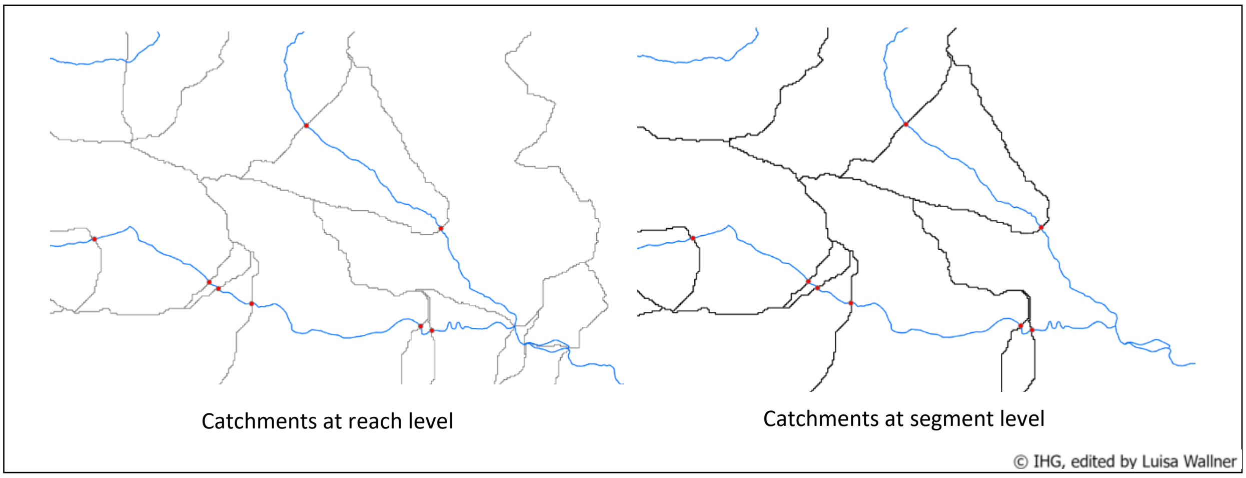

Figure 6: Depiction of individual catchments at the reach level (defined by stream junctions and/or barriers (red points)) and catchments at segment level (defined by barriers only).

Table 4: Fragmentation metrics calculated after Cooper et al. (2017).

Fragmentation metrics			
Metric name	**Description**	**Unit**	**Description/Formula (MS-Access)**
UpMainCnt	Upstream mainstem barrier count	nr.	nUpAlongMain
UpMainDens	Upstream mainstem barrier density	nr./10 km	nUpAlongMain / (dUpMain2Head - LENGTHKM[a]) * 10
UpMain2Dam	Upstream distance to the next dam along mainstem	km	dUpMain2Dam
UpMainDist	Upstream distance along mainstem	km	dUpMain2Head - LENGTHKM
UpMainOpen	Upstream openness along mainstem	%	dUpMain2Dam / (dUpMain2Head - LENGTHKM]) If nUpAlongMain = 0 → 100% If dUpMain2Dam = 0 → 0%
DownMainCnt	Downstream mainstem barrier count	nr.	nDownAlongMain
DownMainDens	Downstream mainstem barrier density	nr./10 km	nDownAlongMain / dToCoast * 10
DownMain2Dam	Downstream distance to the next dam along mainstem	km	dDownMain2Dam
DownMainDist	Downstream distance along mainstem	km	dToCoast
DownMainOpen	Downstream openness along mainstem	%	dDownMain2Dam / dToCoast If nDownAlongMain = 0 → 100% If dDownMain2Dam = 0 → 0%
TotalMainCnt	Total mainstem barrier count	nr.	nUpAlongMain + nDownAlongMain
TotalMainDens	Total mainstem barrier density	nr./10 km	(nUpAlongMain + nDownAlongMain) / (dUpMain2Head + dToCoast) * 10
TotalMain2Dam	Total distance to the next dam along mainstem	km	If nUpAlongMain = 0 & nDownAlongMain = 0 → -99 If nUpAlongMain > 0 & nDownAlongMain = 0 → dUpMain2Dam + dToCoast If nUpAlongMain = 0 & nDownAlongMain > 0 → dUpMain2Head + dDownMain2Dam If nUpAlonMain > 0 & dDownMain2Dam > 0 → dUpMain2Dam + dDownMain2Dam
TotalMainDist	Total distance along mainstem	km	dUpMain2Head + dToCoast
TotalMainOpen	Total openness along mainstem	%	TotalMain2Dam / TotalMainDist
UpNetCnt	Barrier count along the upstream river network	nr.	nUpAnyWay
UpNetDens	Barrier density along the upstream river network	nr./10 km	(nUpAnyWay / AGG_AT_KM[b]) * 10

[a] LENGTHKM = length of river reach

[b] AGG_AT_KM = aggregated river length upstream the river network

2.7 Evaluation of the impact of fragmentation on fish assemblages

The second part of the thesis focuses on the impact of river fragmentation on fish assemblages. Several fragmentation metrics were calculated (Table 3 & Table 4) and help to explain the impact of fragmentation on individual fish metrics.

The FIA (explained in section 2.5 Fish data; Haunschmid et al., 2006) was chosen for the analyses because it represents the overall status of fish assemblages. To examine the impact of river fragmentation on fish assemblages more precisely, the related FIA metrics age structure, biomass (kg/ha), reproductive guilds, and habitat guilds were also evaluated as these fish metrics are sensitive and respond to river fragmentation (Baras & Lucas, 2001; Consuegra et al., 2021; Cooper et al., 2017; Fukushima et al., 2007; Letcher et al., 2007; Schinegger et al., 2013; van Puijenbroek et al., 2019).

The geodata of the river network, which includes the fragmentation metrics was adapted and linked to the geodata of the fish sampling sites by using the tool 'Spatial Join' in ArcGIS. Some sampling sites occurred multiple times, and therefore the sampling sites with the oldest date were removed. Each sampling site is assigned to a unique ID, the so called "Detail Wasserkörpernummer" (DWKNr).

Furthermore, some information on fish metrics were missing in the geodatabase of the fish sampling sites. Hence, fish metrics of interest were extracted from another database, provided by Hayes et al. (2022) and (Schaufler, 2021) (2.5 Fish data), and were connected with the database of fish sampling sites with the aid of DWKNr in MS Access. In addition, fish samples, which were collected before the 2. River Basin Management Plan, were excluded from the analyses. The final database comprises the information on fragmentation metrics (including information on environmental regions from previous analyses) and the fish metrics on level of fish sampling sites (reach level). To set the focus only on a few fish metrics, a correlation matrix in R (4.2.0) was conducted.

2.8 Statistical analyses

The preparation and cleaning of data and results was conducted in MS Excel and MS Access. Statistical analyses were executed in R of which the following packages were used:

- tidyverse packages:
    - 'dplyr' for arranging data frame (Wickham et al., 2023)

    - ‘ggplot2’ for visualization (Wickham, 2016)
        - ‘ggpubr’ for visualization (Kassambara, 2022)
    - ‘readxl’ to import data (Wickham & Bryan, 2023)
- ‘stats’ for statistical calculations (R Core Team, 2013)
- ‘respR’ for import, process, analysis, and calculations (Harianto et al., 2023)
- ‘rpart.plot’ for visualization (Milborrow, 2021)
- ‘psych’ for multivariate analysis (Revelle, 2022)

Fragmentation metrics

To illustrate the extent of river fragmentation across the ecoregions, fish regions, and river size classes, stacked bar charts were generated. Therefore, single fragmentation metrics, which were selected for the analyses, were grouped according to natural breaks (i.e., values grouped in classes by distinct break points) and assigned to distinct groups. Each group was represented by its total river length as a percent according to ecoregion, fish region, and river size class. The areas (km^2) of segment catchments were also grouped according to natural breaks. The relative number of segment catchment groups across the different ecoregions, fish regions and river size classes were represented with pie charts.

Impact of fragmentation on fish assemblages

To analyze the dependency of fish metrics on fragmentation metrics, a Spearman rank correlation was used (Spearman, 1904). A Spearman rank correlation is a non-parametric correlation test, which measures the strength and direction of a relationship between two variables. The Spearman rank correlation transforms the data into ranks, resulting in a test that is robust to outliers. The outcome, the correlation coefficient rho (ρ), describes the strength of a relationship between two variables as either monotonically increasing or decreasing. The correlation coefficient ranges from -1 to +1, whereby ‘1’ represents the strongest correlation and ‘0’ no correlation. The direction of a correlation is described with a positive or a negative sign. In addition to the correlation coefficient, the p-value tests the significance of the relationship (Spearman, 1904).

Impact of additional stressors on fish assemblages

To identify additional influences relating to the number and composition of hydro-morphological and water quality stressors (chapter 2.4) on fish assemblages, Spearman rank correlations were calculated with these stressors as well. Only stressor combinations with more than 20 records were investigated for the statistical analyses. The FIA, biomass and age structure were chosen for detailed analyses, as the FIA should reflect the overall status of fish populations, while biomass and age structure potentially respond more specifically to certain to stressors. Boxplots were used to represent the response of fish metrics to stressors. In addition, the deviation in the impact of stressor number and combination on fish assemblages is illustrated by a line diagram, representing the confidence interval with a probability of 95% and the mean, and was additionally tested with a Wilcoxon signed rank test (Wilcoxon, 1945). The Wilcoxon signed rank test is a non-parametric statistical hypothesis test, which measures the difference between two variables. If the p-value is below 0.05 the null hypothesis is rejected and the two variables show a significant deviation from one another. To avoid binary yes/no test outcomes, as it has been commonly used in statistical tests, the interpretation of the results follows the recommendation of Muff et al. (2022). Results were interpreted as no/weak/moderate/strong/very strong evidence for a certain outcome, according to a p-value range (Table 5).

Table 5: Translation of p-value into a language of evidence recommended by Muff et al. (2022); the ranges are based on Bland (1986).

P-value	**Language of evidence**
0.1-1	Little or no evidence
0.05-0.1	Weak evidence
0.01-0.05	Moderate evidence
0.001-0.01	Strong evidence
0.0001-0.001	Very strong evidence

3 RESULTS

3.1 DESCRIPTIVE ANALYSES OF INPUT DATA

The study area comprises a total river length of 27 288 km, which only considers streams inhabited by fish. The 'Alps' ecoregion covers the largest area of Austria (50 707 km²). Around 47% of the river network is located in the 'Alps', with a total river length of 12 888 km (Figure 7A). The second largest ecoregion is represented by the 'Central Highlands', covering an area of 16 141 km² and 27% of the Austrian river network. The remaining streams flow through the 'Hungarian Lowlands', and the 'Dinaric western Balkan'. The river network is also classified into fish regions and river size classes. The most common fish region in Austria is the epirhithral, and represents around 45% of the total river network, followed by metarhithral (19%), hyporhithral (21%), epipotamal (15%), and metapotamal (0.3%; Figure 7B). Around 57% are creeks with a catchment area between 10-100 km², followed by medium-sized rivers (100-500 km²), comprising 22% of the total river network (Figure 7C). The rest of the river network is shared by the river size classes of '<10' km² (0.01%), '500-1 000' km² (6%), '1 000-4 000' km² (7%), '4 000-10 000' km² (3%), and '>10 000' km² (0.01%).

