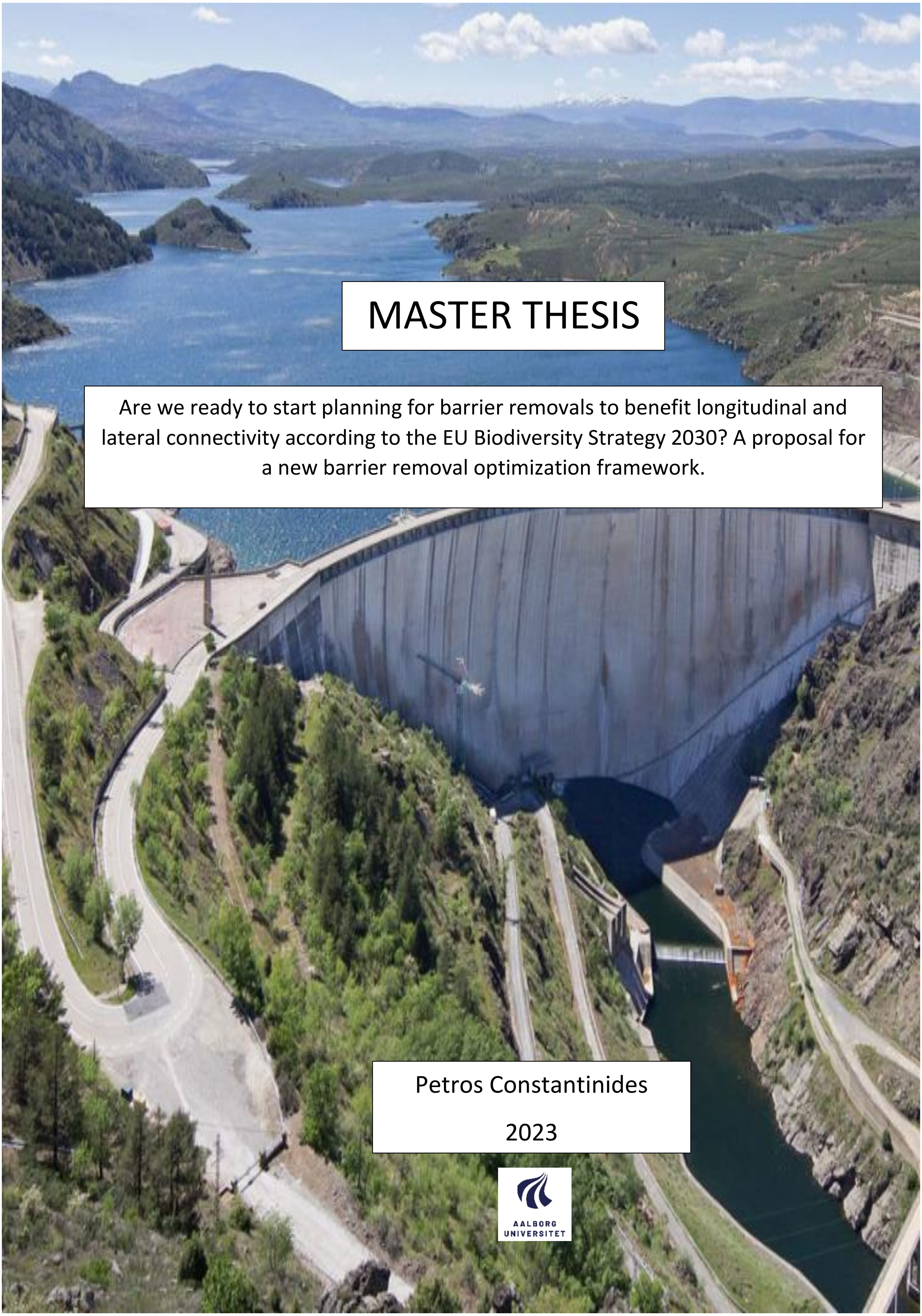

MASTER THESIS

Are we ready to start planning for barrier removals to benefit longitudinal and lateral connectivity according to the EU Biodiversity Strategy 2030? A proposal for a new barrier removal optimization framework.

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Title: Are we ready to start planning for barrier removals to benefit longitudinal and lateral connectivity according to the EU Biodiversity Strategy 2030? A proposal for a new barrier removal optimization framework**.**

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If you had asked me a couple of years ago where I would see myself right now, I would have never guessed it would be here in Denmark. A lot of unexpected things happened over the past few years that lead me to be here. Therefore, I would like to dedicate my thesis to my uncle, George Vakanas who we lost in December of 2021. In a way, that he didn't deserve. In a tragic way that no human deserves to leave this world.

In my eyes he was a hero. He left from Cyprus after his family had lost everything during the war in 1974. He wasn't afraid to move to America in the search for a better life. In the unknown. Alone. And he did it! He became a great scientist. That was one of his biggest dreams after all. In my mind though, I will always remember him as the great human he was. Kind, curious, ready to help everyone … I am always amazed every time that my mother Eleni, my father Pampos and my aunt Doxa tell me about George. From moments I never had the chance to experience with him.

This thesis is a tribute to you George. I hope you can somehow read it from heaven!

This thesis is also my gift to Eleni, Pampos and Doxa. The three people that have supported me especially since December 2021. Since the month I decided to make the step to leave everything behind and move to Denmark for a completely new beginning.

The first year in Denmark was a hard one for many reasons. Yet, it was the year that I met my supervisor, Simone. I don't have many words to describe Simone. An amazing researcher. An even greater human. A supervisor who cares. A supervisor who is there for you. And of course, a supervisor with high standards in terms of delivering a result of high quality. From Simone I learned a lot, possibly more than I have learned from any other supervisor in my life. For these, I will always be grateful to her.

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The project you are about to read was written with a lot of love and care. What I know for sure, is that George would be proud of it. And that makes me extra proud to present my thesis to you. I hope you enjoy reading it as much as I enjoyed writing it.

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Abstract

The development of anthropogenic river barriers has set significant pressures for freshwater ecosystems including the interruption of fish migration, ecosystem deterioration and biodiversity decline. To address that, the EU Biodiversity Strategy 2030 was established. Among others, it aims to reconnect 25 000 km of free-flowing river by 2030 for restoring longitudinal and lateral connectivity through the removal of barriers. However, ***are we ready to start planning for barrier removals for benefiting longitudinal and lateral connectivity in accordance with the EU Biodiversity Strategy 2030?*** Our literature review, gap analysis and pan-European review work indicated a significant number of challenges including among others the lack of a highly reliable barrier removal optimization framework. To address that, we combined the Hydrography90m hydrographic network, the AMBER barrier database, and the Corine land cover data, along with the "prioritizr" problem-solving package and "Gurobi" problem solver to develop a new optimization framework for guiding barrier removals. We tested our optimization framework for three basins 50-100km northwest of Hamburg, Germany by running 54 different optimization scenarios. Our results suggested the potential for reconnecting between 1.3 - 253.6 km of river flow which would contribute up to 1.01 % to the overall EU Biodiversity Strategy 2030 aim of reconnecting 25 000 km of river flow. However, this solution includes uncertainties regarding the presence of unrecorded barriers in the AMBER database. We addressed that by using predictive modelling to identify the main predictor variables of the barrier's types. These can then be used by future studies to identify the locations of unrecorded barriers. The predictive modelling suggested that by using outlet river distance, land use and water flow as predictor variables, we could classify correctly 86% of the barriers. Considering the challenges associated with the collection of on-field barrier data, we are confident that predictive modelling could be a highly beneficial tool for guiding future barrier removal projects.

1.0 Introduction

The development of anthropogenic river barriers has set significant pressures for freshwater ecosystems. The main challenges associated with anthropogenic river fragmentation include the interruption of fish migration and biodiversity decline (Fuller, Doyle & Strayer, 2015). These challenges are expected to increase in the future especially due to the continuous construction of dams as well as the interaction of river fragmentation with climate change (Fuller, Doyle & Strayer, 2015). Although the problem has an international scope, barrier fragmentation is a major challenge especially in Europe where over 1 million river barriers have been suggested to be present (Belletti et al., 2020).

As an early solution, the European Union established the Water Framework Directive (WFD). The WFD is legally applied over the European Union member states along with Norway and targets the protection and restoration of all water bodies (European Commission, 2021). For achieving the goals of the WFD it is necessary among others to have good river connectivity through adaptation or removal of barriers (European Commission, 2021). However, barrier removal plans are not considered as part of the WFD. Therefore, the European Commission (2021) established the EU Biodiversity Strategy 2030. The targets of the EU Biodiversity Strategy 2030 include a) Improvement of implementation of pre-existing legislations on freshwater, b) Restoration of river-flow for at least 25 000 km of rivers by 2030 through the removal of barriers (mainly obsolete ones – barriers not serving anymore any functional purpose) for improving longitudinal and lateral connectivity (as well as vertical and temporal) and c) restoration of wetlands and floodplains (European Commission, 2021).

The aims of the EU Biodiversity Strategy 2030 are expected to be strengthened with the establishment of the new EU Nature Restoration Law**.** The new EU Nature Restoration Law has proposed new obligatory targets that will commit European countries into acting against nature restoration challenges. It targets the long-term and continuous recovery of biodiversity over water and terrestrial ecosystems while also contributing to the European aims for tackling climate change (European Commission, 2022). In the context of barrier removals, the new EU Nature Restoration Law addresses river fragmentation through article 7 regarding the identification and subsequent removal of river barriers for restoring longitudinal and lateral connectivity for achieving the aim of at least 25 000 km restored free-flowing river and is directly related to the targets set by the EU Biodiversity Strategy 2030**.** Article 7 also targets the restoration of floodplains which can be related both to EU Biodiversity Strategy 2030 targets for floodplain restoration and improvement of lateral connectivity (European Commission, 2021; European Commission, 2022).

Despite the recent European efforts to address river fragmentation, it is questionable whether the European countries will manage to meet the targets for the restoration of 25 000 km of free-flowing river. This is because of the several challenges associated with the prioritization of barrier removals plans which earlier studies have encountered. These include a) modelling and methodological challenges (i.e. lack of large-scale barrier removal prioritization projects, low spatial resolution hydrographic networks and incomplete barrier databases, e.g., Belletti et al., 2020; Garcia de Leaniz & O'Hanley, 2022), b) Insufficient knowledge of the freshwater biotic and abiotic environment (e.g., England, & Wilkes,2018) and lack of understanding of socio-political influence on barrier removal project success (Brummer et al., 2017).

In addition, several questions arise regarding the general application of the EU Biodiversity Strategy 2030: What geographical scale will the EU Biodiversity Strategy have? Will the 25 000 km of free-flowing river be allocated only in the European Union countries or all over Europe? How will we determine the amount of free-flowing river that will be reconnected in every country? How will we manage barriers located in country boundaries? How can we plan barrier removals to consider the role of barriers for hydropower generation?

The main goal of this study was to evaluate the following question: *Are we ready to start planning for the EU Biodiversity Strategy 2030 to improve longitudinal and lateral connectivity through barrier removals?*

The specific objectives were:

1. To perform a literature review on available research on barrier removals and a gap analysis on the literature review.

2. To perform a pan-European evaluation over each European country regarding a) established barrier removal actions b) the role of hydropower for energy generation and c) freshwater and biodiversity challenges.

3. To develop and test a barrier removal optimization framework using our findings from objectives 1 and 2 as a guideline.

4. To evaluate the potential of using predicting modelling for improving the developed barrier removal optimization framework.

2.0 Theoretical background

2.1 Free-flowing rivers

River systems are divided into basins (watersheds). Basins are formed of terrestrial areas (e.g., floodplains) and freshwater areas (streams and rivers). Streams and rivers are typically categorized based on their length using different orders. The most widely used is the Strahler order, formed of 1-9. Order 1 represents the smallest streams and order 9 the largest rivers (Khatun & Sharma, 2018). The water that falls in the terrestrial areas is collected in catchments, then flows towards the streams and rivers all which drain in common outlets (USGS, 2019). For a more efficient river basin management, basins are divided into smaller sub-basins based on hydrographic functionalities (e.g., elevation, river/stream distance) (Lehner & Grill, 2013).

The term of river connectivity is typically used to describe the movements of biotic organisms and abiotic factors within a river system (Wohl, 2017). The EU Biodiversity Strategy 2030 refers to river connectivity using the term free-flowing river (European Commission,2021). The European Commission (2021) defines free-flowing river as a river system that supports the connectivity of water, nutrients, organisms, sediments, and matter and is divided in four-dimensions a) longitudinal connectivity, b) lateral connectivity, c) vertical connectivity and d) temporal connectivity (European Commission, 2021).

Longitudinal connectivity refers to the biotic and abiotic movements over the longitudinal length of a river system either upstream (movements towards the river sources) or downstream (movements towards the river outlets). Lateral connectivity refers to the biotic and abiotic movements between the river and its floodplains and is mainly concerned with the exchange of nutrients between floodplain and mainstreams. Vertical connectivity mainly refers to the exchange of abiotic components between the atmosphere and the groundwater. Finally, temporal connectivity considers exchanges in biotic and abiotic components based on temporal trends (European Commission, 2021). A schematic representation is presented in figure 1.

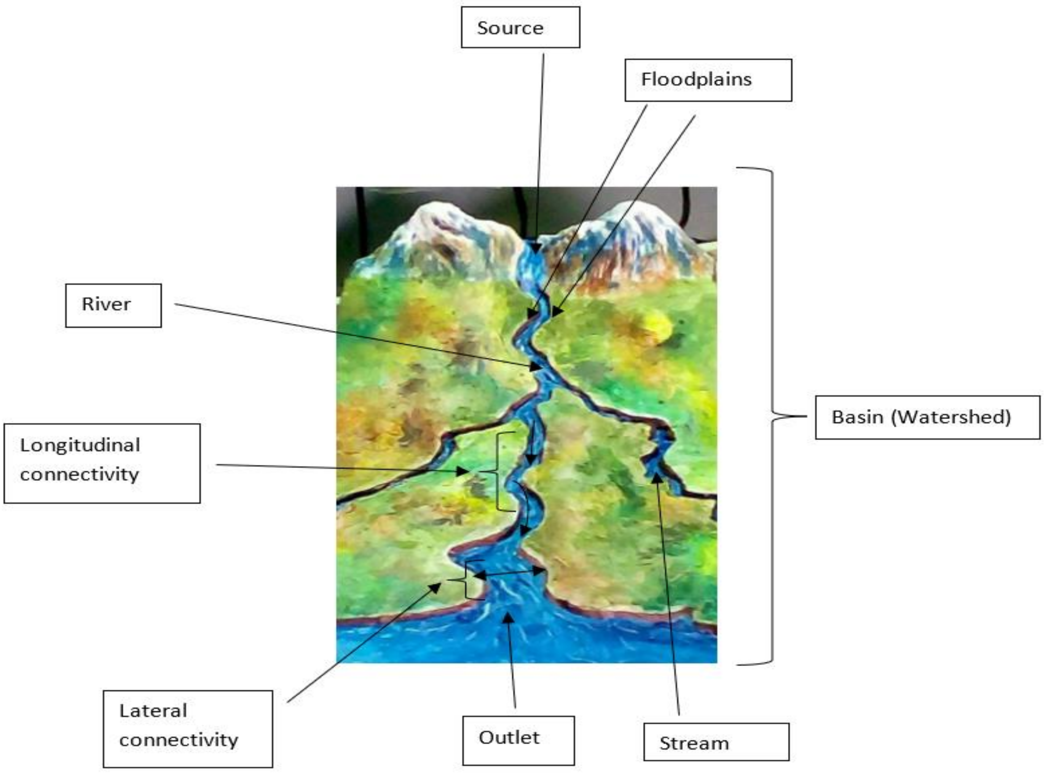

Figure 1. Basin (watershed) structure. Components include a) Source, b) floodplains, c) streams, d) main river, e) outlets as well as f) longitudinal connectivity and g) lateral connectivity. The figure excludes the representation of catchments.

2.2 Socio-economic importance of rivers

Maintaining free-flowing rivers assumes that there is no anthropogenic influence disrupting the water flow (European Commission, 2021). However, there are growing studies indicating that the free-flowing rivers globally are declining more and more and expected to continue to decline in the future (e.g., Belletti et al., 2020; WWF, 2021). This will be a challenge not only for environmental integrity but also for us humans, who we highly depend on the healthy rivers for the provision of several services including water and food provision.

Regarding drinking water, extraction points are typically located over river points. For ensuring that the extracted water is of good chemical quality and therefore safe for human consumption it is necessary to ensure that rivers maintain their self-purification capacities (Wei et al., 2009). Similarly with drinking water extraction, rivers serve as water sources for agricultural fields for sustaining food provision (Grill et al., 2019). The expansion of extensive agricultural intensification over floodplains and wetlands has resulted in the disruption of lateral connectivity (Grygoruk et al., 2013) and the release of chemicals in river systems. Consequently, self-purification capacities of rivers are reduced and so is the freshwater quality (Wei et al., 2009).

Healthy river floodplains contribute in addressing climate change and the effects for humanity (European Commission, 2021). Intact floodplains and wetlands sequester carbon from the atmosphere and store it in the soil layers. Therefore, by maintaining and restoring floodplains and wetlands and therefore lateral connectivity, is expected that atmospheric carbon levels will be reduced leading in a reduction in air pollution (European Commission, 2021). At the same time, water pollution would also decrease through the restoration of lateral connectivity. A reduction both in air and water pollution would then result in positive effect for human health (Tanneru, 2020).

2.3 River barriers

The greatest threat to free-flowing rivers is river fragmentation which is caused by the presence of anthropogenic river barriers. The AMBER Consortium (2020) defines barriers as any physical artificial barriers of any height that influence the components of river ecosystem connectivity including organisms, sediment, water, nutrients, and matter. Although there are high uncertainties regarding the exact number of river barriers, earlier estimations have suggested at least 3 million longitudinal and lateral barriers globally, disconnecting over 60% of rivers globally (Grill et al., 2019).

The most updated longitudinal barrier database in Europe is the AMBER database which includes nearly 630 000 longitudinal barriers (AMBER Consortium, 2021). The longitudinal barriers are divided into six main categories based on the functional traits of each barrier: a) ramp/bed sills, b) fords, c) culverts, d) weirs, e) sluices and f) dams (Figure 2).

Despite the large recordings on longitudinal barriers, there is a higher uncertainty on European lateral barrier numbers. Lateral barriers, include structures on the river floodplains for example for protecting against floods or river navigation structures such as embankments. However, there are currently no datasets available for lateral barriers. This creates a great challenge for restoring lateral connecting according to the EU Biodiversity Strategy 2030.

