Audrey Philippe

Quantifying environmental impacts of river fragmentation from hydropower dams within Life Cycle Impact Assessment

Master's thesis in Industrial Ecology
Supervisor: Francesca Verones
Co-supervisor: Martin Dorber
June 2023

Master's thesis

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Abstract

Increasing hydropower electricity production is one of the ways in which anthropogenic greenhouse gas emissions can be reduced in the coming years in order to limit climate change. However, the operation of hydropower reservoirs is a threat to freshwater habitats and biodiversity. This biodiversity trade-off can undermine the other benefits of hydropower. A major cause of the loss of freshwater biodiversity is the fragmentation of rivers. Life cycle assessment (LCA) is a method for assessing the impact of hydropower dams on ecosystem quality, however not all relevant impacts are included yet. I have developed the first three mid-point characterisation factors (CF) for river fragmentation of hydropower dams in Europe, for both potamodromous and diadromous species. In total, CFs for 62 basins were calculated, ranging from $2*10^{-6}$/GWh to $88.96*10^{-4}$/GWh, for the three methods. No correlation was found between the calculated connectivity indexes and either the number of dams or the amount of hydropower generated. The river basin with the highest CF is located in Greece and the one with the lowest CF is located in Ireland. Hydropower dams do not affect potamodromous and diadromous species in the same way. The CF can vary considerably for different species within a river basin. This is the first step towards the assessment of river fragmentation in LCA.

Sammendrag

Økende produksjon av vannkraft er en av måtene å redusere menneskeskapte klimagassutslippene i årene som kommer, for å begrense klimaendringer. Imidlertid utgjør driften av vannkraftmagasiner en trussel mot ferskvannshabitater og biologisk mangfold . Denne trusselen til biologisk mangfold kan undergrave andre fordeler ved vannkraft. En hovedårsak til tapet av ferskvannsbiodiversitet er fragmenteringen av elver. Livssyklusanalyse (LCA) er en metode for å vurdere påvirkningen av strømproduksjon fra vannkraft på økosystemkvalitet, men ikke alle relevante påvirkninger er inkludert ennå. Jeg har utviklet de første tre midtpunkt-karakteriseringsfaktorene (CF) for elvefragmentering av vannkraftdammer i Europa, for både potamodrome og diadrome fiskarter. Totalt ble CFs for x vassdrag beregnet, med verdier fra $2*10^{-6}$*/GWh til 88.96** 10^{-4}/GWh, for de tre metodene. Det ble ikke funnet noen sammenheng mellom den beregnede tilknytningsindeksen og verken antallet dammer eller mengden produsert vannkraft.Elvebassenget som påvirkes mest av elvefragmentering befinner seg i Hellas, mens det som påvirkes minst befinner seg i Irland. Resultatene viser at vannkraftdammer påvirker ikke potamodrome og diadrome arter på samme måte. CF kan variere betydelig for ulike arter innenfor et vassdrag. Dette er det første skrittet mot vurdering av elvefragmentering i LCA.

Acknowledgements

I would like to thank my supervisor Francesca Verones and my co-supervisor Martin Dorber for their support, availibility and advices through the year. I would also to thanks the other indecol students for the two years, your support, and friendship have made my experience here truly exceptional. I would like to express a special thanks to Le Moulin, for all the laugh and debates, often on nothing. I want also to say thank you to my family for all the interest in my studies, who supported me to spend these two years in Norway. Lastly, to Thomas, I express my heartfelt gratitude for your encouragement and love.

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List of Abbreviations

AoP	Area of protection
CAFI	Catchment area-base fragmentation index
CCI	Conservation connectivity index
CF	Characterization factor
CI	Connectivity index
DCI	Dendritic connectivity index
DCId	Dendritic connectivity index for diadromous
DCIp	Dendritic connectivity index for potamodromous
FFR	Free-flowing river
GHG	Greenhouse gas
HCIU	Habitat connectivity index for upstream passage
HCP	Habitat change potential
IPCC	Intergovernmental panel on Climate change
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
PAF	Potential affected fraction of species
PDF	Potential disapear fraction of species
ROR	Run-of-river
SAR	Species area relationship
SDR	Species discharge relationship
SSD	Species sensitivity distribution

1 Introduction

1.1 Advantages of hydropower

According to the last intergovernmental panel on Climate change (IPCC) the energy sector is the sector that emitted most greenhouse gas (GHG) with 38 $GtCO_2$-eq (IPCC, 2022) That represents 66% of the whole anthropogenic GHG emission in 2019, which are a major reason for the ongoing global warming. In the last 10 years compared to 1850-1900, because of global warming, the temperature increase of 1.1 °C (IPCC, 2022). In order to achieve the Paris Agreement goal, which had settled the objective to limit the global warming to 1.5°C in 2050, the anthropogenic GHG emissions must be reduced (Conference of the Parties, 2015). As energy is used in a large number of sectors, like industry, housing, or transport, reducing the energy sector emissions will have an important impact on the global GHG emissions.

Electricity is one energy source that will be more important in the coming years with the electrification of several sectors, like transport with electrical vehicles (Sugiyama, 2012). Electricity can be provided with renewable sources, for example hydropower, wind or solar, which, compared to fossil-based sources, are emitting a lower amount of GHG emissions (Gibon et al., 2017). Hydropower is the most important source of renewable electricity globally, with a production of 4 325 TWh in 2018 which is more than 3 times bigger than wind production (1 273 TWh) which is the second main source of renewable energy production (IEA, 2020).

Hydropower dams have many environmental, social and economic advantages. Hydropower dams allow more flexibility for electricity in comparison of other renewables energy, they also have the capacity of storage. This last one enables the possibility to produce electricity when the demand is high and not only when is feasible. Moreover, hydropower is a mature technology used for more than a century (IPCC, 2022). As dams may not be only used for electricity production, it can for example also be used for irrigation. Developing of hydropower dams that are used for irrigation can address the growing demand of energy and food, even more with hydropower dams’ construction the irrigation can be more important (Lacombe et al., 2014). The efficiency of hydropower dams for electricity production is high. And the cost of electricity production is lower than for other renewable energy systems (Mukheibir, 2013) , however the construction cost of the dams can be expensive.

1.2 Hydropower overview

The first hydroelectricity power plant was built in 1882 (Brito-Santos et al., 2021), and now it is present all over the world as main source of energy. In 2019, hydropower represented 16% of global electricity generation (IPCC, 2022). Between 2015 and 2019, hydroelectricity generation has grown by 10%, which is less than for wind and solar panel, with growth rates 170% and 70%, respectively (IPCC, 2022). In one of the scenarios of net-zero CO_2 emissions for energy systems developed in the last IPCC assessment, hydropower supply will need to be doubled in 2070 compared to nowadays (IPCC, 2022).

Many projects for the construction of new dams in the coming decades exist with difference on the numbers and size of dams depending on the localization. All these types of dams have benefits and drawbacks for electricity production, economy, and ecology. Therefore, the global situation is presented in section 1.2.1. In section 1.2.2, the drawbacks of hydropower will be briefly explained.

1.2.1 Current development

Although hydropower is produced an all continents (except Antarctica), there are important differences between the countries (Figure 1). Some of them, like Norway or the United States, have dams since more than a century, while other countries are still not producing hydropower, mainly in Africa, or only recently do so (e.g., Estonia has built its first dam in 2010). In parallel, there has been change of dam height over time, most of dams higher than 15 meters were constructed in the last 60 years. The Three Gorges dam is 181 m high. In the last 60 years the hydropower generation have been multiplied by almost 6 times (BP, 2022). However, only 22% of the hydropower production potential is estimated to be exploited (Mulligan et al., 2020), and it is projected that the capacity of hydropower will be twice the one of 2010 (Geist, 2021). The majority of hydropower plants are located in North America, Europe and China (see Figure 1). However, an increase of dams' construction is observed in Brazil. Africa has not a lot of hydropower production, even if most of the countries are producing hydroelectricity. Nevertheless, in one country the electricity production comes entirely from hydropower, but six countries have no hydropower production (Figure 1). As well, in South America and Africa even if the number of dams is not very significant the generation of hydroelectricity compared to other sources is important. Most of the lower dams are located in Europe and North America (Figure 1).

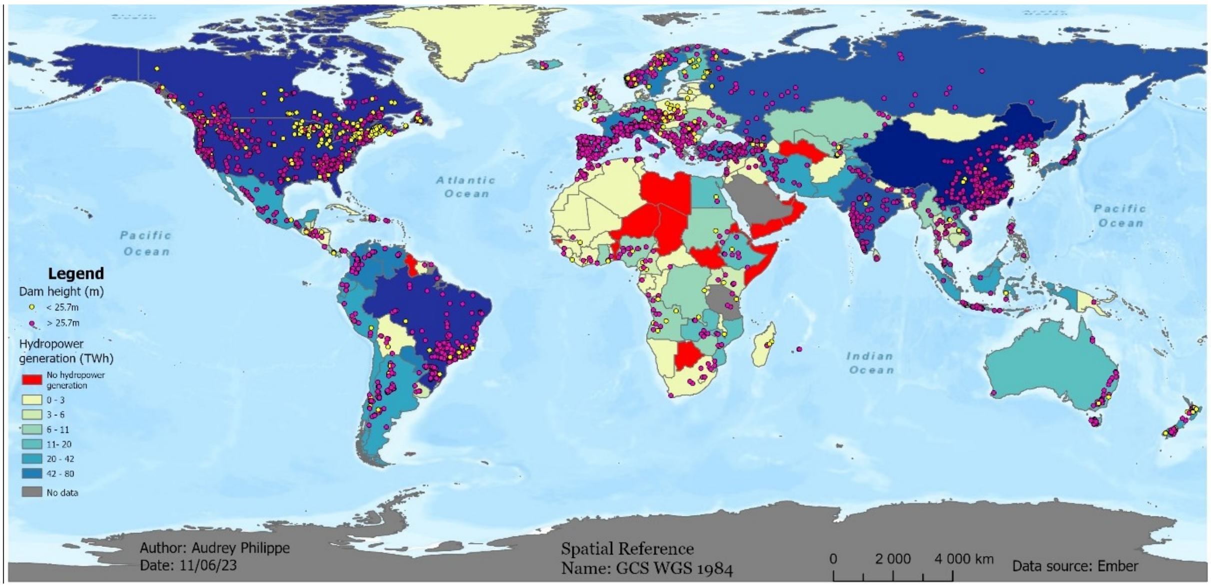


Figure 1: Map of hydropower electricity generation in 2020. Dam height cutoff of 25,7 m is chosen, because dam larger than that are impassable for non-gobies species and for river goby (Patrick B. Cooney & Thomas J. Kwak, 2013). Only large dams are represented, because in the AQUASTAT database only large dams are recorded (Aquastat Database, n.d.). Map made with ArcGIS pro 3.0.0 (ESRI, 2022) Data from the electricity production are from Ember (Yearly Electricity Data, 2022), localization of the dams from AQUASTAT (Aquastat Database, n.d.).

By 2019, 2.8 million dams had a reservoir area exceeding 1000 m²(Grill et al., 2019). And over 40 000 are dams with a capacity over 1MW. In addition, another 3,700 dams are already planned or under construction (Barbarossa et al., 2020) According to Mulligan et al, 58,000 large dams over 15 meters high are being built, but his map shows only 38,000 because dams with reservoirs are easier to see (Mulligan et al., 2020). Where future large dams are planned is not evenly distributed; in Brazil, for example, the number of large dams to be built in the coming years will almost double (from 154 to 277) (Reid et al., 2019). This will leave only three tributaries left free to flow (Reid et al., 2019). Most of the future plans of hydropower dams' construction are in South America, South and East Asia and in Africa.

The future potential production of hydropower worldwide is between 31 and 128 PWh by year (Banerjee et al., 2017; IPCC, 2022) but if the technical or economical constraints are taken in account the potential is reduced to 8 to 30 PWh/yr and 8 to 15 PWh/yr respectively (van Vliet et al., 2016; Zhou et al., 2015). Due to the uneven distribution of the gross hydropower potential (Figure 2) some countries will not be able to develop any hydroelectricity or additional hydroelectricity. The future plans of hydropower dams are overlapping with the regions with the lowest hydroelectricity generation in 2020 (Figure 1) and the regions with the highest hydropower potential. Those new hydropower plants will reduce the undeveloped potential of hydropower, that is mainly located in developing countries (IPCC, 2022).

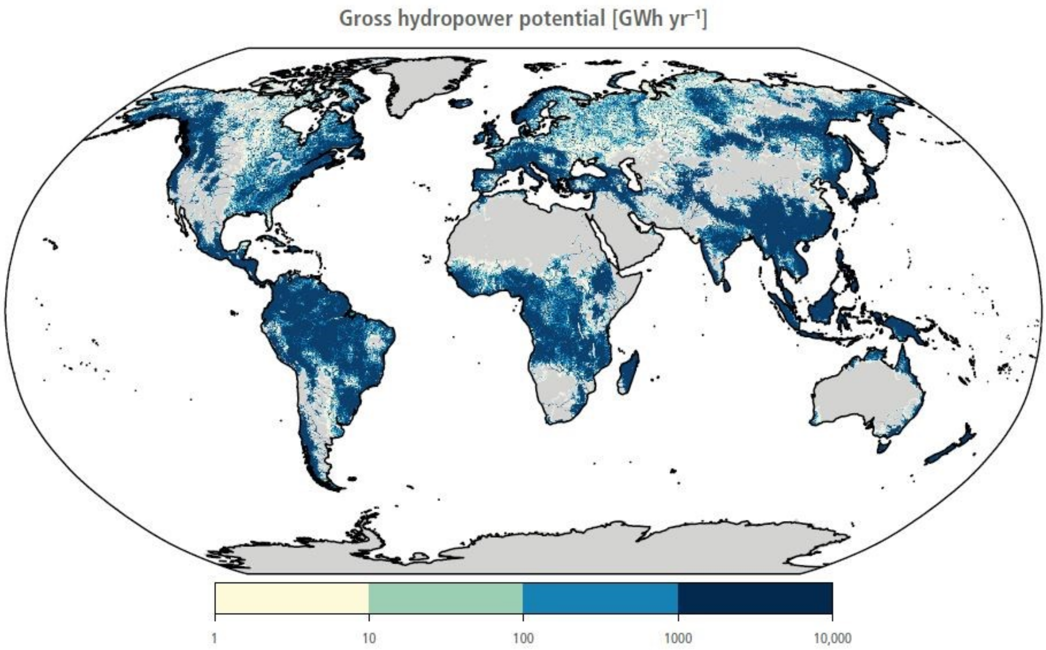


Figure 2: Global map of gross hydropower potential distribution [GWh/yr] from (IPCC, 2022)

Hydropower can store electricity and release it later when the consumption is higher. And worldwide pumped hydro-storage represents 96% in 2017 (IRENA, 2017). In 2019, with 160 GW the pumped storage hydropower represents more than 90% of the whole energy storage capacity (IPCC, 2022).

Hydropower has been used in Europe for decades, so the actual and future increase of capacity is lower than in the rest of the world, which is two times more important and only one third higher in Europe (Wagner et al., 2019). This is also explained by the fact that over 50% of the technical hydropower potential is already developed(Gaudard & Romerio, 2014). To achieve the European Grean deal, it is estimated that hydropower production should increase by 10% in 2030(Carolli et al., 2023). But there are inequality of plan' dams in Europe, like Serbia is planning to build 847 new dams, mainly small ones (Carolli et al., 2023) as France is only planning to increase the production of 5% in 2028 mainly by optimising existing dams (French government, 2023).

1.2.2 Impacts of hydropower

The last IPCC assessment nuances the benefits of hydropower, but also point out that its climate change mitigation potential is depending on how the social and environmental impacts are taking in account during the planning phases, and how they are minimized. It will also depends on the modernization the oldest plants by increasing their capacity and flexibility (IPCC, 2022).

However, besides the climate change benefits hydropower has drawbacks which can affect both terrestrial and aquatic biodiversity, by for example modifying the sedimentology and flooding large terrestrial areas. For the aquatic biodiversity, hydropower dams will change the water level, flow regime, water temperature and create river fragmentations, all of these have impacts on aquatic biodiversity (Silva, S. N. & Castillo, J. Álvarez del, 2021).

The most diverse and important habitat for biodiversity is freshwater habitat, which consists of surface waters, subsurface waters, riparian systems and ecotones between them (Geist, 2011). Freshwater habitats cover less than 1% of the Earth, however around 20% of the global species richness are considering this habitat as suitable for them, for fish species this number is even higher with 40% of them living in freshwater systems (Barbarossa et al., 2020; Wu et al., 2019). This master thesis is focusing on freshwater fish species, which represent 12 740 species according to fishbase (*Fishbase*, n.d.). Freshwater fish species are not equally distributed on Earth, the regions with the highest richness and endemic species are Amazon and Orinoco basins in South America, Asia's Zhu Jiang basin, and in Africa the Congo basin, Gulf of Guinea, Lakes Malawi, Tanganyika and Victoria lakes (Abell et al., 2008).

In parallel, the Living Planet Index has reports that among terrestrial, marine and freshwater vertebrate species, freshwater vertebrate species have the fastest decrease (Grooten, M. & Almond, R.E.A, 2018). Further, it is considered that freshwater habitats are the most threatened ecosystems globally (Geist, 2011).

According to Reid et al., the freshwater biodiversity decrease is caused by 12 different emerging threats, and one of them is hydropower, other are, for example, infectious diseases, harmful algal blooms (Reid et al., 2019).

Several studies have shown that hydropower dams' construction has led to a decrease in species richness and diversity, which can be caused by river fragmentation. However, the impacts of hydropower on the biodiversity depends on the types of the hydropower.

Hydropower power plants can be divided in three main types: 1) run-of-river (ROR); which can be diversion; 2) storage and 3)pumped storage (Gracey & Verones, 2016). Run-of-river hydropower does not require a reservoirs storage as it can be a diversion of the natural flow of the river through turbines to produce electricity, sometimes ROR will have a comparably small reservoir. In this project ROR plants are considered as not having a dam. The reservoir is the main difference between ROR and the two other hydropower plants, as the always have a reservoir. Storage and pumped storage plants have two different ways of working. The first one stock a volume of water that will later be used to produce electricity downstream through turbines. The pumped storage plants work differently if the price of electricity is cheap and the demand low or if electricity is expensive and with a high demand. When the demand is low water will be pumped to the reservoir, which is upstream, before being release downstream when the demand is high (McManamay et al., 2016). Pumped storage plants can use other types of electricity, like solar, wind or nuclear power, when the water is pumped. The absence of reservoir in the ROR allows less flexibility in electricity production, as it will depend on the flows of the river and will be more sensitive to variation of water, which can be seasonal or through climate events, drought conditions for example (Premalatha et al., 2014).

The capacity of electricity production of hydropower plants depends on the size of the plants but also the presence and the size of the reservoir. So, if there is no reservoir or a small one the capacity of electricity will be between few kilowatts to 10MW. And with a bigger reservoir it can generates 10GW (IPCC, 2022).

There are different consequences of hydropower dams' construction (Figure 3). River ecosystems are affected by the construction of hydropower dams in several ways. It can alter the flow regime or sedimentation, changing from lotic to lentic habitat. The hydropower dam will also lead to fragmentation of the river (Gracey & Verones, 2016; Wu et al., 2019). All of this results in a restriction of upstream-downstream movement (Baudoin et al., 2014; Grill et al., 2019).