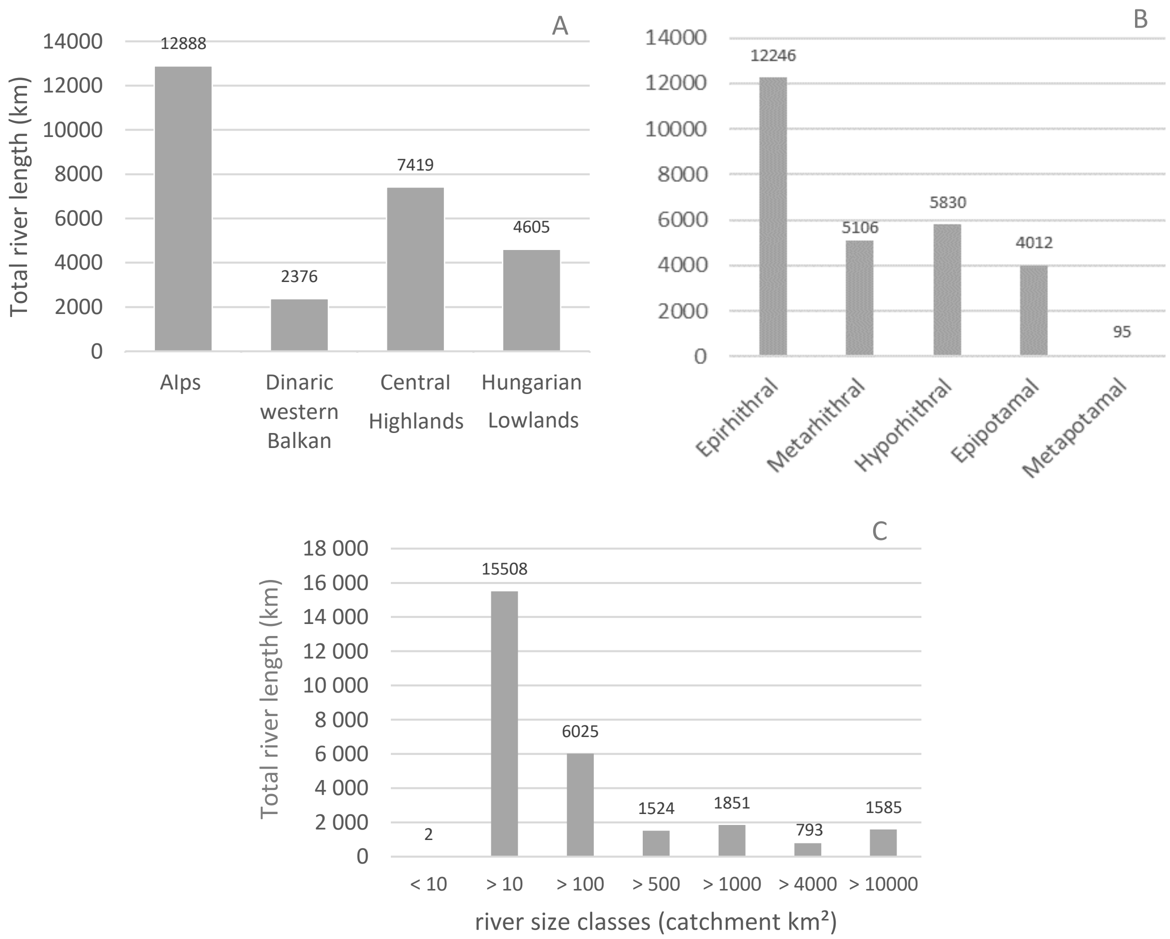

Figure 7: Overview of the total river length (km) in different ecoregions (A), fish regions (B) and river size classes (C) (RBMP; BMLFUW 2015).

Artificial and natural barriers in fish regions were included in the analyses, resulting in a total number of 60 253 barriers. The ecoregion 'Alps' has the highest number of barriers (40 538) and accounts for 67% of the total barrier number in Austria, followed by the 'Central Highlands' with 15%, the 'Dinaric western Balkan' (10%), and the 'Hungarian Lowlands' (8%; Figure 8A). Among fish regions, the epirhithral has the highest number of barriers with 42 064, constituting 70% of all barriers in Austria. The metarhithral represents the second highest amount of barriers at 14%. The rest of the barriers occur in the hyporhithral, constituting 11%, the epipotamal (5%) and metapotamal (0.01%; Figure 8B). Creeks with a 10-100 km² catchment area contain 45 706 barriers, representing 76% of all barriers among the different river size classes. The remaining barriers are located in the river size classes of '<10' km² (0.02%), '100-500' km² (18%), '500-1 000' km² (3%), '1 000-4 000' km² (2%), '4 000-10 000' km² (0.4%), and '>10 000' km² (1%; Figure 8C).

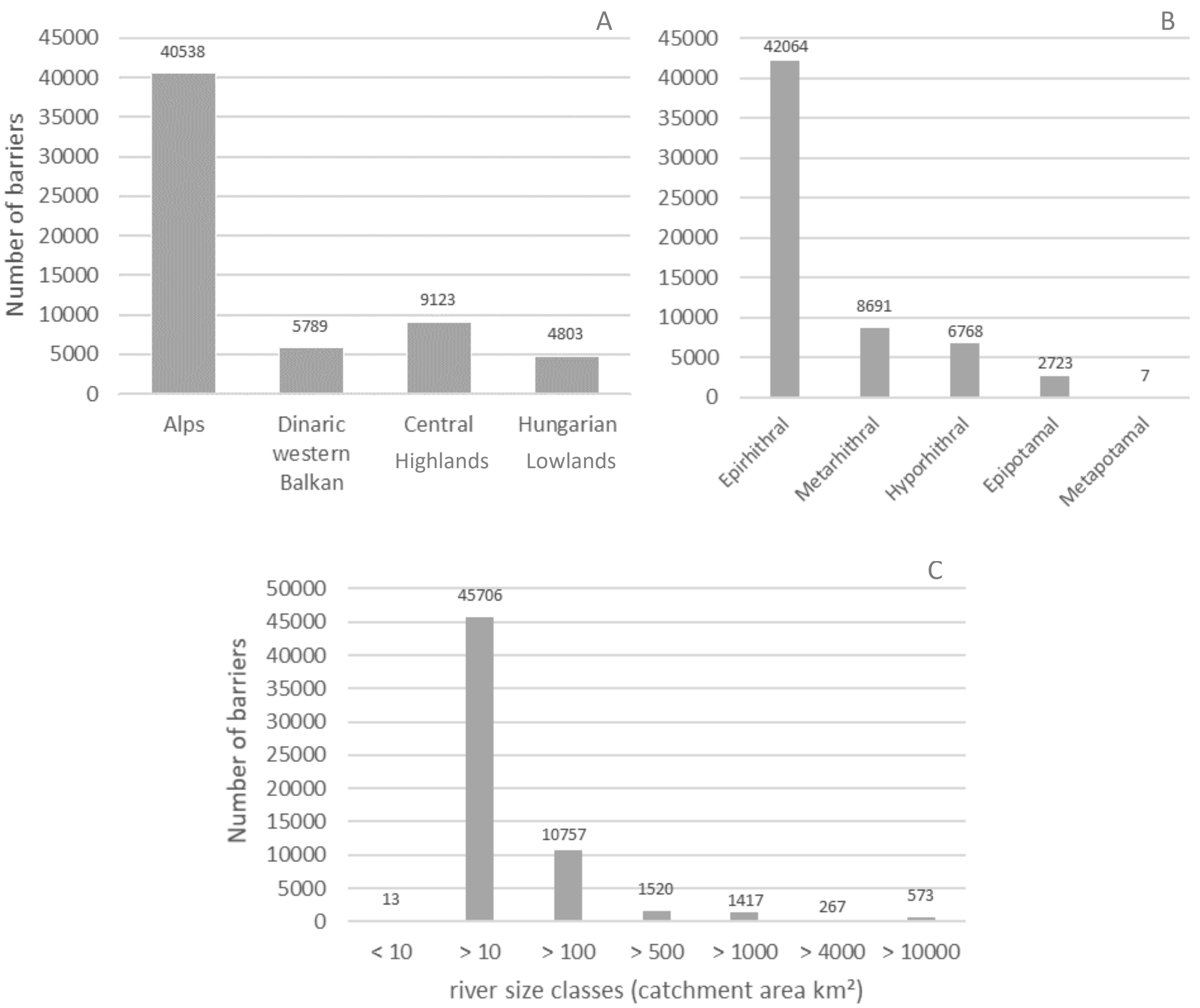

Figure 8: Number of barriers in different ecoregions (A), fish regions(B), and river size classes (C) (RBMP; BMLFUW 2015).

3.2 FRAGMENTATION METRICS

To assess river fragmentation in Austria and identify patterns in different ecoregions, fish regions, and river size classes, shapefiles provided by (BMLFUW, 2015) were analyzed in ArcGIS (chapter 2.6.1). The river network was divided into single river reaches, for which, in the next step, fragmentation metrics were calculated. Since the main focus is set on the impact of river fragmentation on fish assemblages, this study only considers water bodies located in the distribution area of fish.

Pre-selection of fragmentation metrics

According to Cooper et al. (2017), the calculation of river fragmentation resulted in 19 metrics. Table 6 provides an overview of these metrics, including a brief description and an indication, if they were selected for this thesis.

Table 6: Description (obtained from Cooper et al., 2017) and selection criteria of fragmentation metrics applied in this thesis.