Even if most earlier barrier removal prioritization methods focused on longitudinal barrier removals, there is still a great uncertainty on the methodologies applied. In their study, Garcia de Leaniz & O'Hanley (2022) classified barrier removal prioritization methods in two main categories: a) Informal prioritization methods and b) Formal prioritization methods. Informal methods were then divided into two subcategories: a) Opportunistic responses and b) Export judgment. Opportunistic responses are described as barrier removals considering the removal of any barrier at local scale if an opportunity for removal arises (e.g., willingness of the owner to remove it). They require low planning and assume that removals will result in a connectivity benefit. However, opportunistic removals are generally unsuccessful due to inefficient planning by ignoring the effects of removals for the surrounding ecosystems and communities. Expert judgment on the other hand involves better planning as it considers the effects of removals on local ecosystems and communities. Although they can be successful at small scales, it is insufficient to rely solely on expert knowledge when considering removals over a large scale (Garcia de Leaniz & O'Hanley,2022), especially for a pan-European scale as required by the EU Biodiversity Strategy 2030.

Formal methods are divided into four subcategories: a) Scoring and ranking, b) GIS scenario analysis, c) Graph theory and d) Mathematical optimization. Scoring and ranking is the most popular approach and involves the selection of barriers for removal based on a set of criteria over a certain monetary budget. Although this method is simple to use and in a planned manner, it fails because it only considers removals at very small spatial scale. This is because barrier removals ignore other barrier removals upstream or downstream. Therefore, projects only evaluate the local effect of barrier removals, ignoring the overall effect over the entire streams, rivers, or basins.

For ensuring that a benefit is gained for the entire basins, barrier removals need to be coordinated. Although the spatial scale coordination can be addressed through Geographical Information System (GIS) scenario analysis or with graph theory, both methods ignore the cost-efficiency component which is necessary to consider during barrier removal plans. The most reliable method for prioritizing barrier removals has been suggested to be mathematical optimization. Mathematical optimization considers the application of programming and mathematical software that performs optimization over large geographical scales and takes into consideration cost-efficiency as well. However, mathematical optimization is highly complicated and there has not yet been developed a highly reliable barrier removal optimization model.

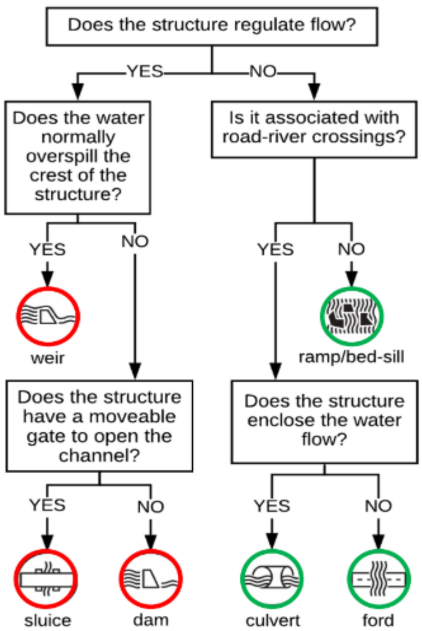

Figure 2 Classification of the six main longitudinal barrier types (Garcia de Leaniz & O'Hanley, 2022)

2.4 Hydrographic networks

The use of a high spatial resolution hydrographic model is crucial for the efficient application of mathematical optimization during barrier removal prioritization. For the development of hydrographic networks, scientists utilize remote sensing Digital Elevation Model (DEM) data (Amatulli et al., 2022). DEMs are Geographical Information System (GIS) data collected for example from satellite or aircraft images, that depict in a digital form the topographical features of the earth's surface, by excluding any surface features, either natural (e.g., forests, grasslands) or anthropogenic (e.g., buildings) (USGS, 2023).

Although there have been several hydrographic networks developed including among others the European catchments and Network Systems (ECRINS), (Belletti et al., 2020), the National Hydrography Plus (NHD+) (Buchanan et al., 2022) or the HydroRIVERS (Lehner & Grill, 2013), they have all been criticized in terms of their reliability. Specifically, none of the earlier models developed could delineate with equally high precision both small streams as well as large rivers. Additionally, small headwater streams were either excluded or underrepresented in earlier model, an issue when planning for the EU Biodiversity Strategy 2030, considering that small headwater streams contribute over 70% to the overall stream length (Amatulli et al., 2022). The models also lacked several topological and topographical information on the derived rivers and streams (Amatulli et al., 2022) necessary to consider during barrier removal prioritization.

These challenges can be addressed using the recently developed hydrographic network "Hydrography90m" (Amatulli et al., 2022). The Hydrography 90m was created using the MERIT Hydro Digital Elevation Model at 90m resolution to create a global and standardized hydrographic network. It provides both detailed topographical information (e.g., slope, elevation) as well as topological information (e.g., stream orders) on the derived streams. Minimum head stream flow accumulation is set at 0.05 km^2 which then allows for the extraction of highly detailed head stream channels. For the estimation of basins and of stream channels, GRASS GIS modules were used, that yielded 1.6 million basins and 726 million unique streams. When comparing to earlier models, Hydrography90m has both the highest spatial accuracy as well as the most delineated streams (Amatulli et al., 2022), making it the most reliable tool to use for mathematical optimization of barrier removal prioritization. The Hydrography90m layers can easily be downloaded using R, bash, or manually through their website, and be used with GIS software (e.g., QGIS, GRASS GIS or ArcGIS).

2.5 Systematic conservation prioritization

Systematic conservation planning is an arising method used for locating and designing environmental areas for conservation (Margules & Pressey, 2000). It is divided in six parts: 1) Application of a set of objectives typically representing the natural conditions within a conservation area, necessary to maintain the ecological conditions the same 2) Set of features that would represent the biodiversity of each conservation area 3) Considers a measurable/quantitative value as goal/targets for each conservation area 4) Evaluation of the extend at which each target was met 5) Use of simple methods for identifying new potential areas for conservation 6) Application of conservation criteria normally applied when not all the targets could be met (Margules & Pressey, 2000).

Systematic conservation planning is a highly complex process. Therefore, it is necessary to apply optimization methods to develop conservation plans in a cost-efficient way. As a solution, Hanson et al. (2023) developed the "prioritizr" package in R. "Prioritizr" provides an artificial environment for the problem formulation where powerful problem solvers are applied. These solvers apply Integer Linear Programming techniques that optimize for solving a problem based on linear relationships between their variables (Hanson et al., 2023). The most common problem solver is Gurobi, which produces more cost-efficient solutions and at lower time in comparison to other available problem solvers (Gurobi Optimization LLC, 2023).

For the problem formulation the user can use three different file forms: csv, raster, or vector files. When using csv input files, the following three data files are required: a) the distribution of the planning units (conservation areas) and the cost value of each planning unit, b) a feature file containing categorical (biodiversity) information on the planning units (e.g., plant species) and c) a numerical file containing the numerical amount of each feature in each planning unit (e.g., amount of each plant species). When using a vector or a raster file as an input, then only the first two files are required, as the numerical data are included in the vector/raster in a spatial form. After defining the problem, the user can add different objectives, constraints and targets that need to be considered. An objective is the mathematical formulation of the overall goal of the specified problem. Constraints are certain criteria added to some variables that make them invalid or for prioritizing them during the optimization. Targets are applied to specify the minimum amount of each feature that needs to be considered during the optimization (Hanson et al., 2023).

The three most common objectives used in optimization are the maximum feature objective (equation 1), maximum cover objective (equation 2) and minimum feature objective (equation 3). By using maximum feature objective, “prioritizr” finds all the planning units that can fulfil all the selected targets for a certain budget value or for the cheapest budget value, in case of multiple solutions. The maximum coverage problem identifies solutions by maximizing equally the number of planning units across the different features without exceeding a specified budget. Finally, the minimum set objective identifies the planning units that minimize the cost under a set of conservation targets (Hanson et al., 2023).

Although systematic conservation planning software is mainly designed for solving conservation problems, earlier studies have adapted them and applied them in the concept of barrier removal optimization. The most widely applied planning software in these studies has been Marxan (e.g., Hermoso et al., 2018; Hermoso, Clavero & Filipe, 2021). However, it has been suggested that the produced solutions of Marxan lack cost-efficiency while the solutions take relatively long time to be produced (Hanson et al., 2023). On the contrary, “prioritizr” produces solutions at a faster time and by identifying the most optimal solutions regarding cost-efficiency, especially when used along the Gurobi problem solver. Additionally, “priotitizr” has been designed to accommodate some of the functions of Marxan, making it as a result easily accessible to users of Marxan (Hanson et al., 2023). Therefore, the use of “prioritizr” along with Gurobi solvers can be considered as a highly prominent methodology during barrier removal optimization methodologies.

$$\text{Maximize } -a\sum_{i=1}^{n} x_i c_i + \sum_{j=1}^{m} y_j$$

Subject to:

$$\sum_{i=1}^{n} x_i c_i \leq B \text{ and } \sum_{j=1}^{n} x_j r_{ij} \geq y_i T_i \ \forall\ i$$

Equation 1. Maximum feature objective equation where: n = planning units, m = conservation features, xi = binary decision deciding whether or not to select a planning unit (i), yjj =binary decision deciding to meet or not the targets for the species(i), ci = cost of planning unit (i), rij = amount of a feature (i) in a planning unit (j), B = budget, Ti = target of feature (i) and a = chosen to ensure that the first term of the objective function < second to ensure that cost only influences decisions between solutions of the same targets (Hanson et al.., 2023).

$$\text{Maximize } \sum_{i=1}^{m} \sum_{j=1}^{n} x_j r_{ij} + \text{ subject to } \sum_{i=1}^{n} x_i c_i \leq B$$

Equation 2. Maximum cover objective where: : n = planning units, m = conservation features, xi = binary decision deciding whether to select a planning unit (i), ci = cost of planning unit (i), rij = amount of a feature (i) in a planning unit (j) and B = budget (Hanson et al.., 2023)

$$\text{Minimize } \sum_{i=1}^{n} x_i c_i + \text{ subject to } \sum_{j=1}^{n} x_j r_{ij} \geq T_i \ \forall\ i$$

Equation 3. Minimum set objective where: n = planning units, m = conservation features, xi = binary decision deciding whether to select a planning unit (i), ci = cost of planning unit (i), rij = amount of a feature (i) in a planning unit (j) and Ti= target of feature (i) (Hanson et al.., 2023)

3.0 Methodology

3.1 Literature review

For the literature review, we created a search term for identifying river restoration projects considering the topics of longitudinal connectivity, lateral connectivity, and river barriers. This was to target the EU Biodiversity Strategy 2030 aim for longitudinal and lateral connectivity restoration through barrier removals and the reconnection of at least 25 000 km river flow. We applied the following search term in Scopus (Elsevier, 2023) to account for projects that consider a) river restoration plans, b) longitudinal or lateral connectivity, c) the presence of river barriers which are usually described in literature as d) dams (Appendix A-D):

TITLE-ABS-KEY (("River restoration" AND "Connectivity" AND "Barriers") OR ("River restoration" AND "Connectivity" AND "Dams") OR ("River restoration" AND "Connectivity") OR ("River restoration" AND "Barriers") OR ("River restoration" AND "Dams")).

3.2 Gap analysis

From the 573 papers identified, we narrowed down to 109 peer-reviewed papers where literature gaps have been identified and reported (Appendix E). The first version of the paper of Pander & Casas-Mulet. & Geist (2022) was removed from Scopus and instead replaced with the new version of Pander & Casas-Mulet & Geist (2023). For that reason, we considered the new version in the gaps analysis table.

We consider the literature review gaps in the context of EU Biodiversity Strategy 2030 and particularly for the aims of barrier removals for the restoration longitudinal and lateral connectivity, and the aim for 25 000 km free-flowing rivers. We divided the identified gaps into the following categories: a) Modelling/Methodology approaches (barriers): Technical gaps that have been reported to compromise the efforts for barrier removal projects b) Biotic environment: Data gaps on our knowledge on biological components of a river ecosystem directly related to river barriers or which we have identified as important to consider in response to longitudinal and/or lateral connectivity c) Abiotic environment: Data gaps on our knowledge on physical or geomorphological components of a river ecosystem either reported to be related to river barriers or which we have identified as important to consider in response to longitudinal and/or lateral connectivity d) Social/political influence: Social or political challenges which have not been considered during barrier removal projects or which we have identified as important to consider in response to longitudinal and/or lateral connectivity e) Modelling/Methodologies (Other): Technical gaps which have not been reported to affect barrier removal projects but which we have identified as useful to consider for longitudinal and/or lateral connectivity in response to gaps a-f.

3.3 Pan-European overview

The next step was to investigate the parameters for the barrier removal optimization framework over a pan-European scale. To the best of our knowledge, the most informative study providing a pan-European view on river management projects is the survey done by Verheijl, Fokkens & Buijse (2021). Following that, we built on the survey's suggestions regarding potential conflict between barrier removals and barrier function for hydropower production.

We used the publicly available energy data tool developed by Ritchie, Roser & Rosado (2022) to derive data for the role of hydropower for energy production in each European country. We first considered the use of the following metric: Energy dependency in the form of "Share of energy consumption by source". This metric addresses national dependencies on every energy source for the total production of energy. However, this metric presents data gaps as there is missing information for a few European countries. To address this gap, we considered instead the following metric: "Average share of electricity production by source".

The data were used to create a map in QGIS 3.28 Firenze (QGIS Development Team, 2023). The map was created by using HCMGIS plugin -> Download OpenData -> "Global Administrative Areas by Country from GADM" to download the administrative boundaries of each of the 49 European countries in the form of multi-polygon shapefiles. Each country was then manually classified based on the "Average share of electricity production by source" (Appendix F).

In addition, we were also concerned with the following questions. What are the levels of Carbon dioxide (CO2) emissions per European country? What are the main sources of CO2 emissions per European country? What are the main challenges for managing water bodies per European country? What are the main challenges for biodiversity per European country?

We utilized the publicly available data tool developed by Ritchie, Roser & Rosado (2022) to derive information for CO2 emissions per European country. Data are presented in the form of a map, created in QGIS 3.28 Firenze using the same steps as earlier, but by classifying based on the share of fossil fuels for electricity production per European Country (Appendix G). Data are also presented regarding the amount of CO2 emissions per country and the share of each source of emissions (Appendix H).

Finally, data were derived for water and biodiversity challenges per European country as they may create conflicts or synergies with barrier removal projects. The data were collected from national government sources and European or international organizations. If no information was available, data were derived from scientific studies (Appendix I).

3.4 Barrier removal optimization framework

3.4.1 Development of a simplified barrier removal optimization framework

Throughout our review, investigated several parameters that to consider during the development of a barrier removal optimization framework. For the purposes of our study, we focused on the development of a framework that would meet the targets of the EU Biodiversity Strategy 2030 regarding the optimal removal of barriers for the improvement of longitudinal and lateral connectivity and the aim for the reconnection of 25 000 km of free-flowing river.

The first part of the methodology included the data analysis and manipulation, performed in QGIS 3.28 Firenze (QGIS Development Team, 2023) and Excel (Microsoft Corporation, 2023). The second part included the optimization which was performed in R (RStudio Team, 2023) using “prioritizr” (Hanson et al., 2023) and “Gurobi” (Gurobi Optimization LLC, 2023). The third part of the methodology included the export of the solutions from R using QGIS 3.28 Firenze and Excel.

3.4.2 Methodology description: Part A - Input data manipulation

The aim of the first part of the methodology was to acquire the input data for our study area. The first part was divided in 4 steps. Firstly, the input data were downloaded: AMBER (AMBER Consortium, 2020), river segments, points, outlets (Amatulli et al., 2022), basins (Lehner & Grill, 2013), and land use (European Environment Agency, 2023), (Figure 4). The second step included the extraction of the study area (Figure 5). The studied area was 50-100 km Northwest of the city of Hamburg in Germany, and parallel to Elba River (Figure 3). It included the basins with id numbers 526, 527 and 530. Then, the AMBER, points and outlets were integrated into a single file and simplified (Figure 6). Finally, the land use data file was used to extract the dominant land use type around each AMBER/source/outlet point (Figure 7). The land use files were categorized in five major categories: Artificial surfaces, agricultural areas, forest (and semi natural areas), wetland and water bodies. Each category was divided into several sub-categories. For this part of the study, we only considered the five major land use categories.”

3.4.3 Methodology description: Part B – Estimation of connected river length

The aim of the second part of the methodology was the estimation of connected river length between all the AMER barrier pairs. This included the use of GRASS within QGIS for the calculation of the distances between all the pairs of AMBER/sources/outlets within the river segment network for the basins 526, 527 and 530. The result was a line shapefile which was then exported as a csv file (Figure 8). Pair id was chosen so that each barrier would only be represented once as this is a requirement when using the “prioritizr” package for the optimization in R. Because of the large number of data derived when using the selected GRASS function (v.net.allpairs), some data were lost during the export of the files. Therefore, missing pair distances were estimated using the “measure line” tool. Figure 9 shows a simple example that illustrates this process.

3.4.4 Methodology description: Part C – Optimization in R

The general optimization framework applied was formed of six steps (Table 1). The first step included the problem formulation, formed of three file inputs: a) Cost file, b) Features file and c) Representation Matrix (RIJ file). The second step included the addition of objectives to the problem. Three objectives were tested: a) Maximum feature objective b) Maximum cover objective, and c) Minimum set objective. The third step included the addition of targets to the problem. Relative targets were used to specify the minimum proportion of each feature in the optimization solution. The fourth step included the addition (or exclusion) of constraints. Constraints were included as columns: “Locked in” and “Locked out” in the “Cost file”. For scenarios where constraints were not considered, the “Locked in" and "Locked out" columns were excluded from the "Cost file". The fifth step included the solution of the problem using "Gurobi" as the problem solver.

Our overall aim was to identify the optimization scenarios that would yield the highest connected free-flowing river. For the optimization we followed two different approaches regarding the problem formulation. In the first approach the primary aim was to run different optimization scenarios to optimize for cost-effectiveness. We tested for optimization scenarios that would maintain the monetary costs of barrier removals under certain budgets or as low as possible. Therefore, we used cost of barrier removals as the cost column in the "cost" file during the problem formulation. The secondary aim was to identify the optimization solution that yielded the highest connected free-flowing river distance.

In the second approach the aim was entirely to optimize for connected distance-effectiveness. We tested for optimization scenarios that would provide solutions where connected free-flowing river distance solutions would be close to the distance values set as budgets. Therefore, we used river distance as the cost column in the "cost" file during the problem formulation. We did not test for minimum set objective as this optimization scenario would minimize the connected river distance which was not our aim. Then, we compared all the results to evaluate which of the optimization results had yielded the highest connected free-flowing river distance, the contribution to the EU Biodiversity Strategy 2030 aims for reconnecting 25 000 km of free-flowing rivers and the costs of removals. In total we tested 54 optimization scenarios.

An example of the R code used is presented in Appendix N. For simplicity all the cost values used were divided by 1000. For example, weirs were recorded as 116.113 euros instead of 116113 euros while budget for 100 million euros was set to 100 000 euros. The methodology for the cost estimation of the removal of each barrier type is presented in Table 2. Overall statistical results are presented in Appendix O. The results from all the optimization scenarios regarding cost of removals and connected free-flowing river distance are presented in Appendix K. Additional statistics regarding barrier types removed and land use are presented in Appendix L and M. Additionally, the results from the optimization scenarios that have yielded the ten highest reconnected river distances are presented as maps (Figures 12-21). The figures show information regarding the locations and the types of removed barriers as well as the location of the unremoved barriers.