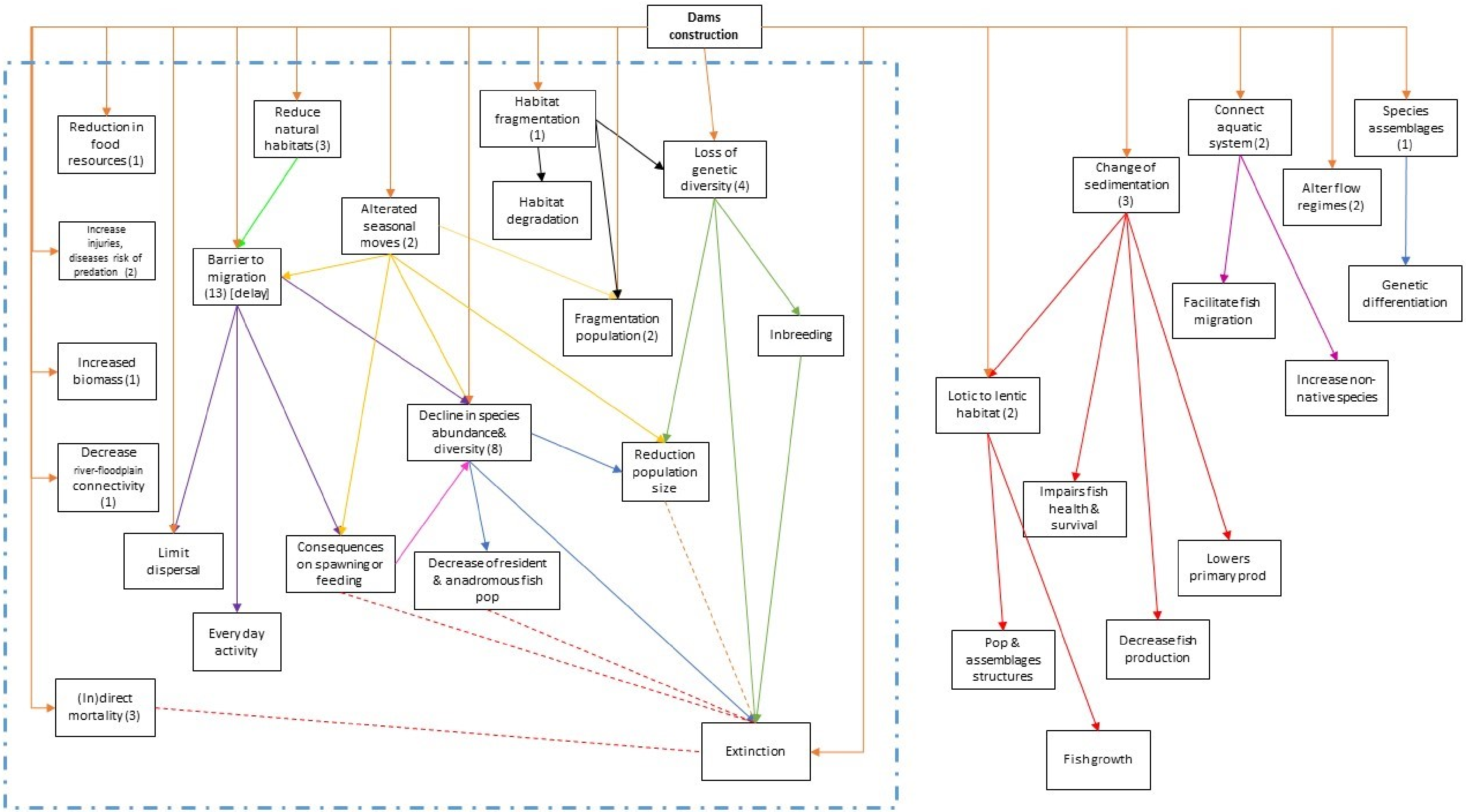


Figure 3: Framework of dams construction impacts on biodiversity. The colors of the arrow are only to facilitate the reading with all arrows that go out of one box have the same color. The blue box on the left represents the impacts directly link to river. From(Philippe, 2021)

Hydropower turbines can also be a source of mortality or injury to fish during movement or migration. All these changes alter and mainly reduce species richness and diversity (Liu et al., 2022; Turgeon et al., 2021; Wu et al., 2019). This decline can lead to population reduction or extinction, for example. The magnitude of the effect depends on the number of dams in the river. With a higher impact for the first one construct, and also the location of the barrier will modify the impact, the impact is more significant for barriers at the mouth, for diadromous fish (Cote et al., 2009). Extinction of species can be associated with dam construction (Khedkar et al., 2014; Turvey et al., 2007).

Regions that have high endemism and species richness are, for the moment, protected from most of the dam's construction localizations (Figure 4), except China. However, the future development of dams will overlap with these basins.

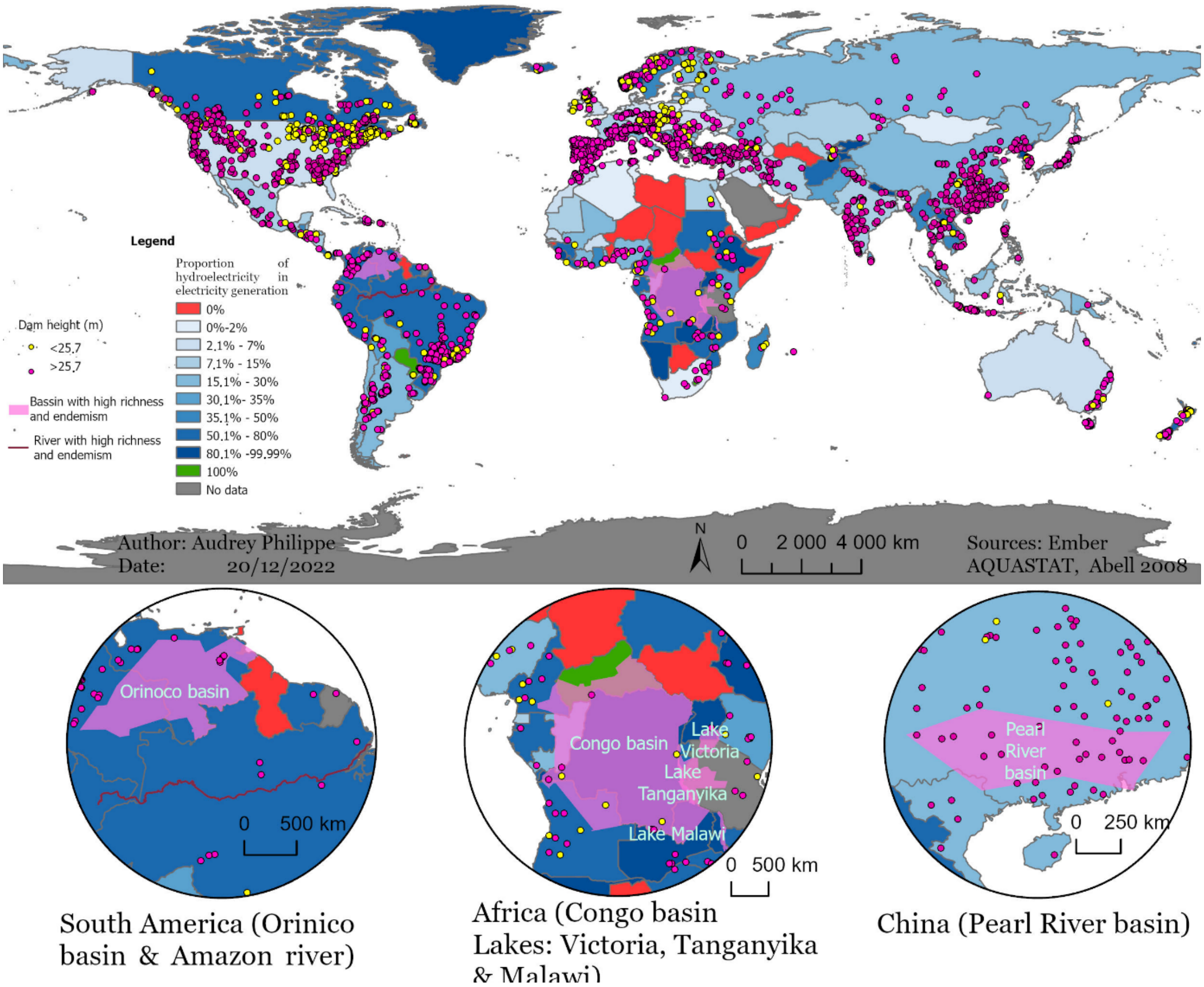


Figure 4: Map of hydropower proportion in electricity generation in 2020 from Philippe, 2021 Dams higher of 25.7 m are impassable for non gobies species and for river goby (Patrick B. Cooney & Thomas J. Kwak, 2013). Only large dams are represented, because in the AQUASTAT database only large dams are recorded (Aquastat Database, n.d.). Some river's basins with high species richness and endemism are represented. Some zooms were made on three areas with high richness and endemism. Map made with ArcGIS pro 3.0.0 (ESRI, 2022) Data from the electricity production are from Ember (Yearly Electricity Data, 2022), localization of the dams from AQUASTAT (Aquastat Database, n.d.) and the basins with high richness and endemism are derived from (Abell et al., 2008)

Hydropower will also be affected by climate change (Lehner et al., 2005) and the capacity of hydroelectricity will reduce with the augmentation of droughts.

Construction of hydropower dams can have social consequences, as a decrease in the number of fish that will affect local population fishing activities. Or areas are inundated when the reservoir is filling, and population may have to be resettle (Khanal et al., 2021). It can also be reduction or loss of livelihoods (Khanal et al., 2021) or be the origin of conflicts (Del Bene et al., 2018).

1.3 Life cycle assessment

The different impacts previously mentioned need to be quantified and to be compared to other source of energy. Life cycle analysis (LCA) is a tool, used in industrial ecology, that is quantifying the impacts on the environment and human health.

1.3.1 Definition

LCA is quantifying the impacts through the whole life cycle, from the resource extraction to the end-of-life, including production and use phase. It assesses multiple pressures impacts, like GHG emission, land use, water use, particulate matter. LCA is defined as a multicriteria analysis with a holistic view. For these reasons, LCA helps to reduce burden shifting, by improving one impact while other pressures can be more important (Hellweg & Milà i Canals, 2014). A new product, for example, can reduce the water use but will increase fossil fuel depletion. LCA cannot be used to determine if a product or a construction is acceptable or not for the environment. It must be used for comparing several products, services, or processes by determining which one has the better environmental performance.

The four steps of an LCA are goal and scope definition, inventory analysis, impact assessment and finally the interpretation (Muralikrishna & Manickam, 2017). During the first step, the reason and the application of this study will be decided, and with the scope the products to evaluate will be chosen, the functional unit, the system boundaries and the environmental impact categories that will be evaluated through the LCA. During the second step, all the inputs and outputs occurring during the life cycle will be quantified. The last phase is done during all LCA as it will interpretate the inventory and the results and also evaluate the uncertainties.

During the life cycle impact assessment (LCIA) step the emissions and resources, from the inventory, are converted with characterization factors (CF) in impacts categories with the same impact units. After this step the different products impacts can be compared between them. LCIA has two level of impacts, mid-point level, that gives metrics for every impact category, and damage level, that is aggregated mid-point level impact in three area of protection (AoP): Human health, resources scarcity and ecosystem quality. The first one is more precise but more difficult to compare than the end-point level. For ecosystem quality the unit for end-point level CF are potential disappear fraction of species (PDF) or potential affected fraction of species (PAF).

1.3.2 Hydropower in LCA

The CF developed in this master thesis is focusing on the use phase of hydropower and the AoP ecosystem quality. Five end-point CF have been developed to quantify the impacts of human activity on freshwater fish species. End-point CF for three biomes (boreal, temperate and tropical) have been calculated with the changes in fish species richness after a hydropower dam was built and the steady state reach (Turgeon et al., 2021). Then impact scores in PDF*m²*y/kWh was developed and can be used with electricity consumption. Those CF are quantifying all the species richness loss for all the consequences of hydropower construction (river fragmentation, water changes, alteration in flow regimes etc).

Construction of hydropower dams and climate change can lead to an increase of temperature, which will affect freshwater biodiversity. Li et al. (2022) have calculated regional and global end-point CF on the impact on freshwater species of increasing water temperatures. They have calculated CF for both disappear and affected species with species sensitivity distribution (SSD). Even if, this study pathway did not take into account directly the presence of hydropower dams, those CF can be used to assessed hydropower dams' impacts on freshwater biodiversity as the units are PDF/°C and PAF/°C. A global CF on the impact of climate change, and so on water temperature changes, on freshwater fish was recently developed for 207 GHG. The CF are derived from the species area relationship (SAR) (De Visser et al., 2023). Like previously, those CF are not developed directly from hydropower dams' impact but can be used.

And end-point CF on water consumption on the aquatic biodiversity has been developed. The CF are calculated for Europe at several scales (eco-region, country and continent) with the species discharge relationship (SDR) (Tendall et al., 2014). SDR formula links the species richness with the water discharge, and the CF model is based on the change of discharge and the change it involves in species richness. This model is based on natural river discharge but can be used to determine the impact of evaporation from hydropower reservoirs on aquatic biodiversity. Pierrat et al. (2023) have updated this framework to calculate CF worldwide at a basin scale.
The previous model of water consumption CF has been adapted for hydropower. The impact of hydropower reservoir on terrestrial and aquatic biodiversity from water consumption and methane emissions have been calculated worldwide (Dorber et al., 2020). They have also used the SDR formula to obtain the impact on the biodiversity, linked with the water consumption from the reservoir. Water consumption due to hydropower dams reservoir have been calculated for Norway with the same method as previously (Dorber et al., 2019).

In addition to end-point CF, two mid-point CF on the water consumption has been developed. Boulay et al. (2018) developed a consensus regional CF for water consumption, based on the water that is still available after human and environmental consumption by area. As hydropower dams lead to water consumption this CF can be used with the inventory data from water consumption by hydropower. Another water consumption mid-point CF was developed, with more precision for France and in a more generalized model in Europe (Damiani et al., 2021). It is based on the habitat change potential (HCP) effect factor, only usable with French data (Damiani et al., 2019). They have developed CF, at watershed level, with the HCP and the change in water discharge divide by water consumption as fate factor. This mid-point CF model is based on microhabitat suitability.

According to Gracey & Verones (2016) some impact categories are still missing in hydropower LCIA, especially those concerning biodiversity impacts. According to these authors flow alteration, geomorphological alteration, changes in water quality have been identified as main cause effect pathways. In parallel, they highlight that no CF for river fragmentation in LCIA exists. Dorber et al. (2020) specifies that damage to biodiversity from hydropower can also come from habitat fragmentation and those impact have to be quantified and considered.

To fill this gap this master thesis goals are to calculate river connectivity in Europe with three different indexes. The focus of this thesis is river fish species. So, two indexes calculate the loss of river connectivity for diadromous fish, the last one is made for potamodromous species. And with those values develop a mid-point characterization factor of river fragmentation impacts by electricity production.

2 Methods

2.1 River fragmentation

2.1.1 Definition

The definition of river fragmentation used in this master thesis is the one defined in the autumn project: "The river fragmentation consists of a loss of the longitudinal river connectivity, which separate the river environment into several fragments with barriers (anthropogenic or natural ones). The different fragments are more or less connected." (Philippe, 2021) According to Grill et al. (2019) and Ward (1989), the river connectivity is defined with four dimensions: longitudinal one, movement through the river channel (upstream and downstream); lateral one, movements between the river channel and floodplain, the vertical dimension, exchange between the river and groundwaters or atmosphere; and the one that follows the change in a temporal scale; the temporal dimension.

River fragmentation may also occur through natural obstacles, waterfall for example, during this work the presence of waterfalls is not taken in account. It will also occur through several anthropogenic construction, like levees, roads bridge and weirs (Belletti et al., 2020; Carolli et al., 2023). It is estimated that over 1 million obstacles fragment Europe with 9.8% that are dams (Belletti et al., 2020).

2.1.2 River fragmentation by hydropower and the impacts on aquatic biodiversity

Freshwater fish species can be separated in two groups: diadromous and potamodromous species. Salmons (*salmo salar*) and trouts (*salmo trutta*) are part of the first group, that has the specificity to migrate between sea and freshwater. The group is composed of anadromous, who live mainly in sea water and breed in freshwater, and catadromous species, who are doing the opposite with spawning in sea water, as the eel (*Anguilla Anguilla*) (Baudoin et al., 2014). Potamodromous species spend their whole life cycle inside freshwater. This does not prevent some of them to have long distance migration shifts, inside their freshwater habitat. All fish species will have migration movements, from few centimetres to thousands of kilometres, as well upstream and downstream movements. These migrations can be for moving from lentic to lotic zone through the daily life, or ontogenetic shifts, with annual or whole life period (Baudoin et al., 2014). All these migrations movements are shown, in Figure 5, with two examples diadromous species. Potamodromous species have different migrations paths, these migrations will be between a shelter habitat, more commonly a lentic area, and an area of activities, lotic zones in general (Baudoin et al., 2014). Both these habitats are in freshwater. Their migration pathway can be seen in the figure through the daily and seasonal migrations.

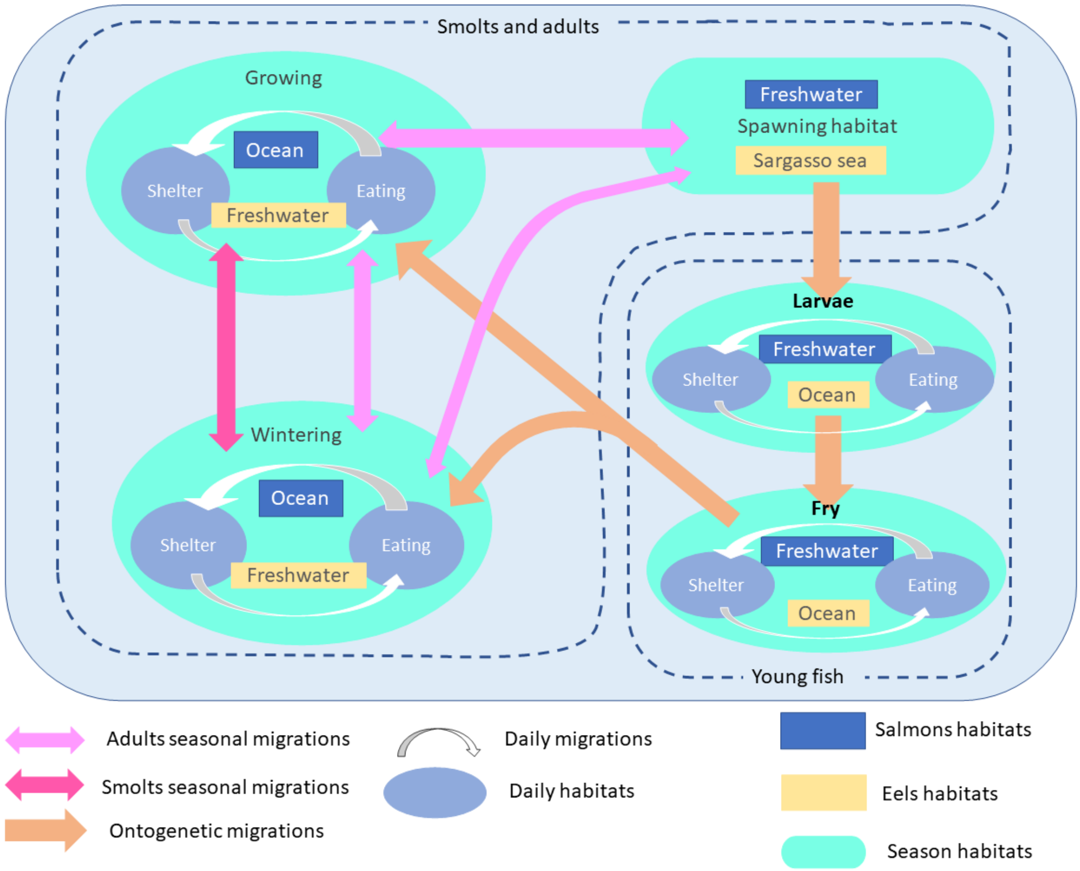


Figure 5 : Migration paths through life cycle of fish from (Philippe 2021). For Salmon (anadromous), and eel (catadromous specie), specific migrations paths and localization are represented.

The river fragmentation by hydropower dams leads to several impacts on the fish communities (Figure3). Change in these communities are mainly caused by variation in river connectivity (Geist, 2021)

One main consequence of dams on river fragmentation and aquatic biodiversity is that they are blocking migration road of fish. Some species need very specific habitat requirements, *Salmo trutta* needs habitat enough loose and oxygenate or *Esox Lucius* need vegetation areas. While other species (like *Rutilus Rutilus, Abramis brama)* for which the migration are not a requirement for a successful reproduction. The migration path is both upstream and downstream, and both are impacted by river fragmentation (Noonan et al., 2012). The impacts during the downstream movements can be an increase in injuries, which can lead to a direct or indirect mortality. This can be attributed to an entrainment of fish, particularly small fish and larvae, into the turbines (Baudoin et al., 2014; Fjeldstad et al., 2018; Geist, 2021). For large dams, the downstream passage rate can be considered as almost null (Wu et al., 2019). The presence of dams will not only completely block the migration it can also delay it, which can have consequences on spawning, because too much energy has been consumed to pass the obstacle or it is too late for spawning (Baudoin et al., 2014).