	Fragmentation metrics	Description	Application	Selection criteria
1	**UpMainCnt**	Number of barriers upstream along the mainstem (= longest path upstream)	No	The barrier count continuously increases with increasing distance to the source and is, therefore, no expressive metric.
2	**UpNetCnt**	Number of barriers upstream along all paths.	No	Same selection criteria as **1.**
3	**UpMain2Dam**	Distance along the upstream mainstem to the first dam.	No	According to the calculations, if a dam separates a river into sub-river reach, the distance to the next barrier is zero. Due to a high number of barriers in Austria, the distance between barriers was largely 0 m; therefore, this metric is not representable and does not show the real distance between barriers.
4	**UpMainDist**	Distance along the upstream mainstem to the headwaters. (Dam locations do not affect this calculation).	No	Is needed for the calculation of UpMainDens, UpMainOpen, TotalMain2Dam, TotalMainDist, and TotalMainDens.
5	**DownMainCnt**	Number of barriers along the downstream mainstem.	No	The barrier count continuously increases with increasing distance to the outlet, and therefore, no expressive metric.
6	**DownMain2Dam**	Distance along the downstream mainstem to the first dam.	No	Same selection criteria as **3.**
7	**DownMainDist**	The distance to the coastline.	No	Is needed for the calculation of DownMainDens and DownMainOpen, TotalMain2Dam, TotalMainDist, TotalMainDens.
8	**UpMainDens**	Barrier density along the upstream mainstem	No	This metric is restricted to the mainstem. Concerning that fish often migrate into tributaries, this metric will not be considered for the analyses.
9	**UpMainOpen**	Percentage of free-flowing river section of the total upstream mainstem)	No	Same selection criteria as **8**.
10	**DownMainDens**	Barrier density along the downstream mainstem	**Yes**	Fish migrate downstream. Therefore, this metric will be considered in the analyses.
11	**DownMainOpen**	Percentage of free-flowing river section of the total downstream mainstem	No	Same selection criteria as **8.**
12	**TotalMainCnt**	Barrier count along the total mainstem (up- and downstream)	No	The single river reaches refers to the same mainstem, consisting of the same barrier number; therefore, no clear differentiation between the single river reaches, the ecoregions, fish regions and river size classes can be done.
13	**TotalMainDens**	Barrier density along the total mainstem (up- and downstream)	No	Same selection criteria as **12**.
14	**TotalMain2Dam**	Total distance between barriers along the mainstem (up- and downstream)	No	Same selection criteria as **3.**
15	**TotalMainDist**	Total distance along the mainstem (up- and downstream)	No	Is needed for the calculation of TotalMainOpen.
16	**TotalMainOpen**	Total openness along the mainstem (percentage of free-flowing river sections)	No	Same selection criteria as **8** & **12.**
17	**UpNetDens**	Barrier density per river reach along the upstream river network	**Yes**	An important metric for assessing fish because it represents the barrier density upstream of the whole river network (incl. tributaries) and the cumulative effects.
18	**TotalSegLength**	Total segment river length	**Yes**	An important metric illustrating the total free-flowing river length of a river network isolated by barriers. It is crucial for the impact analyses on fish.
19	**SegArea**	Catchment area on segment level	**Yes**	Shows the catchment area bounded by barriers. An important factor in explaining the sediment and nutrition input.

Four fragmentation metrics in Table 6 were chosen for further analyses: DownMainDens, UpNetDens, TotalSegLength, and SegArea. A Spearman rank correlation test was applied to test for redundancies between the four metrics (explained in chapter 2.8). None of the four metrics showed a significant correlation (Spearman's r >0.7; Schinegger et al., 2013), and therefore, they all were considered for further statistical analyses.

Distribution and patterns of fragmentation metrics

Barrier density upstream of the river network

Around 51% of the river network is affected by a barrier density of more than ten barriers per 10 kilometers upstream the river network. In contrast, only 15% of the river network shows no barriers upstream. The map in Figure 9 visualizes the barrier density in Austria. The Federal State of Carinthia shows the longest distance with no barriers upstream along the river network, rather Styria represents the highest barrier density upstream.

The 'Alps' ecoregion has the highest share of river length with no barriers upstream, but also the highest percentage of river length with >200 barriers/10 km (1.3%) compared to the other ecoregions. The 'Dinaric Western Balkan' represents the smallest ecoregion in Austria but has the highest share of river length with a barrier density ranging from 50-200 per 10 km, representing 18.9% of the ecoregion's total river length. The 'Central Highlands' and 'Hungarian Lowlands' ecoregions are dominated by the density classes 0-10 and 10-25 barriers per 10 km (Figure 9A).

The epirhithral fish region, which is primarily coincides with to the 'Alps' ecoregion, has the highest percentage of stream length with no barriers upstream (25%) but also represents the highest length of river network with barrier densities >200 barriers/10 km compared to the other fish regions. About 65% of the epipotamal region has an upstream barrier density of more than 10 barriers/10 km. The metarhithral fish region has the longest river distance with more than 25 barriers /10 km in the upstream river network. Hence, the metarhithral and epipotamal regions have the highest upstream barrier densities compared to the other fish regions. Generally, the amount of river length with barrier densities of 10-25 per 10 km increases from up- to downstream, subsequently the amount of river network with zero upstream barriers decreases from the rhithral to potamal regions (Figure 9B).

For river size classes, the same pattern observed for the 'Alps' and the epirhithral region applied to rivers with catchment areas ranging from 10-100 km², which consisted of the highest percentage of river length with no barrier upstream (21%), however also had the most river length with more than 200 barriers/10 km. In general, larger rivers have higher barrier densities in the upstream river network compared to smaller size classes. A significant shift in barrier density occurs for rivers with a catchment area >4 000 km², where river length with an upstream barrier density of 10-25 per 10 km is almost double that compared to smaller rivers (Figure 9C).

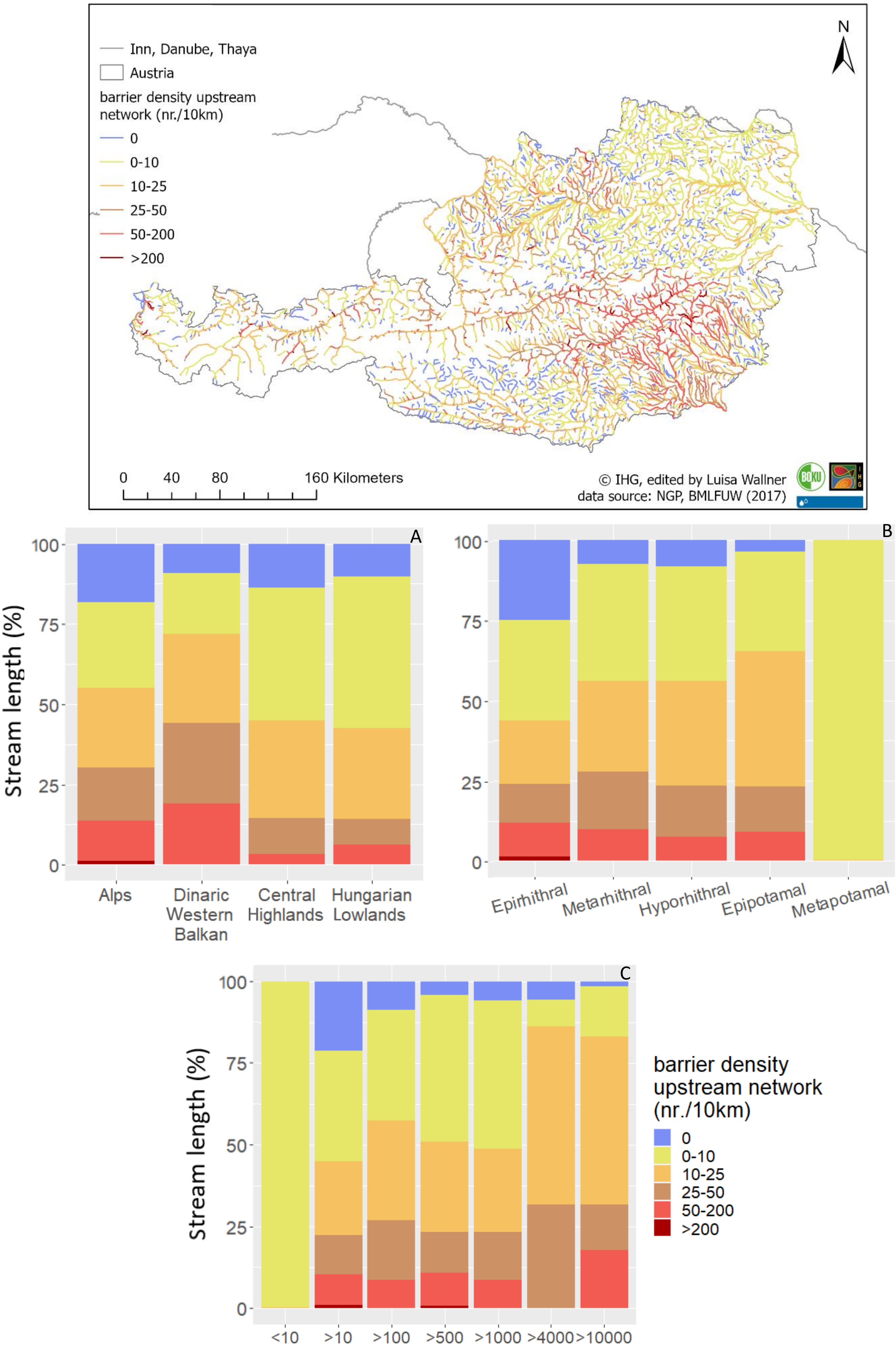

Figure 9: Distribution of barrier density upstream across the Austrian river network (map on top). The single stacked bar charts show the percentage of stream length within each density class by different ecoregions (A), fish regions (B), and stream size classes (catchment area in km²; C). Class breaks were established according to natural breaks.

Barrier density downstream along the mainstem

The most abundant barrier density class downstream along the mainstem is 0-5 per 10 km, covering 77% of the total river network of Austria.

The map of Austria (Figure 10) shows the distribution of barrier density classes downstream along the mainstem. It highlights particularly high barrier density in Styria compared to the rest of Austria. Differences in barrier density between the environmental regions can be observed too. The ecoregion ‘Central Highlands’ shows the lowest barrier density with 0-5 barriers/10 km downstream along the mainstem, covering 96% of the total river length. In comparison, the ‘Dinaric Western Balkan’ shows the highest barrier density downstream, with significant length of river with >5 barriers per 10 km, particularly >25 barrier per 10 km (Figure 10A).

Across the fish regions, decreasing barrier density downstream along the river mainstem from rhithral to potamal regions can be observed. Accordingly, the epirhithral comprises the highest barrier density downstream and the metapotamal the lowest (Figure 10B).

Rivers with a catchment area of 100-500 km² have the highest share of river length with >10 barriers per 10 km (12%) downstream. In contrast, large rivers (>10 000 km²) comprise the lowest barrier density along the downstream mainstem (Figure 10C).

Generally, patterns in barrier density up- and downstream across the ecoregions, fish regions, and river size classes can be observed, whereas the ‘Dinaric Western Balkan’ is most severely affected by river fragmentation.