3.5 Random Forest Classification

As an additional step to our study, we also evaluated the potential of using hydrologic and land use river properties from the Hydrography90m and the Corine land use data as predictor variables of the AMBER barriers. Specifically, we predicted AMBER barrier types using a set of predictor variables. Then we evaluated the importance of each predictor variable for predicting the barrier types. We tested a Random Forest Classification model imported from "scikit" package (Pedregosa et al., 2011). The model was executed using Python 3 in Jupyter notebook (Perez & Granger, 2007). We used the studies of Belletti et al. (2020) and Buchanan et al. (2022) as a baseline for our methodology.

The methodology was divided in two major steps. The first step (Figure 10) included the extraction of the predictor variables using QGIS Firenze 3.28. The second step (Figure 11, Appendix O) included the training and testing of the prediction model using Random Forest Classification in Python and the identification of the major predictor variables for barrier classification. The prediction was divided into the following steps: 1) Data import 2) Data split into features (predictor variables) and targets (barrier types) 3) Data scaling 4) Data split into training and test datasets (60% of the data for training and 40% for testing) 5) Creation of the Random Forest Classifier 6) Training of the prediction model using the training data 7) Test of the prediction model using the training data 8) Export of the predictions and 9) Estimation the predictors' importance.

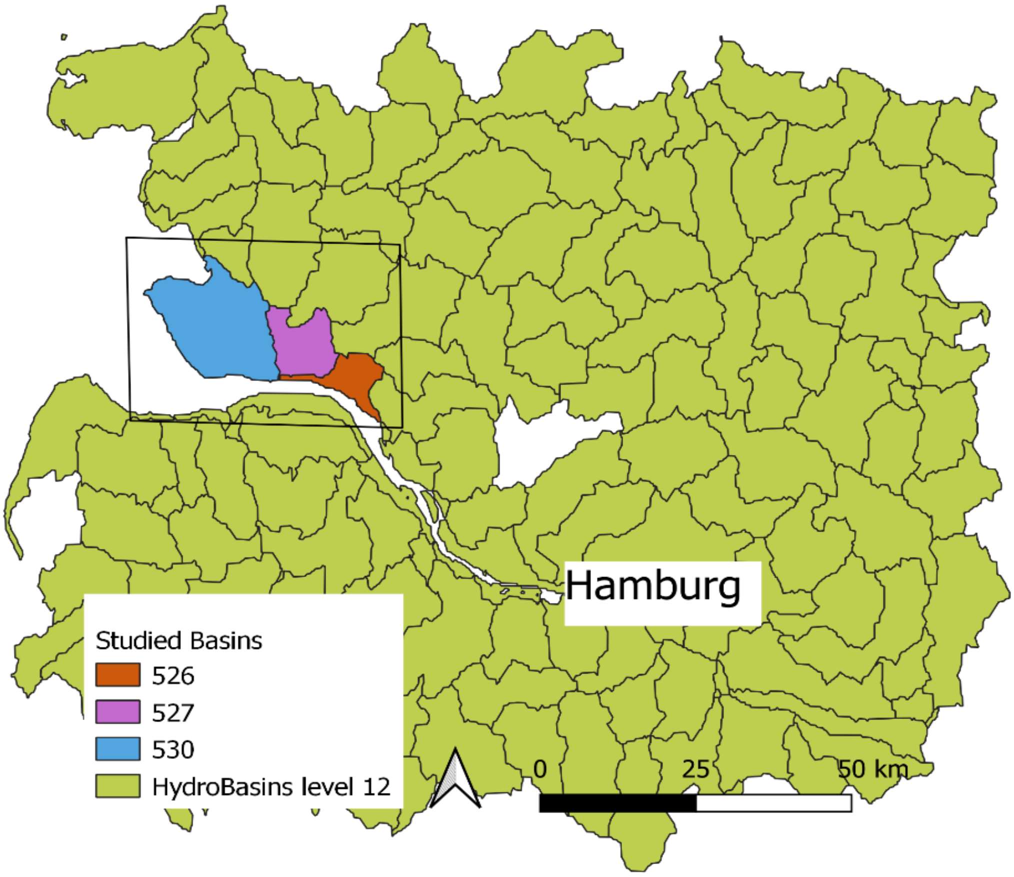

Figure 3. Studied location showing the studied basins, located 50-100 km Northwest of Hamburg, Germany.

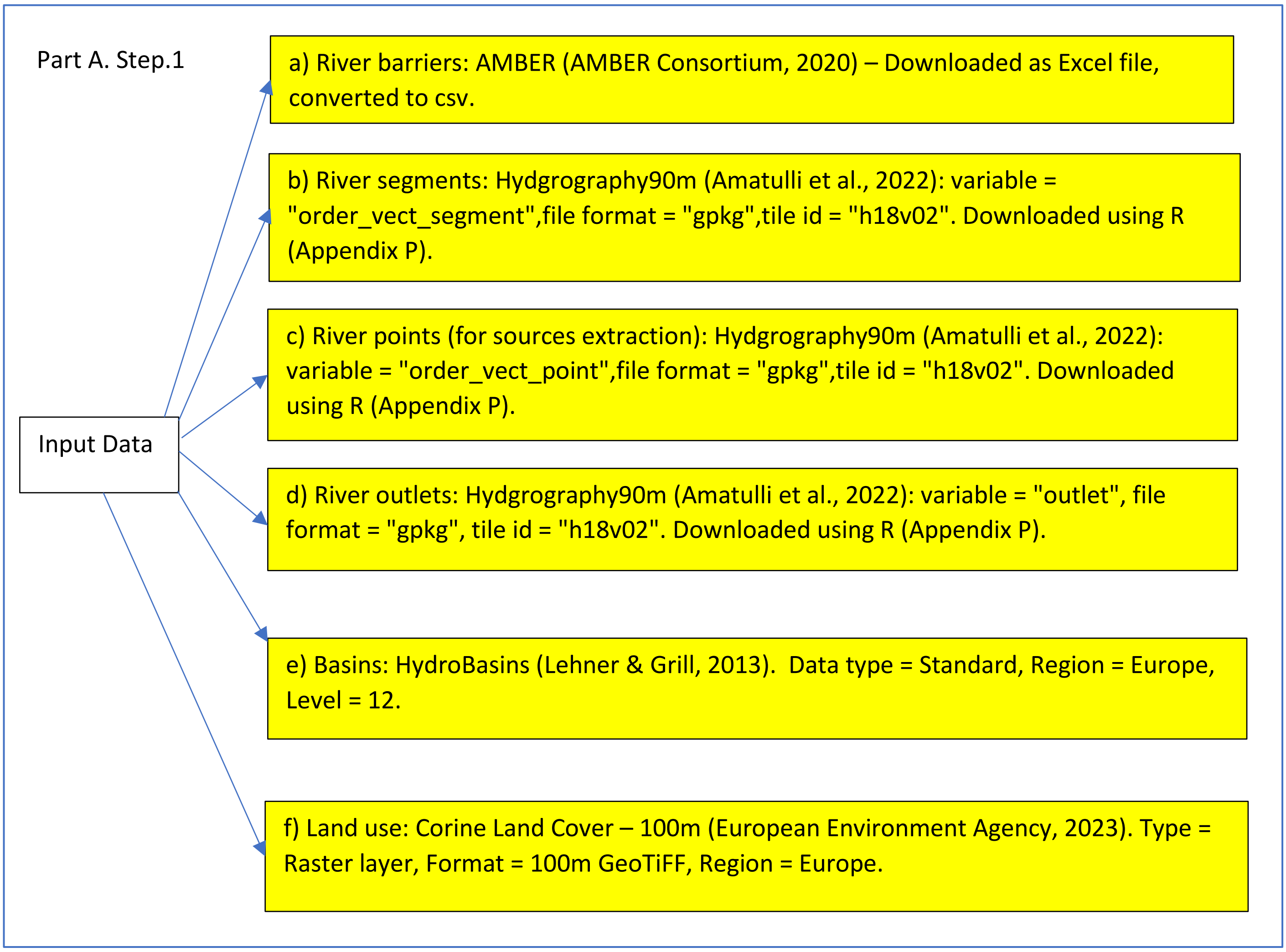

Figure 4 Methodology description: Part A - Input data manipulation, Step 1

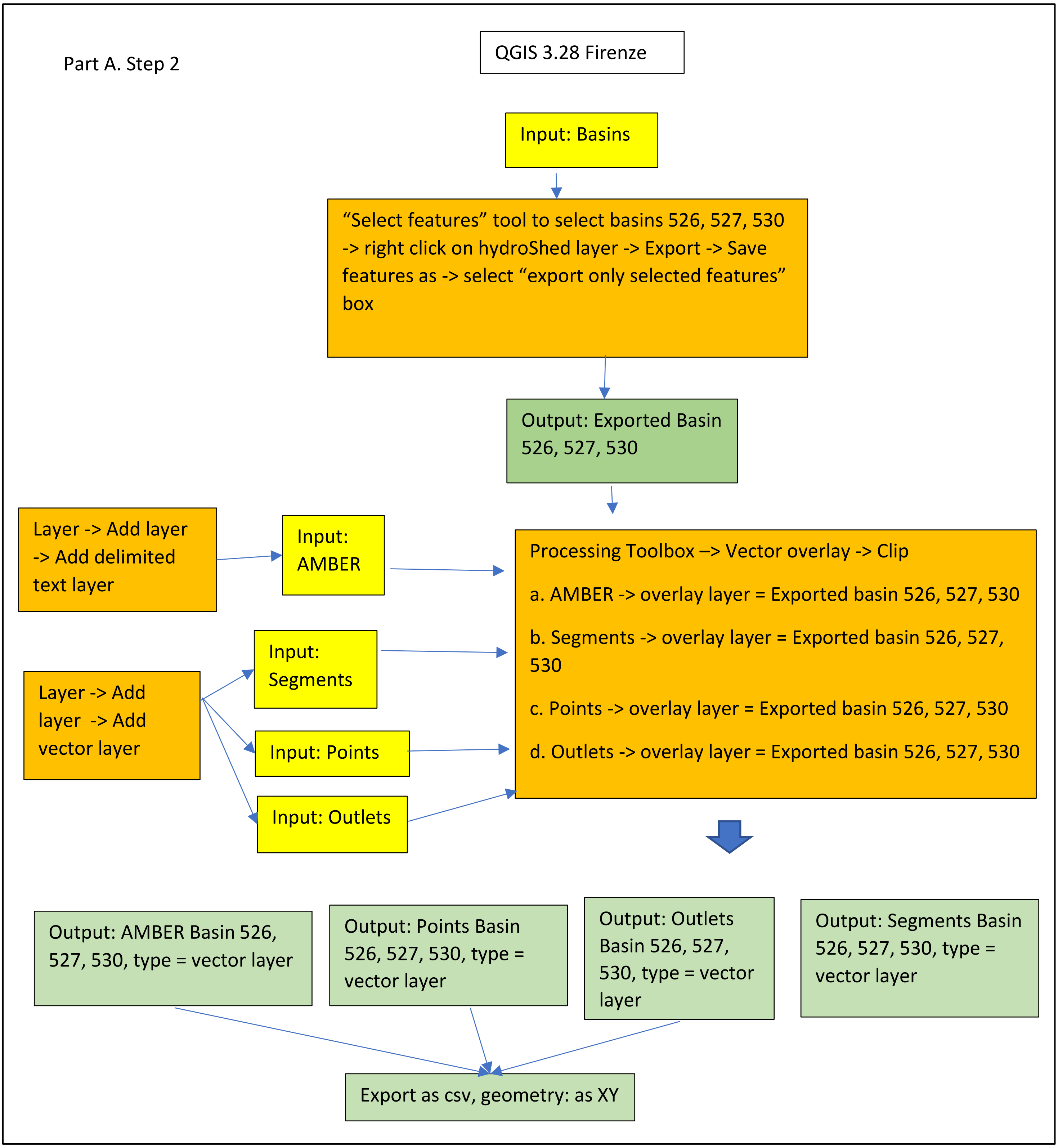

Figure 5 Methodology description: Part A - Input data manipulation Step 2

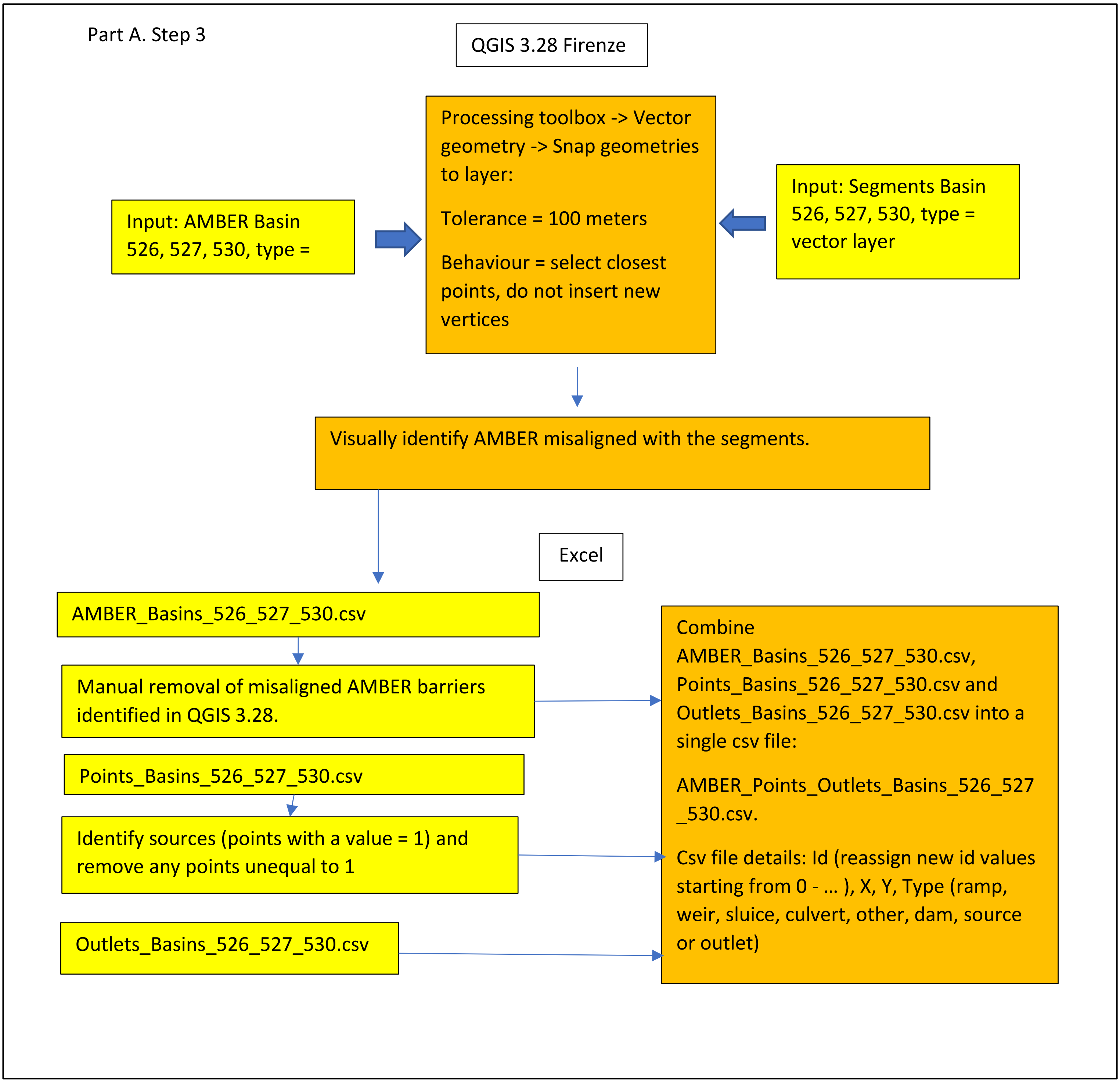

Figure 6 Methodology description: Part A - Input data manipulation, step 3.

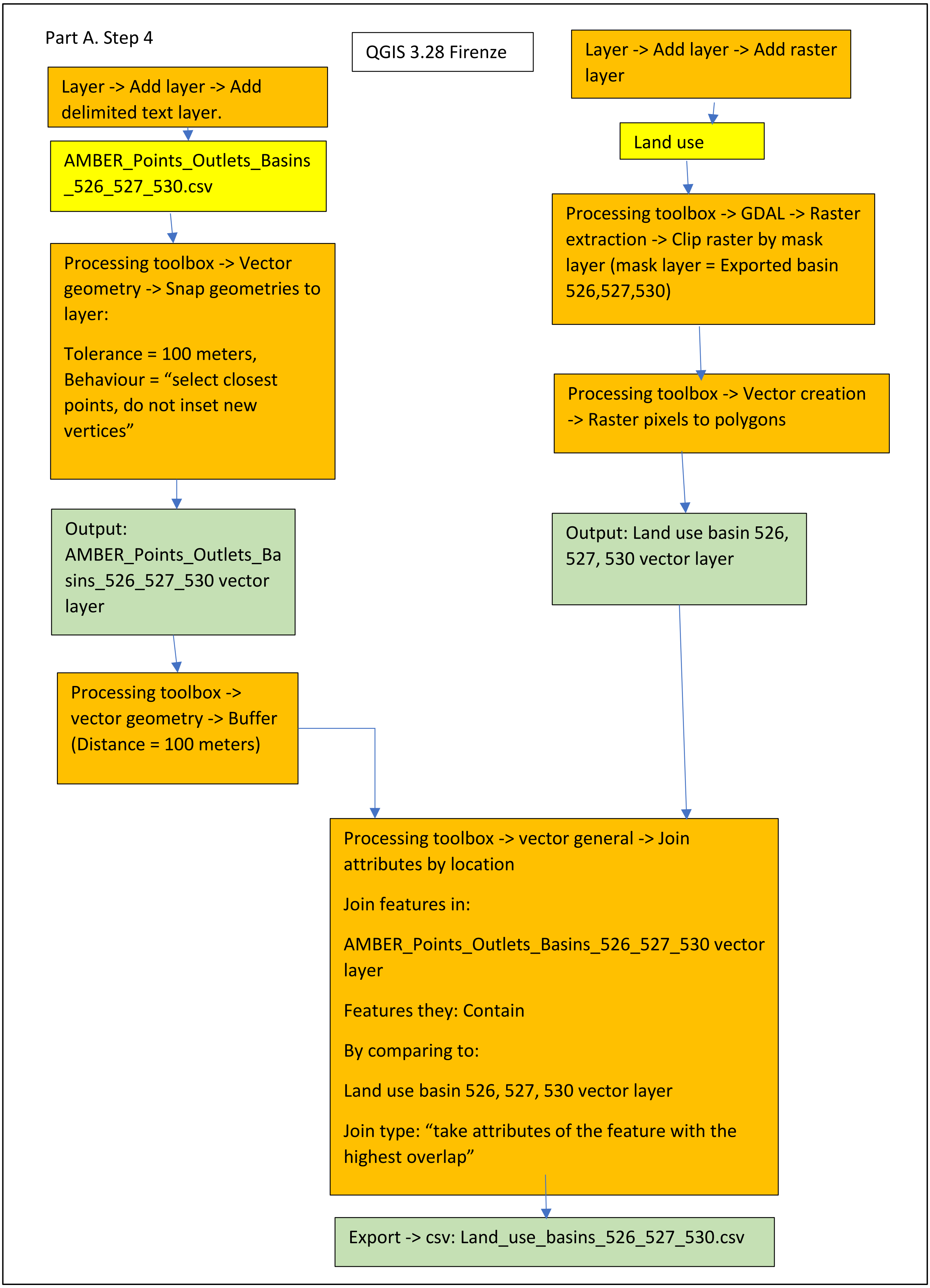

Figure 7 Methodology description: Part A - Input data manipulation, Step 4.