River fragmentation can also lead to a loss of habitat, for example spawning, feeding or shelter habitats. A loss of habitat has consequences on the different stages of life, and may have affect reproduction and feeding, which can be a reason in species richness and diversity decline (He et al., 2021; Khedkar et al., 2014). The impacts of the hydropower dams will depend on the species, and the localization and type of the habitat loss.

Population fragmentation is another consequence of river fragmentation (Fjeldstad et al., 2018; Khedkar et al., 2014). For example, Chinese sturgeon (*Acipenser sinensis*), Yangtze sturgeon (*A. dabryanus*) and Chinese paddlefish (*Psephurus gladius*) populations declined after dam closure at Gezhouba Dam in China (López-Pujol & Ren, 2009). Loss of genetic diversity has also been observed following fragmentation of rivers through dams (Khedkar et al., 2014; Lopes et al., 2014). The different fragments of the river may completely separate the fish population into different groups, limiting gene movement between the different populations in the river. As a result, genetic differentiation between upstream and downstream populations can be observed (Baudoin et al., 2014; Khedkar et al., 2014; Lopes et al., 2014; Wu et al., 2019). These changes in genetic diversity can then lead to inbreeding, a reduction in the size of the population and direct or indirect extinction (Khedkar et al., 2014). The genetic change will take place over several generations following the closure of the dam and the fragmentation of the river (Wu et al., 2019). This project will not use genetic effects on the fish community to assess the effects of river fragmentation on fish, as there is no framework or methodology for using genetics in LCIA (Curran et al., 2011). However, the genetic studies show the importance of the time after the closure of the dam for the level of impact, which may be higher if the river has been fragmented for a long period of time. Variation in species biomass and taxa richness varies with time since dam closure, increasing shortly after and then decreasing.

A decrease in river connectivity can lead to a decrease in food resources (He et al., 2021).

Extinction can occur as a direct or indirect consequence of river fragmentation, as in the case of the Yangtze river dolphin (*Lipotes vexillifer*)(Turvey et al., 2007). It may occur because the species has declined in abundance or genetic diversity, or because the habitat is unsuitable. Even if none of the articles clearly expresses an extinction due to mortality or due to difficulties in spawning and feeding. These two consequences have been included in the framework because a significant mortality of a species can lead to the local extinction of a population or a species, and if the species is unable to feed itself or to carry out an important reproductive activity, the species will decline and may become extinct.

2.2 River connectivity index

2.2.1 Choice of the index

As the goal of this study is to calculate mid-point characterization factors of river, focused on river fragmentation and fish biodiversity at a basin scale, it was decided to use river connectivity index that take in account all the dams already on the river. The dendritic connectivity index (DCI) (Cote et al., 2009) is one of the index that was used to calculate the river connectivity, first because most of the index found were based on this one (CCI (Rodeles et al., 2020), RCI (Grill et al., 2014) and CAFI (Jumani et al., 2022)), also because two values can be calculated one for the potamodromous fish the other for the diadromous fish and both of them are affecting in a different way by river fragmentation. The final reason is that the data for the DCI index are easier to find as only the length is needed, not the volume, the area, or the biological index. DCI index is considering both downstream and upstream passability in opposite of habitat connectivity index for upstream passage (HCIU) (McKay et al., 2013).

The DCI (Cote et al., 2009) is a calculation of the connectivity of the river as a whole. It calculates the average connectivity of the different sections, and the value is the probability that fish can move from point i to point j. The probability depends on the length of each reach, the distance between two obstacles, the total length of the river and the passability of each obstacle. The DCI considers upstream and downstream passability. The DCI formula varies depending on whether the fish are potamodromous or diadromous. The main difference between potamodromous and diadromous fish is that in the case of diadromous fish, the DCI is the weight average of the probability of migration from the estuary into a reach. For potamodromous fish the DCI is based on migrating from one point to another. The formulas used are:

$$DCI_P = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} \frac{(l_i * l_j)}{L * L} * 100$$

For the potamodromous fish, with n the number of sections (e.g., the number of barriers plus one), L the total length and l_i the length of the section i. c_{ij} is the probability to pass the barriers between the section i and the section j.

$$DCI_D = \sum_{i=1}^{\mathrm{n}} \frac{(l_i)}{L} \prod_{m=1}^{M} (p_m^u p_m^d) * 100$$

For diadromous and if the probability to cross successive barrier is independent. With M the number of barriers between the mouth and the section i and p_m^u the probability to upstream migration of the barrier m and p_m^d for the downstream migration.

These two equations show that the first barriers will have the greatest effect. It also shows that a barrier at the mouth would have a greater effect on diadromous fish, which would have to pass through the first barrier to access each section. And in the case of potamodromous fish, a barrier in the centre of the river will have a greater impact than on diadromous fish, because the length of the longest region will be lower if the dam is in the middle of the river and not at one of its extremities.

HCIU (McKay et al., 2013) was also used to calculate the connectivity index of rivers in Europe. This index is based on a graph theory and does not need any information about the length, the size or the flow of the river only the network of the river, from is main channels to all its affluents. This index can be assessed for several species as the same time, which need less data about the capacities of passing an obstacle for the different species present in Europe and will give values that can be used in LCIA without doing any more aggregation.

$$HCIU = \frac{AH}{TH}$$

With AH the accessible habitat and TH the total habitat

$$AH = \sum_{i=1}^{n} AH_i = \sum_{i=0}^{n} UH_i * cp_i$$

With UH_i the upstream habitat of the node i, the possible values are 0, 1 or 2 and it is determined with the adjency matrix. n the number of nodes in the river and

$$cp_i = p_i * \prod_{j=1}^{i-1} \partial_{j,r} * p_j$$

With p_i the passability rate of node i, r the road from the mouth to node i, it is a list of nodes between these two segments, and $\partial_{j,r}$ the Kronecker delta equal 0 if j not in r and equal 1 else.

$$TH = \sum_{i=1}^{n} UH_i$$

River fragmentation concerns diadromous fish, which can need to cross all the river for their reproduction, as well potamodromous fish, which have daily or seasonal migration moves through the river with different distances, from some centimetres to kilometres. Consequently, when the river fragmentation is quantifying it is important to take in account all the species that will be affected by dams. Most of the index are only evaluating the fragmentation for diadromous fish and are not taking in account both upstream and downstream movements, like the HCIU index.

All these connectivity indexes have values ranging from 0 to 1, with a connectivity index of 0 meaning that the river is completely fragmented and that no fish can move inside the river. The value is 1 for all the index if there is no dam in the river or if all the dams can be passed for all fish. For DCId and HCIU the value is 0 if a dam is located to the mouth of the river with a passability of 0. The value cannot be 0 for DCIp, because fish can always move inside a region of the river.

2.2.2 Dam passability

Even if the connectivity index is calculating for the whole river, its value depends on the passability of all dams in the river in addition of the localization of them. Each specie has different competences for passing a dam, for example eels can climb on a vertical wall, some species can easily jump over low obstacles (Baudoin et al., 2014; Patrick B. Cooney & Thomas J. Kwak, 2013; Sheer & Steel, 2006). But for this project, it was decided to only take one value of passability for all the species. This was made for several reasons, first to use passability values depending on each specie it is necessary to know which species are located at every dam which will need more data and can increase the uncertainties, then after having the value for every species for each river it is necessary to have an average of these values with a weighting scheme. Both of these can increase the precision of the CI value but can also increase the uncertainties, as some values can be missing for some species or the presence or not of species can be affected by how the data are identifying.

The presence of a fish pass at the dam is not taking in account. Because first the dataset used does not have information about it, then because fish pass are not always successful for both upstream and downstream migration and are more often mainly concerning salmonoids (Noonan et al., 2012; Reid et al., 2019). So, the dam passability is only depending on the height of the dam. If the dam was higher than 25.7m the dam was considering as impassable (Patrick B. Cooney & Thomas J. Kwak, 2013), then if the dam was lower of 2m the dam was considering as fully passable because according to Baudoin et al. all the species can jump higher than 2 meters (Baudoin et al., 2014). If no height was found in the dataset, it was supposed that the dams were relatively small, but not necessary under 2 meters so the passability was put at 50% and finally for all the other situations it the passability values are 30%.

2.2.3 Fish ladders

Dams can have fishways with the goal to facilitate the migration of fish. Different systems exist, such as, pool and weir, pool and slot, denil and fish locks or elevators. Most of fishways are designed for upstream migration and for a specific species, which makes it less efficient or impassable for other species. Noonan et al. (2012) estimate that the mean efficiency of fishways is 41.7%, but important disparities are observed between upstream and downstream migration and if the species are salmonoids or not, so the passage rate varies from 21.1% to 74.6%. Fishways limitations of use are delay in migration, not enough attraction of the species to the fishways (Noonan et al., 2012), fishways are only taking in account fish not other species that also need to migrate through the river (Reid et al., 2019). Sometimes the fishways are not working at all and can be qualified as "failed technology (Reid et al., 2019). As mortality happens through fish migration, fishways do not need to be fully passable to be considered as efficient, if the passage rate is over 90% the fishway is judge efficient (Fjeldstad et al., 2018; Noonan et al., 2012), as the dams are less blocking downstream movements, so studies about downstream migrations are missing. And the absence of easier downstream migration through fishways can lead to an important mortality of fish that is linked with it size (Fjeldstad et al., 2018).

Data on fishways presence and efficiency are often missing from dams' databases. The efficiency of fishways depends on the localization, the species how it is built, so analysis need to be done for each dam. The complexity to have data on fishways and the uncertainties about their efficiency made me choose to not take in account the presence of fishways.

2.2.4 Index and basin values

The connectivity index values will be used in a LCIA so an index was used in order to obtain values between 0 and 1, with an index of 0 that signifies no impact and 1 that the river is completely fragmented.

$$\text{Index} = 1 - \text{CI}$$

The three index values, with HCIU, DCIp and DCId, were calculated for each river then an average for each basin was made with a weighting made by the length of the river (Barbarossa et al., 2020; Grill et al., 2014). Finally, the mean of each basin was divided by the whole hydroelectricity production in the basin.

$$Index_{basin} = \frac{\sum index_i * L_i}{L * E}$$

With $index_i$ previously define as the value of the index for the river i, L_i the length of the river i, L the total length of the basin and E the hydropower electricity production in the basin. Index basin is in kWh^{-1}.

2.3 Data

2.3.1 Hydropower in Europe

In 2021, for the whole Europe hydroelectricity was the largest source of renewable energy with more than 16% of the whole electricity that is from hydropower (BP, 2022). But there are differences between whole of Europe and the European Union (EU), where hydropower is the second source of renewable energy, in 2022, after wind power, with respectively 33

% and 36% of renewable energy production (Eurostat, 2022). Hydropower capacity installed in Europe is 248.6 GW (Wagner et al., 2019) with a production of around 650 TWh (BP, 2022). However there are important disparities in Europe on hydropower generation and proportion of electricity production, from almost 100% in Norway to no hydropower in Malta (BP, 2022; *Yearly Electricity Data*, 2022). The three countries with the highest capacity are Norway, Turkey and France (BP, 2022; Wagner et al., 2019).

In the EU, there is a directive with a goal of a "good ecological status" of rivers, and that favours dam's removal across the EU, so hydropower capacity may reduce in the coming years (Wagner et al., 2019).

As in the rest of the world, development of hydropower can overlap with rivers with important freshwater biodiversity, that is observed in the Republic of Georgia (Japoshvili et al., 2021).

2.3.2 Dams

The project is focusing on river and dams in Europe as there are the easiest and most complete datasets to acquired. The localization of the dams is from the JRC hydro-power database (European Commission, Joint Research Centre (JRC), 2019), which is the most complete database at an European level. This database is identifying both dams and run-of-river (ROR) hydropower plants, the ROR plants were deleted for this study, which only focusing on dams. So, 2120 ROR were deleted, and 2062 dams can be used. The dams are separated in two reservoir based and pumped storage plants.

The goal of this project is to have a mid-point characterization factor (CF) that quantifies the river fragmentation due by hydropower dams and its consequences on the aquatic biodiversity. The CF need to be in GWh^{-1} at a midpoint However, the JRC database does not provide hydroelectricity generation for most of the dams. Thus, the hydroelectricity productions are from the global Database of power plant (World Resources Institute et al., 2018), which have the estimated generation in GWh for several years for most of the plants that produced hydroelectricity. Only the plants with hydroelectricity as the primary fuel was selected in this study, there are 7151 power plants with hydropower as primary fuel all around the world on 34936 power plants, hydroelectricity power plants represent 20,5% of the plants globally. There are 24 277 on 34 936 power that are not situated in a basin in Europe, some of them are plants that produced electricity for Europe but that are situated in the sea, or the ocean so not taken in account. And on the 10659 power plants situated in the basins 2100 have hydroelectricity as the primary fuel.

Then with ArcGIS pro(ESRI, 2022) the plants were associated with the basin it belongs to. And finally for each basins the electricity generated in 2019 was summed.

2.3.3 River and basins

In order to calculate the river connectivity index, a database with the river data, localization, length, nodes, are needed. As well, in LCIA, the CF are not calculated specifically for each river but at a basin level. Therefore, first basin delimitation from GSGM was used as it is the basin delimitation commonly used in LCIA, and "a basin is defined as an area draining to a common outlet" (Pierrat et al., 2023). But, the river description from the ECRINS database (European environmental agency, 2012) was not consistent with the GSGM database, some rivers were on two basins or several rivers can be on the same basin. To this extent, the basin delimitation from ECRINS database was used for calculating the CF. Those basins can have several rivers in their delimitation although a river was never crossing two basins. The localization and the path of the river are from the European database ECRINS which covers all the rivers in Europe.

With the JRC database and the basins from the ECRINS database only basins with dams were selected (on ArcGIS Pro), so 53 basins on 117 were deleted. Then two basins were also deleted even if they have dams because they cover several basins at different places in Europe. On Figure 6, the different Europeans basins and dams from ECRINS and JRC datasets are shown, also the utilization or not of the basins or dams in this project is shown.

Then only the main drain rivers which represent 1484 rivers and will reduce the risk of error from the database, like two small rivers that have the same id located in the same basin or not or segments that are missing between two parts of the river. 385 rivers have no id so they are not used. There are 1 090 704 segments link to main rivers on 1 170 727 segments in total, so the study takes in account 93% of the segments. To calculate the river CI, the dams need to be added to the rivers, thus with ArcGIS Pro a spatial join with match option as the closest within a distance of 2600m. This distance was chosen because most of the dams with a longest distance to the closest dam are located on non-main river. Only the rivers that are in the 63 basins with dams where the CF will be calculated have their CI calculated, in consequence 562 rivers on the 1484 were not used because not present in the basins. In the ECRINS database there are some errors: three rivers with a dam have a missing segment between two parts of the river, they are all in different basins and one river is separated in two at the mouth which is not working in the code. This river is also in a distinct basin. Finally, one basin is also excluded because of error in the database. And for 3 basins a river segment was manually added to be able to calculate the CI.

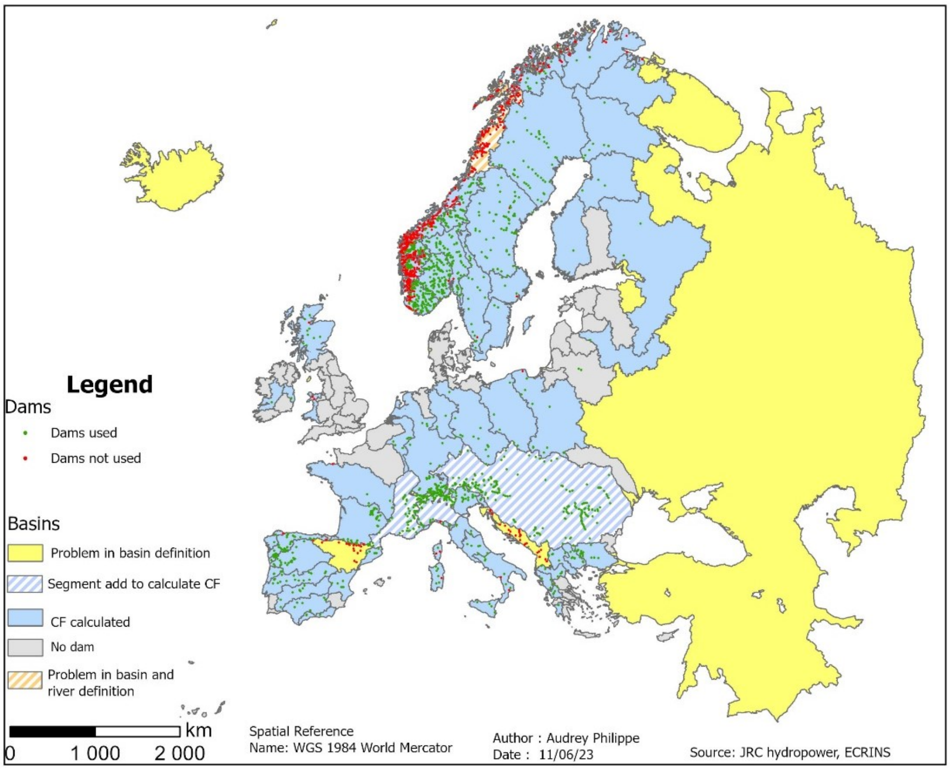


Figure 6: Map of the european basins and dams used in this thesis, it shows the different status of the basins and dams for this master thesis

2.4 Coding

All the river CI calculations were done in Python 2.7 or Python 3.8.3, with the libraries pandas, numpy, sql3. The code is in supplementary file.

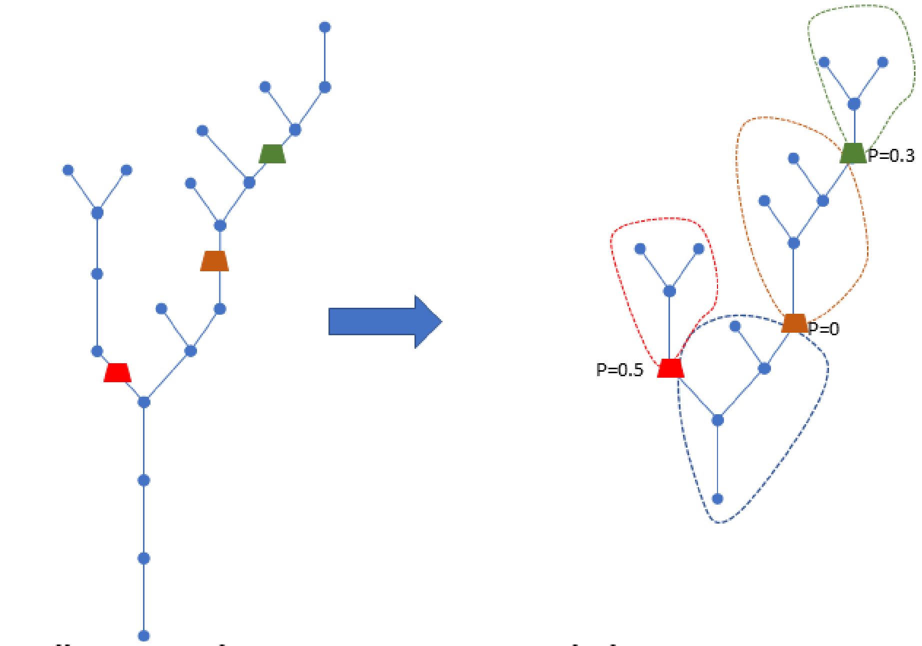
In the ECRINS database the rivers are represented by segments and nodes. Each segment is a straight line between two nodes and each node will be connected to one to three segments. If a node is only connected to one segment that signifies that this segment is at the mouth of the river, the node is the down node of the segment, or the segment is at one end of the river, the node is a up node of the segment. If the node is linked with three segments the node is at a place where the river separates in two and there are tributaries in addition of the main steam, thus the node is an up node for one segment and down node for two segments. For these two cases, no modification in the data needs to be done in order to calculate the different river connectivity index. In the last case, a node connects with two segments, that signifies that the river is running both downstream and upstream, it is often done when the river is changing direction in order to follow the shape of the river. When I am calculating river CI, I only need to know the length of the segments and the different branches that will continue after the segments. When the nodes were between two segments, the segments dataset were modifying by deleting the upstream segments until there are not two branches and the length of the different segments were added, and the upstream node was modified. Hence, at the end of this step the segments dataset is only composed of segments that have zero or two segments upstream.