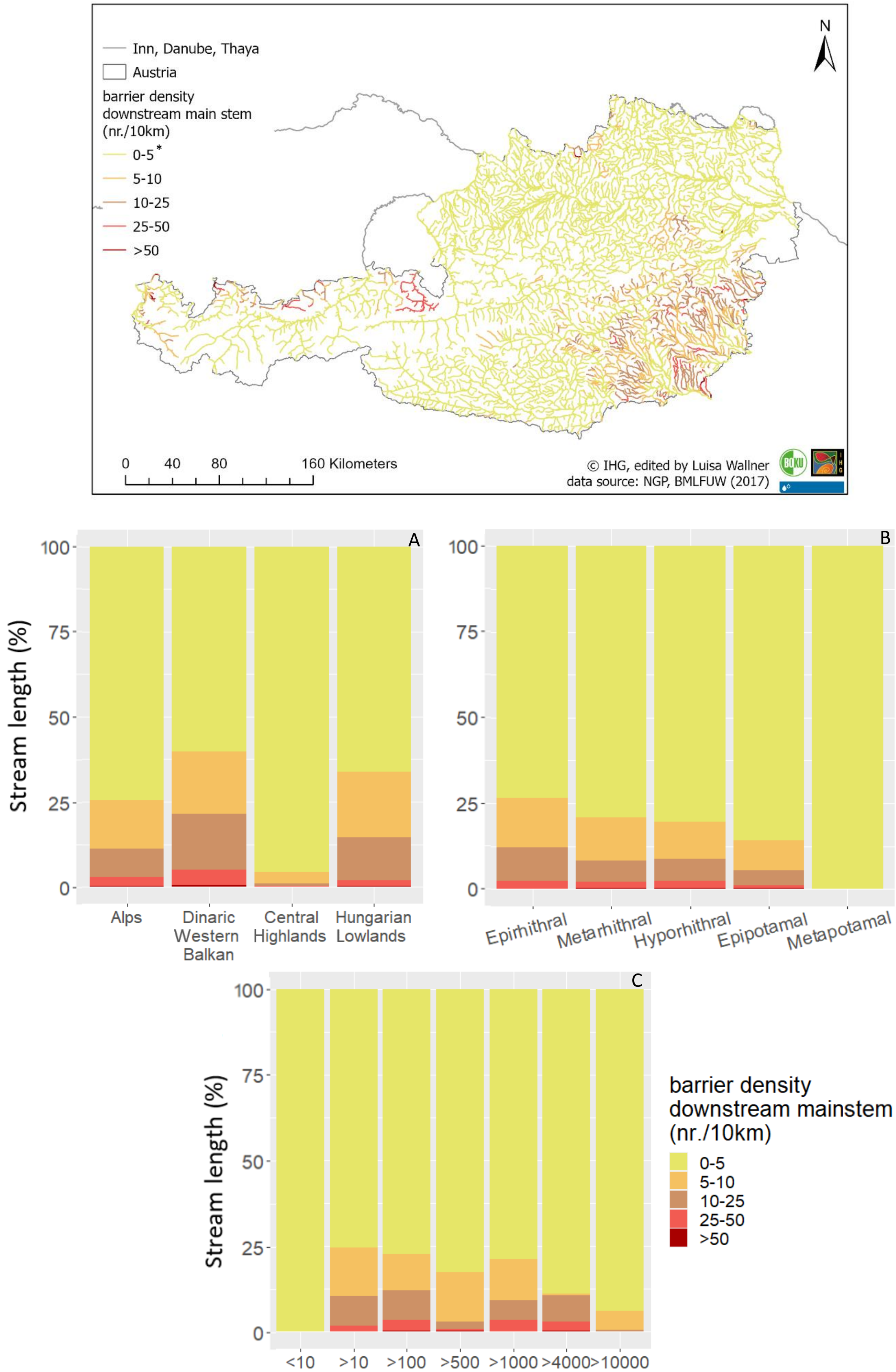

*Figure 10: Distribution of barrier density downstream along the mainstem (nr./10 km) across the Austrian river network (map on top). The single stacked bar charts show the percent of stream length within each density class by the different ecoregions (A), fish regions (B), and stream size classes (catchment area in km²; C). Class breaks were established according to natural breaks. *The density class '0' was excluded since no river reaches without barriers downstream exist.*

Total segment length

The fragmentation metric 'total segment length' represents a 'free-flowing' river stretches, which are bounded by barriers locations (explained in chapter 2.6.2).

Around 40% of the Austrian river network is characterized by a segment length between 0-2 km, and only 7% of segments have a length of more than 60 km. The river network of Carinthia mainly consists of segment lengths >15 km. On the contrary, the river network of Styria consists mainly of river segments <2 km (Figure 11).

Around 45% of the river network in the ecoregions 'Alps' and 'Dinaric Western Balkan' have a segment length of 0-2 km, whereas the 'Dinaric Western Balkan' is characterized by more river stretches with >5 km segment length compared to the 'Alps'. The 'Hungarian Lowlands' comprises the highest share of river stretches >15 km, representing 22% of its entire river network. Further, 11% of rivers have a segment length of >60 km. Generally, an increase in segment length can be observed from the 'Alpine' ecoregion to the high-/lowlands (Central Highlands, Hungarian Lowlands; Figure 11A).

Similar to the trends among ecoregions, a continuous increase in the percentage of longer segments from rhithral to potamal can be observed. Over 50% of the total river length in the epirhithral comprises a segment length of 0-2 km, and only 0.9% is longer than 60 km. In contrast, 22% of the epipotamal has a segment length >60 km. Moreover, 91% of the 95 km long metapotamal show a segment length of >60 km.

The continuous increase in segment length also applies to the river size classes. Small rivers show shorter river segments compared to large rivers. Accordingly, 49% of creeks (10-100 km^2) have a segment length between 0-2 km, whereas less than 10% of large rivers (>4 000 km^2) show such short distances. Another significant increase in segment lengths >5 km, from 54% to 82%, can be observed between medium- and large-sized rivers with catchment areas of 500-4 000 and >4 000 km^2.

Further information like the mean and median values as well as the standard deviation of segment length in the single ecoregions, fish regions and river size classes can be found in the supplementary material (Table 9), highlighting a 965-fold increase in the number of segments due to barrier construction compared to conditions without barriers, and an overall decrease in mean segment length from 7 121.25 km to 3.63 km. The mean segment length with the existence of barrieres increased three times from creeks to medium-sized rivers and from epirhithral to hyporhithral, respectively. Moreover, the mean segment length with the existence of barriers increased thirteen times from creeks to large rivers, and from epirhithral to epipotamal fish regions, respectively.

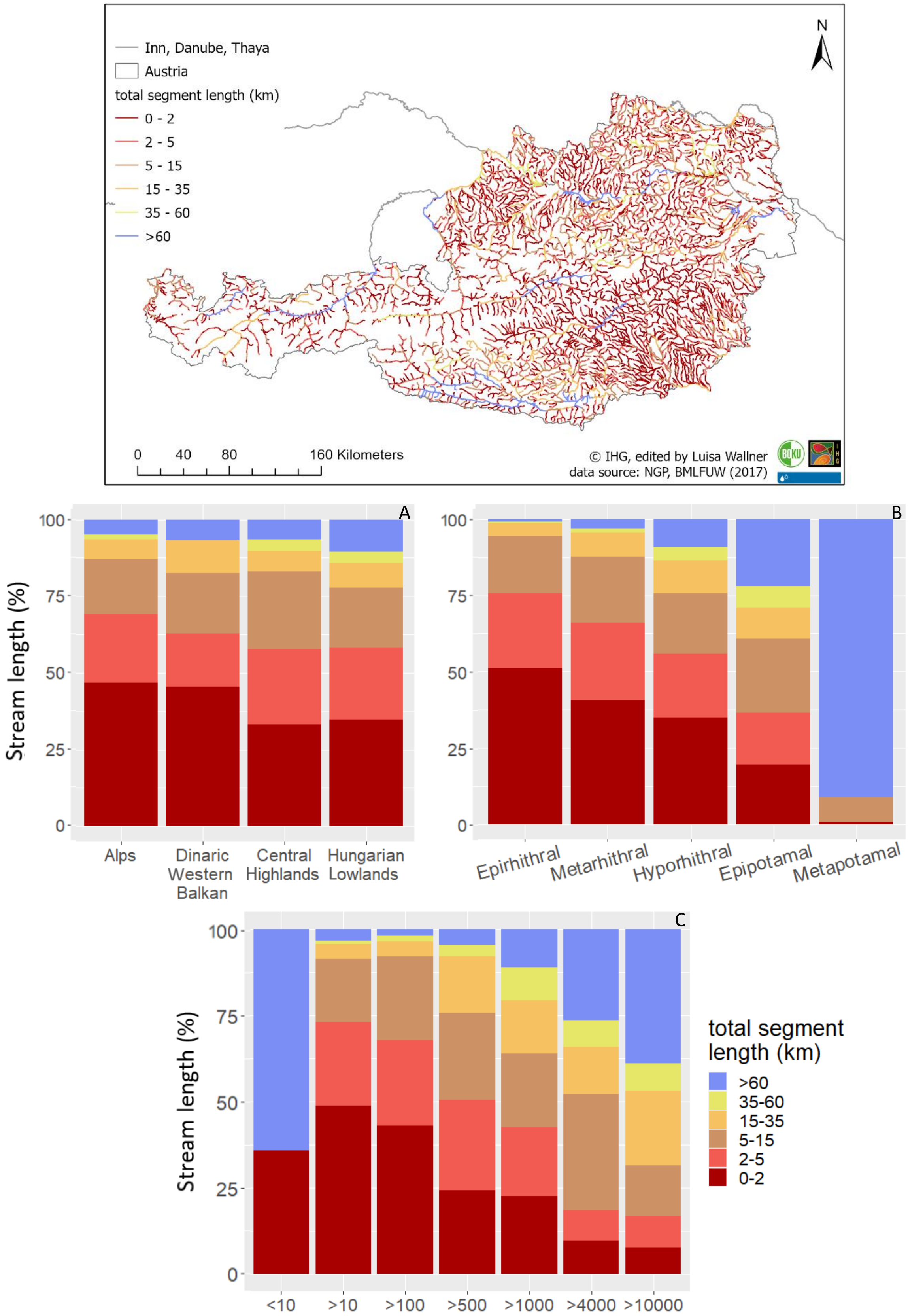

Figure 11: Distribution of total segment length (free-flowing stream length in km) across the Austrian river network (map on top). The single stacked bar charts show the percent of stream length within each total segment length class (km) by the different ecoregions (A), fish regions (B) and stream size classes (catchment area in km²; C). Class breaks were established according to natural breaks.

Segment catchment area

The segment catchments were established in ArcGIS by the use of the Austrian digital elevation model and the river network (chapter 2.6.2). Based on the presence of barriers, catchments were divided into sub-catchments according to barrier locations (Figure 12B). For comparison, Figure 12A shows segment catchments without barriers, showing unobstructed river basins in the absence of barriers. Also, for this analysis, the segment catchments were established for the river network belonging to fish regions.