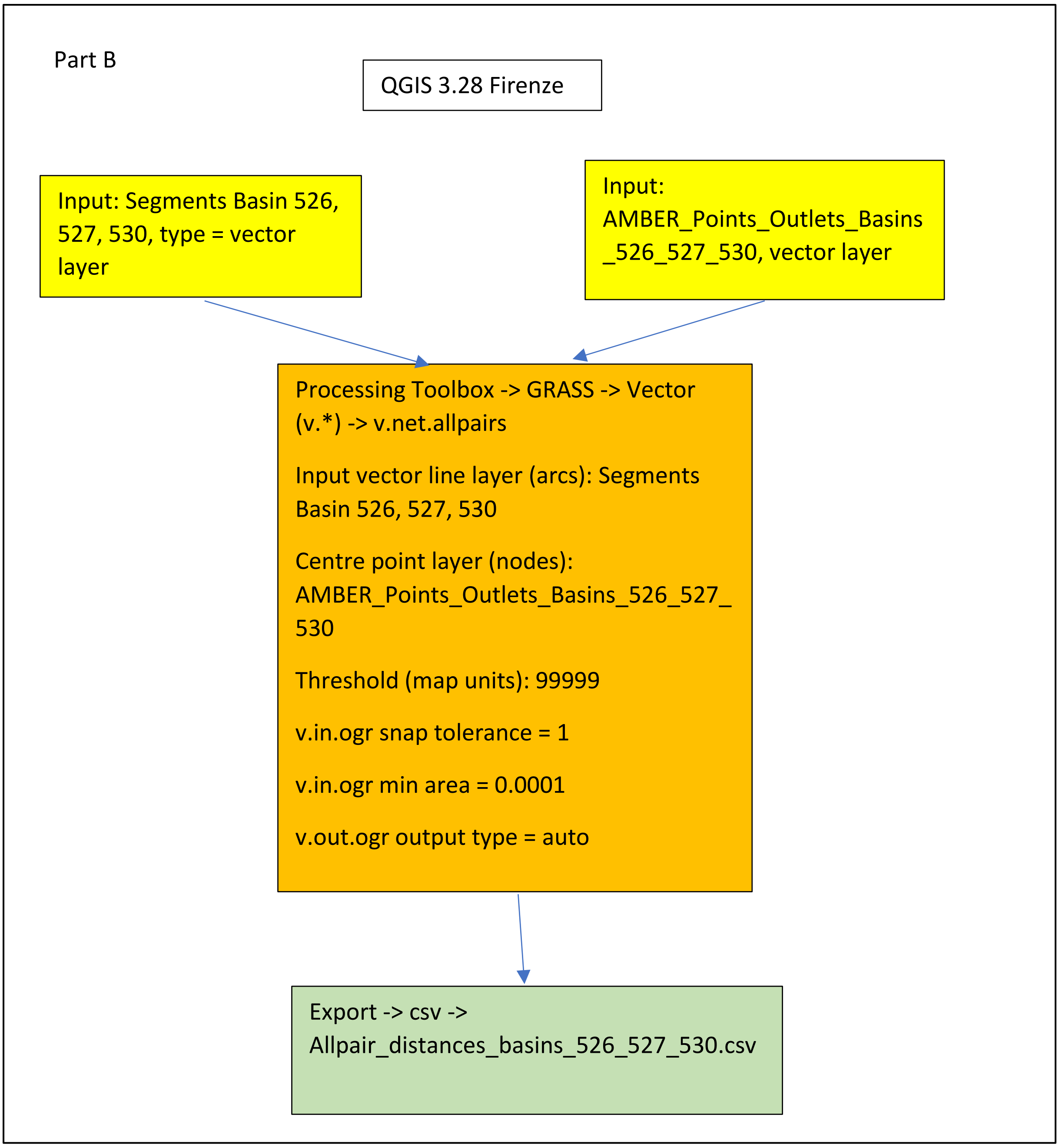

Figure 8 . Methodology description: Part B – Estimation of connected free-flowing river length.

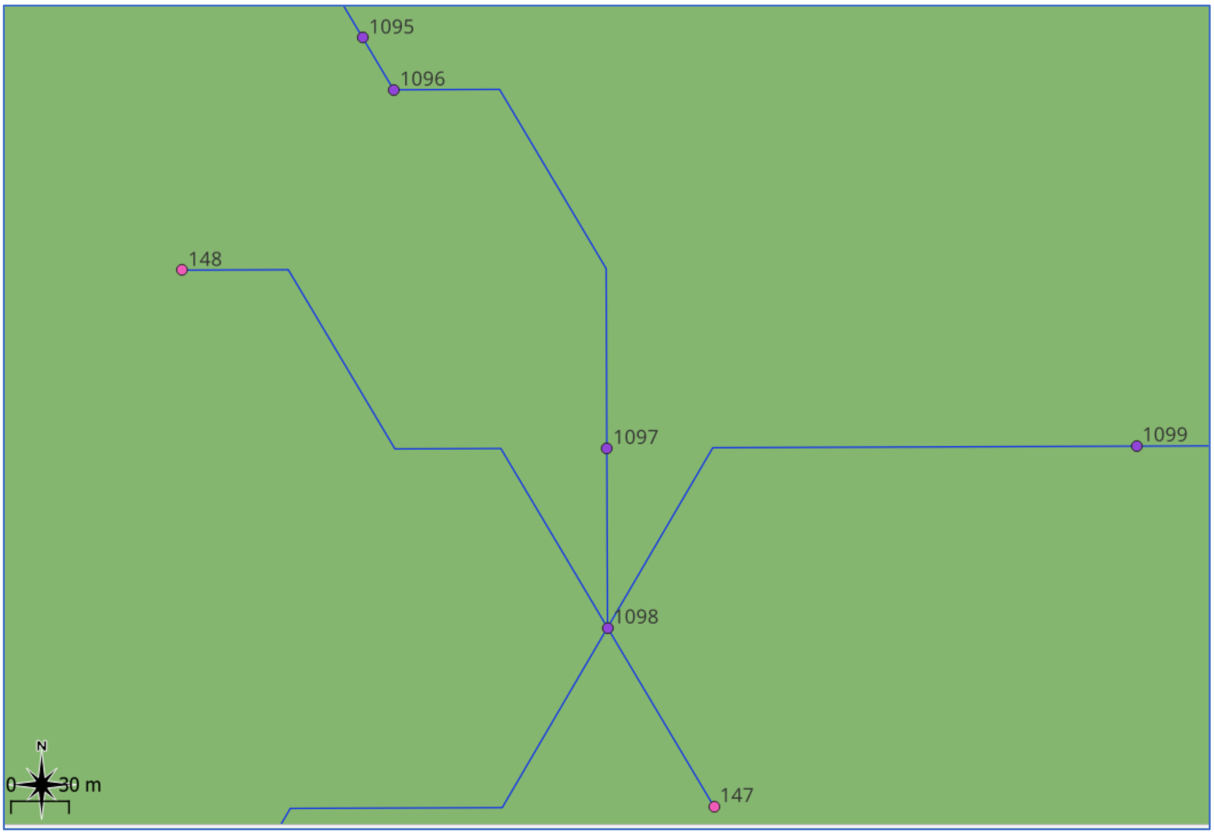

Figure 9 Simplified example illustrating the process used to calculate AMBER barrier pair distances for basin 526 (¬70km Northwest of Hamburg, Germany). In this example we assume that points 1095,1098 and 1099 are the last points in the network (although the actual dataset points 1095,1098 and 1099 are also connected to further points downstream). Points 147 and 148 represent the sources. Points 1098, 1096, 1097, 1098 and 1099 represent the AMBER barriers. V.net.allpairs function would yield the following combinations: 147-1095, 147-1096, 147-1097, 147-1098, 147-1099, 148-1095,148-1096,148-1097,148-1098,148-1099,1095-1096,1095-1097,1095-1098,1095-1099,1096-1097,1096-1098,1096-1099,1097-1098,1097-1099 and 1098-1099. The final barrier pairs would be as followed: 1095-1096 (id 1095), 1096-1097 (id 1097), 1097-1098 (id 1098), 147-1098 + 148-1098 (id 1098) and 1098-1099 (id 1099).

Table 1. Methodology description: Part C – Optimization in R

Steps

Step 1: Problem formulation:

Requires 3 file inputs:
a) Cost file: cost of each planning unit (barriers)

Table 3.a. Example of Cost file where "cost" = barrier removal cost in euros.

id	cost	locked_in	locked_out	Type
1052	413.253	FALSE	FALSE	culvert
1053	413.253	FALSE	FALSE	culvert
1054	413.253	FALSE	FALSE	culvert
1055	413.253	FALSE	FALSE	culvert
1056	11663.61	FALSE	FALSE	other

b) Features file:
Approach 1
AMBER barrier type ranked from the barrier with the lowest removal cost (id=1, name = weir) to the planning unit (barrier) with the highest removal cost (id = 8, name = dam). Planning unit with id = 4 and name = culvert_culvert represents points where 2 planning units classified as culverts were located at the same location. Planning unit with id = 6 and name = other_sluice represents points where 1 planning unit classified as other and 1 planning unit classified as sluice were located at the same location. Planning unit with id = 7 and name = culvert_other represents points where 1 barrier classified as culvert and 1 barrier classified as other were located at the same location.

Table 3b Features file, cost file = removal cost

id	name
1	weir
2	sluice
3	culvert
4	culvert_culvert
5	other
6	other_sluice
7	culvert_other
8	dam

Approach 2:
Strahler order ranked from the lower to the higher order. Where id 1-5,7-9 = order 1-5, 7-9. No barriers in a Strahler order 6 were present so order 6 was not included as a feature.

Scenarios

Two optimization approaches:

Approach 1: Optimizing for cost of barrier removals.

For example:

cost column in "cost" file = cost of each planning unit (barrier) removal (Euros) (Table 3a).

"amount" input in the Representation matrix RIJ = connected free-flowing river distance length (meters) following the removal of each planning unit (Table 3b).

Approach 2: Optimizing for connected free-flowing river distance.

For example:

cost column in "cost" file = connected free-flowing river distance length (meters) following the removal of each planning unit (barrier).

"amount" column in the Representation matrix RIJ = cost of removal (Euros) of each planning unit (barrier).

c) <u>RIJ file</u>: table with the quantities of each features' "within" each planning unit (=Representation matrix – RIJ, Table 3c). *Table 3c. Example of RIJ file where "amount" = connected distance length of each barrier in meters.* pu | amount | species | Type 1052 | 8349 | 3 | culvert 1053 | 4820.066 | 3 | culvert 1054 | 4640.938 | 3 | culvert 1055 | 5641.497 | 3 | culvert 1056 | 2364.907 | 5 | other	
<u>Step 2:</u> Adding an objective: *Approach 1:* Three objectives tested: 1. Maximum feature objective 2. Maximum cover objective 3. Minimum set objective *Approach 2:* Two objectives tested: 1. Maximum feature objective 2. Maximum cover objective	1. Maximum feature objective & 2. Maximum cover objective *Approach 1* ➢ Budget = 1 million euros, ➢ Budget = 10 million euros ➢ Budget = 100 million euros, *Approach 2* ➢ Budget = 112.692 km ➢ Budget = 225.384 km ➢ Budget = 338.077 km 3. Minimum set objective Does not require a specified budget.
<u>Step 3:</u> Adding targets: Three targets tested for each objective. ■ Maximum feature objective ■ Minimum set objective ➢ Target 1 & Target 2 (t1 and t2):	1. Maximum feature objective *Approach 1* ➢ Target 1 (t1): c (0.4,0.1,0.1,0.1,0.1,0.1,0.1,0) Where: Proportion 0.4 -> feature id = 1

These targets set the highest priority on planning units where in the "Features file" had an id=1 and lower priority on planning units with higher id value. ■ Maximum feature objective ➢ Target 3 (t3): This target maximized equally the prioritization of all the planning units. ■ Minimum set objective ➢ Target 4 (t4): This target minimized equally the prioritization of all the planning units to. ■ Maximum cover objective ➢ No targets required.	Proportion 0.1 -> feature id = 2-7 Proportion 0 -> feature id = 8 *Approach 2* ➢ Target 1 (t1): c (0.4,0.1,0.1,0.1,0.1,0.1) Where: Proportion 0.4 -> feature id = 1 Proportion 0.1 -> feature id = 2-6 *Approach 1* ➢ Target 2 (t2): c(0.5,0.3,0.1,0.025,0.025,0.025,0.025,0) Where: Proportion 0.5 -> feature id = 1 Proportion 0.3 -> feature id = 2 Proportion 0.1 -> feature id = 3 Proportion 0.025 -> feature id = 4-7 Proportion 0 -> feature id = 8 *Approach 2* ➢ Target 2 (t2): c(0.4,0.3,0.2,0.033,0.033,0.033) Proportion 0.4-> feature id = 1 Proportion 0.3 -> feature id = 2 Proportion 0.2 -> feature id = 3 Proportion 0.033 -> feature id = 4-6 *Approach 1* ➢ Target 3 (t3): c (0.9,0.9,0.9,0.9,0.9,0.9,0.9,0.9) Where: Proportion 0.9 -> feature id = 1 -8 *Approach 2* ➢ Target 3 (t3): c (0.9,0.9,0.9,0.9,0.9,0.9) Where: Proportion 0.9 -> feature id = 1 -6 2. Minimum set objective: *Approach 1 only* ➢ Target 1 (t1): c (0.4,0.1,0.1,0.1,0.1,0.1,0.1,0) Where: Proportion 0.4 -> feature id = 1 Proportion 0.1 -> feature id = 2-7 Proportion 0 -> feature id = 8

	➢ Target 2 (t2): c(0.5,0.3,0.1,0.025,0.025,0.025,0.025,0) Where: Proportion 0.5 -> feature id = 1 Proportion 0.3 -> feature id = 2 Proportion 0.1 -> feature id = 3 Proportion 0.025 -> feature id = 4-7 Proportion 0 -> feature id = 8 ➢ Target 4 (t4): c (0.1,0.1,0.1,0.1,0.1,0.1,0.1,0.1) Where: Proportion 0.1 -> feature id = 1 -8
<u>Step 4:</u> Addition of constraints Constraints were added in the "Cost file" as "Locked in" and "Locked out" columns. Where: ➢ Locked in = TRUE Planning units with land use classified as "forest (and semi natural areas)" or "Water bodies" were locked in to ensure they would be prioritized during the optimization. This was to ensure that solutions would include barrier removals over natural areas. No wetlands were present in the studied site. ➢ Locked out = TRUE Planning units with land use classified as "artificial area" were locked out to ensure that they would be excluded during the optimization. ➢ Locked in = FALSE + Locked out = FALSE Planning units with land use classified as "agriculture" were neither locked in nor locked out. This means that agricultural areas would receive lower prioritization during the optimization.	➢ Addition of constraints ➢ Exclusion of constraints
<u>Step 5</u>: Solving the decision problem	➢ Gurobi solver

Table 2. Methodology description: Part A - Estimation of cost of removal for each barrier type.

Barrier type	**Estimation method**	**Estimated cost of removal (Euros)**
Ramp (absent from the final dataset)	Proxy of the cost of repairing or replacement of Bed rock ramps (USBR, 2007).	4679
Ford (absent from the final dataset)	Based on the cost of removal of Jackdaw scar ford in UK (AMBER Consortium, 2019).	6676
Weir	Average cost of 3 weir removals in UK: Lowmill weir, Carleton weir and Sheepmount weir (AMBER Consortium, 2019).	116 154
Sluice	Average cost of 2 sluice removals in UK sluices as part of Tichborne river restoration project (RESTORE, 2019).	337 552
Culvert	Average cost of 3 culvert removals in UK: Wandle Park, Ravensbourn and Tanners (European Centre for River Restoration, 2019).	413 253
Dam	Average cost of 5 dam removals in USA: Matillja, Clamath, Sam Clemente, Condit and Elwa dams (AMBER Consortium, 2019).	57 446 392
Other	Average cost of Ramp, Ford, Weir, sluice, culvert, and dam removals	11 663 606
Additional note: For barriers located at the same geographical coordinates the cost of removal was summed up to account for the expense of removing all barriers present. For example, if 1 sluice and 1 culvert were located at the same geographic location, then the cost of removal for the planning unit would be: Cost of sluice + Cost of Culvert = 337552 + 413253 = 750805 Euros.		