Then, the dams present in this river need to be add in the dataset. Another database was used for the dams where the closest segment from the initial database of the river is known. With this database and the modify one for the river, dams were added by creating new segments where the dam is the down node, and the up node is the up node of the segment where the dam is. The segment of the river, where the dam is added, has now the dam node as up node, and only one segment upstream. The new segment created has two segments upstream, the two that were upstream of the initial river segment. Then for both of the segments the length is half the total length of the segment. It is only in the case there is a dam in the segment that river segments can have only one upstream segment, and it is always the case.

After the dams was added to the river segments dataset, the adjency matrix need to be created. For the HCIU formula, all the habitats, represented by each segment, need to be known and in the adjency matrix. In this case, the adjency matrix is a square matrix with the size of the number of segments, and for each column the values are 0 if the segment is not linked and downstream of the segment in the row and 1 in the other case. As the HCIU is calculated with the number of accessible habitats, for each segment the cumulative passage rate needs to be calculated, this cumulative passage rate depends on the previous cumulative passage rate and the passability of the next node, which can be a dam or only a bifurcation (passability =1). Finally, the adjency matrix sum every column, the vector will have values equal to 0, 1 or 2. And each value of the vector is multiplied by the cumulative passage rate of the segment and this result is summed and the accessible habitat is obtained.

For the DCId and DCIp, the CI is calculated from regions, with each region that represents a part of the river between 2 dams, or between 1 dam and the end or the mouth of the river. So, with the river segments dataset with the dams, a new matrix is created that which regroup all the regions with the total length the passability to enter this region and the regions upstream. With this matrix the DCIp and DCId can be calculated by taking in account for each region which region can be joined and with which passability.

All the different steps for the 3 CI are shown in the Figure 7.



Adjency matrix

$$
\begin{pmatrix}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0\\
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0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0
\end{pmatrix}
$$

Cumulative passage rate

(1 1 0.5 0.5 0.5 1 1 1 0 0 0 0 0 0 0 0)

Upstream habitats

(2 1 2 0 0 2 0 1 2 0 2 0 1 2 0 0)

Accessible habitats

(2 1 1 0 0 2 0 1 0 0 0 0 0 0 0 0)

Total habitat: 15

HCIU= 7/15=0.47

Region matrix

Id	Length	Passage rate	Number of accessible region upstream	Region 1	Region 2	Region 3
Blue	904	1	3	Red	Orange	Green
Red	3810	0.5	0			
Orange	63024	0	1	Green		
Green	587	0.3	0			

Figure 7: Framework of river connectivity index calculations

3 RESULTS

3.1 Rivers connectivity index values

3.1.1 Proportion of rivers fragmented by basin

In all the basins where the connectivity index was calculated there are 524 rivers and 170 rivers, 32,4% of the rivers, have at least one dam. A connectivity index different of 1 signifies there is one or more dam in this river. The proportion of rivers with at least one dam by basin vary between 0 and 100%, with a mean at 41,9% of rivers in each basin that have a dam. Only one basin, in Great Britain, has dams in the basin but not located in the main rivers so the CI for this one is 1. On the 62 basins 10 have all the main rivers that are fragmented by hydropower dams. The number of basins with less than 50% of rivers fragmented by dams are 48 (Table 1) which is most of the basins. However, if the same work is done on the length of the rivers, the proportion is also between 0 and 100% for the same basins as previous. But the second lower proportion is 15.6% and not 5.3%. and 49 basins have more than half of their total length that are considered as fragmented, as it can be seen inTable 1. In average, the proportion of length of rivers with a dam compared to all the river length is 75.7%. Except for one basin, all the basins have a higher proportion of length that is fragmented than the number of rivers proportion (Figure 8). That signifies that the dams used to calculate the CI are mainly on the longest rivers.

Table 1: Proportion of fragmented length and rivers in basins

	0-25%	25-50%	50-75%	75-100%
Proportion river	26	22	3	11
Proportion length	3	10	12	37

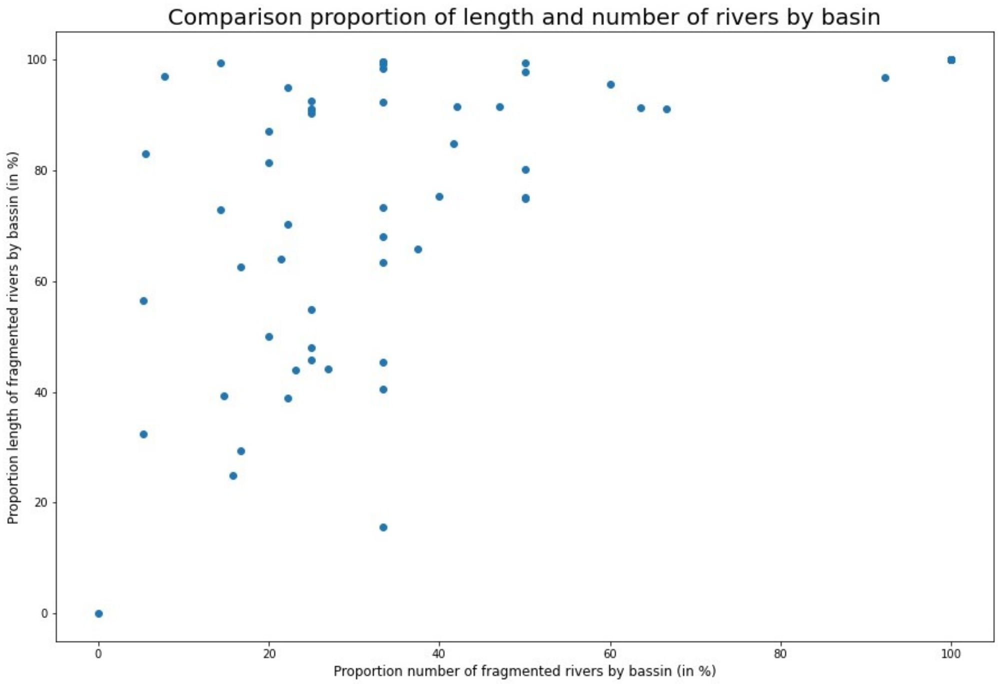

Figure 8: Comparison of length proportion of fragmented rivers with the proportion of rivers fragmented in each basin

3.1.2 Specific river values

While looking into river index (1-CI) values, for rivers with dams, for the three CI methods, all of them are ranging between almost no loss of connectivity, respectively 0,04%, 0,1% and 0,05% for HCIU, DCIp and DCId, and an almost complete loss of connectivity, respectively 99,88%, 95.409% and 99.90% for HCIU, DCIp and DCId. Even if the river with the lowest loss of river connectivity is the same for both DCIp and DCId, and with a low value for HCIU (0.056%) and the river with the lowest value for HCIU the dendritic connectivity indexes are low as well.

For the highest loss of river connectivity, the river is different for all the methods. And it can have important difference in CI between the methods used for diadromous fish (DCId and HCIU) and the one for potamodromous species (DCIp), for example the river with the highest value for HCIU have a value of almost 57% for DCIp but the value for DCId is very high, it is the second most fragmented river with this method. This is explained, in this case, by the presence of a high dam (almost 200m height) close to the mouth of the river, so all the river is blocked for HCIU. For the DCIp, the movements inside each region are taken in account, that explained the lower fragmentation for this CI. And for DCIp even if several dams are along the main part of the river the non-main parts of the river are still accessible, for example if the height of the dam is not mentioned. For the most fragmented river according to DCId, the same thing is observed with the HCIU value corresponding to its third highest value and for DCIp the value is almost 56%.

The highest fragmented river according to DCIp is also highly fragmented with the two other index. These values are obtained because there is a high dam at the beginning of the river, so the river is inaccessible for diadromous fish for which the level of fragmentation is evaluated through HCIU and DCId. This river has a lot of dams through all the river which also block the movement of potamodromous fish, their ability to move is calculated with DCIp.

3.1.3 Diadromous species

For DCId and HCIU index, most of the rivers have very low fragmentation values, respectively 36% and 38% of the rivers fragmented less than 20%, or high fragmentation with 32 and 28% of rivers fragmented at more than 80%. For DCId, there are less rivers that are fragmented between 20 and 80% than those fragmented less than 20% or those more than 80% (Figure 9.d).

No link between the numbers of dams or the number of dams by kilometre of the river and the index values was found. As one dam can completely fragment the river or not at all. But globally, if the number of dams in the river increase higher the index is, with one exception for a river with 67 dams all located at the end of the river.

One dam can fully block all movements for diadromous fish, so adding a dam whatever the height is, will not have more consequences on those species.

3.1.4 Potamodromous species

The river fragmentation values calculated with DCIp method are lower that with the other methods with 35% of the rivers that have a CI value lower than 20% and only 8.8% of the rivers with a CI value superior at 80%. And the number of rivers that have CI value in each fifth of CI possible value (between 0 and 1) is globally decreasing as the CI value getting higher. Cote et al. also observed that for DCIp the connectivity index is never equal to 0 (1 with our index) (Figure 9.d). And to obtain a CI lower than 0.2 (0.8 with our index) the passability of dam must be lower than 80%, and the number of dams should be more than 5 if all the barriers have no passability or higher than 10 if the passability is 60% (Cote et al., 2009).

There is no correlation between the number of dams in the river or the number of dams by km of the river and the value of the CI calculated through DCIp. Even if when there are more than 10 dams in the river the CI is higher than 0.25, except for one river, and that the river with the most dams (215) is not in the 10 rivers with the highest loss of longitudinal connectivity. The river is less fragmented than other even with the important number of dams because dams are often located close to each other in several area along the river or at the end of the river, which allow an important length that is not fragmented. The river with 67 dams, with a DCIp index with a value of 17.31%, has all its dams situated at the different end of the river. That shows the importance of the localization of the dam in the river with dams located at the extremities of the river reduce less the longitudinal connectivity for potamodromous fish than dams in the middle of the river.

So, hydropower dams can impact potamodromous species from almost no consequence to fully fragmented river with a linear increase. Each new dam can have a new impact on these species and depending on where it is located the impact will me more or less important.

3.1.5 Comparison

We can see that DCId and HCIU have in general closest results. And with DCId that can considered some rivers more fragmentated than HCIU, up to 25% more, especially for fragmented river with a value between 30 and 70%. Some rivers have a highest value for HCIU than DCId but the difference is lower than previously. (Figure 9.c)

By comparing both DCId and HCIU with DCIp, we can see that if the index for the river is low for DCId or HCIU it will also be the case for DCIp (Figure 9.a and Figure 9.b). The difference between diadromous index and DCIp will start for values higher than 0.4 and 0.5 respectively for HCIU and DCId. There is a little bit less differences between DCId and DCIp than DCIp and HCIU, it may be explained that the two dendritic connectivity index are calculated with the river length. We can see that for index for diadromous species, and values between 0.9 and 1, DCIp values can be between 0 and 1. (Figure 9.a and Figure 9.b)

So, if the river is not affected for diadromous species, it will not be fragmented for potamodromous species. However, rivers can still have a high connectivity value, an index close to 0, for potamodromous fish and be totally or almost totally fragmented for diadromous species. If the connectivity index is calculated only for diadromous species the final results can be worse than reality if all the species are then taken into account.

DCIp is the method that have more differences with the other methods, it is explained because with this index all the movements possible along the river are taken into account. For example, one dam situated at the mouth of the river will completely fragment the river for diadromous fish but if there is no other dam the value of DICp is low (5.9%). This important difference is mainly observed when the number of dams is 1 or 2, even if only 1 dam can be fragmented with a value higher than 40% according to DCIp.

By comparing the values of HCIU, DCIp and DCId for all the rivers with dams, DCId values and HCIU are closest. As both HCIU and DCId are calculated for movement in the river from the mouth, however only upstream for HCIU while DCId is looking for both upstream and downstream movements. And DCIp for both upstream and downstream movements inside the river. So, the different dams characteristic, as well their localizations and their height, will have different values for the different CI methods.

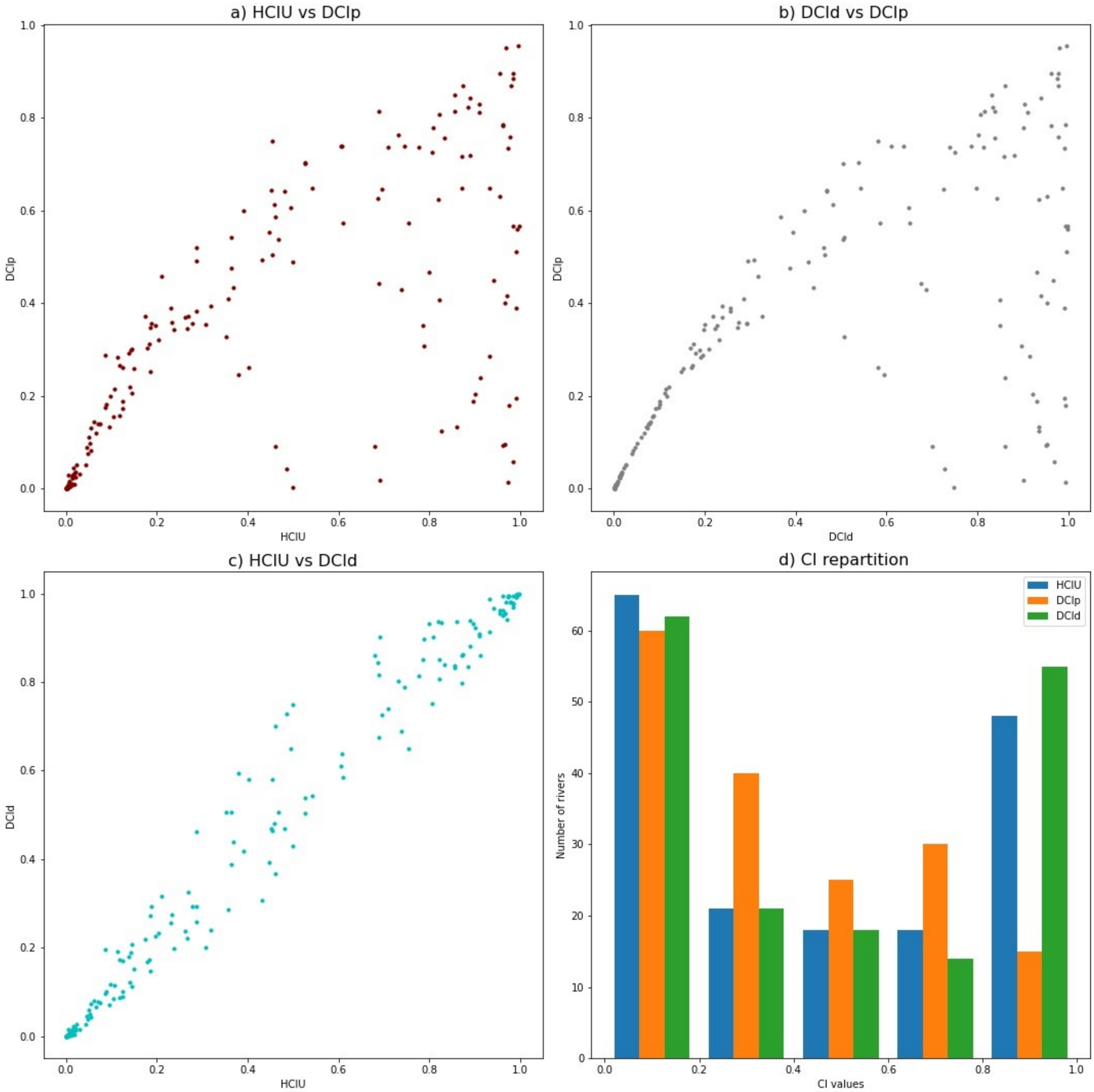

Figure 9: Rivers connectivity index, comparison of HCIU and DCIp (a), comparison of DCId and DCIp (b), comparison of HCIU and DCId (c) and the number of fragmented rivers for each CI for each 20% steps (d)

3.2 Basins connectivity index values

As in LCIA is not the fragmentation of each river that will be used during LCA calculations but the values at a basin scale, that will also take into account the rivers that are not fragmented in each basin. In this chapter, the three CI values by basins will be presented without taken into account the electricity production.

3.2.1 HCIU

CI values, calculated with HCIU, are going from 0, with the basin that have no dam on the main river, to 97.1% (See appendix for all the values). This basin as only rivers that have dams, and the longest river is almost completely fragmented (CI =99.5%). The most fragmented basins in Europe according to HCIU calculations are located in Southern Norway, Spain and Portugal, Sweden and the Elbe, Danube and Daugava basins. The less fragmented basins are in the UK, Ireland, Italy, West of France, Northern Norway, Southern Sweden and Meuse and Oder basins (Figure 10).

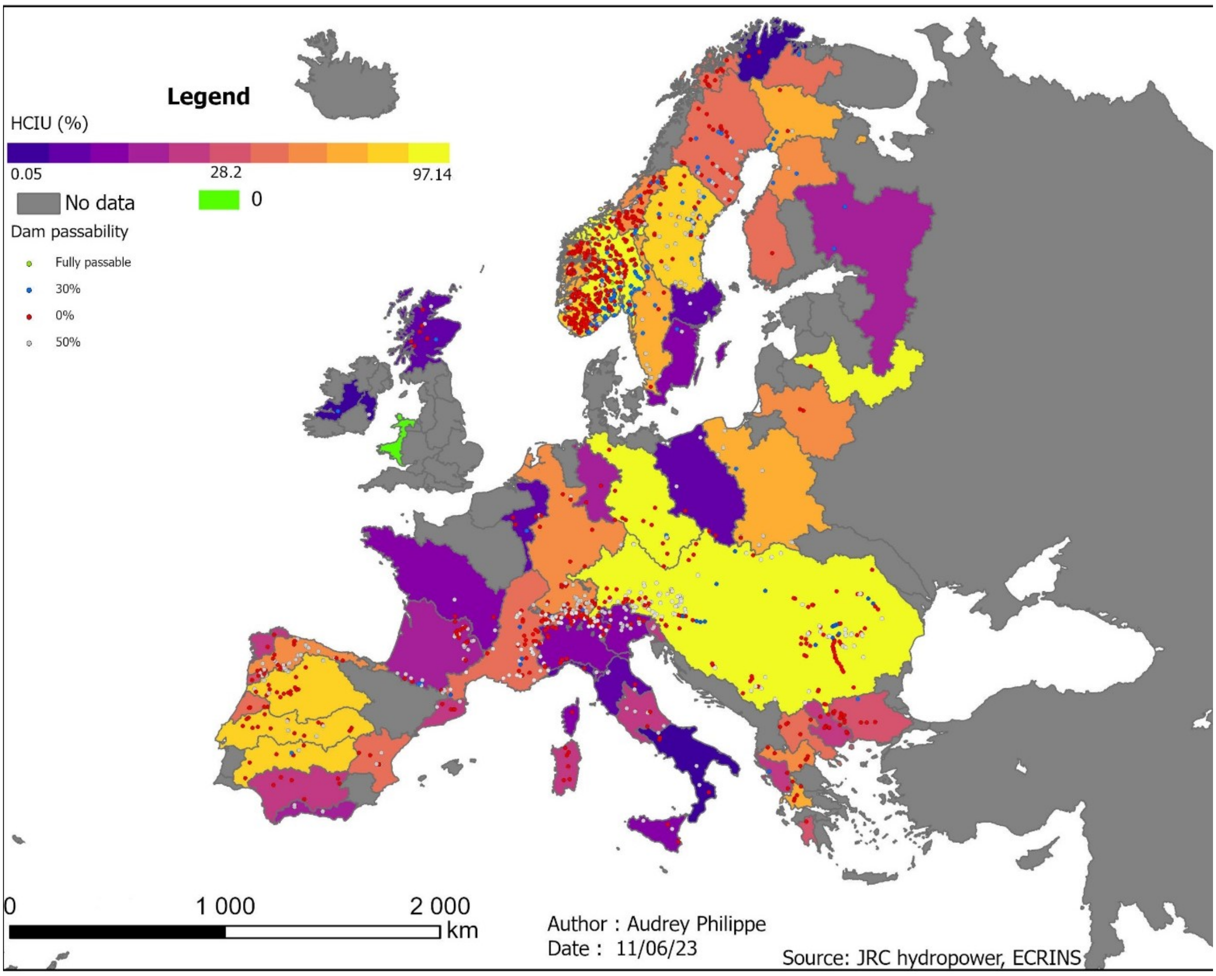

Figure 10: River connectivity index calculated with HCIU connectivity index. This map shows the river connectivity status of basins in Europe with hydropower dams and the basin that are not fragmented by hydropower dams.