Figure 12 shows the significant decrease in the catchment area due to barriers. Without barriers, about 98% of the river catchments represent an area of >150 km². The remaining 2% consisting of small catchments mainly result from the river network's end at the Austria border, where the river catchment delineation ended based on the extent of Austrian digital elevation model. Therefore, most of the small catchments would be larger if the river network were to extend beyond the Austrian border. With the presence of barriers, 85% of catchments significantly decreased to 0-5 km², and only 2% remained with an area >150 km². Due to barriers, the mean catchment area decreased from 18 494 km² to 8 km² (Table 10).

Across the federal states of Austria, Styria has the highest share of river catchments with 0-5 km² catchment area size range. On the contrary, Carinthia mainly comprises large catchments (>15 km²).

Differences in the catchment area between the environmental regions with the existence of barriers are shown in Table 10 as part of the Appendix. A significant increase in the mean catchment area from the 'Alps' ecoregion to the lowlands can be observed. Moreover, the mean catchment area doubles from the 'Alps' to the 'Central Highlands' and even increases five times compared to the 'Hungarian Lowlands'. The same pattern applies to the fish regions, where the mean catchment area increased from 3 km² in the epirhithral to 16 km² in the hyporhithral and 49 km² in the epipotamal. In terms of river size classes, the smallest mean catchment area is represented in medium-sized rivers (100-500 km²), and the largest mean catchment area can be observed in large rivers (>4 000 km²; Table 10).

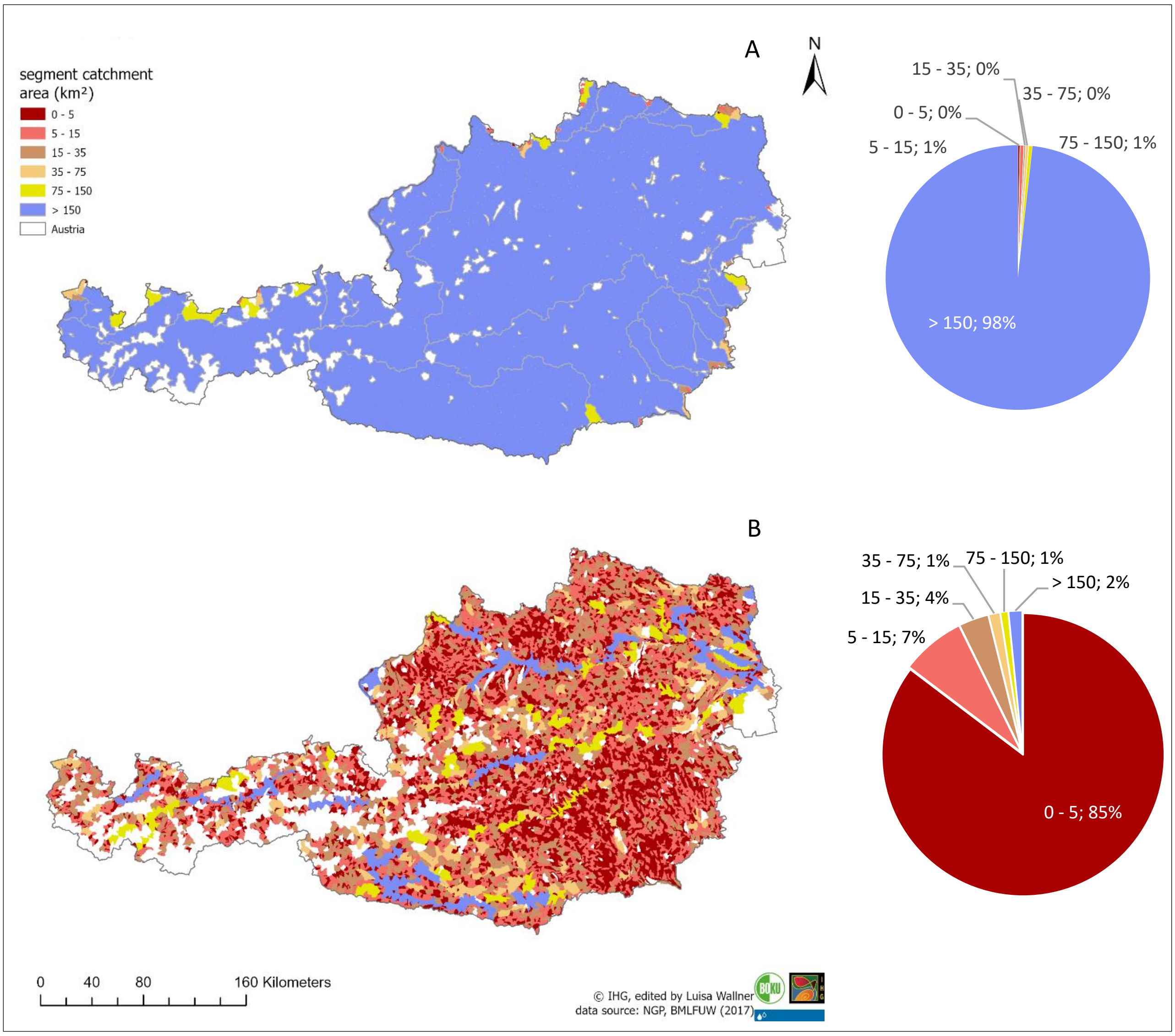

Figure 12: The size of segment catchment area in fish regions (km²) without barriers (A - top) and with the existence of barriers (B - bottom). The classification of the catchment area follows natural breaks. The pie chart shows the relative number of segment catchment areas by size classes.

3.3 IMPACT OF RIVER FRAGMENTATION ON FISH ASSEMBLAGES

The next step aimed to assess the correlation between the fragmentation metrics described above and fish assemblage metrics (chapter 2.7 & 2.8).

Surprisingly, the results show only small signals between fragmentation and fish metrics (Table 7). Figure 14 in the Appendix shows the response of the single fish metrics to fragmentation metrics more precisely. In addition to the Spearman rank correlation test, further investigations through descriptive statistics and visual observations with boxplots were conducted. Also, boosted regression trees were calculated to find potential responses of fish metrics to fragmentation metrics in different ecoregions, fish regions and river size classes. However, none of these analyses showed clear patterns.

Table 7: Spearman rank correlation (rho-value) with p-value conducted for fish metrics (FIA, age structure, biomass, status of reproductive guilds, and habitat guilds) and fragmentation metrics.

	UpNetDens		**DownMainDens**		**TotalSegLength**		**TotalSegArea**	
	rho-value	**p-value**	**rho-value**	**p-value**	**rho-value**	**p-value**	**rho-value**	**p-value**
FIA	-0.04	0.11	-0.11	0.00	0.13	0.00	0.10	0.00
Age structure	-0.02	0.39	-0.13	0.00	0.11	0.00	0.09	0.00
Biomass (kg/ha)	0.09	0.00	0.03	0.34	-0.08	0.00	-0.08	0.00
Status of reproductive guild	-0.12	0.00	-0.26	0.00	0.21	0.00	0.16	0.00
Status of habitat guild	-0.03	0.21	-0.14	0.00	0.15	0.00	0.13	0.00

3.4 IMPACT OF STRESSORS ON FISH ASSEMBLAGES

In my dataset river fragmentation metrics did not exhibit a strong effect on fish metrics. However, the negative effects of barriers are clearly described in the literature. Therefore, the impact of additional stressors was analyzed to identify other potential factors that might influence applied models and tests. To this end, the effect of river morphology, impoundments, residual flows, hydropeaking, and water quality alteration on fish assemblages was considered in addition to river fragmentation. Single stressors were summarized into counts and specific stressor combinations, according to Schinegger et al. (2018).

Even though Spearman's rank correlation test resulted only in weak correlations between the number of stressors and the fish metrics (Table 8), the detailed analyses for the FIA, age structure, and biomass via boxplots did reveal a response of fish assemblages to stressors (Figure 13).

Table 8: Spearman rank correlation calculated for fish metrics and the number of stressors. The outcome of the correlation shows the rho-value and p-value.

	N stressor	
	rho-value	**p-value**
FIA	0.13	0.00
Age structure	0.10	0.00
Biomass (kg/ha)	0.04	0.17
Status reproductive guild	0.15	0.00
Status habitat guild	0.12	0.00

In Figure 13, the impact of the ‘number of stressors’ and ‘combinations’ on the FIA were separately analyzed for headwaters (i.e., epirhithral, metarhithral) and lowland rivers (i.e., hyporhithral, epipotamal, metapotamal).

Generally, the FIA shows higher (i.e., more impacted) values in the lowland rivers than headwaters. Furthermore, the FIA worsens with increasing number of stressors, notwithstanding river stretches facing four stressors, where the FIA recovers again. Especially in headwaters, the FIA shows evidence of a difference between the single stressor numbers and the stressor combinations. In the lowland rivers, the FIA shows weak evidence of differing between increasing stressor number, and moderate evidence of differences between the stressor combinations. However, there are contradictory response to FIA and stressor combinations in headwaters and lowlands. In particular, ‘stressor combination’, which has the lowest impact in headwaters, shows the strongest influence in lowland rivers and vice versa. This applies to the single stressors of B and C, to BC, MC, RBM and IBM.

The age structure and biomass show nearly identical responses to the ’number of stressors’ and ‘stressor combination’ as the FIA and are, therefore, not shown.