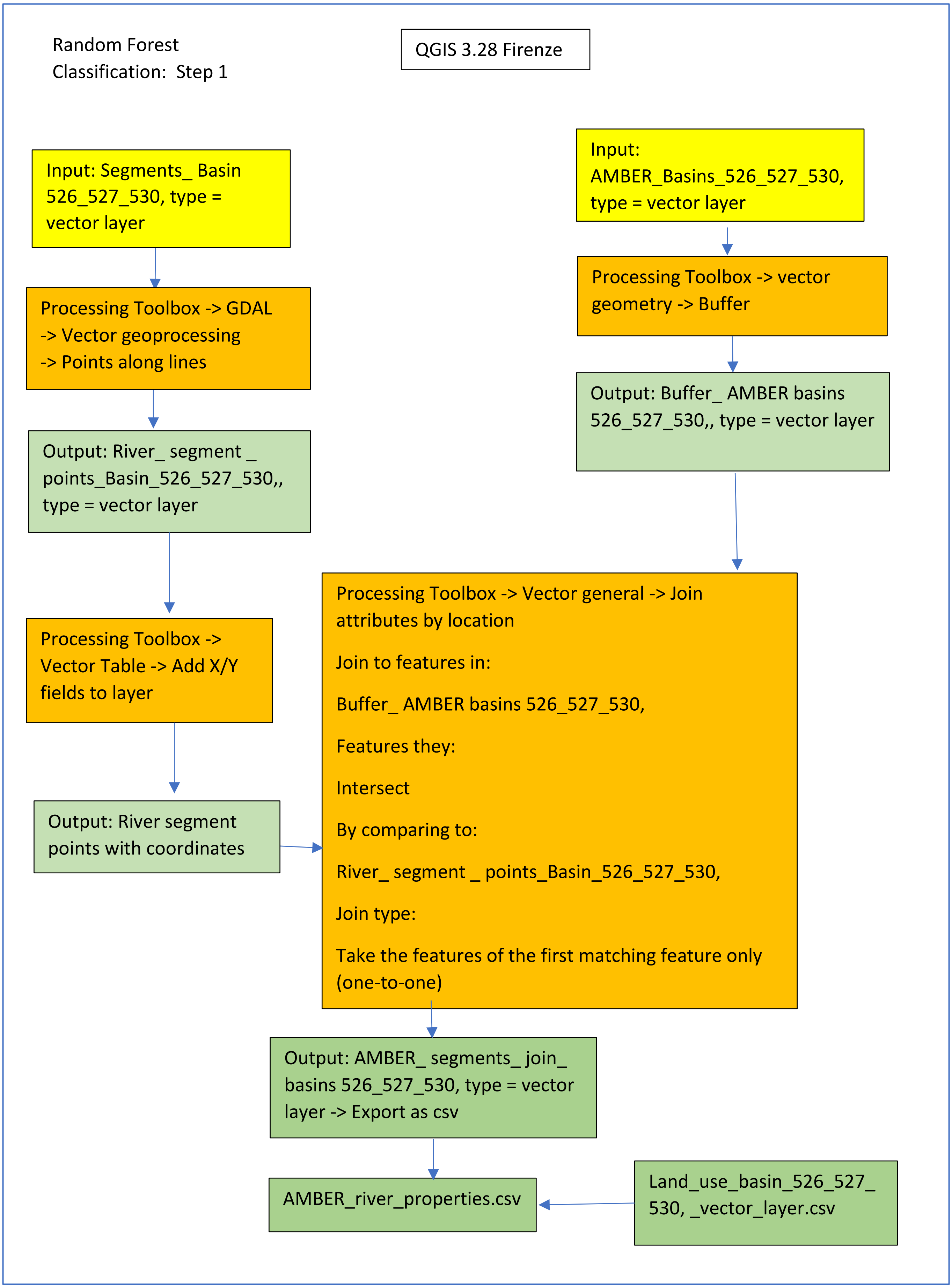

Figure 10 Random Forest Classification, Step 1.

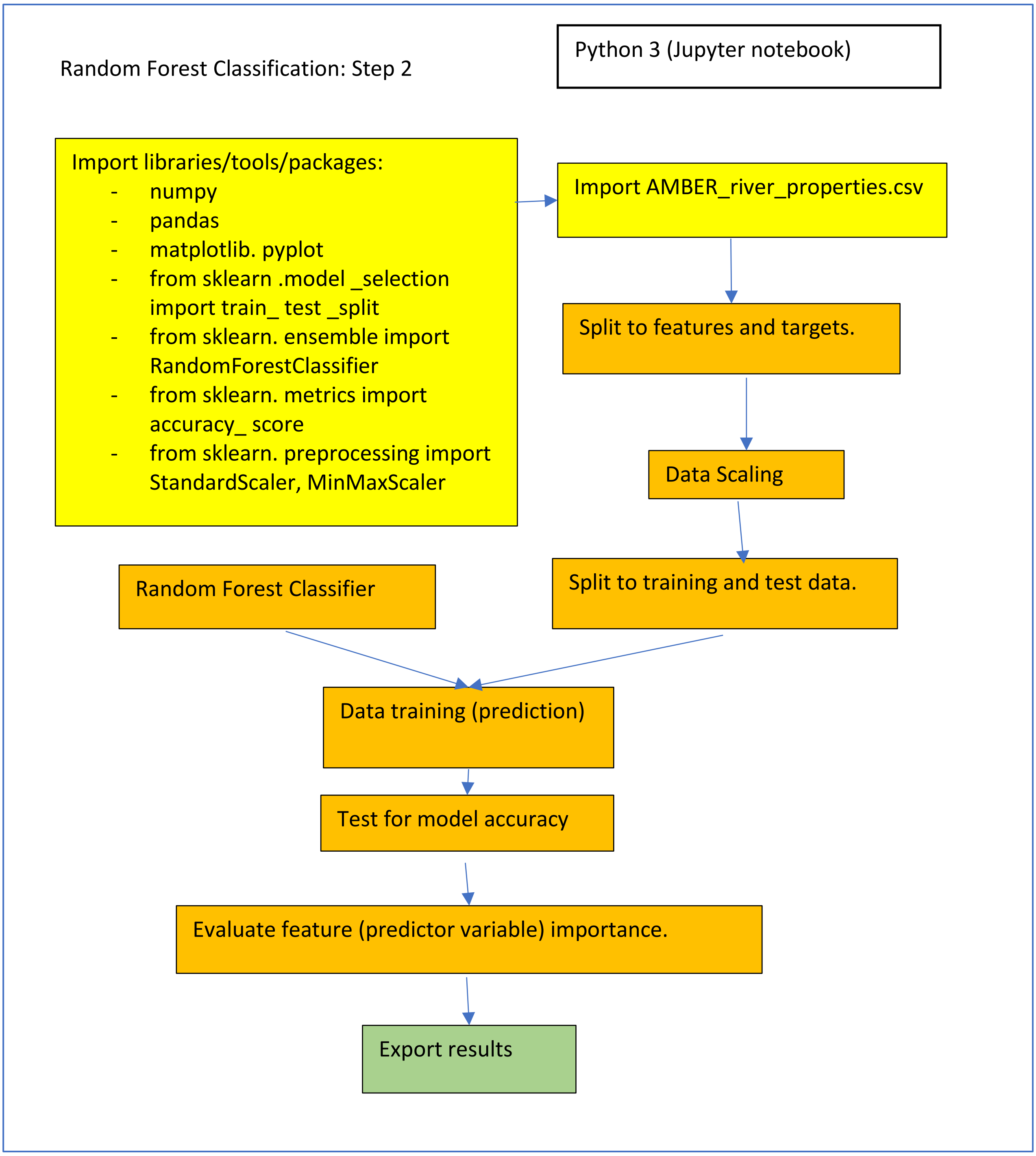

Figure 11. Random Forest Classification, Step 2.

4. Results:

4.1 Literature review Scopus

In total, our search term yielded 575 peer-reviewed papers. Our findings clearly demonstrate an increasing trend in the publications of peer-reviewed papers from only 3 papers in 1993 to 40 papers in 2022 (Appendix A). Most institutions affiliated with the publication of the papers were based in Europe and North America (Appendix B). Additionally, the data show a general increasing global interest in the topics of river restoration, connectivity, and barriers/dams. Every continent has recorded the highest percentage of publication involvements during the last 10 years (Appendix C). In Europe, the UK has recorded the highest number of publication affiliations, followed by Germany and France (Appendix D).

4.2 Gap analysis

From the 575 peer-reviewed papers, we identified gaps relative to river connectivity restoration and barrier removal plans in 110 papers (Appendix E). Gaps related to the scientific knowledge on biotic environment were identified in 70 studies while gaps related to the abiotic environment were identified in 61 studies. Gaps related to the modelling or methodological approaches followed during barrier removal projects were identified in 25 studies. Out of these, 18 studies were published since 2013, while 3 studies had been published in 2022. Finally, sociopolitical gaps had been identified in 10 peer reviewed studied. Other modelling or methodological gaps were also identified in 10 peer-reviewed studies.

4.3 Pan-European overview

The study of Verheijl, Fokkens & Buijse (2021) showed that not all the countries appear to have established policies to improve river connectivity. Specifically, twenty-nine countries including: Austria, Bosnia and Herzegovina, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Hungary, Republic of Ireland, Latvia, Lithuania, Malta, The Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Russia, Slovakia, Spain, Sweden, Switzerland, UK: England, UK: Scotland, UK: Northern Ireland, and UK: Wales , reported on plans to improve river connectivity, while five countries reported that they did not have river connectivity management plans (Malta, Croatia, Russia, Latvia, Bosnia and Herzegovina). Latvia, for example, justified this by having more important environmental challenges than restoring river connectivity such as pollution. The results of the survey showed that the highest conflict arises when a barrier is used to produce energy in the form of hydropower. From the twenty-four countries which have answered as having established river connectivity restoration measures, only Cyprus had reported to have no conflicts with hydropower.

When investigating the European hydropower dependency using the energy data tool developed by Ritchie, Roser and Rosado (2022), the average share of hydropower for electricity production (2010-2021) was as followed (Appendix F): Fourteen countries recorded a dependency of 0-5%: Belarus, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Germany, Hungary, Estonia, Ireland, Malta, The Netherlands, Poland, and the UK. Eleven countries recorded a dependency of 5-25%: Finland, France, Greece, Italy, Moldova, Luxembourg, Lithuania, Poland, Portugal, Slovakia, and Spain. Seven countries recorded a dependency of 25-50%: Bosnia and Herzegovina, Latvia, N. Macedonia, Romania, Serbia, Slovenia, and Sweden. Five countries recorded a dependency of 50-75%: Austria, Croatia, Iceland, Montenegro, and Switzerland. Finally, two countries recorded a dependency of 75-100%: Albania and Norway.

The average share of fossil fuels for electricity production (2010-2021) was as followed (Appendix G): Five countries recorded dependency of 0-5%: Albania, Iceland, Norway, Sweden, and Switzerland. Four countries recorded a dependency of 5-25%: Austria, Finland, France, and Slovakia. Thirteen countries recorded a dependency of 25-50%: Belgium, Bulgaria, Croatia, Denmark, Hungary, Latvia, Luxembourg, Montenegro, Lithuania, Portugal, Romania, Slovenia, and Spain. Ten countries recorded a dependency of 50-75%: Bosnia and Herzegovina, Czech Republic, Germany, Greece, Ireland, Italy, N. Macedonia, Malta, Serbia, and UK. Finally, six countries recorded a dependency of 75-100%: Belarus, Cyprus, Estonia, The Netherlands, Moldova, and Poland.

The three countries with the highest CO2 emissions in 2021 were Germany, UK, and Italy (Appendix H). The combined emissions of UK and Italy were almost the same as the emissions from Germany. Germany was the country with the highest CO2 emissions in 2021, with emissions reaching 672.94 million tonnes while the combined emissions from UK and Italy were 673.53 million tonnes in 2021. The main sources of CO2 emissions in Germany were oil (248 million tonnes), coal (230.22 million tonnes) and gas (173.48 million tonnes). The second highest CO2 polluting country in 2021 was UK with emissions reaching 346.77 million tonnes. The main source of emissions was gas (158.86 million tonnes), followed by oil (154.11 million tonnes) and coal (23.69 million tonnes). Italy was the country with the third highest CO2 emissions reaching 326.58 million tonnes in 2021. The main source was gas (150.96 million tonnes) followed by oil (141.81 million tonnes) and coal (24 million tonnes).

Regarding water challenges, we identified the followings (Appendix I): a) Water pollution (thirty-one countries), b) Floods (seven countries), c) Eutrophication (seven countries) and d) High water extraction levels or high levels of water scarcity (five countries). Wastewater releases were identified as the main pressure on water bodies (twenty-one countries) followed by agricultural pressure (eighteen countries). Direct industrial pressures on water bodies were identified for seven countries. Insufficient infrastructure/plans for managing floods were identified for four countries. Insufficient infrastructure/plans for managing climate change/extreme weather events were also identified as a challenge for four countries.

Regarding biodiversity challenges, we identified the followings (Appendix I): a) Insufficient measures for biodiversity conservation (twenty-five countries), b) Human induced pressures (eighteen countries) and c) Climate change (seven countries).

Considering the effect of climate change for biodiversity identified in Appendix I we also identified the following threats for European countries regarding temperature and precipitation changes. Albania, Belarus, Bosnia and Herzegovina, Belgium, Bulgaria, Denmark, Estonia, Hungary, Germany, Italy, Republic of Ireland, Latvia, Luxembourg, Malta, North Macedonia, Moldova, Montenegro, The Netherlands, Portugal, Romania, Serbia, Sweden, Switzerland, and the UK are expected to face increasing temperatures leading in certain situations to heat waves and drought events. These countries are also expected to face increasing precipitation resulting in certain situations in increasing floods (The World Bank Group, 2021; Climate-adapt 2021). Austria, Czech Republic, France, Finland, Greece, Lithuania, Poland, Slovakia, Slovenia, and Spain are expected to face fluctuating temperatures leading both to extreme cold and heat wave events. The countries are also expected to face extreme precipitation fluctuations leading to floods and drought events (Climate-Adapt, 2021). Therefore, restoration of lateral connectivity in response to the EU Biodiversity Strategy 2030 could be an important measure for preventing flood risks. On the contrary, Croatia, Cyprus, and Norway are predicted to be affected by increasing temperatures and decreases in precipitation levels where in the cases of Croatia and Cyprus, the countries are also expected to face increasing drought events (Kythreotou & Mesimeris, 2018; The World Bank Group, 2021). Information on Iceland is currently not available (Climate-adapt, 2021; The World Bank Group 2021).

4.4 AMBER data

The AMBER database suggests the presence of 348 barriers in the studied basins. Before snapping, none of the 348 recorded AMBER barriers were correctly aligned with the Hydrography90m river segments. Following 100-m snapping, 170 barriers became correctly aligned with the river segment layer and used during the optimization analysis. The remaining 178 barriers were incorrectly aligned with the Hydrography90m segments and were not used during the optimization (Appendix J). The results show that the selected basins were dominated with culverts forming almost 88% (before snapping) and 85% (after snapping) of all the recorded barriers (Appendix J).

4.5 Optimization results

We estimated the total cost of removals for the entire disconnected river length (338.077 km) of the studied basins at 535 million euros. After running all the 54 different optimization scenarios the scenario that yielded the highest reconnected river length following barrier removals was the following: "A.3.9: Maximum feature objective without constraints and a budget of 100 million Euros with target id 3". **This scenario yielded a reconnected distance of 253.6 km (Figure 12)**. This solution would reconnect 75% of the disconnected river length in the selected basins and would contribute 1.01% to the target of the EU Biodiversity Strategy 2030 for reconnecting 25 000 km of free-flowing river. When optimizing for river distance, the highest reconnected river length was yielded when using the following optimization scenario: "A.2.7. Maximum feature objective, with constraints, a budget of 338.077 km and with target id 1". This scenario yielded a reconnected distance of 69.6 km (Figure 14). This solution would reconnect 20.6% of the disconnected river length in the selected basins. The solution would contribute 0.28% to the target of the EU Biodiversity Strategy 2030 for reconnecting 25 000 km of free-flowing river and was the optimization scenario that yielded the third highest reconnected distance percentage.

Regarding barrier types, culverts were the dominant barrier type selected for removal (Appendix L). Regarding land use, agriculture was the dominant land type around the selected barriers for removal (Appendix M).

4.6 Random Forest Classification

In total, 100 barriers were used for testing (Figure 23) and 70 for training (Figure 24). The Random Forest Classification prediction model showed that by using the selected predictor variables, we could predict with 87% accuracy the barrier type (Table 3) where 60 barrier types were correctly predicted (Figure 25) and 9 barriers incorrectly predicted (Figure 26). The three most important predictor variables were a) River outlet distance (importance = 0.28), b) Land use (importance = 0.16) and c) water flow accumulation (importance = 0.12) (Figure 22).

4.7 Figures and tables - Optimization framework

Below are presented the maps of the optimization scenarios that have yielded the highest percentage of reconnected distance and the highest percentage contribution to the EU Biodiversity Strategy 2030 aim for the reconnection of 25 000 km of free-flowing river (Figures 12-21).

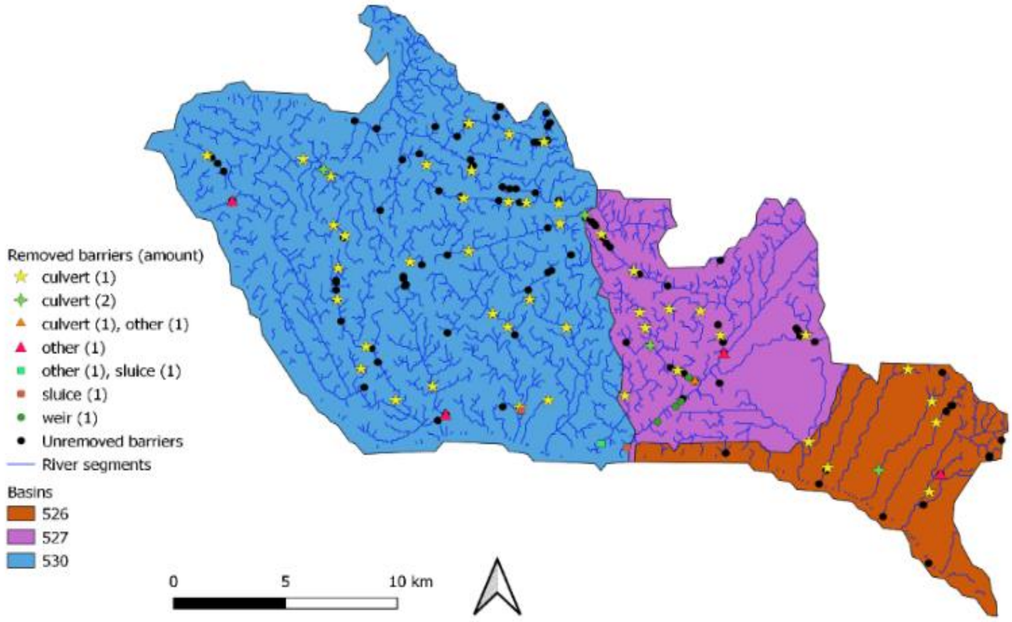

Figure 12. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.3.9. Maximum feature objective, without constraints: Cost file = Euros, RIJ file = meters, Targets = t3, Budget = 100 million., Reconnected River = 75% (1.01 % contribution to EU Biodiversity Strategy 2030).

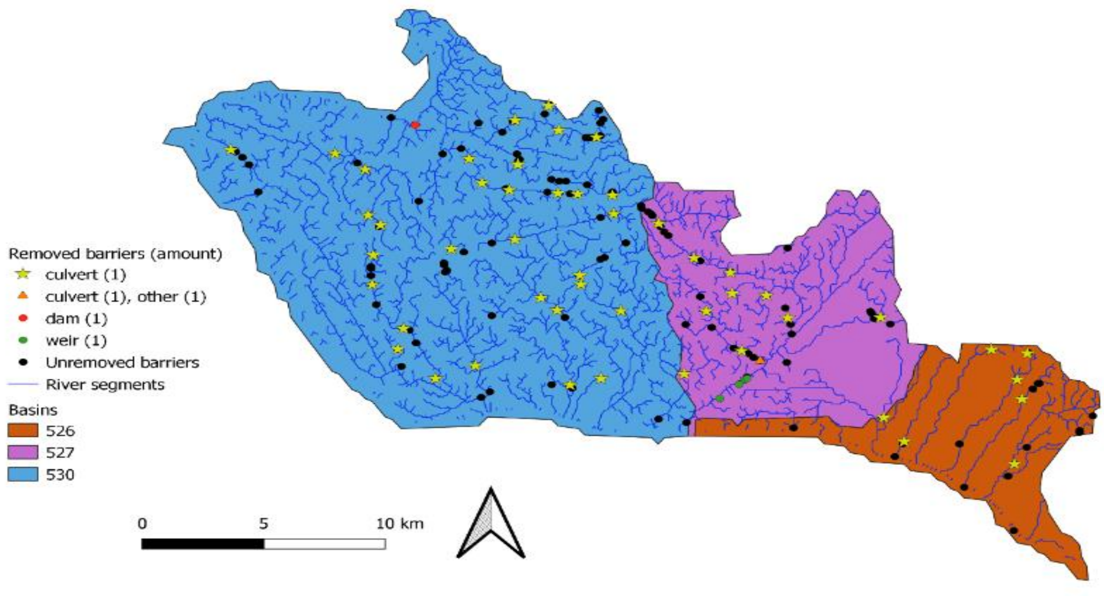

Figure 13. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.1.9. Maximum feature objective, with constraints: Cost file = Euros, RIJ file = meters, Targets = t3, Budget = 100 million., Reconnected River = 65.9% (0.89% contribution to EU Biodiversity Strategy 2030).