3.2.2 DCId

Overall, the CI values with DCId are close to those with HCIU with the most and the less fragmented basins situated at the same place (Figure 11). However, some differences exist. Except for 2 basins the difference between DCId and HCIU by basins are less than 10 points, and 11 basins have a difference of more than 5 points between HCIU and DCId values. There are 30.6% of the basins that have a connectivity index higher than 50%, with 4 that have a CI between 94.5% and 97.3%. In the other hand 19.4% of the basins have their rivers fragmented less than 10% So, even if 53% of the basins in Europe have at least one dam, the majority of these basins are not highly fragmented (See appendix for the values).

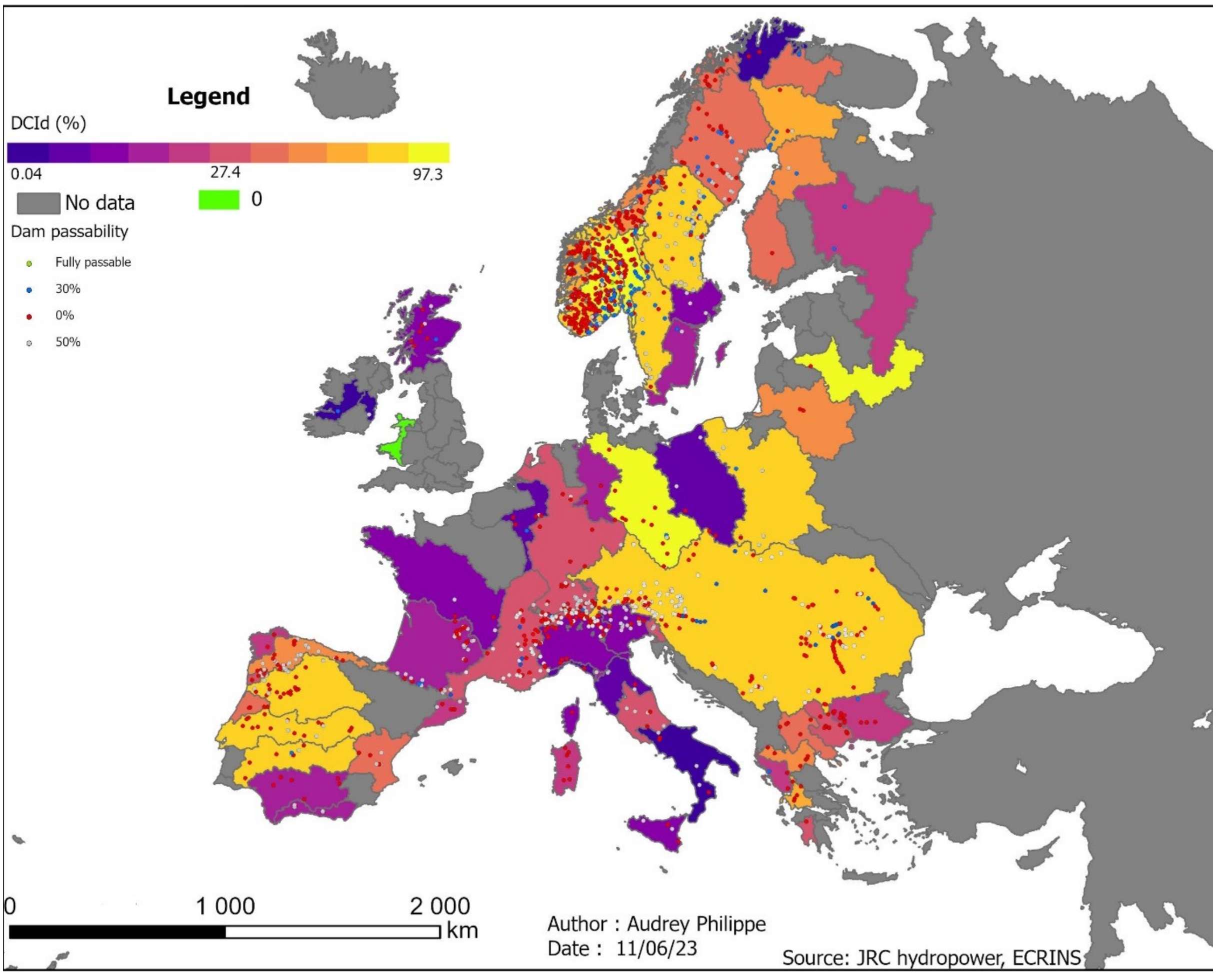

Figure 11 : River connectivity index calculated with DCId connectivity index. This map shows the river connectivity status of basins in Europe with hydropower dams and the basin that are not fragmented by hydropower dams.

3.2.3 DCIp

The results for potodramous fish are different than the two previous ones. There are 21% of the basins that are fragmented less than 10%, and also 13 basins (21% of all basins) that are fragmented more than 50%. The less fragmented basins are still located in Ireland, the UK and Italy, North West of France, Northern Norway, Meuse and Oder basins. For the most fragmented ones, there are still Southern Norway, Spain and Portugal, Sweden and Danube basins (Figure 12). However, some important differences exist. For example, the Daugava basin is one of the less fragmented basins with the DCIp calculations, the same is observed for the More og Romsdal basin even if the CI value with DCIp is higher than for Daugava basin. For the last basin the difference between diadromous species fragmentation and potamodromous species are higher than 80 points. In Sardegna, the DCIp values are almost three times lower than DCId and HCIU values. In some cases, the values of DCIp CI are higher, like in Rhine, Rhône, and Gironde basins. In Southern East Sweden the basins are always more fragmented for potamodromous fish, it can go to a fragmentation level twice higher.

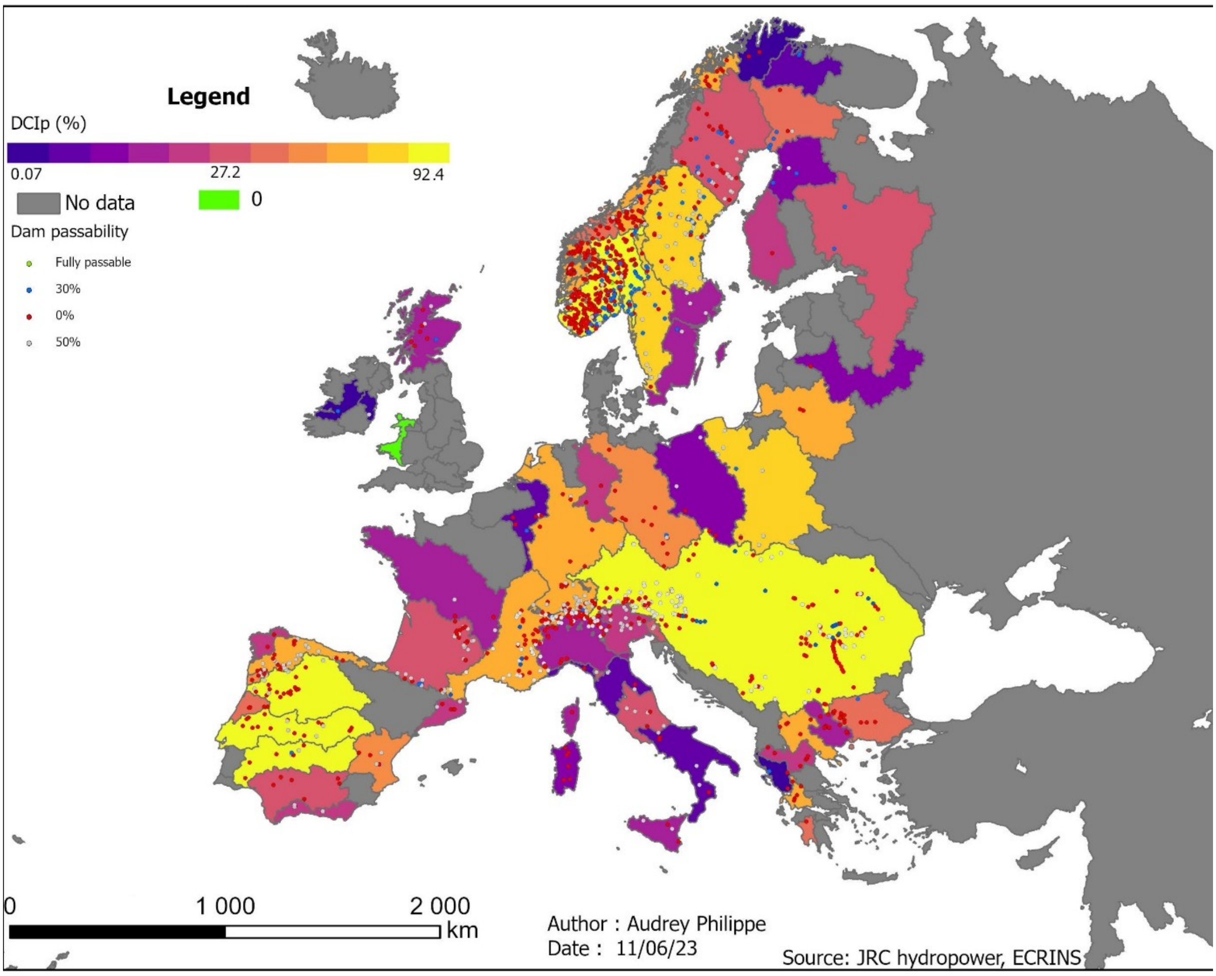

Figure 12 : River connectivity index calculated with DCIp connectivity index. This map shows the river connectivity status of basins in Europe with hydropower dams and the basin that are not fragmented by hydropower dams.

The basin the most fragmented is the same with the 3 methods, with the highest value obtained with DCId (97.3%) and the lowest value obtained with DCIp (92.4%). This basin is the Glåma basin in Southern Norway. If the basin that have no dam in main river is not taken into account, a basin in Ireland is the one that have the lowest loss of connectivity cause by hydropower dams for all the CI, with respectively 0.05%, 0.08% and 0.04% for HCIU, DCIp and DCIp.

3.3 Electricity production

As the inventory in LCA will be the electricity consumption in kWh, it is important to look to the electricity production from hydropower in the different basins in Europe. The reference year for hydropower production is 2017. The basins that produce the most hydroelectricity are the Danube (67 645 GWh) and the Rhône (53 202 GWh). Only two basins have a production lower than 100 GWh, one in Greece (36.85 GWh) and in Northern Italy (92.67GWh). The mean production of hydroelectricity is 7085GWh in 2017. The lower hydropower electricity production is mainly located in Southern Spain and Italy, Ireland. The basins that produced the most hydroelectricity are in Norway, Sweden, Garonne, Po, Rhine, Douro and Miño basins (Figure 13).

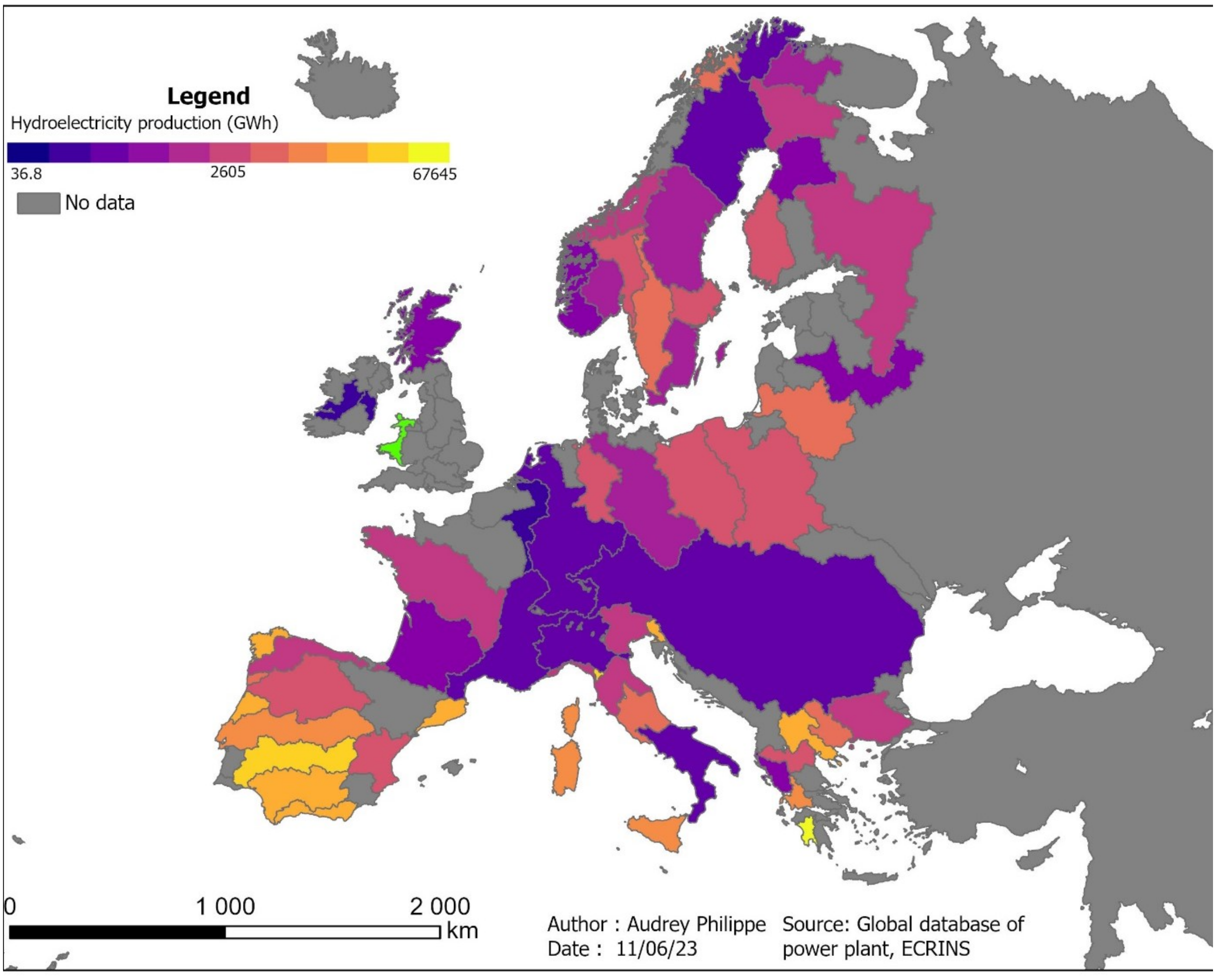

Figure 13 : Hydropower production in Europe in basins with dams in 2019

However, it does not exist a correlation between the CI, with the three methods and the energy production (Figure 14). High loss of connectivity can occur in basin with a low hydroelectricity production, but an important hydroelectricity production leads to a minimum of CI of 30% for potamodromous and diadromous fish species. On the 13 basins that are producing more than the mean hydroelectricity production, there are always only 5 basins (38.5%) that are on the 10 worst values of CI for DCIp, DCId and HCIU. And the 10 basins that have the lowest CI values are all in basins that are producing less than the average hydroelectricity production, expect one.

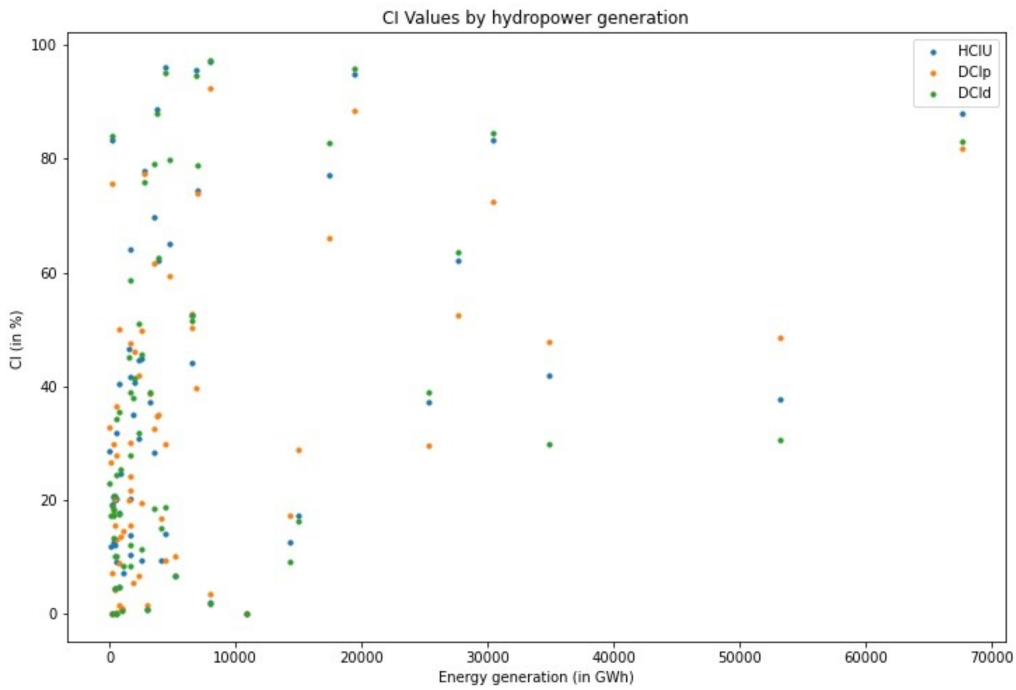

Figure 14 : Comparison of the three CI of each basin with the hydropower generation

3.4 Mid-point characterization factor values

3.4.1 CF with HCIU

The characterisation factors calculated with the CI HCIU have values between $1.88*10^{-6}$ CI/GWh, in Ireland, to $7.77*10^{-3}$ GWh, located in Greece, with an average value of $3.73*10^{-4}$ CI/GWh. The basin in Ireland has only one river that is fragmented and the CI of this river is only 0.06%. So even if it is the basin with one of the lowest hydropower productions it is still the basin with the lowest CF. However, the 6 basins with the highest CF are basins where hydropower production is among the 10 lowest. And in the next 4 basins with high CF 2 are among basins with the lowest hydroelectricity production. In the 19 basins with the lowest CF there are the 10 basins with the highest energy production. So, a high level of fragmentation can lead to a relatively low level of fragmentation by GWh, like in the Danube basin or in Norway and Sweden. The basin the most affected by GWh is the basin with the lowest hydropower production, and the CF_{HCIU}=28.6%

The basins that are the most affected by river fragmentation are in Southern Europe, in Spain and Portugal, Vardar basin, Sardinia and Greece. The less affected are the Danube, Rhône, Meuse, Garonne, Rhine, and Po basins, and in Ireland, the UK, Southern Italy and Northern Sweden (Figure 15).