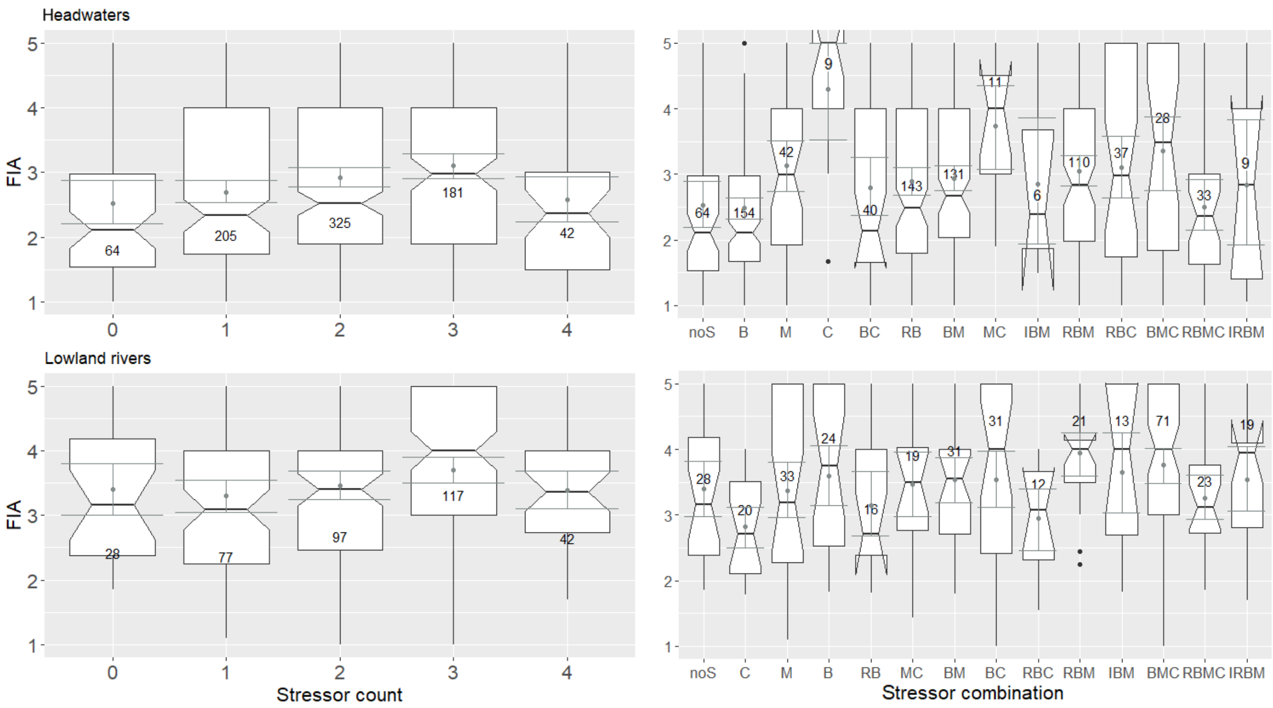

Figure 13: Response of FIA to stressor metrics at the fish sampling sites in the headwaters (N = 817) and the lowland rivers (N = 361); stressor combinations consist of: water quality (C), morphological alteration (M), connectivity disruption (B), residual flow (R), and impoundment (I). The line diagram (grey) shows the confidence interval of barrier density with a probability of 95% and the mean.

4 DISCUSSION

This thesis investigates the fragmentation of the Austrian river network due to barriers across different ecoregions, fish regions, and river size classes and analyzes related impact on fish assemblages. The first goal was to adopt a method developed in the United States by Cooper et al. (2017) for the Austrian context, resulting in the calculation of 19 fragmentation metrics.

The second goal was to assess the fragmentation of Austria's river network across ecoregions, fish regions and river size classes. The third goal was to evaluate if the impact of river fragmentation on fish assemblages can be explained in a multi-stressor environment.

This study establishes an overview of the state of river fragmentation in Austria and its extent over different environmental regions. Thereby, this thesis findings can support to understand connectivity problems and derive restoration measures pertaining to the numerous barriers that exist in Austria.

4.1 ADAPTATION OF THE RIVER FRAGMENTATION CALCULATION AFTER COOPER ET AL. (2017) FOR THE AUSTRIAN RIVER NETWORK

Four of the 19 fragmentation metrics proposed for the United States (Cooper et al., 2017) made sense to adopt for the Austrian case study based on study objectives.

Most of the metrics could not be properly applied because the metrics were either only used to calculate further fragmentation metrics or were not expressive enough to explain the impact on fish assemblages, such as the barrier distance, where the calculation procedure was not suitable for high barrier densities. While Cooper et al. (2017) did not consider all barriers in the USA (only large dams were analyzed, as further information was not available at that stage), this thesis analyzed a comprehensive dataset for Austria, including all kinds of barriers. Accordingly, many more barriers were included in the current analyses, and conflicted with the calculation procedure of Cooper et al. (2017). The metric ‘barrier distance’ is set to zero if the up- or downstream node of the river reaches is confined by a barrier. Due to the high number of barriers in Austria (approximately one barrier per river kilometer), reach-based distances to barriers often were zero. Therefore, this metric was not a useful representation of the barrier distance.

Furthermore, the barrier counts upstream along the mainstem and river network was not expressive enough to explain the precise local impact of barrier on fish assemblages as it continuously increases with increasing distance to the source and vice versa (e.g. barrier count downstream along the mainstem). Hence, this metric is not able to represent the individual state of river reaches, such as barrier density and its effect on fish assemblages. Additionally, all fragmentation metrics restricted to the mainstem are not expressive enough to explain the impact on migrating fish, since fish disperse along the whole river network and stressors of all barriers (incl. barriers in tributaries) act cumulative on downstream sections. For this reason, the barrier density upstream of the river network was used. Nevertheless, barrier density downstream along the mainstem was also considered, as fish migrate in up- and downstream direction, and barriers directly impact the downstream mainstem habitat availability. Furthermore, Cooper et al. (2017) used some fragmentation metrics in combination with other factors (e.g., reservoir storage capacity). Hence, he was able to calculate the degree of regulation. If the data on reservoir storage capacity had been available for the barriers in Austria, more metrics could have been used for the analyses.

In the end, the remaining metrics (UpNetDens, DownMainDens, TotalSegLength, SegArea) were deemed suitable for the current study as they reflect the local condition of river fragmentation for each river reach and are representative of explaining the impact on fish assemblages.

4.2 DISTRIBUTION AND PATTERNS OF FRAGMENTATION METRICS ACROSS ECOREGIONS, FISH REGIONS AND RIVER SIZE CLASSES

This thesis affirms a significant difference in the extent of river fragmentation across ecoregions, fish regions and river size classes in Austria. Even though the ‘Alps’ contains the highest share of river length without barriers upstream, this ecoregion generally shows a high barrier density. Particularly, the ‘Dinaric Western Balkan’ ecoregion exhibits the highest barrier density up- and downstream of all ecoregions. The main reason for this high share of river length with no barriers in the upstream river network in the ‘Alps’ ecoregion is that the source of these river is mainly in a mountainous region. Accordingly, the calculations of barrier density upstream of the river network start counting at the source, respectively the epirhithral fish region or creeks (10-100 km²). However, the mountainous region shows a high barrier density and, accordingly, short river segments and small catchment areas, which is confirmed by various studies (Angarita et al., 2018; Lehner et al.,2005; Parasiewicz et al., 2022). It can be explained by a favored barrier construction in the mountainous region because of its geology, topography, river flow and storage capacity of impoundments (Hoenke et al., 2014). Beside hydropower production, barriers are commonly built in mountain regions for flood protection and torrent control (Nõges et al., 2016). These results align with the studies of Parasiewicz et al. (2022) and Lehner et al. (2005), which show that barrier density and habitat loss are more significant in mountainous regions than in the lowlands.

Beside the epirhithral fish region, the metarhithral, hyporhithral, and epipotamal regions also have high barrier densities. They are mainly represented in the 'Dinaric Western Balkan', which is highly fragmented. Furthermore, the main rivers, such as the Inn, Salzach, Traun, Enns, Mur, Drau, Danube, and March, are located in the hyporhithral and epipotamal fish zones, represented by the river size classes of '4 000-10 000' and '>10 000' km², and similarly have high barrier densities. Compared to tributaries, Cooper et al. (2017) and Grill et al. (2017) described higher barrier density in main rivers. This pattern may be related to flow regulation to support shipping, flood control, and land reclamation for agricultural use, industrial production, and domestic needs. All the aforementioned uses are frequently associated with large valleys in which main rivers flow, supporting higher settlement rates than smaller valleys. Moreover, large rivers are more favorable for energy production compared to small tributaries as they have higher discharge and storage capacity (Grill et al., 2017; Haidvogl, 2018).

In addition to differences in river fragmentation between the mountainous region and lowlands, as well as tributaries and main rivers, a clear pattern of fragmentation between the federal states in Austria can be seen. According to the data analyses, the most fragmented federal state of Austria is Styria. It has the highest barrier density up- and downstream and has the highest share of short river segments and catchment areas. Compared to Styria, the neighboring province Carinthia comprises the lowest barrier density and the highest percentage of long river segments and large catchment areas. Vorarlberg, Tyrol, Salzburg and Upper Austria show an almost homogenous distribution of the classes of river fragmentation, whereas Lower Austria mainly consists of the same barrier density class. Barrier density of Vienna was not representative due to its low number of rivers. Fragmentation metrics may differ because some federal states are more covered by mountains than others, so the barrier density is higher. Furthermore, the different distribution of fragmentation metrics indicates an inconsistent quality/degree of detail in data collection. For example, Styria shows a high barrier density due to precise observations of barrier locations compared to other federal states. The inconsistent barrier data collection between Austria's federal states also might influence the varying patterns of river fragmentation across ecoregions, fish regions, and river size classes. Especially the high barrier density in the ecoregion ‘Dinaric Western Balkan’ might be due to more precise data collection in Styria and the highly fragmented main river Mur.

4.3 RESPONSE OF FISH ASSEMBLAGES TO RIVER FRAGMENTATION

Even though disruption of the river continuum is seen as one of the key threats to fish, in this thesis, river fragmentation showed hardly any effect on fish assemblages. These results do not mean that fragmentation has no effect on Austrian fish assemblages, but that the effects of fragmentation on fish are too complex to illustrate with these metrics and/or spatial resolution. Hence, the results underline the high complexity of river ecosystems and highlight the need to consider more factors to explain the impact of river fragmentation on fish assemblages.

A reason for these results could be Austria's highly fragmented river network with a small number of reference sites, which are needed to make a reliable comparison to impacted areas. Even if some references with free-flowing river sections exist, they cannot be automatically considered 'reference sites' as they can be influenced by other stressors, such as hydro-morphological, physicochemical and chemical stressors (Schinegger et al., 2016).

Another explanation for why the fragmentation metrics do hardly explain the impact on fish assemblages is the lack of the construction date of barriers. Less than 1% of the barriers had information on the construction date, which is important, since the time period between the appearance of stressor and effect on fish assemblages is essential to thoroughly analyze the impact on fish assemblages (Fuller et al., 2015; Montgomery, 2000).

Furthermore, in this study, all barriers, including natural and artificial, as well as small and large barriers, were used to calculate river fragmentation metrics. The consideration of barrier height could make a significant difference in the impact of river fragmentation on fish assemblages. While large barriers may act as a complete barrier, the permeability of small obstacles depends on discharge. Small barriers may be passable during high flow, whereas during low flow, even small barriers may fragment the river channel. As a consequence, the permeability of barriers greatly changes between storm events, from wet to dry season/year, climate change, and water withdrawals (Fuller et al., 2015). Therefore, the height of barriers and the discharge in response to environmental events should be considered for further investigation.

Moreover, information on barrier location is crucial for the assessment of impacts on fish assemblages. Barriers further downstream disconnect the whole river network upstream, while barriers in upstream river sections disrupt only small proportions (Cote et al., 2009). In particular, barrier location differently impacts potamodromous and diadromous fish species. Diadromous fish species are more affected by barriers in close proximity to the river mouth, whereas barriers further upstream have higher impact on potamodromous fish species (Duarte et al., 2021). Moreover, the connection within a river network is crucial for migratory fish species to fulfill their life cycle (Benejam et al., 2016). Therefore, it is recommended to evaluate the impact of barriers upstream differently from barriers in downstream sections (Cote et al., 2009).