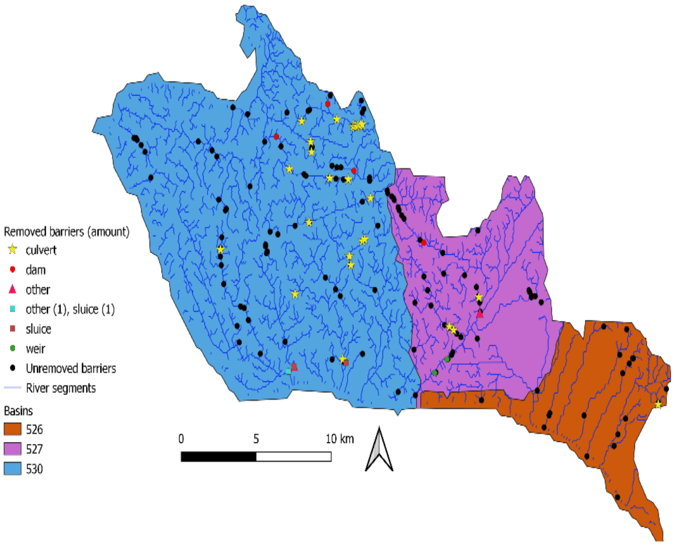

Figure 14. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.2.7. Maximum feature objective, with constraints: Cost file = meters, RIJ file = euros, Targets = t1, Budget = 338.077 km, Reconnected River =20.6% (0.28 % contribution to EU Biodiversity Strategy 2030).

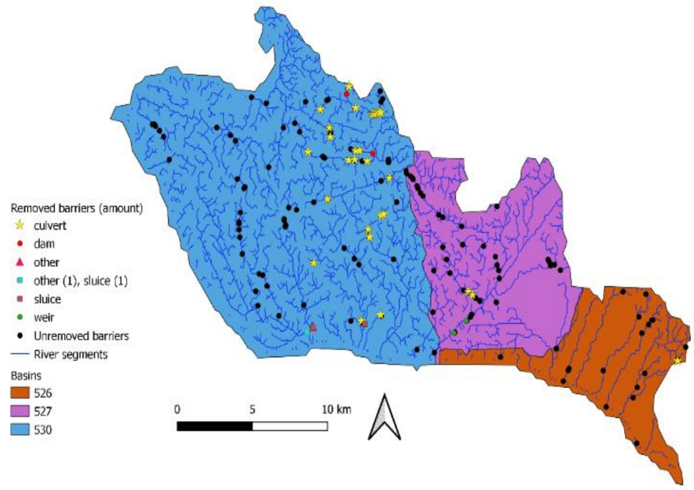

Figure 15. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.2.8. Maximum feature objective, with constraints: Cost file = meters, RIJ file = euros, Targets = t1, Budget = 338.077 km, Reconnected River =18.8 % (0.25 % contribution to EU Biodiversity Strategy 2030).

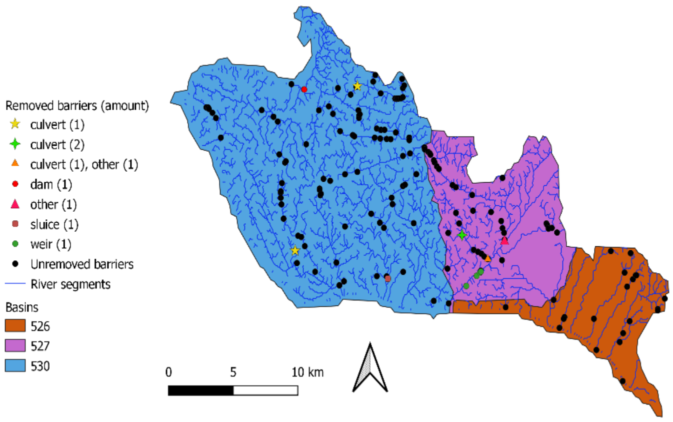

Figure 16. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.1.7. Maximum feature objective, with constraints: Cost file = Euros, RIJ file = meters, Targets = t1, Budget = 100 million, Reconnected River = 15.7 % (0.2 % contribution to EU Biodiversity Strategy 2030).

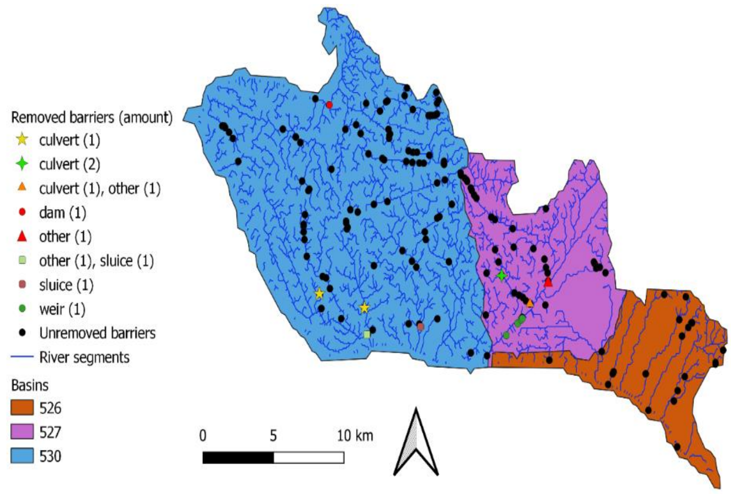

Figure 1712. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.1.8. Maximum feature objective, with constraints: Cost file = Euros, RIJ file = meters, Targets = t2, Budget = 100 million, Reconnected River = 15.4% (0.2 % contribution to EU Biodiversity Strategy 2030).

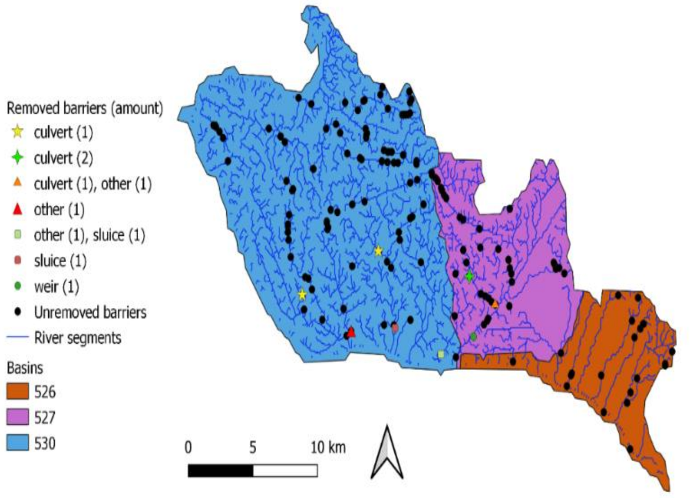

Figure 18. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.3.7. Maximum feature objective, without constraints: Cost file = Euros, RIJ file = meters, Targets = t1, Budget = 100 million, Reconnected River = 15.3% (0.2 % contribution to EU Biodiversity Strategy 2030).

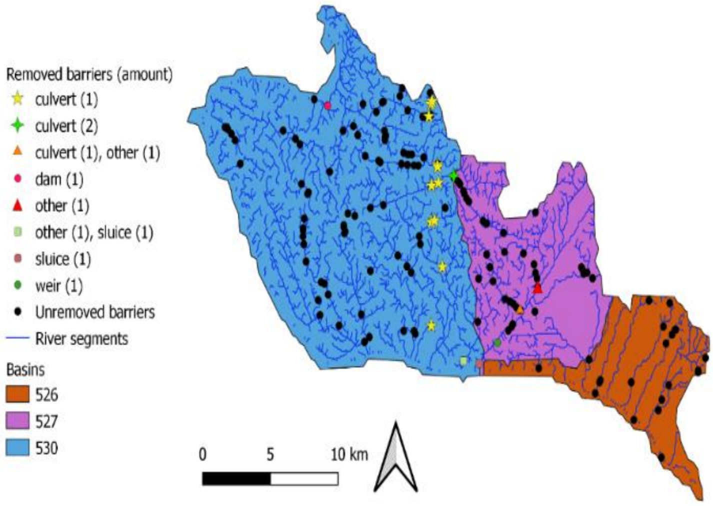

Figure 19. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" C.2.3. Minimum set objective, without constraints: Cost file = Euros, RIJ file = meters, Targets = t4, Reconnected River = 14.8% (0.2% contribution to EU Biodiversity Strategy 2030).

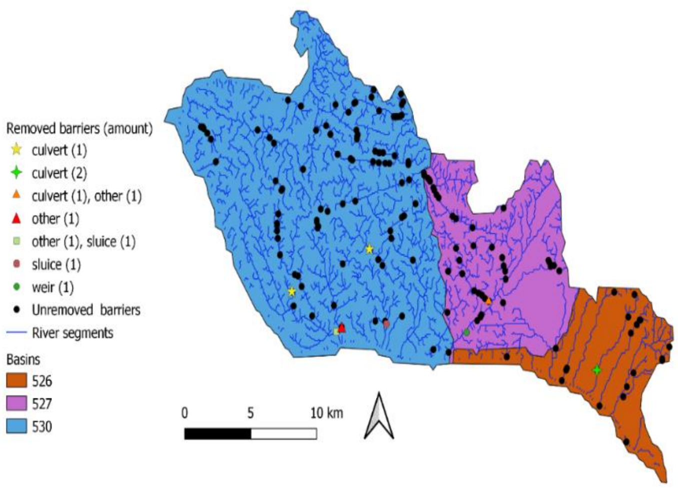

Figure 20. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" A.3.8. Maximum feature objective, without constraints: Cost file = Euros, RIJ file = meters, Targets = t2, Budget = 100 million, Reconnected River = 13.8% (0.19% contribution to EU Biodiversity Strategy 2030).

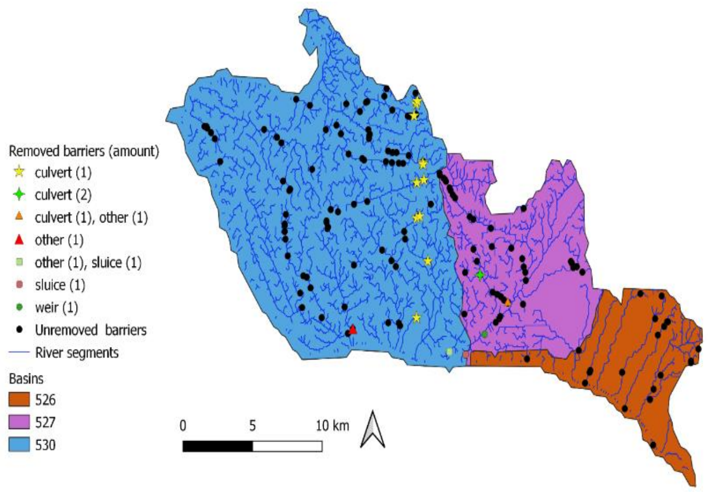

Figure 21. Map showing all the barriers removed and the unremoved barriers for basins 530, 527 and 526 for the optimization test:" C.2.1. Minimum set objective, without constraints: Cost file = Euros, RIJ file = meters, Targets = t1, Reconnected River = 12.6% (0.17 % contribution to EU Biodiversity Strategy 2030).

4.8 Figures and Tables - Random Forest Classification

Below are presented the main results of the random forest classification.

Table 3. Random Forest Classification predictions

Correct classifications	Correct predictions	Incorrect predictions	Total	% accuracy
Weir	2	0	2	100
Sluice	2	0	2	100
Culvert	52	8	60	85
Other	2	1	3	66
Dam	3	0	3	100
	61	9	70	87

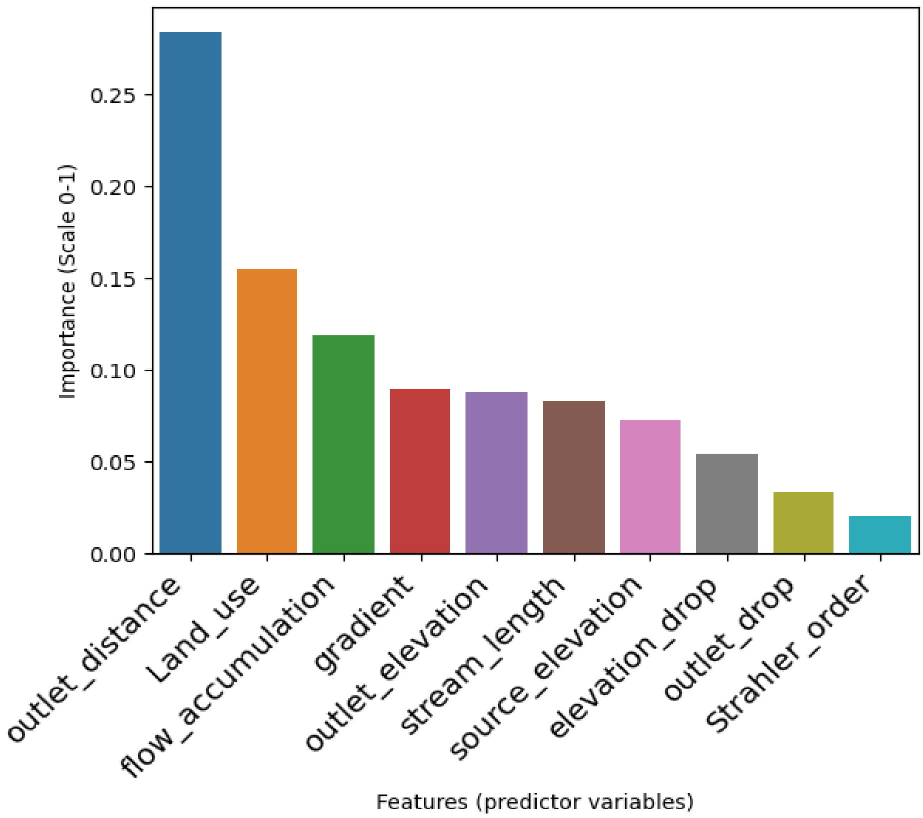

Figure 22. Figure showing the importance of each feature (predictor variable) for predicting barrier types. More information on each predictor variable is available on Amatulli et al. (2022).

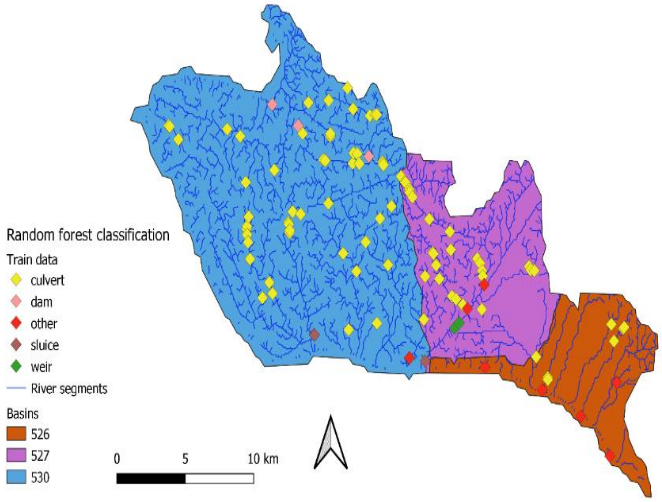

Figure 23. Figure showing the locations of the training barrier data during Random Forest Classification.

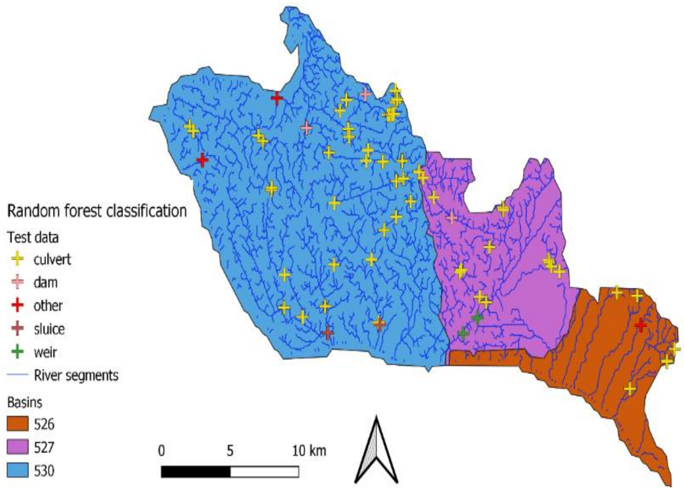

Figure 24 Figure showing the locations of the test barrier data during Random Forest Classification

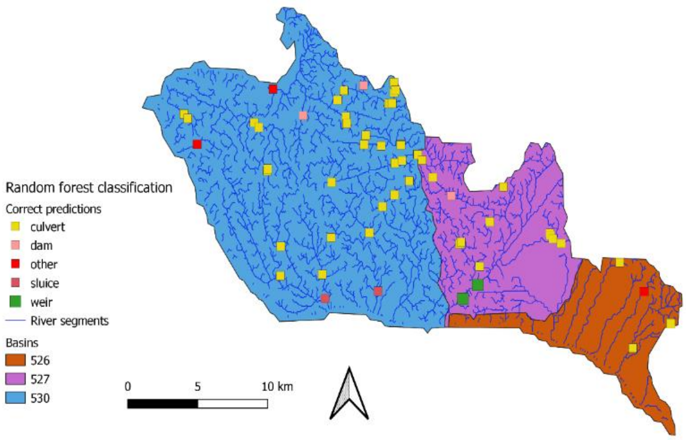

Figure 25. Figure showing the correctly predicted barriers from Random Forest Classification

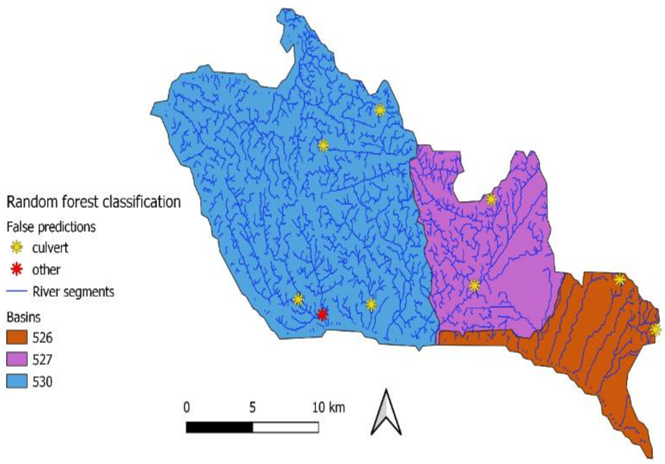

Figure 26. Figure showing the false barrier predictions from Random Forest Classification

5.0 Discussion

5.1 Literature review

The first part of the study was divided in three sections: The first section included the development of literature review using Scopus (Elsevier, 2023) to identify general global trends regarding the interest of the scientific community on the topics of river connectivity, river restoration and the barrier/dam removals over a national scale. The second section focused on identifying all the knowledge gaps, from the literature review. The third section focused on identifying all the challenges faced by the European countries that could influence the implementation of the EU Biodiversity Strategy 2030. We therefore focused on acquiring information that would answer the following questions: How many studies have been concerned with river connectivity, restoration, and barrier/dam removals globally over the years? Which continents have been mostly affiliated with the publication of studies? When were the most papers published? What was the level of involvement of institutions from each European country?