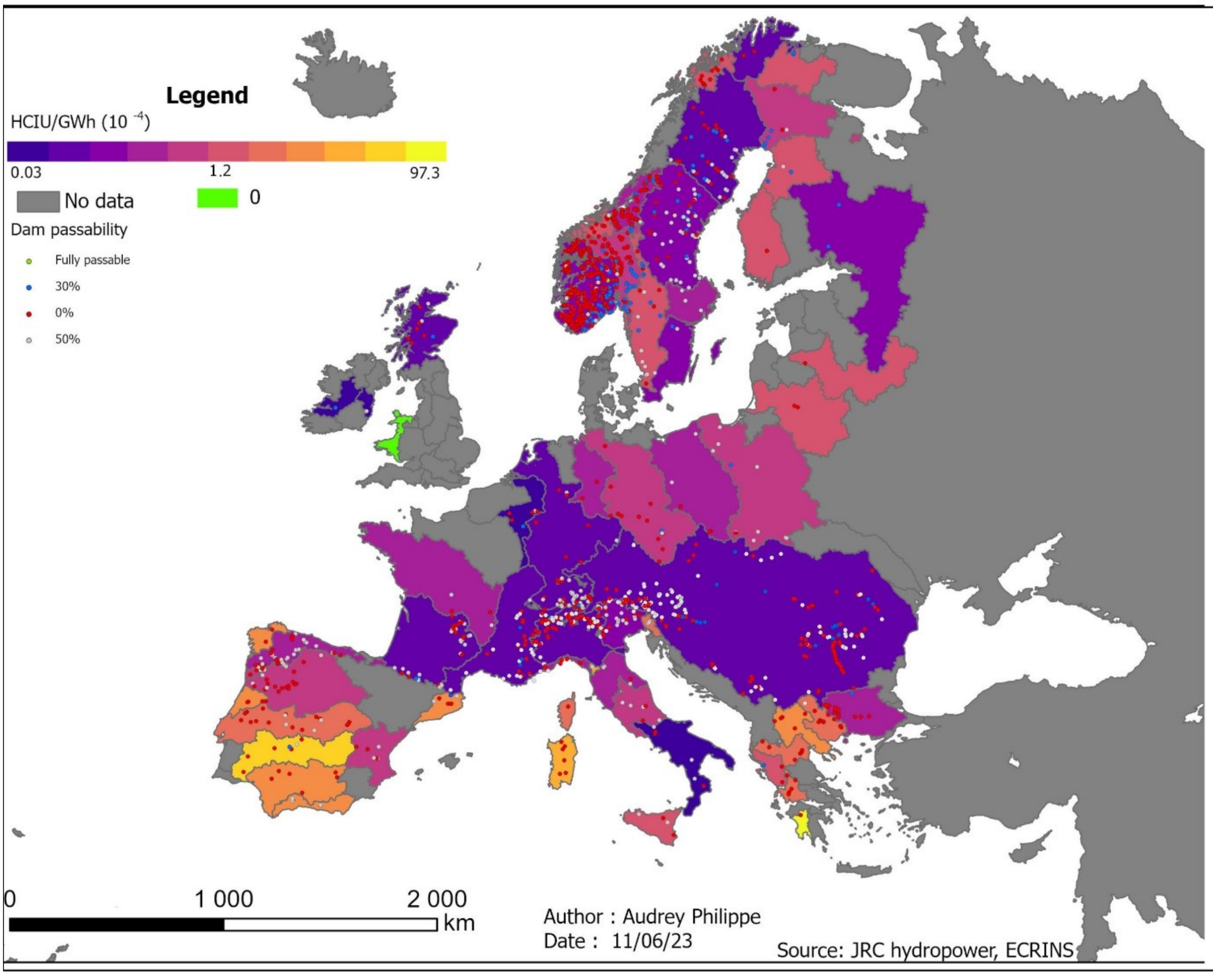

Figure 15 : mid-point characterization factors calculate with HCIU in European basins. The values are obtained with the connectivity index of each basin divided by the hydropower production.

3.4.2 CF with DCId

Characterisation factors for river connectivity calculated with DCId are ranging from 1.61 10^{-6} CI/GWh, in Ireland, to 6.23 10^{-3} CI/GWh, in Greece, with an average of 3.54 10^{-4} CI/GWh. Like for HCIU in the 10 basins that are the most affected 8 are among the basins with the lowest hydroelectricity production. And the 10 basins that are producing the more hydroelectricity are among the 19 basins with the lowest CF.

The basins with the highest and lowest CF calculated with DCId are the same than those calculated with HCIU (Figure 16).

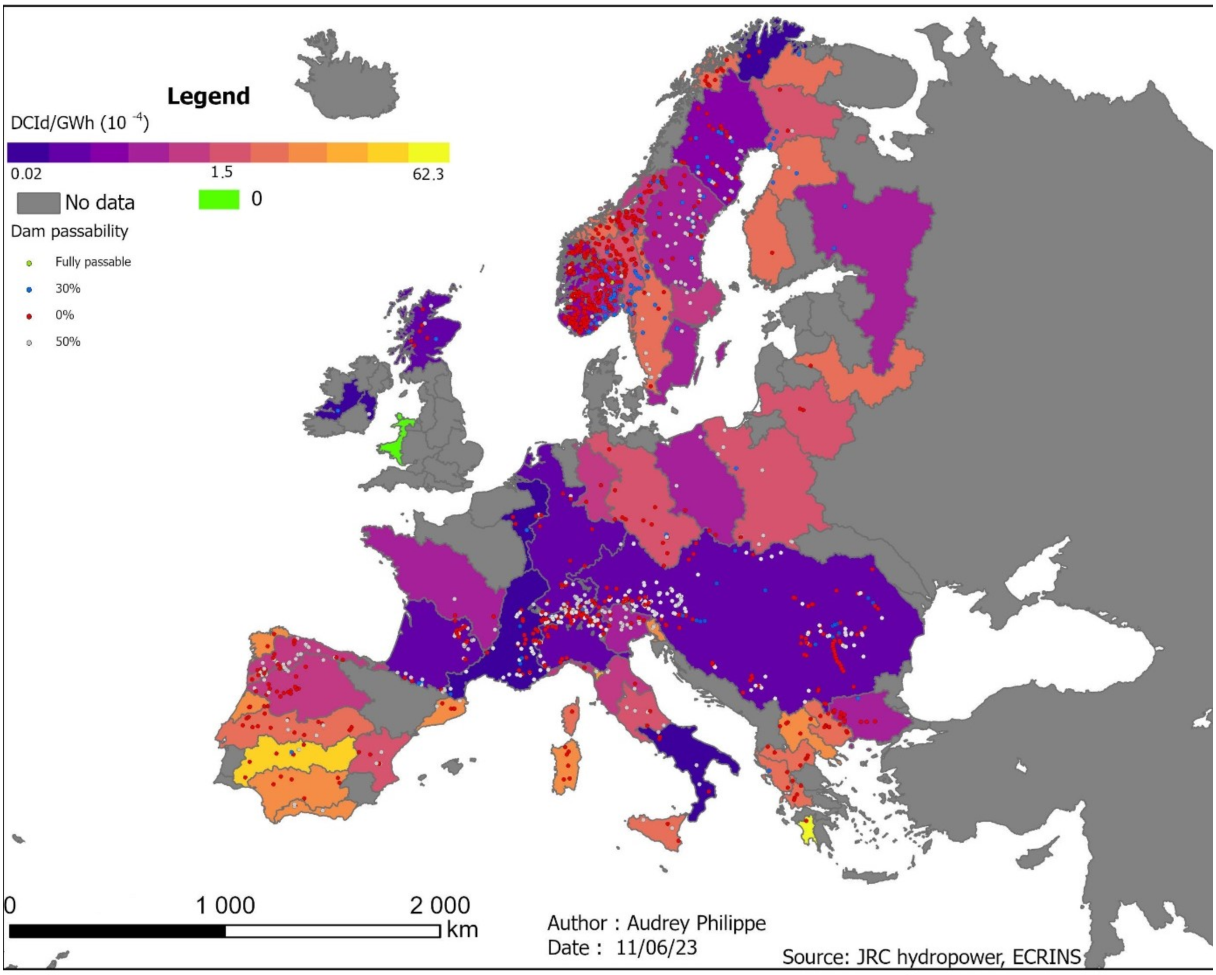

Figure 16 : mid-point characterization factors calculate with DCId in European basins. The values are obtained with the connectivity index of each basin divided by the hydropower production.

3.4.3 CF with DCIp

The CF values go from 3.21*10^{-6} CI/GWh, in Ireland, to 8.90*10^{-3} CI/GWh, in Greece, with an average value of 4.01*10^{-4} CI/GWh.Like for diadromous species, the basins that are most affecting potamodromous fish are the basins with the lowest hydropower production, with 9 of the basins which producing the less hydroelectricity that are among the 12 basins with the highest CF. And for the basins with the highest hydroelectricity production are in the 21 basins with the lowest CF.

Even if, the basins that are the most affected by river fragmentation by GWh are still in Southern Europe and are almost the same as those that are affected for diadromous fish, it is the same for the lowest CF (Figure 17).

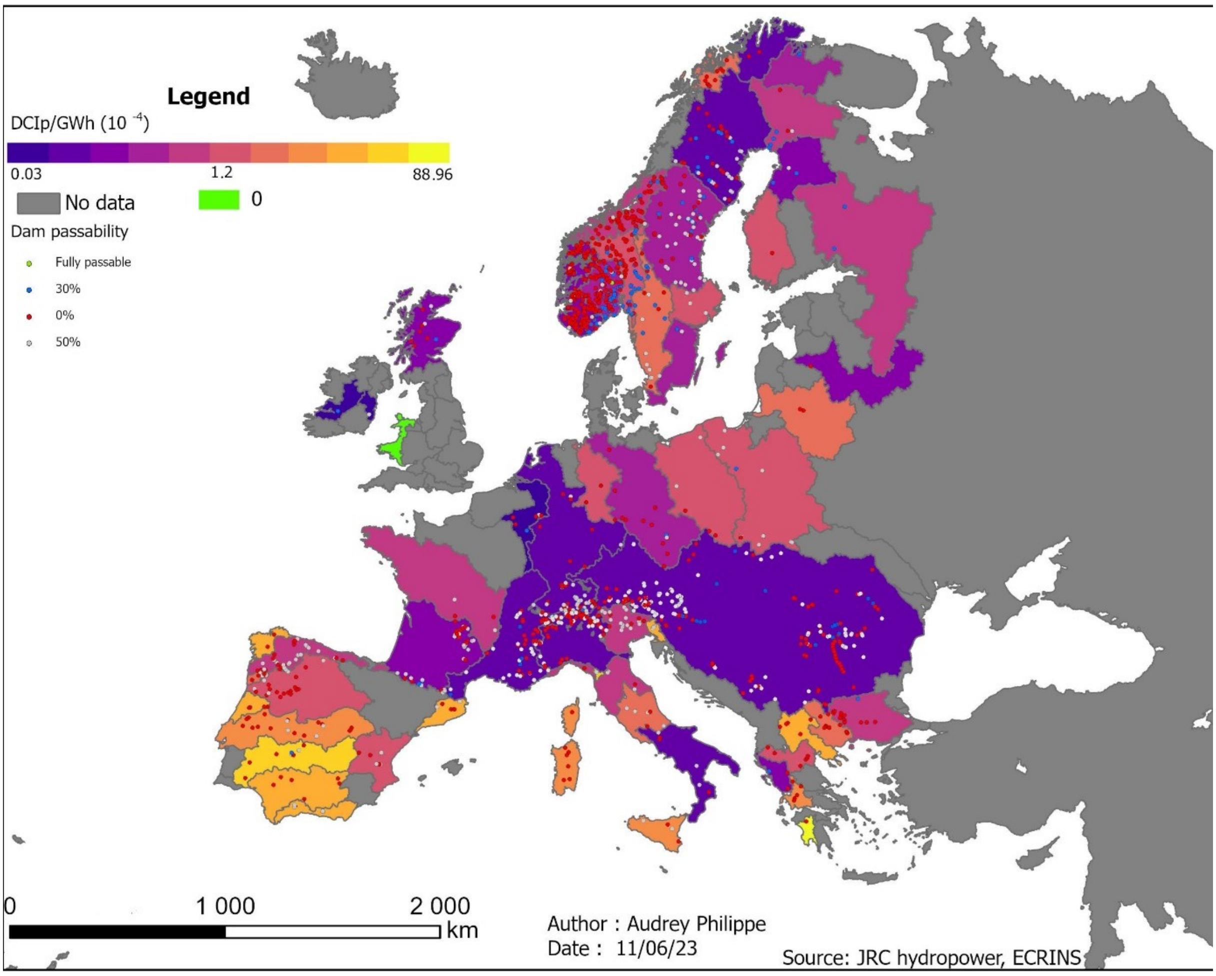

Figure 17 : mid-point characterization factors calculate with DCIp in European basins. The values are obtained with the connectivity index of each basin divided by the hydropower production.

3.4.4 Comparison

The results are different for potamodromous fish and diadromous species in some basins, like it was the case for rivers. However, the basins with the extrema values are the same for all the three methods. For the Daugova basin, the CF calculates with DCIp is 10 times lower than the CF for diadromous fish and for the Neva basin the CF is almost two times higher when it is calculated with DCIp than HCIU (2.1 times) and DCId (1.6 times). River fragmentation most affect diadromous fish in the Elbe basin and potodramous species in the Oder basin.

Like for rivers, DCId and HCIU are highly correlated (Figure 18.c), small differences can be observed and in most of the case the value of DCId is higher than the one for HCIU. For DCIp and HCIU it is not correlated (Figure 18.a) but we can see that in general higher is DCIp higher will be HCIU, the same is observed for DCId and DCIp (Figure 18.b). And a basin that is fragmented for DCIp will be fragmented, sometime less, for HCIU, but a basin can be not fragmented for DCIp and be fragmented for HCIU. Even if the highest CF is higher than $8*10^{-3}$ CI/GWh most of the CF are lower than 0,001 CI/GWh (Figure 18.d).

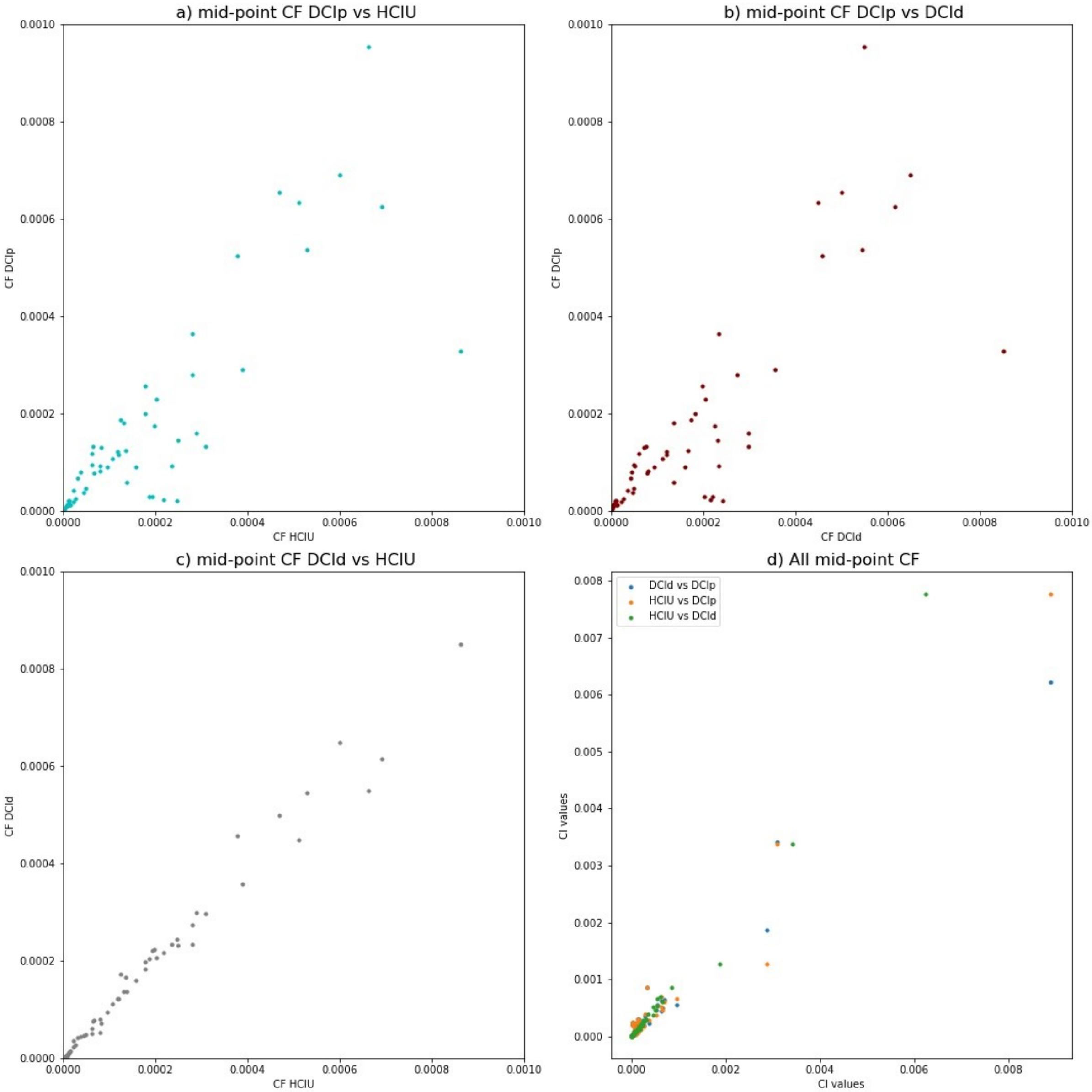

Figure 18 : Mid-point CF values comparison, all the values (d) and a selection of values lower than 0,001/GWh for DCIp vs HCIU (a), for DCIp vs DCId (b) and DCId vs HCIU (c)

4 DISCUSSION:

4.1 Comparison with the literature

Grill et al. have determined the connectivity status index for the river all over the world and for each continent and according to the length of the river classify the rivers in free-flow rivers (FFR) or non-free-flow rivers (NFFR) (Grill et al., 2014). I have compared the number of rivers for each category in Europe to the rivers I have calculated the CI. There are 525 rivers used here to calculate the CF and 29 688 in the article. There are only 25 rivers longer than 1000 km in Grill et al., compared to 519 in this master thesis. To calculate the CF all the tributaries that are going to a main river and one mouth is considered as one river, which is probably not the case in Grill et al. There are 67.6% of the river unfragmented in this study and 92.1% in Grill et al. The difference can be explained by the presence of non-main rivers in the article and that basins without dams are taking in account, and that leads to a higher proportion of FFR.

The CI between this study and Barborossa et al. are different (Barbarossa et al., 2020). The less connected basins are in Spain, the Rhône Basin and some basins in Norway and Sweden. For the basins the most fragmented are in general the same in both studies. However, the Danube basin is not one of the most fragmented according to Barborossa et al., even if the fragmentation rate is high. They have compared diadromous and non-diadromous species, and the basins are in general more fragmented for diadromous species than non-diadromous species, like in the CI calculated with HCIU, DCId and DCIp. To calculate the river CI they have used all the dams situated in Europe, not only the hydropower ones, but that can also explain the difference in the results.

A study calculated the DCIp in Spain for 8 different basins (Rodeles et al., 2020) The basins delineations are not the same in the article and in this work. In all the basins the DCIp is range from 3.76% and 19.94%, so with the index between 80,06% and 96,24%, which is higher than all the values obtain with only hydropower dams. In Rodeles et al, all the dams are taking in account, that may explain the higher values for the fragmentation.

4.2 River connectivity

4.2.1 River connectivity index

All the index used in this study are not taking in account the biological, geomorphological and geological characteristics of the river and so the suitability of the different regions or segments for the fish. So, if the fragments of the river that are inaccessible after the dam construction are the most suitable for the aquatic biodiversity the impact of the dams will be higher that estimated in this study, in the opposite it can also be lower if the regions that are still available are the more suitable ones.

4.2.2 Dam passability

The value of river CI is highly dependent on the dam passability, and to calculate CI in Europe several choices were made and that can influence the final CF values. Some choices, like not using fish ladder, can give higher results than reality.

Only hydropower dams were using for the calculations of river CI, no natural barrier or habitat characteristics were using. According to Grill et al. waterfalls are natural obstacles which are acting like barrier to fish migration and they considered that fragmentation effect of dams cannot go beyond the waterfalls (Grill et al., 2014). So, if dams' localization were used in this study the fragmentation index will be different, and the impacts of using waterfalls will be different for potamodromous CI (DCIp) and diadromous CI (HICU and DCId). For diadromous species, if all the dams of a river are situated above a waterfall, those dams are not fragmented this river and if all the dams are located downstream the waterfall, the total accessible length or habitats will be reduced to the length or habitats under the waterfall and those the CI values will be higher then. For potamodromous fish, the presence of waterfalls will create new regions which cannot be connected, so if the calculations are made without any change the CI values will be higher. But the goal of LCIA is to know the impacts of hydropower dams' construction on fish biodiversity, so the CI should be compare to the one before dam construction. This can be done by a subtraction or by considering that the different regions created by the dams are different parts of the river and that they are independent, and the CI values will be a mean of the different DCIp for each region that can be weighted by the length of each part for example.