Besides the long-term effect of barriers on fish assemblages, reintroduction of fish is also carried out in disconnected river sites, where fish no longer recover (Van Puijenbroek et al., 2019). Hence, stocking and reintroducing fish species may lead to contrary and manipulated state of fish populations, which the evaluation of the impact of river fragmentation on fish assemblages must consider.

Also, further studies have been unable to observe the effects of fragmentation on fish assemblages. (Branco et al., 2012; Fuller et al., 2015; Mahlum et al., 2014; Tonkin et al., 2014). Even though river fragmentation is supposed to be a primary driver of population loss, it is probably the outcome of interactions with other factors rather than the individual effect of fragmentation (Fuller et al., 2015). Therefore, different stressors such as river morphology, residual flow, impoundments, hydropeaking and water chemistry alteration, often resulting from the operational modes of barriers, were further considered in this thesis to detect effects on fish assemblages.

4.4 RESPONSE OF FISH ASSEMBLAGES TO ADDITIONAL STRESSORS

With the aid of stressor factors described by Schinegger et al. (2018), i.e. the number and combination of additional stressors (residual flow, impoundment, disruption of river continuum, hydropeaking, river morphology, and water chemistry), a trend in the change of fish assemblages could be observed. Even though the Spearman rank correlation test resulted in low correlations between fragmentation metrics and fish metrics as well as additional stressors and fish metrics, further detailed analyses on the impact of additional stressors on fish assemblages, such as boxplots, showed a trend compared to the fragmentation metrics.

According to Figure 13, the resulting effects on the Fish Index Austria in lowland rivers is more evident than in the headwaters, which means that the existence of stressors shows a stronger negative impact on FIA in lowland rivers than in the headwaters (Hering et al., 2006; Schmutz et al., 2015b). Nevertheless, due to the low number of observations for lowland rivers, results should be interpreted cautiously. However, the results for lowlands are logical for several reasons. First, it has been observed that headwaters are less impacted by stressors than lowland rivers (Trautwein et al., 2013). Even though hydro-morphological pressures are more dominant in mountainous regions and multiple stressors are more present in lowland rivers, river sites in higher elevations are often less affected by morphological alteration. The reason is that headwaters are more constrained due to their origin in the river network and therefore are not as severely affected by morphological alteration and accordingly show a lower impact on fish assemblages. On the contrary, lowland rivers are often braiding and meandering. If they are straightened due to agricultural and urban land use, it causes a higher impact on river morphology (Schinegger et al., 2018).

Furthermore, the operation mode and type of barriers differ between headwaters and lowland rivers, which can significantly impact fish assemblages, too. The height, storage capacity and hydropower generation increase from headwaters to lowland rivers (Jager et al., 2015). Moreover, barriers and their associated stressors act in a cumulative manner along the downstream river sections, as barriers' effects extend, and are noticeable very far downstream (Schmidt & Wilcock, 2008).

Besides the fact that lowland rivers are more affected by stressors than headwaters (Schinegger et al., 2018), which in turn influence the corresponding fish populations, in this thesis, the impact of some single and multiple stressor combinations on the FIA differ significantly between the headwaters and lowland rivers. Water quality as a single stressor affects FIA more in headwaters than in lowland rivers, whereas continuum disruption highly impacts the FIA in lowland rivers. This trend also applies to water quality and continuum disruption in combination with other stressors (e.g., BC, MC, RBM, and IBM). Concerning the impact of water quality in headwaters, the dominant fish species, *Salmo trutta*, is more sensitive to water pollution than other fish species (Maceda-Veiga & De Sostoa, 2011). However, water quality is not documented as a significant stressor in headwaters in this study. Therefore, the results are not reliable enough for generalization and must be treated carefully. In lowland rivers, the FIA is mainly affected by continuum disruption, which the longitudinal development of a river may explain. Natural cascades decrease from headwaters to lowlands, therefore fish species in lowland rivers are not adapted to higher and more frequent cascades. Consequently, fish species are more sensitive to barrier construction and different barrier types in lowland rivers with increasing barrier height, storage capacity and hydropower generation (Jager et al., 2015).

Furthermore, the home ranges of fish species grows from headwaters to lowland rivers, which suggests that fish species in headwaters (e.g. trout) are more adaptable to connectivity loss than species in lowland rivers (Barry et al., 2020; Branco et al., 2012).

In addition, a difference in the impact of the stressor number on the FIA can be observed. Although fish species react to single stressors, they respond more to multiple stressors, which (Schinegger et al., 2016) confirmed. The relatively poor FIA in river sections without stressors is caused by the composition of the stressor metric, because sampling sites assigned to ‘0’ stressors do not necessarily represent river sections without stressors. As described in chapter 2.4, sampling sites that are unimpacted or only slightly impacted are summarized in one group. Accordingly, such river stretches may be influenced by stressors and impact fish assemblages, but to a lesser extent.

Moreover, some residual flow stretches in Austria are assigned to environmental flow due to the presence of specific size classes of dominant fish species and seasonal dynamic flows. Consequently, such residual flow stretches, which are assigned to environmental flow, are considered as reference sites and could lead to misinterpretation of unimpacted reference sites conditions.

Furthermore, the FIA gets better with four stressors present. In some cases the reason could be the relatively short time period of assembled data, as the fish sample data and stressors were derived within the time period of the 2nd RBMP (BMLFUW, 2015). Thus, the time of stressor appearance and fish sampling might have been too short to see any effect. Furthermore, stocking fish species may have occurred in highly disturbed river sections with multiple pressures, where fish populations did not recover naturally, leading to artificial short-term population growth.

4.5 UNCERTAINTIES, LIMITATIONS AND OUTLOOK

This thesis constitutes a first comprehensive assessments of river fragmentation across different ecoregions, fish regions and river size classes along the Austrian river network. Additionally, the impact of river fragmentation on fish assemblages was assessed. Nevertheless, the study showed some limitations. However, the findings should help to improve the assessment and management of river fragmentation and its impact on fish assemblages.

The most decisive uncertainty of this study was the quality and the lack of data. The results of river fragmentation especially highlight the different quality of data collection in terms of barriers between the federal states. Therefore, this study underscores the need for a standard data collection protocol for barriers in Austria.

Moreover, the construction date of many barriers was not available for analyses. As discussed before, in some cases this can lead to problems evaluating the full extent of the impact of river fragmentation on fish assemblages, as fish sampling should be done many years after barrier construction since the effects of river fragmentation may take a long time to become noticeable and without the construction date we cannot be sure if this is the case (Fuller et al., 2015). Fish sample data was derived from the 2nd National River Basin Management Plan which ranged from 2009 to 2018. Therefore, in some cases, the time range between barrier construction and fish sampling might have been too short to account for the impact of river fragmentation on fish assemblages, leading to an underestimation of its effect.

Moreover, the evaluation of river fragmentation could be improved by considering more parameters and differentiating among barrier types. The total effect of river fragmentation will appear according to the interaction of many drivers rather than the single impact of continuum disruption. Hence, the height of barriers, the discharge and the existence of fish passes are essential parameters that define a barrier's permeability and capacity to promote fish migration. In addition, information on the storage capacity of impoundments is critical to assess impacts on fish assemblages, as storage capacity influences the flow alteration downstream, affecting water depth, temperature, water chemistry, and sediment composition (Bunn & Arthington, 2002; Cooper et al., 2017; Poff et al., 1997). Sediment composition is also crucial for habitat availability. If vital habitats are continuously present along the river, it consequently improves river connectivity and the migration route for fish species (Baras & Lucas, 2001). Also, water temperature and water chemistry impacts fish migration, as they can act as natural habitat barriers. Natural habitat barriers are considered as thermal barriers (Nelson et al., 2002), hypoxic river reaches (Talling F, 1957) or tributaries with distinctive water chemistry (Winemiller et al., 2008). Even though such natural habitat barriers are partially permeable and are species-specific, contingent on the tolerances of species to temperature and water chemistry, they can delimit the movement of organisms (Fuller et al., 2015). Therefore, change in water temperature and water chemistry due to impoundments may affect migratory behavior of fish.

As previously mentioned, barrier location along the river course is also crucial for analyzing the extent of river fragmentation, as some river sections are more vulnerable to fragmentation than others. Barriers in downstream river sections disconnect the entire river network upstream, whereas barriers in upstream river sections interrupt smaller portions of the river network. In addition, long-distance migrating fish are more abundant in lowland rivers, which rely on the upstream river network. In this context, the Austrian RBMP prioritizes lowland rivers for restoration measures and favors investigations into the passability of barriers (Birnie-Gauvin et al., 2017; Cote et al., 2009; RBMP, 2015). Hence, it is recommended to include the named parameters (e.g. barrier type, construction date, barrier location) to analyze the impact of river fragmentation on fish assemblages.

Besides the suggestion of considering more comprehensive barrier parameters, information on type of river network structure, flow regime, and the annual discharge in rivers over time (=duration of permeability) should be incorporated too (Fullerton et al., 2010).

In addition, environmental conditions such as droughts (Perkin et al., 2013), floods, chemical spills, and diseases may also impact fish populations (Fuller et al., 2015). Such environmental events will appear more frequently and become increasingly important due to climate change. Moreover, to account for a shift in fish populations, overfishing, stocking, and invasive species should be considered since non-native fish species act as competitors and influence fish populations (Van Puijenbroek et al., 2019).

With respect to fish metrics, the Fish Index Austria related metrics, age structure, biomass, habitat guilds and reproductive guilds were considered for the analyses. For future investigations, it is recommended to incorporate data about single fish species, particularly migratory fish species e.g., Danube Salmon (*Hucho hucho*), as their biology and fitness are crucial for analyzing the impact of river fragmentation on fish assemblages. Furthermore, it is recommended to focus on assessing the effects of river fragmentation on fish assemblages in lowland rivers due to different fish species, which may not be resilient to disruption of river connectivity as trout in headwaters (Barry et al., 2020; Branco et al., 2012). Also, the impacts of upstream barriers accumulate, and their full effect plays out further downstream. Generally, lowland rivers face more substantial consequences on river morphology and continuum disruption than headwaters (Fuller et al., 2015).

While in the conducted analyses the single effect of connectivity disruption was not reflected in a response of fish assemblages, additional stressors, such as impoundment, residual flow, morphology, continuum disruption and water chemistry, showed a trend in the shift of populations. Nevertheless, the results should be considered with caution. This is due to the lack of information on the year of stressor appearance. Knowing more about the quantity and time of appearance of stressors will help to explain and discuss the impact of stressors on fish assemblages more accurately. Furthermore, every stressor combination was represented by at least twenty observations to conduct statistical analyses. The division into headwaters and lowland rivers however resulted in some stressor combinations with less than ten observations. Hence, the impact of such few stressor combinations is not representative enough to draw a conclusion, and results should be interpreted carefully. Nevertheless, only trends, but no significant effect of the stressors on fish assemblages could be observed in the conducted analyses. This result is confirmed by the study of Nõges et al. (2016), in which the variance of biotic indicators was low and could not be clearly explained by stressors and found a lack of explanation in stressor-indicator relationships.