The use of Scopus provided several advantages when analyzing general trends regarding the publication of scientific papers. For example, Scopus provided statistics regarding among others the year of publication, authors, or the country of publication affiliation of each country. This allowed us to develop a general understanding of the global changes in the interest of research institutes and universities to invest resources for investigating the topics of river connectivity, restoration, and barrier removals. The disadvantage of using Scopus was that it did not provide any information on the countries where a study had been carried on. For example, the studied location in the paper of Langhans et al. (2016) was Berlin, Germany (Appendix E). Although the publication affiliation of the two main authors was the same as the studied area (German institutes), the study also included the collaboration with a researcher affiliated with a Spanish institute. Therefore, in Scopus, the paper was affiliated both with Germany and Spain at a national scale. Consequently, the data from using Scopus were insufficient for evaluating how much progress had been done within each country regarding connectivity, restoration, and barrier removals and further for planning for the EU Biodiversity Strategy 2030.

5.2 Gap analysis

5.2.1 Biotic and abiotic environment

The gap analysis table indicates four main challenges that could compromise the effectiveness of barrier removal prioritization plans for improving longitudinal and lateral connectivity. These challenges included a) modelling and methodology approaches, gaps in scientific knowledge regarding b) the biotic and c) abiotic environment as well as insufficient on knowledge d) the social and political factors that can influence barrier removal prioritization plans.

Since 1993, peer-reviewed studies revealed continuing gaps on our understanding on the effects of barrier removals for the river ecosystem. Even though most of the studies in the gap analysis table address the topic of biotic and abiotic river responses to barrier presence and/or removals, the challenge to completely understand ecosystem responses to barrier removals remains. This can be explained by the large complexities that underline river ecosystems across the globe which vary between regions and ecosystems. This is for example due to different biotic and abiotic compositions, and the different pressures applied on (e.g., land use, climate change). It is critical that these gaps are identified and addressed to guide future barrier removal plans.

For guiding our decisions in response to the EU Biodiversity Strategy 2030, we will need to depend on currently available knowledge and data recordings. We can only develop the best barrier removal prioritization plan based on the currently available data with the expectation that these data would be further enriched. Further studies are needed for collecting biodiversity data upstream and downstream of barriers before and after removals, predicting ecosystem responses to barrier removals and climate change. Additionally, an open-source platform must be developed to gather existing and newly acquired data for sharing river ecosystem data (e.g., biodiversity, benthic soil composition and floodplain soil composition).

5.2.2 Tools and methodologies (barriers)

Doyle, Harbor and Stanley (2003) were the first to propose the need of a systematic method for prioritizing barrier removals. Although several studies have attempted to develop solutions since then (e.g., Kemp & O' Hanley, 2010; Thomas, 2014; Fitzpatrick & Neeson,2018; Belletti et al., 2020, Buchanan et al., 2022, Appendix E) there has still not been developed a highly reliable barrier removal prioritization framework for improving longitudinal and lateral connectivity. Recently, there has been made great progress, with the development of the AMBER barrier database (AMBER Consortium, 2020) which provides a significantly improved barrier information over Europe (Belletti et al., 2020). The AMBER database demonstrates that the highest number of barriers exist in Germany and Switzerland while Eastern European countries such as Serbia, Romania and Slovakia demonstrate a lower number of recorded barriers. However, the database has been criticized due to large numbers of unrecorded barriers (Belletti et al., 2020). This creates challenges in interpreting the results of the database, because they may not be indicative of the exact level of barrier fragmentation that each country faces.

In addition to the barrier datasets availability, a major challenge has been the absence of high spatial resolution hydrographic data. Due to the absence of fine hydrographic models that contain all the streams in a river network, earlier studies have been compromised in developing barrier removal prioritization plans that reconnect significantly less river length (e.g., O 'Hanley, 2011; Magilligan et al., 2016; Belletti et al., 2020; Guetz et al., 2022). As a solution to these challenges, Amattulli et al. (2022), developed "Hydrography90m" a hydrographic model with very high spatial resolution in contrast to the earlier available models. The combination of new tools and their application as part of new optimization frameworks could help guide the development barrier removal optimization frameworks for meeting the targets of the EU Biodiversity Strategy 2030.

5.2.3 Socio-political influence

Barrier removal projects may create conflicts between local communities and politicians. Although a barrier removal might be favored for example from social point of view it might develop conflicts due to the importance of the barrier for the entire country. Therefore, it would be necessary to have a complete understanding not only the function of each barrier but also the willingness from local communities and politicians to remove it. The challenge is that this information is not available to decision makers or researchers before the development of barrier removal prioritization projects which can influence the implementation of barrier removal plans (e.g., Magilligan, Sneddon & Fox, 2017). A possible solution would be the development of cost-benefit analysis of the barrier removals. Cost-benefit analysis allows for the prioritization of barriers for removal by integrating both national and local community needs. By locating the barriers that would be both socially and politically acceptable for removal we could then include them as part of the developed optimization framework and increasing the chance of success of the projects.

5.3 Pan-European overview

5.3.1 Hydropower, fossil fuels and CO_2 emissions

Hydropower energy is an increasingly popular sustainable energy source. Therefore, the removal of hydropower dams might not be the most optimal solution from a national as well as an environmental perspective. Therefore, it would be more feasible that the implementation of the EU Biodiversity Strategy 2030 begins from a country with low hydropower dependency. This could also be enhanced by choosing a country with a high dependency on fossil fuels, where environmental challenges and especially air pollution would be expected to be higher, due to the high levels of CO_2 emissions typically associated with such operations. Based only on energy production source criteria, we narrowed down to the following countries from where the pan-European barrier removal projects could potentially start from: Belarus, Cyprus, Czech Republic, Estonia, Germany, Malta, The Netherlands, Poland, Republic of Ireland, and UK.

All the leading countries in CO_2 emissions had a low dependency on hydropower for electricity production. Additionally, five (Germany, Italy, The Netherlands, Poland, and UK) out of the seven highly emitting CO_2 countries had a high dependency on fossil fuels for energy production. However, France and Spain showed a lower dependency on fossil fuels despite the low dependency on hydropower. Both countries have expressed their support in barrier removal plans (European Commission, 2021) suggesting a good starting point for start planning for the EU Biodiversity Strategy 2030. Nevertheless, any of the seven suggested countries could set a good starting point considering the low hydropower dependency and the air pollution levels associated with high CO_2 emissions.

5.3.2 Water and biodiversity pressures

Plans for improving longitudinal and lateral connectivity should begin by identifying barriers in regions close to the point sources of high wastewater and/or agriculture and/or industrial pollutant releases. This would improve river water quality through enhancement of water bodies self-purification capacity. For lateral connectivity, plans should also identify areas vulnerable to floods for initiating floodplain/wetland restoration measures.

We should also consider the different biodiversity challenges that each country faces for different ecosystems that would favor or prevent countries from taking necessary measures for improving longitudinal and lateral connectivity. For example, countries with year-round river bodies and with well-identified freshwater challenges such as Austria (European Commission, 2021), would be expected to invest a higher number of resources for addressing the targets of the EU Biodiversity Strategy 2030. On the contrary, countries with seasonal rivers and fewer freshwater challenges such as Cyprus (Kythreotou & Mesimeris, 2018) would be expected to invest less resources on the targets of the EU Biodiversity Strategy 2030 and more for improving marine and terrestrial biodiversity. This would be important when considering the available monetary investments that different countries would be willing to invest for developing plans for improving longitudinal and lateral connectivity.

5.3.3 Uncertainties

There are many uncertainties underlying the overall application of the EU Biodiversity Strategy 2030. For example, would the 25 000 km of river to be reconnected be distributed across the entire Europe? Consequently, should there be policies for each country to restore their own share of rivers according to the river coverage per country, the number of barriers per country or according to the ability of a country to remove barriers without interacting with hydropower production or other barrier functions? In addition, we also need to consider the financial needs for barrier removals, so this sets the question on who is going to pay for removing the barriers? Would a lower budget compromise the barrier removal efforts in countries with high dependency on hydropower and low economic welfare?

Additionally, would the EU Biodiversity Strategy 2030 address only members of the European Union or rather the entire continent? So, does the goal take a complete pan-European consideration? Moreover, who will account for river restoration plans concerning river areas that form a natural boundary between countries, especially for barriers on boundaries between EU and non-EU nations?

5.4 Developing and testing the optimization framework

5.4.1 Methodology and studied location

In our study we addressed the development of a more robust optimization framework methodology as the most important literature gap. We focused on using the most accurate hydrographic network along with the most recently and well-updated barrier dataset for acquiring the most optimized solutions for guiding barrier removals and land use data collected by highly reliable sources. For the optimization we also decided to use one of the fastest problem solvers currently available or solving complex optimization problems. For that reason, we used "Hydrograph90m" as our hydrographic network, AMBER as our barrier database (AMBER Consortium, 2020), Corine land cover for land use data (European Environment Agency, 2023) as well as "prioritizr" package as the problem solver interface (Hanson et al., 2023) and "Gurobi" problem solver for the optimization (Gurobi Optimization LCC, 2023). To the best of our knowledge, our study is the first one to combine these tools for the development of a barrier removal optimization framework in the context of the EU Biodiversity Strategy 2030. This makes our study unique and could set the foundations for future studies addressing the targets of the EU Biodiversity Strategy 2030.

We decided to test the optimization framework for a small area in Germany. The reasoning behind the selection of Germany as our study area was the low hydropower dependency (Appendix F), which would reduce the interference between barrier removal projects with electricity generation. Additionally, we considered that barrier removals would help with ecosystem restoration and more specifically with the increase of carbon sequestration capacities of the restored river floodplains. This would be particularly important for reducing the extremely high atmospheric CO_2 levels recorded in Germany (Appendix H), especially due to the high dependency of fossil fuels for electricity production (Appendix G). Moreover, we expected that barrier removals would help addressing additional water challenges, especially water pollution as well as increasing the conservation status of many species (Appendix I). Finally, when considering the AMBER barrier database, Germany was the country with the highest number of recorded barriers (178996 barriers; Barrier type: ramps = 76895, fords = 337, weirs = 19236, culverts = 72795, other = 4953 and dams = 4250). The studied area was Hamburg, one of the largest cities in Germany with air pollutant levels ranging from low to high between sampling points, according to the European Environment Agency (2023). The studied location were three basins located 50-100 km Northwest of Hamburg. The reason for choosing an area outside of the centre of Hamburg was the higher potential for the feasibility of a floodplain restoration project and therefore of higher carbon sequestration potential over less human dominated areas.

5.4.2 Evaluation of optimization results when optimizing for cost and distance

During the optimization we used two different approaches for identifying the optimization scenario that would yield the highest reconnected free-flowing river distance. In the first approach we optimized for cost-effectiveness of barrier removals and then selected the optimization scenarios with the highest free-flowing reconnected river distance. In the second approach we optimized only for free-flowing river distance. Surprisingly, when comparing the results of the two approaches we observed that optimizing for the cost of barrier removals yielded in general higher reconnected distances than when optimizing for distance. A possible explanation for this, was the feature values selected for the "features" file during the problem formulation. For approach 1 (optimizing for monetary cost of removal), we selected feature values that represented the cost of removal of each feature, and we set the targets accordingly (Table 1). However, for approach 2 (optimizing for distance), we selected as the feature value the Strahler order. The explanation behind this was that removals should be facilitated easier in lower order streams than in higher order streams. However, this might also be considered as a monetary feature than a hydrological river features. As a result, the problem solver optimized partially for distance and partially for monetary cost. This could be improved by identifying different feature categories that would group the barriers entirely based on hydrological properties (e.g., elevation, slope).

5.4.3 Longitudinal distance estimations

In our study we mainly utilized Hydrography90m for estimating the reconnected free-flowing river distance following barrier removals. Our study required a reconnected distance estimation method that would calculate the reconnected distances between multiple neighbouring pairs (barriers, sources, outlets) over the Hydrography90m line network. QGIS provides a few tools for estimating distance between points over a network. Additionally, QGIS provides some tools for estimating distance between neighbouring points. However, QGIS does not provide any available tools that match exactly the requirements for our study. For that reason, we identified the tool that met our needs the closest. Therefore, we used the GRASS command "v.net.allpairs" for estimating the distances between all the pairs. Although the command estimated accurately the distances between the barriers, it also provided with an extremely high amount of unnecessary data. This was because the command estimated the distances between all the possible combinations of points in our node layer over the line network, rather than just the necessary pair points. This procedure required a significantly high amount of computational power and time for many estimations not necessary for our purposes. Due to the extremely large csv files created, we encountered issues in successfully exporting the pair distances as csv files in Excel leading to data losses. Therefore, the results of some of the pair distances were not successfully exported and were instead manually derived using the "measuring line" tool in QGIS, a procedure which was time consuming. Because of the size of our studied area, we did not face significant challenges relative to human error that could be caused using "measuring line" tool. However, when applying the optimization framework over larger scales, this method would most likely result in major challenges regarding time of execution as well as human error. As a solution, we are currently exploring alternative options such as the development of a more specialized Python code focusing only on the estimation of the distances between barriers and other neighbouring points (barriers/sources/outlets).

5.4.4 Lateral connectivity

The high reliability of the river segment network from the Hydrography90m for estimating longitudinal river distances makes it ideal for targeting the EU Biodiversity Strategy 2030 targets for reconnecting longitudinal connectivity. However, using this hydrographic network alone might not be enough for meeting all the targets of the EU Biodiversity Strategy 2030. This is because Hydrography90m only provides data for longitudinal distance but no information for lateral river distance length, therefore only addressing the targets for the reconnection of longitudinal connectivity. In our study, we addressed lateral connectivity through the inclusion of land use data from Corine land cover dataset (European Environment Agency, 2023) as part of our optimization framework. Nevertheless, we suggest that the Hydrography90m could be improved through provision of data on lateral river distance as well, to help develop an optimization model that would also optimize for the removal of barriers based on lateral connectivity gains, rather than only on longitudinal connectivity gains.

Lateral distance is also critical for predicting the effects of barrier removals in terms of flood risks over a floodplain. Specifically, the removal of barriers can cause alterations in the water level and the water flow causing potential floods downstream of a removed barrier. Therefore, knowing the lateral river length can be an important component of models predicting the lateral water movement following the removal of a barrier and therefore the susceptibility of floodplains to floods. These are necessary to consider both over short term as well as over long term for countries expected to face increasing precipitation and flood events with climate change such as Germany (Climate-adapt, 2021).

5.4.5 Land use

Additional challenges in the execution of our barrier removal optimization framework may arise due to the dominance of agricultural land. In our studied area, agricultural land was the dominant land use type surrounding the barriers' location. Therefore, most of the selected barriers for removal were selected in agricultural areas. When testing for an optimization scenario with constraints, planning units with land use classified as forest (and semi natural areas) or water bodies were generally prioritized first and selected for removal. However, the inclusion of targets in a scenario would restrict the solution. For example, when testing for maximum feature objective scenarios with budgets either 1 million Euros or 10 million Euros, both were infeasible. This suggested that the removal of all the planning units that would meet the specified targets and with land use classified as forest (and semi natural areas) or water bodies was more expensive than the selected budgets and so no optimized solution could be obtained. Once the budget was set to 100 million Euros, more planning units with land use classified as forest (and semi natural areas) or water bodies were selected. Since maximum feature objective identifies the solution that maximizes the use of a specified budget, many planning units classified as agriculture were selected as well.

The inclusion of constraints in an optimization scenario should increase the number of planning units with a more natural dominant land use type and decrease the number of artificial areas and agriculture, in contrast to optimization scenarios where constraints were excluded. However, this was not necessarily the case, especially when targets were considered. For example, when optimizing for cost with targets set as "Target 1" and "Target 2", only few of the planning units with land use classified as forest (and semi natural areas) or water bodies were selected. This was because the planning units were classified as barriers with high removal cost (e.g., dams which received a weight of 0% when optimizing for cost of removal target scenarios "t1" and "t2"). On the contrary, there were more planning units with land use classified as agriculture that also had a lower removal cost and therefore selected as part of the optimization solution.

Although our optimization solutions have identified agricultural areas as optimized areas for barrier removals, they might not be the best sites for starting barrier removal plans. This is due to potential biological/chemical water contamination associated with agricultural sites. While the presence of barriers near agricultural areas may restrict the spread of these contaminants, the removal of barriers could help spread these contaminants and pollute intact rivers downstream. Moreover, the removal of barriers from a privately owned site could create social conflicts between the owner, the community, and the executing government. However, since there was a lack of information regarding the presence of these two challenges for the studied location, they were not considered during the optimization.

Social conflicts could also arise with the removal of barriers from artificial (human populated) areas. For example, the solution that yielded the highest reconnected free-flowing river distance also excluded the use of constraints, allowing for the selection of six planning units for removal with dominant land use as artificial areas. Considering the potential social conflicts that may arise in these areas, it might be more feasible to consider only optimization solutions where barriers are not removed from artificial areas. Therefore, it might be more realistic to consider instead optimization scenario "A.1.9: Maximum feature objective, with constraints (Figure 13, Appendix K): Cost file = Euros, RIJ file = meters, Targets = t3, Budget = 100 million., Reconnected River % = 65.9 (0.9)) " as the most optimal solution.

More broadly, it is hard to predict the social conflicts that may arise from the removal of barriers not only from agricultural and human, but also from natural areas. Even barrier removals from natural areas could cause social conflicts, depending on the use of the areas from the local communities. For example, the removals of barriers from forests as part of local or larger scale restoration projects could compromise local activities such as hunting or fishing for leisure purposes. Therefore, future optimization scenarios should put higher priority on the removal of barriers from natural areas that are already located within protected areas, and which have also gained social support from local communities.