For 22% of the hydropower dams the height is missing. We can suppose that the dams without any information on the height are small dams but global database for dams have in majority data about large dams. So, the dams without data on the height can also be high dams that are fully unpassable and thus the results are lower than reality. On the other hand, the dams can also all be lower than 2m and so fully passable. In order to have results closer to the reality more precise data on the height of the dams, through country or region-specific database can be used.

To calculate the three indexes the passability of each dam were independent, so the probability to pass a dam is not linked to the probability to pass another dam. If the dams are considered as dependent, passing the worst dam of the river signify that all the other dams with a higher passage rate can be passed. Also, Cote et al. shows that in case of dams' dependency for potamodromous fish after 5 to 20 dams that the connectivity index is not changing a lot (Cote et al., 2009). There are 47 rivers that have more than 5 dams along it, which represent 27.6% of all the rivers, and only 13 rivers (7.6%) have more than 20 dams on it. And there are 33.5% of the rivers that have only one dam. So take in account the dependency of dams will affect between 38.8% to 58.8% of rivers CI results, which will probably give lower CF if the dams were dependent on each other.

The passability value for each dam is determined by the height of the dam and it is the same for all the species. However, each specie has their specific characteristics and cannot go over the same obstacles, in particular the height of the barrier is varying a lot. As for river goby the height that blocks 95% of the migration is 25.7 and for non gobies diadromous species it was in average 4.1m (Patrick B. Cooney & Thomas J. Kwak, 2013) . Japoshvili et al. have calculated the DCI values in the Republic of Georgia and each species have a different values ranging from 14.6 to 93.4 (Japoshvili et al., 2021).In this master thesis, different calculations were made for potamodromous and diadromous fish which takes in account the specificities of these two groups of fish on their migratory movement, but to have CI closest to the reality we have to calculate the CI for the different species present in the river and then take the average. Barborossa et al. have calculated the CI by basin for each specie and then take the average and it shows the fragmentation of river worldwide for diadromous et non-diadromous species. While calculating DCI values for migratory species in main stream in Europe important differences can be observed on the different species (Puijenbroek et al., 2019).

Only the height of the dam is used to determine the passage rate of each hydropower dam along the river. However, to mitigate the impact of river fragmentation on the environment some dams have fishways to facilitate the migration of fish. But these fishways are not always well working (Fjeldstad et al., 2018; Noonan et al., 2012), for example in Norway on the 344 fishways 71% are functional or partly functional (Fjeldstad et al., 2013). Nonetheless, the study was only made for Atlantic salmon and other species were not take into account, and Noonan et al. (2012) have shown that fishways are more efficient for salmonoids species. It is also difficult to have data on which dams have a fishway with their efficiency. For these three reasons, missing data, inefficiency of fishways and the fact that fishways are more efficient for salmonoids species, the presence of fishways is not used to determine the passage rate. If the presence of fishways have been taken into account the CF will be lower as the passage rate will be higher, at least for some dams and some species. Shaad et al. (2018) have shown that if the number of dams increased too much the efficiency of fishway is low, those calculations were made with DCI.

The same passage rate is used for both upstream and downstream migration. It is not possible to consider that a downstream migration will be always successful, as during downstream migration injuries and mortality can be observed (Baudoin et al., 2014; Noonan et al., 2012). Noonan et al. find that downstream migration is more efficient through fishways than upstream one, on the other hand the downstream migration is blocked by the reservoir and not the dam itself (Pelicice et al., 2015) so fish in some case can go upstream and not downstream through the same dam. To improve the results different values should be taken for upstream and downstream passage rate.

4.3 Data

Several uncertainties in this work are from the different datasets used or the choice made, like using only the main rivers, the position of the dams.

4.3.1 Hydropower information

By using the JRC hydropower database (European Commission, Joint Research Centre (JRC), 2019) at an European level, many small hydropower dams are missing in this study. Belleti et al. estimated that over 1 000 000 obstacles exist in European rivers, and they have recorded 61 522 dams in Europe (Belletti et al., 2020), which is almost 30 times more than hydropower dams from JRC hydropower plant database. However, the 61 522 dams are not all hydropower dams as dams can also be used for flood control for example, so there is less than 30 times more hydropower dams in Europe. The main difference between the two numbers comes from the fact that mainly only large dams are in the JRC database and that Belleti et al. have looked for all the barriers, and they estimated that 68% of the barriers are lower than 2 m (Belletti et al., 2020) . And these dams cannot be identified easily through satellite images.
The JRC hydropower plants database was used in this study because it is the most complete database on hydropower dams at a European scale. It was possible to look for more country

or region-specific datasets, however there were several limitations. It can be language limitations, as not every country has hydropower dams' data in English, time consuming, as the goal of this master thesis was to have CF for river fragmentation by hydropower dams for Europe, it will be complicated to look to many database and formatted them all in the same way. Moreover, dams that are in the JRC database are probably the large dams, like it is the case for GOOD and GranD (Belletti et al., 2020; Mulligan et al., 2020), which have the most impact on river fragmentation, as dams under 2 meters can be considered fully passable(Baudoin et al., 2014). Even if lower obstacles can have important consequence on biodiversity, especially for potamodromous species (Jones et al., 2021). So, even if the river fragmentation calculated in this study is lower than the reality the dams that will fragment the most the rivers are taken into account.

Some ROR plants have dams and so they will also fragment the river, but ROR plants where not used in this master thesis. There are 241 ROR plants that have a dam height in the JRC database, on a total of 2120 ROR, but in the JRC database not all the dams have a height, by choosing only ROR with a dam height data some ROR plants may have been missing. It was decided not to use the ROR plants to avoid any overestimation of river fragmentation with considering all the ROR as dams. Moreover, almost three-quarters of ROR plants with dam heights are located in Spain and mainly in one basin.

All the pumped storage dams were used, even if the dam can be located not at the same place as the plant. So, the position of the dam can be wrong. Or even the storage can be an artificial lake not located on a river.

4.3.2 Dam position

The value of the CI is mainly dependent on the position of the dams in the river, as a dam at the mouth have a higher impact on diadromous species than a dam in the middle of the river, which will have a higher impact on potamodromous species. To calculate the different CI the dams were located on the closest river segment and in the middle of the segment. Both of these choices may have influenced the CI values.

The position of the dam in the segment will only modify the values of the dendritic connectivity index, because HCIU only depends on the number of segments. To test the choice of adding the dam in the middle of the segment and see how it influences the results, the CI were calculated for DCIp and DCId, with the dam positioned at different interval from the beginning of the segment to the end of the segment with an increase of 10% at each time. To avoid that a segment has a length of 0 and change a lot the results the first step is at 1*10E-10 and the last one 1-1E-10. While the dam is higher in the segment highest the CI is, it is always the case for DCId and in most of the case for DCIp. In more than 80% of the rivers the difference is less than 0.01 point, and it can be 0.07 point in maximum for DCIp and 0.04 for DCId. The influence of the position of the dam will be more important as the total length of the river is low, a change in the length of the accessible regions will have in proportion a highest change. The same is observed longest the segment is.

It can exist some uncertainties on the coordinate of the dams and on the position of the river so by choosing the closest segment for position the dam in the river it can place the dam on the wrong tributary. For example, the dam on the Figure 19 is positioned on the grey segment which is an upstream segment and if it was positioned on the blue segments, it will be on the main tributary of the river and the river will be more fragmented.

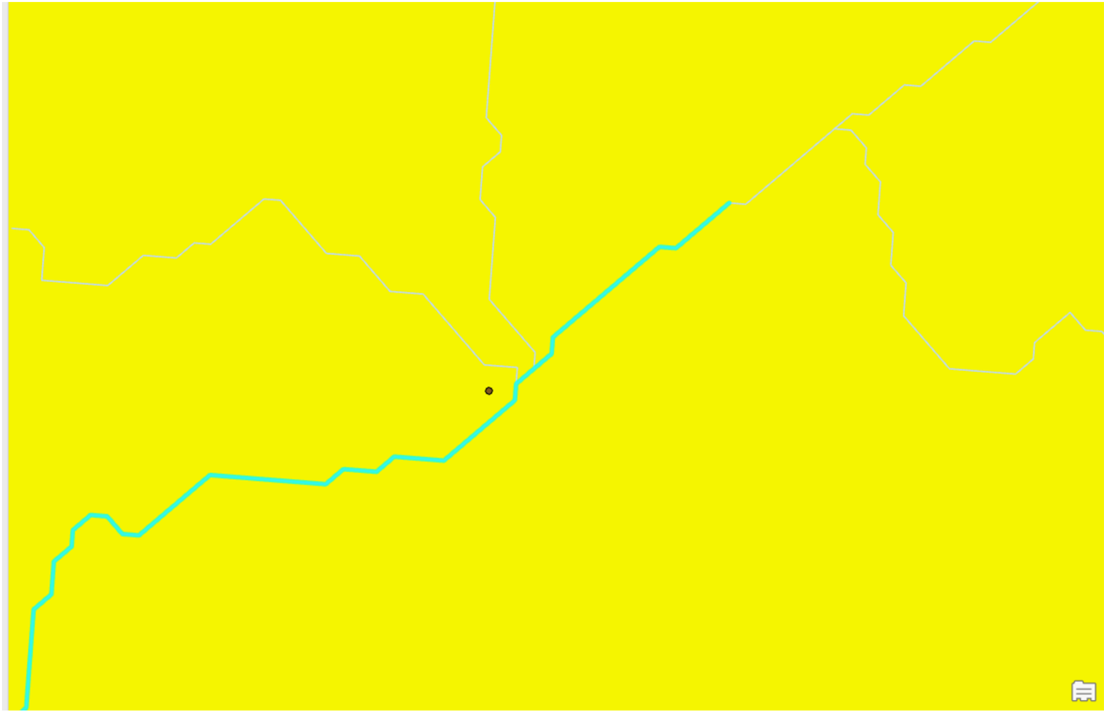

Figure 19 : Uncertainties on the segment on which the dam should be. In this work the dam is in the grey segment.

In some situations, a dam can be closest to a river that are in another basin than the dam (Figure 20). This can come from an error in the dam position, the river trajectory or the basins delimitations. So, a wrong affiliation of a dam to a river can lead to a river with one more dam, or one less dam, a river can be considered as unfragmented although it is not the case and vice versa. The same thing can happen at a basin scale.

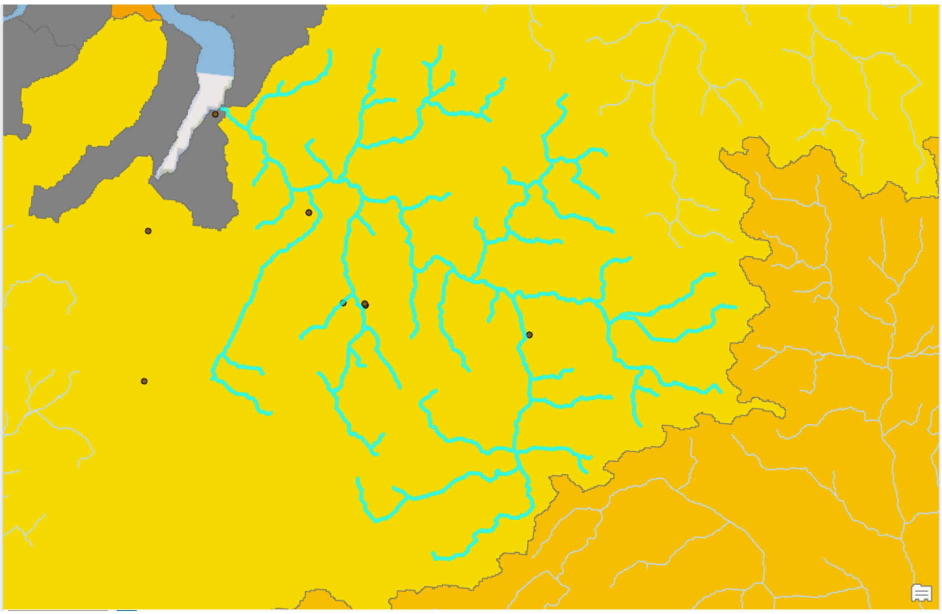

Figure 20 : Dam closest to a river not in its basin. The dam in the grey basin is considered as being part of the blue river. As the dam is situated at the mouth it is fragmented highly the river for diadromous species.

4.3.3 River

For three basins there is a river with a dam where a segment was missing (Figure 6), it was then not possible to go upstream anymore in the river. To calculate the CI of these basins and so the CF, a segment was added in the code to fill this gap. An example of the segment add is the red dots line on the Figure 21. All the blue segments have the same id. And on the basemap we can see the river going where the segment is missing. However, adding this data allow the calculations of the CI but some uncertainties exist. First, the length of the segment is the crow flies, which, like in the example, can be lower as it is not following the bed of the river. And the choice of the position of the segment on the point 1 is arbitrary, as well on the position on the segment and on which segment it is added. All of these may change the value of the CI on these three basins.

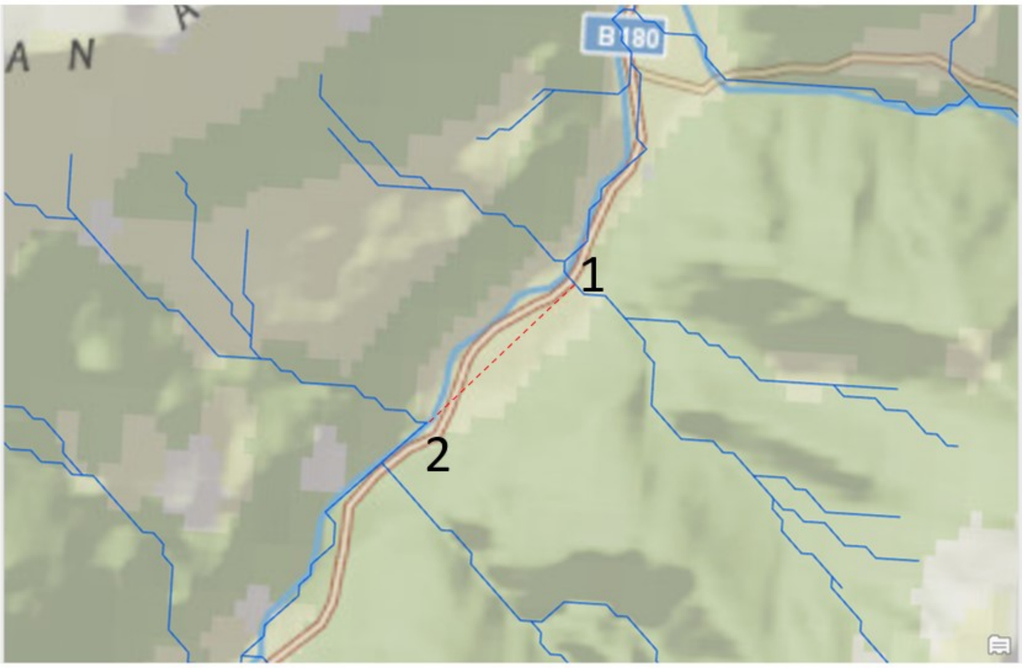

Figure 21 : Segment add (in red) in a river (in blue) with an error in the database.

The previous problem exists in 11 basins if all the rivers, and so the dams located at less than 2.6km from a segment, are taking in account and not only the main river. For this reason, it was decided to only use main river. However, to see the difference on the CF the CI was calculated with all the rivers except for 8 basins, because 3 of them only have problem on the main river and it was previously corrected.

When all the rivers are taken into account there are 2568 in the 54 basins where the CI index were calculated, with 132 rivers fragmented. To find the rivers, the segments that is starting the river was used. But there are some errors when they were associated with each basin, some segments are in majority in one basin but associated to another one or are not in a basin so not used during the calculations. Despite this for most of the basins the CI found with all the rivers, and so all the dams, are lower. Only 4 basins have higher impacts and only one have important differences. This basin has only fragmented river in both cases and when all the rivers are used the additional river is highly fragmented (between 48.6% to 71.9% depending on the index). So, this basin has between 2 and 6 points more when all the rivers are used. On the other hand, the CI can be 14 points lower when all the rivers are used because it will only add unfragmented rivers. But for 32 basins the difference between the CI with all the rivers and only the main one is less than 2 points. To have calculate CI with only the main rivers give results for more basins and the CI are not varying a lot when all the rivers are used.

Several rivers have no id, it was then not possible to know to which basin is belonging this river and all the rivers unnamed was not used. That concerns 14 324 segments on the main river in the whole Europe, with some of them in basins with no dam. Several rivers, in basins without a dam, are without any id, however the segments without any river and located in basins with dams are mainly a single segment. So not using these rivers will not have an important consequence on the final value of the CF.

It is estimated that 74% of the length are missing in the ECRINS database (Belletti et al., 2020). But it is the most consistent database for river network in Europe. The influence of this underestimation on river connectivity can be as well an underestimation of the fragmentation, if barriers are missing, or overestimate, if the total length of river with barriers is underestimate (Belletti et al., 2020).

4.3.4 Basins delineation

The basins used are the basins from ECRINS database, it was first decided to use the GSGM basins delineation which is the one commonly used in LCIA. However, between the ECRINS database river delineation and GSGM basin delineation there are some problems. Some rivers were overlapping several GSGM basins, it was then not possible to determine in which basin the river belong to. Not using the good basin delineation will make it more complicated to use the CF calculated in an LCA calculations.

A basin can be defined as "an area draining to a common outlet" (Pierrat et al., 2023), and in this case each basin is supposed to have only one river, which is not the case with the basin delimitation from the ECRINS database. If the basin delimitation is defined with only one river in each basin, that will avoid the problem of taking the average value of each basin. And if the CF is continued in an end-point CF only the loss of species in river with dam will be taken in account. That is particularly important for potamodromous fish that cannot go from one river to another one. So, if a specie live in only one river that is affected by river fragmentation, this fragmentation will have an important impact on this specie which cannot be seen if the basins have several rivers.

Several basins are in several parts, which are not necessary linked to each other. There are 10 basins that are separated in several parts, for 2 of them there is no dam inside, so those basins were not used. For the one show in Figure 22 and another one dams are situated in several parts it was decided to not calculate the values for them as it will be complicated to calculated the average and the river fragmentation cannot be the same in several parts and the species impacted by that will not be the same in Russia, Iceland and Spain. And for 7 of them a CF value is found, because dams are only present in one part of the basin and most often the other parts are small area with no main river. However, the fact that a basin can have river situated far from the main part may have increase the total length of the basin and so decrease the CF values.

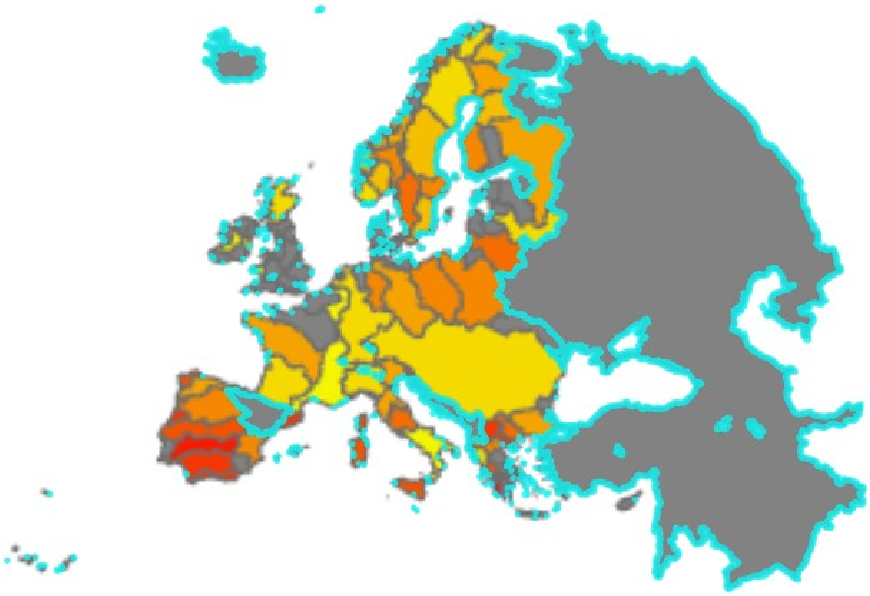

Figure 22 : Problem in basin delineation, all the basins surround in blue have the same id

4.4 River connectivity index proportion

4.4.1 Average for basin

For calculating the CF of each basin, it was decided to weight the CI values by the length of the different rivers. The environmental characteristics that are the most correlated with fish species richness are surface area of the drainage basin and discharge (Oberdorff et al., 1995). The length data for each river was found with the ECRINS database. Some connectivity indexes are calculated with the river length, like the dendritic connectivity index. So, it is possible to weight the CI by the length of the river and the length data were consistent with the data used for the DCI and do not need a new database which can be not consistent on the river definition of ECRINS database like the area data will be. In Africa, it is considered that fish richness is more linked to discharge rate than length (Oberdorff et al., 1995). But for the same reason as for area discharge rate will need a new database, and hydropower dams are modifying discharge rate.