All the above suggests that river fragmentation is a very complex topic and evaluating a shift in fish populations by only considering river fragmentation is not possible. Hence, many studies and among others Belletti et al. (2020) concluded that factors and their interaction can contribute to a shift in fish populations rather than river fragmentation.

5 CONCLUSION

This thesis is the first step in implementing a comprehensive assessment method to calculate river fragmentation for the Austrian river network on the reach and segment level, which concurrently consider barriers over the whole river network. The method following Cooper et al. (2017) might help future investments to evaluate the impact of river fragmentation on fish assemblages. The reduction of river catchments due to barriers was calculated for the first time for the Austrian river network. Furthermore, the results underscore the need for improvements in analyzing the impacts of river fragmentation on fish assemblages.

The outcome of this thesis confirms a difference in barrier density across ecoregions and along fish regions and river size classes. It highlights the high barrier density in the 'Alps', 'Dinaric Western Balkan', and main rivers. Moreover, barrier density differs between the federal states, indicating that the sampling efforts differ across the federal states. The fish regions most influenced by a high barrier density were the meta-, hyporhithral and epipotamal and the related river size classes of '4 000-10 000' and '>10 000' km². The high barrier density of these fish regions and river size classes mainly results from the highly fragmented ecoregion, the 'Dinaric Western Balkan' and main rivers. Concurrently a drastic decline in segment length and catchment areas due to barriers could be observed. Due to barrier construction, the mean segment length decreased from 7 121 km to 4 km, and the catchment area declined from a mean size of 18 494 km² to 8 km². These results highlight the dramatic influence on river networks due to barrier construction.

However, the evaluation of the impact of river fragmentation on fish assemblages hardly showed any effect. Hence, further stressors induced by barriers were analyzed and revealed an effect on fish assemblages. Particularly the FIA in lowland rivers was mainly impacted by stressors as compared to headwaters. In general, the FIA got worse with increasing stressor numbers. Water quality strongly affected FIA in headwaters, whereas continuum disruption mainly influenced the lowland rivers. According to these findings, a more substantial impact of stressors on the FIA in lowland rivers may be caused by cumulative effects from upstream to downstream river sections. As a result, focusing on the lowland rivers is recommended for future investments in river fragmentation and its impact on fish assemblages.

Nevertheless, to analyze the full extent of river fragmentation on fish assemblages, a comprehensive analysis of the impact of fragmentation will depend on accurate observation of species biology, disturbing occurrences, human influences, barrier types, river network characteristics, and time (Fuller et al., 2015). Recent studies on aquatic ecosystems concluded that interactive stressor effects seem to be inevitable for the analysis of the impact of river fragmentation on fish assemblages (e.g., Côté et al., 2016; Crain et al., 2008; Nõges et al., 2016; Piggott et al., 2015; Schinegger et al., 2016). Moreover, it would be beneficial to have more reference sites to enhance the capability of analyses to evaluate the effects of river fragmentation on fish assemblages. It will be essential to improve the lack of information on the date of barrier construction, with a consistent sampling proceeding across the federal states being highly recommended.

This study can support efforts opportunity evaluating large-scale river fragmentation in a simple and comprehensive way. Considering some of the suggested improvements, this method will help to assess river fragmentation and observe changes in barrier development over the years. It will support future investments in river restoration or even dam removal projects. The method could also supplement strategic tools such as the 'Hy:Con' from Seliger et al. (2016) to balance barrier construction and conservation needs.

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APPENDIX

Table 9: Comparison of the number and the mean segment length (km) with and without barriers. The mean segment length with the existence of barriers is listed in different ecoregions, fish regions and river size classes.

	Without barriers		
Number of segments	61		
Segment length (km)	**Mean**	**Median**	**Standard deviation**
	7 121.25	11 644.16	4954.39
	With barriers		
Number of segments	58901		
Segment length (km)	**Mean**	**Median**	**Standard deviation**
	3.63	0.08	22.37
Ecoregions mean segment length (km)			
Alps	1,69	0.04	11.03
Dinaric Western Balkan	2.76	0.10	14.74
Central Highlands	6.71	0.45	28.21
Hungarian Lowlands	12.20	0.51	52.85
Fish regions mean segment length (km)			
Epirhithral	1.05	0.04	7.90
Metarhithral	2.94	0.21	12.78
Hyporhithral	6.72	0.40	26.01
Epipotamal	24.86	1.46	67.99
Metapotamal	211.00	331.09	156.67
River size classes mean segment length (km)			
<10 km²	74.12	74.41	73.40
>10 km²	2.58	0.05	19.19
>100 km²	2.37	0.18	12.81
>500 km²	7.14	0.66	33.13
>1 000 km²	9.74	0.69	27.54
>4 000 km²	26.15	3.73	54.26
>10 000 km²	40.50	3.25	80.15

Table 10: Comparison of the number and the total segment area (km²) with and without barriers. The mean segment area with the existence of barriers is listed in different ecoregions, fish regions and river size classes.

	Without barriers		
Number of segment catchments	61		
Catchment size (km²)	**Mean**	**Median**	**Standard deviation**
	18 494.43	29 769.81	12 410.85
	With barriers		
Number of segment catchments	58901		
Catchment size (km²)	**Mean**	**Median**	**Standard deviation**
	8.42	0.06	51.47
Ecoregions mean catchment area (km²)			
Alps	5.23	0.02	34.94
Dinaric Western Balkan	7.19	0.06	43.43
Central Highlands	11.12	0.55	40.01
Hungarian Lowlands	27.17	0.64	123.69
Fish regions mean catchment area (km²)			
Epirhithral	2.94	0.02	23.29
Metarhithral	7.48	0.20	33.05
Hyporhithral	16.38	0.51	65.10
Epipotamal	49.28	2.21	144.89
Metapotamal	492.12	777.40	371.98
River size classes mean catchment area (km²)			
<10 km²	158.61	264.09	129.18
>10 km²	62.41	1.97	171.94
>100 km²	11.69	0.47	44.47
>500 km²	48.30	4.41	159.94
>1 000 km²	30.84	3.75	88.94
>4 000 km²	107.03	23.95	121.29
>10 000 km²	124.01	18.33	217.12

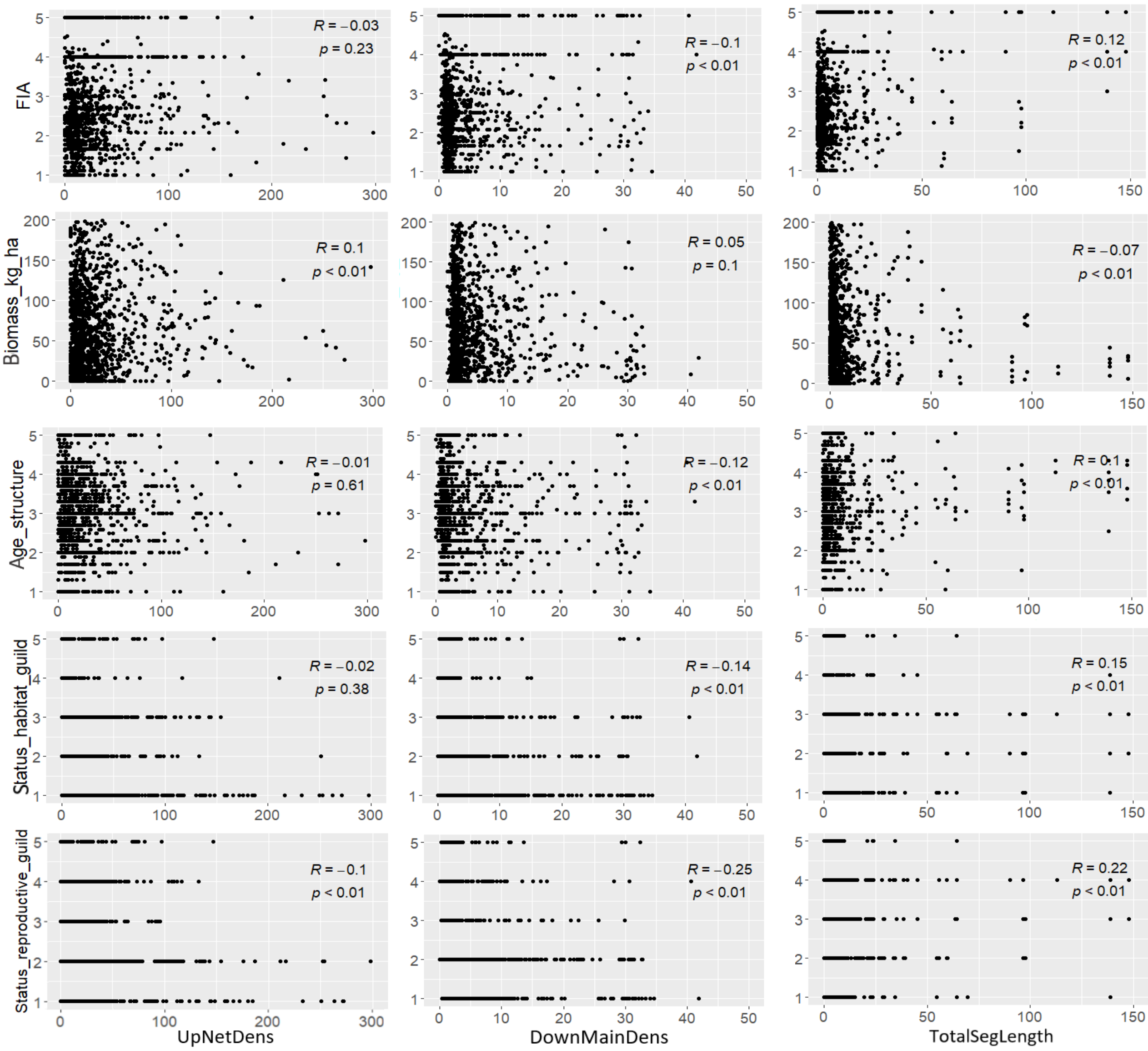

Figure 14: Scatter plots showing the response of fish metrics to stream fragmentation. In addition to the scatterplot the rho-value (R) and the p-value (p) were calculated. For density-based fragmentation metrics the x-axis upper limit was capped to in order to make the data distribution more visible by excluding a small subset of points with very high values; UpNetDens (nr./10 km), DownMainDens (nr./10 km), and TotalSegLength (km).