Although systematic conservation planning has been taking in place, there are still several challenges underlying the development of conservation areas. Many European countries, including Germany, have insufficient measures for the conservation and protection not only aquatic but also terrestrial biodiversity. For making the absolute optimal decisions for the selection of barrier removal locations, it would be necessary for every country to complete their plans for biodiversity protection and protected areas designation and ensure the support from the local communities to avoid potential social conflicts during barrier removals.

The question is: ***Will the European countries have their plans available on time to meet the aims of the EU Biodiversity Strategy 2030?*** The answer based on our literature review data seems to be unlikely. As a solution, we suggest that barrier removal plans are considered along national plans for biodiversity improvement. Additionally, in our study, we assumed that barrier removals would benefit lateral connectivity in natural areas, but we did not evaluate the exact derived benefit. We suggest that future studies investigate the precise benefits on lateral connectivity following barrier removals to help policy makers to design better measures for driving their national plans for biodiversity protection. The decisions made by the policy makers could then ensure the success of the barrier removal projects, for example through the development of better management plans over the areas selected for barrier removals.

5.4.6 Cost of removals

The approximate cost of removals of the barrier removal optimization scenario that reconnected the highest amount of river-km was 81 million euros, contributing 1.01% to the EU Biodiversity Strategy 2030 aim for the reconnection of 25 000 km of free-flowing river. If every 253.6 km of every reconnected length would cost 81 million euros, then the total cost for achieving the 25 000 km aim would in fact be 8 billion euros. One of the reasons behind such high costs, was the dominance of culverts across the studied basins. Therefore, we expect that the cost of removal would decrease when applying our developed barrier removal optimization framework over other basins dominated by a least costly barrier type. However, our methodology for estimating cost of removals for each barrier could use significant improvements in the future. Specifically, we derived our estimation costs mainly based on earlier barrier removal projects from the UK and USA which may not be representative for the costs of barrier removals from the studied area in Germany. Also, there was lack of information provided by the AMBER database regarding the specific type of each barrier classified as "other". Therefore, the cost values used during our approach for cost estimation may differ significantly from the actual costs of removal.

We should also consider that barrier removal costs can vary significantly based on different factors (e.g., barrier size, function, age). Additionally, costs may decrease when barrier removals occur in clusters, for example because of the lower effort that the removal operator would have to account for (e.g., less transportation costs). Ideally, we believe that our efforts for cost estimation could have been facilitated more easily with the presence of an accurate and updated online database recording all the barriers removed over European scale, along with other data useful including cost of removals, barrier size, method of removal and operator that carries the removals. To the best of our knowledge, such a database does not exist over a European scale and so we strongly suggest the development of such an online tool, to help guide future barrier removal optimization projects. As an alternative solution we are currently working on acquiring barrier removal costs from companies across Europe that currently undertake barrier removal projects.

5.4.7 AMBER database

Even though AMBER is the most complete barrier database in Europe (AMBER Consortium, 2020), there is a significant degree of uncertainty (Garcia de Leaniz & O'Hanley, 2021) which we have also observed in our study. Specifically, when aligning the AMBER barriers along the Hydrography90m river segment layer, none of the recorded AMBER barriers were correctly aligned with the Hydrography90m river segments. For addressing the misalignment issue, we applied a 100-m snapping to the barriers. We selected the snapping distance at 100-m with the assumption that the misalignments were a consequence of technical reasons resulted from imprecise recording locations by the observers. This is also in accordance with the recent study of O'Hanley, Neeson & Ioannidou (2023) who used a snapping distance of 100-m to snap NHDPlus with a barrier dataset collected in Maine, USA.

Despite the snapping, 51% of the barriers remained misaligned to the Hydrography90m network. To investigate that further, we visually compared the river segments from Hydrogrpaphy90m with the river networks delineated in Google Maps. Interestingly, the misaligned barriers in Hydrography90m were correctly aligned with the Google Maps river segments. After further investigation, we concluded that the most possible explanation behind that was that Google Maps delineates both artificial river segments (e.g., channels constructed for human use) and natural river segments, while the Hydrography90m only delineates natural river segments. Such an example is demonstrated on Figure 27 where three unsnapped and misaligned culverts were in Peuser Wettern channel, in basin 526, approximately 50 km northwest of Hamburg. Although the barriers appeared to be correctly aligned with the river segments on Figure 27, the base map we used for this figure was from Google Maps rather than the Hydrography90m. In fact, no river segments from the Hydrography90m appear in the figure because **there were no natural rivers present in this location**.

This raises the following question: How many of the recorded AMBER barriers are aligned in natural rivers? Therefore, how many of the AMBER barriers can we really consider for removal during the development of barrier removal projects for meeting the targets of the EU Biodiversity Strategy 2030 for restoring free-flowing rivers? For the development of our optimization framework, we only used the correctly aligned barriers following the 100-m snapping, as these were the barriers with the highest reliability in terms of their location. However, during the data analysis we did not investigate more information regarding the location of the unsnapped barriers, but we only performed a brief visual data inspection. Therefore, we urgently ask that the AMBER database is improved with further information regarding a barrier's presence on a natural river or an artificial channel that would be critical in the context of the EU Biodiversity Strategy 2030.

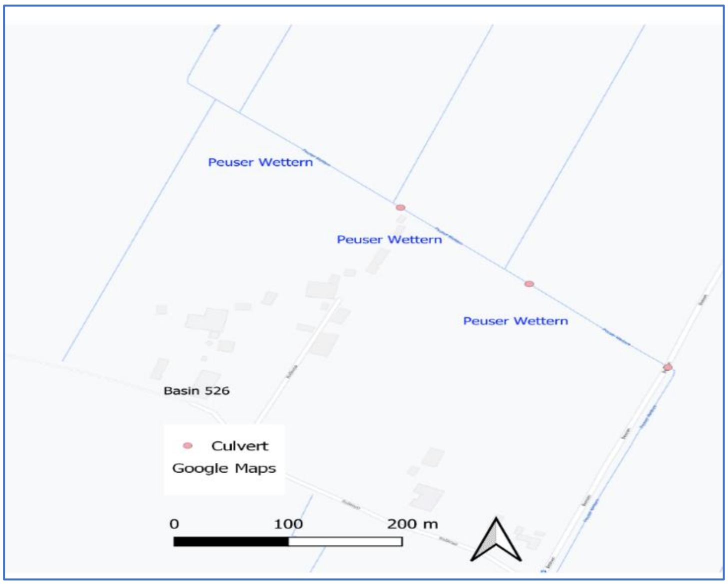

Figure 27 Example of barriers recorded over artificial channels. The barriers are of class culverts, and located in Peuser Wettern channel, in Basin 526, nearly 50km Northwest of Hamburg, Germany. The base map is from Google Maps. No river segments from the Hydrography90m network are included in the map

Further uncertainties with the AMBER database are also highlighted in terms of the actual number of AMBER barriers not only for our study area but also at a pan-European scope. When evaluating the number of recorded barriers in the AMBER database, the total number was 629 955 barriers for the entire Europe. In general, there were more barrier recordings in central, north, and western Europe and with a variety of recorded barrier types. On the contrary the Eastern European countries showed fewer barrier recordings, with the recorded barriers mainly being constrained to barriers classified as dams or other. Specifically, Germany and Switzerland had the highest number of recorded barriers with both countries recording over 100 000 barriers. While eight countries (Austria, France, Sweden, Italy, Spain, Poland, The Netherlands, and the UK) recorded between 1000-100000 barriers, nineteen countries (Albania, Bosnia and Herzegovina, Belarus, Cyprus, Croatia, Greece, Iceland, Slovenia, Slovakia, North Macedonia, Malta, Bulgaria, Romania, Estonia, Latvia, Finland, Montenegro, Serbia, Moldova, and Luxembourg) had recorded the lowest number of barriers (less than 1000 barriers). Although this might suggest that countries with the highest number of barriers might be the countries with the highest level of concern regarding fragmentation, the results can in fact be misleading in certain situations. For example, in countries that have recorded less than 1000 barriers (e.g., Greece, Romania, Albania) there was a significant number of barriers classified as “other” and dams but no data regarding any other barrier. Although this might simply suggest the absence of any other barriers, we believe that this might be due to insufficient data collection. Our observations on the AMBER database strengthen the observations of Belletti et al. (2020) who suggested that over 300 000 barriers might be missing from the AMBER database.

Additionally, the AMBER database lacks several pieces of information that we believe would be necessary for the development of our optimization framework. One of the main information that the AMBER database lacks is a barrier’s status regarding its current function. Specifically, the EU Biodiversity Strategy 2030, requires that barriers categorized as obsolete structures are prioritized for removal, as they serve no purpose, and their removal would be easier facilitated. However, such information is currently not available in the AMBER database. Other information that the database lacks or is recorded only for some barriers and could be used during the optimization include the barrier's height (data only for approximately 15% of total recorded barriers in Europe), width (no data), capacity (no data) and construction year (no data). The main reason for this lack of information was the fact that the guidelines of the AMBER database only required the observers to include the location and the type of the barriers, while other information were considered as optional. Moreover, new barriers have recently been constructed and may continue to increase in the future. This is the case for example for Albania which is the country with the highest dependency on hydropower for energy production in Europe (Appendix F), with large number of hydropower stations being constructed over the past two decades (WWF, 2021). Yet, only a few numbers of barriers have been identified by the AMBER database (518 barriers). Considering the high energy dependency on hydropower and the low energy dependency on fossil fuels, it would be expected that more hydropower dams will be constructed in the future.

Considering all the uncertainties described, the question is: What approach should we take from now on regarding the EU Biodiversity Strategy 2030? Should we focus on updating the information on the AMBER database for the existing recorded barriers? Should we focus on more on-field barrier data collection? Or is it simply enough to develop barrier removal optimization frameworks based only on the available barrier data, as we have done in our study? Currently, it seems highly unlikely that new data collection will occur for the AMBER data. This is because of the high costs, time, and effort that the on-field reviews require. Therefore, the question is: How can we improve the accuracy of our barrier removal optimization framework, with low cost and time effort? In the following section we present a potential solution for targeting the uncertainties regarding the unrecorded barriers in natural streams.

5.5 Random Forest Classification

Recent studies have examined the potential of using predictive modelling and remote sensing data for predicting the locations of unrecorded barriers (Garcia de Leaniz & O'Hanley, 2021). For example, Belletti et al. (2020) used predictive modelling to predict the locations of unrecorded AMBER barriers. Their study used random forest regression to model densities based on environmental and anthropogenic predictors and used the ECRINS database for hydrographic mapping system. Although the random forest regression model was highly reliable for predicting barrier locations, the drawback was the use of ECRINS as the hydrographic network, which underestimated the river length by 74%. Therefore, the results of their study were considered unreliable to use (Belletti et al., 2020).

Another example comes from the study of Buchanan et al. (2022) who focused on predicting barrier locations for two subbasins in New York, USA. For the collection of the barrier locations, the study used a pre-collected barrier dataset along with a desktop approach to identify barrier locations using Google Earth, Google Maps and Bing Maps instead of using a field-based approach for the collection of the barriers' dataset. Following the barrier collections, the study of Buchanan et al. (2022) was divided into the following steps: a) Collection of predictor variables (variables that would be used to predict the locations of unrecorded barriers), b) validation of predictor variables (validation of the significance of each predictor variable for the prediction of unrecorded barriers), and c) random forest classification.

For predictor variables, data collection occurred using different predictor variables such as slope, elevation, cumulative upstream area, or stream order. The predictor variables were derived data sources including Lidar, NHDPlus, National Wetlands Inventory (NWI) and Modified Normalized

Difference Water Index (MNDWI). Validation occurred in response to the pre-collected field datasets and desktop collections. However, the model also faced challenges, especially with misalignments between the dams and their geographic location. False recordings were also an issue due to the failure of the model to classify between different types of barriers but rather was only focused on presence/absence of dams. When comparing the study of Buchanan et al. (2022) with the study Belletti et al. (2020) both studies were associated with challenges regarding data misalignments due to the low spatial resolution from the ECRINS or the NHDPlus as hydrographic networks. With the development of the Hydrography90m hydrographic network, we can use the two barrier prediction methodologies as a basis for a more reliable barrier prediction model. The new prediction model would then be used for improving the AMBER database. In the following section we explore this possibility.

Following the methodologies of Belletti et al. (2020) and Buchanan et al. (2022) we tested the possibility of using predictive modelling in the context of our study. We only focused on identifying the major predictor variables that could predict barrier classes rather than predicting barrier locations. In other words, we were interested in evaluating which of the selected predictor variables from the Hydrography90m (Amatulli et al., 2022) and land use from the Corine land cover tool (European Environment Agency, 2023) could be used to classify the AMBER barriers with a high level of accuracy. For that reason, we used Random Forest Classification as the predictive modelling method.

As Belletti et al. (2020) and Buchanan et al. (2022) suggested, barrier presence can be identified through distinct and predictable environmental patterns (predictor variables) such as changes in water flow accumulation or drop in elevation between upstream and downstream of a barrier. Additionally, certain barrier types may be present in river segments of similar length for example due to the function of the barrier. So, we would expect larger barriers (e.g., dams and culverts) to be present in larger streams while smaller barriers (e.g., weirs and sluices) to be present in smaller streams. Similarly, we might expect that dams used for water storage would be closer to agricultural areas and cities (Belletti et al., 2021) to facilitate a quicker water transport.

We trained and tested the prediction model to identify and learn the distinct and predictable environmental changes (predictor variables) within our data that underline each barrier class. We only used the barriers that had been correctly aligned with the river segments after the 100-m snapping. We evaluated the accuracy of the model, meaning how well had the model been trained to classify the barriers correctly based on the predictor variable values. We also investigated the main predictor variables used to classify the barriers. Our results suggested that river outlet distance, land use and water flow accumulation were the most important predictor variables for classifying barriers. In other words, the barriers showed a distinct and predictable environmental trend in their values regarding river outlet distance, land use and water flow accumulation. Therefore, we expect that by using these variables we will be able to identify the locations of unrecorded barriers within our river network. On the contrary, elevation drop, outlet drop, and Strahler order showed the lowest importance as predictor variables. In other words, the barriers did not show any distinct and predictable environmental trend regarding elevation drop, outlet drop, and Strahler order.

Our results however are also associated with limitations. The main challenge was in terms of the high number of culverts present in the area and the low number of weirs, sluices, dams, and other barriers. For training a dataset correctly, we would require a large amount of data for each data category on which we want the random forest classifier to classify. However, because of the large number of culverts in our study site, the algorithm was limited in identifying the patterns with the highest level of accuracy. Therefore, it will be essential that future studies apply the methodology over a scale with higher barrier densities and heterogeneity. We should also consider the importance of already collecting data regarding the barrier function as an obsolete structure as required by the EU Biodiversity Strategy 2030. It is likely that obsolete structures are distinguished by a different set of predictor variables. However, in the absence of any obsolete data information, it is hard to predict the predictor variables for obsolete structures. Consequently, we strongly recommend that barrier location predictions are contacted alongside efforts to improve the information on the already collected datasets.

Interestingly, our data suggested that the Strahler order had the lowest importance in the classification of the barriers. This can be explained by the fact that there were no clear patterns recorded for the locations of the barriers in terms of the Strahler order. For example, culverts were recorded both in smaller streams and larger rivers (Strahler order = 1,2,3,4 and 5). Similarly, weirs were also recorded both in smaller streams and larger rivers (Strahler orders = 1 and 7) which was highly unexpected. Unfortunately, due to the lack of additional information on the barriers from the AMBER database, we could not evaluate the reason behind this. Equally interesting was the low importance of outlet drop and elevation drop. Specifically, we would have expected that the different barrier classes would be identified through their height resulting in distinct patterns in elevation drop and outlet drop. To evaluate the reason behind this we would require information on the dimensions of each barrier, which the AMBER barrier database does not provide for the studied area. Therefore, we urgently suggest the need to improve the AMBER database.

6.0 Conclusion

Although river fragmentation caused by anthropogenic barriers has been considered in literature since the early 1990s, it was not until the last decade that the topic received an increase in interest, especially in Europe. The need for barrier removals has been emphasized through the implementation firstly of the EU Biodiversity Strategy 2030 and is expected to be strengthened with the implementation of the new EU Nature Restoration Law. In our study we addressed the following question: ***Are we ready to start planning for the EU Biodiversity Strategy 2030 for improving longitudinal and lateral connectivity?*** Based on our gap review analysis we suggest that we are still far away from it. In fact, our gap review analysis suggested several gaps both over European as well as an international level, including among others in the methodologies and tools available for barrier removals. From the methodological gaps identified, we emphasize the small scale of earlier projects, the lack of hydrographic models with high spatial resolution, as well as the incomplete barrier datasets. In other words, we lack a highly reliable barrier removal optimization framework for guiding the barrier removals over a pan-European scale which would be necessary to develop before start planning for the EU Biodiversity Strategy 2030.

For addressing the methodological gaps identified, we used a combination of the most newly developed and reliable methodological tools to develop an optimization framework for prioritizing barrier removals. These tools included the hydrographic network "Hydrography90m" (Amatulli et al., 2022) the AMBER barrier database (AMBER Consortium, 2020), Corine land cover data (European Environment Agency, 2023), "prioritizr" package as the problem-solving interface (Hanson et al., 2023) and "Gurobi" as the problem solver (Gurobi Optimization LCC, 2023). The main advantage of this method was that we produced an optimization framework that addressed challenges from earlier studies that used lower spatial resolution hydrographic networks in terms of underestimating or overestimating the free-flowing river distance gains, following barrier removals. Therefore, we confident that our methodology can provide a robust guideline for future studies aiming to meet the targets of the EU Biodiversity Strategy 2030 for reconnecting 25 000 km of free-flowing river.

We tested our optimization framework for three basins Northwest of Hamburg in Germany. Our optimization results suggested the potential for reconnecting between 1.3 -253.6 km of free-flowing rivers (0.4%- 75% of the disconnected rivers) which contributed up to 1.01 % to the overall EU Biodiversity Strategy 2030 aim of reconnecting 25 000 km of free-flowing river. These amounts depended on the different optimization scenarios applied. Therefore, our optimization results could better be interpreted as the potential of free-flowing river reconnection for the studied basins based on a range of budgets, constraints, and targets.

However, we also encountered several challenges during the development of the optimization framework. The main challenge was regarding the reliability of the AMBER barrier database. The two main challenges we encountered included the precise number of recorded barriers present in natural streams and the barrier status as obsolete structure. As a potential solution for improving the AMBER database, we applied a Random Forest Classification prediction model to help identify the main predictor variables of barriers in the natural rivers of the studied area. Our results suggest that by using outlet distance, land use and water flow accumulation as environmental predictor variables we could help identify hydrological trends relative to each barrier type. By identifying these hydrological trends on-field we could then locate the potential locations of more barriers.

Finally, we urgently emphasize that our developed optimization framework as well as the predictive modelling would better work with an updated AMBER database. Therefore, we strongly recommend that AMBER database is updated with new data for maximizing the efficiency of our barrier removal optimization framework in response to meeting the targets of the EU Biodiversity Strategy 2030.

7.0 References

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