If we consider that all the rivers have the same influence on the fish richness independently on ecological or physical characteristics (length, discharge rate, etc), in most of the case the CF are decreasing a lot. This is explained by the fact that most of the basins have more rivers without dams but that rivers with dams are the longest ones. For 5 basins there is no difference, as there is only one river in the basin. And for 3 basins, the CF is increasing when there is no weighting. This the case when the rivers with dams are the shorter one or when there is no important difference in the size of the rivers with and without dams and the number of rivers with dams is significantly higher, or because all the rivers have dams, but the most fragmented river is the smallest one. Not weighting the river CI can lead to an underestimation of the CF for the different basin in Europe.

4.4.2 Hydropower generation

To know the hydroelectricity generation in each basin the global power plant database (World Resources Institute et al., 2018) was used with all the plants that have hydropower as primary fuel. But as some dams are missing from the JRC database the total generation is probably higher than the hydroelectricity generates by the dams that are used. It was not possible to associate each dam to a specific plant because a plant can be used for several dams or be far from the dam. If the total amount of hydropower generates in each basin is higher than the one that was really generates by the dams used in this thesis, the CF found are lower than the reality. And because the plants can be running with several fuels the total generation cannot be completely allocated to hydropower.

4.5 Application in LCA

The mid-point CFs developed here are the first one developed for river fragmentation. And as the impacts of river fragmentation are varying on the different basins and between diadromous and potamodromous species, so these regional CFs should be included in LCA. It can also change the results from previous analysis, like in Dorber et al. (2020).

Midpoint CFs are normally developed for all environmental impacts not for specific specie, like fish in this project. It was decided to have this specific species, because the final aim of this mid-point CFs are to obtain end-point CFs.

These CFs can be used in addition of the previously mentioned midpoint CF developed in LCIA: AWARE (Boulay et al., 2018) and HPC (Damiani et al., 2019). The different CF are not evaluating the same changes and impacts made by hydropower dams.

5 Future work

Hydropower dams exist all over the world and many plans of new hydropower plants exist. It is then important to calculate the mid-point characterization factor developed in this master thesis at a global scale. However, the CF developed can be improved in several ways. More data about dams' localization, as well in Europe and worldwide if CF are calculated at a global scale, it is also important to have more information on the dams' height, and electricity generation. All of these data will give results closest to the reality.

Improving the values of the connectivity index can also be done by improving the passability rate choice for each dam. This can be done by adding new passability rate according to the dam height. Perhaps, a continuity curve of passability rate depending on the height, with for a height under 2 m a passability value of 1 and a height higher of 25.7m a value of 0 and between those two values a linear or exponential curve.

As the population of fish highly depends on the river discharge the average value of each basin can also be done with river discharge values.

The CF developed in this master thesis can be used as starting point to develop end-point CF, which will give the impact of river fragmentation by electricity generation on the fish species. The goal will be to have CF with the unit PDF/kWh or PAF/kWh, with PDF the potential disappeared species and PAF the potential affected species. PDF is the recommended unit in LCIA (Verones et al., 2017). It has been shown that DCI can be used to assess change in biodiversity because of river fragmentation (Perkin & Gido, 2012)

The IUCN red list of threatened species (IUCN, 2022)lists the different threats that each species can be affected by. And three of the threats directly concern river fragmentation by dams, depending on the size of the dams (Large, small or unknow). And there are respectively 635, 996 and 2737 wetlands species threatened by large, small, and unknown size dams all over the world. These species can be classified as extinct (18), extinct in the wild (4), critically endangered (347), endangered (565), vulnerable (603), near threatened (356), least concern (1614) or with not enough data (487) (IUCN, 2022). With the range maps of the IUCN red list, it is possible to know where each specie lives and then for each basin the number of species present and threatened by dams and so to obtain the PAF or PDF for each basin.

Another possibility to obtain end-point CF is to used CI that already take in account the biodiversity in the river. For potamodromous species the CCIp index (Rodeles et al., 2020), based on the DCIp index, calculates a CI value for a whole river depending on the biodiversity index. This last one is calculating through the vulnerability score obtain with the IUCN red list and the number of segments in which the specie was found on the total number of segments.

And when CF will be calculated at a global scale and at an end-point level, if the basins delineation as not been changed it will be necessary to adapt the CF values to scale that can be used for LCA calculations.

6 Conclusion

Freshwater habitats and biodiversity are the most threatened habitat and the group of species that know the fastest decrease (Geist, 2011; Grooten, M. & Almond, R.E.A, 2018). Decrease in fish richness and diversity is observed, the main reason is the loss of river connectivity (Geist, 2021). A loss of river connectivity can be done by river fragmentation through hydropower dams' presence in the river. River fragmentation by hydropower dams have several impacts on fish biodiversity and those impact are not quantified in LCIA.

A first step of this quantification has been made through this master thesis with the development of a mid-point CF model of river fragmentation, with the connectivity index HCIU, DCId and DCIp (Cote et al., 2009; McKay et al., 2013). This model has been applied in Europe at a basin scale and CF values are between $2*10^{-6}$/GWh and $88,96*10^{-4}$/ GWh, for the three methods. River fragmentation is not correlated to the number of dams or the energy production, even if a high production of hydroelectricity (>15000 GWh/yr) is linked to a river connectivity higher than 30%. But an almost complete loss of connectivity can be observed in basin with a low generation of electricity. The basins with the lowest CF for the three methods are the basins that are generating the most and the basins with the highest CF are in the opposite the basins with the lowest generation. The choice made on the position of the river have not an important impact on the results.

However, the previous results need to be improved, with dam passability values that are closer to reality and by adding new data on dams. Some calculations can be made to have the same basin delineations as commonly use in LCIA.

The method developed in this project, with an application case, can be used in a global scale, if the rivers and dams' data are used. And can then be the starting point of an end-point CF for the ecosystem quality AoP. Those two CF can be then used in LCA calculations each time there is electricity in the inventory.

Hydroelectricity is a way to reduce anthropogenic GHG emissions in the coming years, to limit climate change. For these reasons there are many plans for future dams, mainly in Africa and South America and South and East Asia (Zarfl et al., 2019). For example, the number of large dams in Brazil will almost doble in the coming years (Reid et al., 2019). And in the world, there are more than 3700 dams with a capacity higher of 1MW that are planned (Barbarossa et al., 2020). Those plans dams are overlapping with areas with the highest species richness and diversity.

In order to have a sustainable future, the impacts of hydropower on biodiversity should be understand and integrated in LCA calculations with new CF. That will also help to choose the best localization for new dams. And a CF on river fragmentation can be used in the European goal to have "good ecological status" of rivers, to choose which dams should be removed or improved with a fishway.

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Appendices

Appendix 1: CI values calculates with only the main river

Appendix 2: mid-point CF values for the 3 indexes

Appendix 3: CI index calculated with all the rivers

Appendix 4: Code (in a supplementary file)

Appendix 1: CI values calculates with only the main river

FRBD	HCIU	DCIp	DCId
WFD0000001	0.103445391	0.156404096	0.084158288
WFD0000002	0.744119897	0.73896904	0.787667733
WFD0000003	0.778835208	0.773631035	0.758089633
WFD0000004	0.83202403	0.756928843	0.839507725
WFD0000007	0.000456258	0.000778083	0.000389246
WFD0000008	0.17187035	0.288067213	0.164281225
WFD0000009	0.441301111	0.502432189	0.515099116
WFD0000010	0.317770448	0.364991543	0.343607838
WFD0000013	0.20758709	0.298558417	0.172068875
WFD0000015	0.200228788	0.203120194	0.206658676
WFD0000016	0.307990421	0.419956851	0.318515677
WFD0000019	0.40602878	0.461069723	0.415278261
WFD0000021	0.524746576	0.526243928	0.524445139
WFD0000022	0.887234599	0.347523665	0.880215693
WFD0000029	0.001086186	0.002277012	0.001149775
WFD0000031	0	0	0
WFD0000034	0.971385673	0.923743797	0.973357806
WFD0000035	0.956905478	0.396477251	0.945980922
WFD0000036	0.138947966	0.218411398	0.120411205
WFD0000037	0.419000208	0.47833843	0.299272156
WFD0000038	0.832632586	0.724972829	0.844698369
WFD0000039	0.947410107	0.885674508	0.95715131
WFD0000043	0.019159262	0.033825705	0.017105072
WFD0000047	0.620902315	0.525299619	0.634666383
WFD0000051	0.06809759	0.102690026	0.066388014
WFD0000052	0.141291515	0.298154601	0.187998115
WFD0000053	0.447520863	0.497561512	0.456494352
WFD0000054	0.650305816	0.593925876	0.798568278
WFD0000055	0.048209011	0.089038569	0.04652339
WFD0000056	0.69744151	0.616263674	0.791519436
WFD0000057	0.371831693	0.296320647	0.389470548
WFD0000058	0.621308782	0.350004771	0.624834074
WFD0000061	0.961286408	0.094242918	0.950420405
WFD0000066	0.772231597	0.660168622	0.828909826
WFD0000067	0.446419169	0.066525046	0.50943194
WFD0000068	0.416702717	0.242235836	0.388626816
WFD0000074	0.093214196	0.168379419	0.149586241
WFD0000075	0.070937696	0.145958341	0.084942641
WFD0000080	0.372835451	0.387883028	0.389046476
WFD0000082	0.376247447	0.486321018	0.305496026
WFD0000083	0.201342758	0.300899959	0.279639589
WFD0000084	0.125803143	0.175612118	0.134161822
WFD0000086	0.206023952	0.186331133	0.18393507
WFD0000087	0.044677653	0.041934592	0.043858631
WFD0000088	0.007530359	0.015009132	0.008103192
WFD0000089	0.118269231	0.26561533	0.1724679

WFD0000092	0.120982496	0.156742253	0.100809571
WFD0000093	0.191808171	0.073039782	0.189624272
WFD0000094	0.125269215	0.172391718	0.090589287
WFD0000095	0.282827853	0.326429624	0.184662966
WFD0000096	0.092039656	0.131629416	0.102637502
WFD0000097	0.247042736	0.13636641	0.254625013
WFD0000098	0.093277674	0.19540925	0.113769849
WFD0000099	0.201774115	0.279530922	0.244193223
WFD0000101	0.466736565	0.200230499	0.451913193
WFD0000102	0.403637454	0.499541713	0.355199627
WFD0000103	0.17770513	0.01422335	0.175295334
WFD0000104	0.639694258	0.476109286	0.58612753
WFD0000105	0.286440935	0.32782533	0.229582379
WFD0000114	0.880503265	0.81861165	0.830335204
WFD0000117	0.349128055	0.05421296	0.379918617
WFD0000118	0.008137471	0.010864143	0.005577555

Appendix 2: mid-point CF values for the 3 indexes

FRBD	Hydropower generation	HCIU CF	DCIp CF	DCId CF
WFD0000001	1666.03	0.0000621	0.0000939	0.0000505
WFD0000002	6994.78	0.000106	0.000105646	0.000112608
WFD0000003	2767.67	0.000281	0.000279524	0.000273909
WFD0000004	245.82	0.00338	0.0030792	0.003415132
WFD0000007	242.52	0.00000188	0.00000321	0.00000161
WFD0000008	14930.89	0.0000115	0.0000193	0.000011
WFD0000009	6563.36	0.0000672	0.0000766	0.0000785
WFD0000010	528.82	0.000601	0.0006902	0.000649763
WFD0000013	313.2	0.000663	0.000953252	0.00054939
WFD0000015	379.25	0.000528	0.000535584	0.000544914
WFD0000016	2325.67	0.000132	0.000180575	0.000136957
WFD0000019	2013.36	0.000202	0.000229005	0.000206261
WFD0000021	6537.58	0.0000803	0.0000805	0.0000802
WFD0000022	3759.67	0.000236	0.0000924	0.00023412
WFD0000029	520.1	0.00000209	0.00000438	0.00000221
WFD0000031	10850.7	0	0	0
WFD0000034	8004.45	0.000121	0.000115404	0.000121602
WFD0000035	6879	0.000139	0.0000576	0.000137517
WFD0000036	1672.92	0.0000831	0.000130557	0.000072
WFD0000037	34885.73	0.000012	0.0000137	0.00000858
WFD0000038	30460.06	0.0000273	0.0000238	0.0000277
WFD0000039	19457.79	0.0000487	0.0000455	0.0000492
WFD0000043	7996.15	0.0000024	0.00000423	0.00000214
WFD0000047	27689.23	0.0000224	0.000019	0.0000229
WFD0000051	5162.65	0.0000132	0.0000199	0.0000129
WFD0000052	4422.24	0.000032	0.0000674	0.0000425
WFD0000053	2499.1	0.000179	0.000199096	0.000182663
WFD0000054	4775.26	0.000136	0.000124376	0.00016723
WFD0000055	764.56	0.0000631	0.000116457	0.0000608
WFD0000056	3522.24	0.000198	0.000174964	0.00022472
WFD0000057	25330.64	0.0000147	0.0000117	0.0000154
WFD0000058	3905.9	0.000159	0.0000896	0.000159972
WFD0000061	4389	0.000219	0.0000215	0.000216546
WFD0000066	17394.77	0.0000444	0.000038	0.0000477
WFD0000067	2301.47	0.000194	0.0000289	0.000221351
WFD0000068	1672.37	0.000249	0.000144846	0.000232381
WFD0000074	4129.56	0.0000226	0.0000408	0.0000362
WFD0000075	1114.84	0.0000636	0.000130923	0.0000762
WFD0000080	3197.46	0.000117	0.00012131	0.000121674
WFD0000082	53202.76	0.00000707	0.00000914	0.00000574
WFD0000083	1608.78	0.000125	0.000187036	0.000173821
WFD0000084	268.33	0.000469	0.000654463	0.000499988
WFD0000086	298.66	0.00069	0.00062389	0.000615868
WFD0000087	464.17	0.0000963	0.0000903	0.0000945
WFD0000088	2996.61	0.00000251	0.00000501	0.0000027

WFD0000089	92.67	0.00128	0.002866249	0.001861097
WFD0000092	431.65	0.00028	0.000363123	0.000233545
WFD0000093	222.56	0.000862	0.00032818	0.000852014
WFD0000094	14283.3	0.00000877	0.0000121	0.00000634
WFD0000095	3516.6	0.0000804	0.0000928	0.0000525
WFD0000096	515.73	0.000178	0.000255229	0.000199014
WFD0000097	852.25	0.00029	0.000160008	0.000298768
WFD0000098	2492.26	0.0000374	0.0000784	0.0000456
WFD0000099	533.32	0.000378	0.000524134	0.000457874
WFD0000101	1516.44	0.000308	0.00013204	0.000298009
WFD0000102	790.32	0.000511	0.000632075	0.000449438
WFD0000103	718.33	0.000247	0.0000198	0.000244032
WFD0000104	1639.24	0.00039	0.000290445	0.000357561
WFD0000105	36.85	0.00777	0.00889621	0.006230187
WFD0000114	67645.01	0.000013	0.0000121	0.0000123
WFD0000117	1864.87	0.000187	0.0000291	0.000203724
WFD0000118	1018.31	0.00000799	0.0000107	0.00000548

Appendix 3: CI index calculated with all the rivers

The basin WFD0000075 has one river that is fragmented but the down segment is not in the basin delineation so not taking into account during the calculations.

Basin name	HCIU	DCIp	DCId
WFD0000001	0.0985185068022933	0.148954902057681	0.0801500078570559
WFD0000002	0.742987305218805	0.737844288420752	0.786468858842997
WFD0000003	0.755723235644882	0.750673496608533	0.73559328633196
WFD0000004	0.831093423112521	0.756082229830711	0.838568748489456
WFD0000007	0.000399086171367366	0.000680584658913795	0.000340471076946151
WFD0000008	0.16882594381942	0.282964567308373	0.161371247945613
WFD0000009	0.407023521338679	0.463406309022256	0.475089346251738
WFD0000010	0.294835559608572	0.338648501331047	0.318808152625814
WFD0000013	0.202664318879095	0.291478329689008	0.167988391942518
WFD0000015	0.112408816111268	0.114067770904405	0.115821536427553
WFD0000016	0.290698087616465	0.396378086117965	0.300632396008584
WFD0000029	0.000822394418849562	0.00172401587886017	0.000870540393187617
WFD0000034	0.943332711069975	0.897066699411165	0.945247889457788
WFD0000035	0.956514392090212	0.39631521140606	0.945594300647381
WFD0000036	0.137075077665282	0.215467416779163	0.118788175258113
WFD0000037	0.41771206041461	0.476867856286698	0.298352092120296
WFD0000039	0.918802604661695	0.858523673590946	0.927975515576889
WFD0000043	0.0188251614520366	0.0332358497235706	0.0168067922861646
WFD0000051	0.0431527889631734	0.0650727166541182	0.0421330854936073
WFD0000052	0.141316326970514	0.298206959062191	0.188031128369609
WFD0000053	0.443775439002101	0.49339728456836	0.452673826549449
WFD0000054	0.645666014812983	0.589888882816635	0.792823254372813
WFD0000055	0.047521308241216	0.0877684312535119	0.0458597332064339
WFD0000056	0.660460082835543	0.583990163559505	0.749684980054232
WFD0000057	0.362089380357605	0.288984014531118	0.379316067090688
WFD0000058	0.615645574734451	0.347039767395132	0.619056917042163
WFD0000061	0.961286407767	0.094242918404	0.950420404508699
WFD0000066	0.729030768523306	0.633793444106311	0.777206206615606
WFD0000067	0.433751653223127	0.0646373420431799	0.494976384125177
WFD0000068	0.381143705688045	0.221564824293687	0.355463640430007
WFD0000074	0.0763855297087777	0.137980603788686	0.122580301135626
WFD0000075	0	0	0
WFD0000080	0.324129800570335	0.337211625790361	0.338223085779443
WFD0000082	0.36615430785004	0.473275066592765	0.297300849759382
WFD0000083	0.179811769622116	0.268722623050011	0.249735773408934
WFD0000084	0.0934174520682991	0.130404027833224	0.0996243432048187
WFD0000086	0.169709368679571	0.153487683008596	0.151513959454031
WFD0000087	0.0388988101399281	0.0369424857204444	0.037522542055216
WFD0000088	0.00556839996461601	0.011313413791509	0.00614901961060326
WFD0000089	0.176549085497249	0.287020675048801	0.212329394545363
WFD0000092	0.0572562723405213	0.074583941447793	0.0583063699420424
WFD0000094	0.125263613699833	0.172384009512162	0.0905852360990845

WFD0000095	0.272322506756563	0.31430473484094	0.177803852372755
WFD0000096	0.0492526020450278	0.0704380215772792	0.0549237608392304
WFD0000097	0.225768885086505	0.124623345710949	0.232698221286023
WFD0000098	0.0910789727749501	0.190803147977639	0.111088115313657
WFD0000099	0.189534284643349	0.262574281302388	0.229380205099693
WFD0000101	0.426758108547152	0.183079697533862	0.413204436991777
WFD0000102	0.402843785720581	0.498559468336366	0.354501200989515
WFD0000103	0.175853208604146	0.0109593818103313	0.173203320404349
WFD0000104	0.501704589893222	0.373406844631785	0.459692843523703
WFD0000105	0.1756267915578	0.201000987671892	0.140764854469919
WFD0000114	0.880263568437972	0.818388556304878	0.83010801121191
WFD0000117	0.347092487264707	0.0538968754227814	0.377703527133303

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