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Environmental effects of water
derivations on watercourses in Catalonia



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Abstract

Watercourses are often impacted by hydraulic infrastructures and water withdrawals. It has been demonstrated that these alterations affect the availability of habitats for aquatic species. Consequently, it is necessary to define a method to quantify the effects on the species and to define the proper e-flow level required to ensure the conservation of biodiversity and the ecological services provided by the rivers.

Therefore, for the e-flow definition, the Meso-HABSIM methodology (Meso-habitat SIMulation Model) [1, Parasiewicz, 2001] is adopted in Italy. It is a well-established method for river habitat modelling, designed to assess the spatial and temporal habitat availability for fish fauna. This methodology operates at the mesoscale, through the combination of the hydraulic and geomorphic units, describing the river's physical and biological characteristics. The parameters employed are current velocity, water depth, substrate type, and presence of refugees or cover. Furthermore, a crucial phase is the creation of a biological model based on the random forest method, an accurate machine learning technique. These models define the suitability of river habitat to host target species, based on the environmental existing conditions.

The purpose of this thesis project is to assess the impact of flow alteration on the rivers Aigua de Valls and Foix in the Catalonia region (Spain) exploiting the MesoHABSIM methodology. This research is a part of a larger initiative commissioned by the ACA (Agència Catalana de l'Aigua), that involves a larger number of rivers. The main purpose is to perform an assessment of the environmental flows and, if needed, to make adjustments for future planning cycles. The study has been carried out on ten different rivers, subjected to a flow alteration; the dataset used to develop the biological models for native Catalan species has been collected in natural rivers.

The work of this thesis includes field work and data processing. The field data collection activities on the Aigua de Valls and Foix rivers have been carried out between June 2021 and February 2022. During the period between April 2021 and February 2022, the data needed to develop the biological models for each season have been collected on different rivers all around Catalonia.

Sommario

I corsi d'acqua spesso vengono modificati da infrastrutture idrauliche e prelievi d'acqua. Inoltre, è dimostrato che queste alterazioni modificano la disponibilità di habitat per le specie acquatiche. È quindi necessario definire un metodo in grado di quantificare gli effetti sulle specie e determinare il deflusso ecologico che assicuri la conservazione della biodiversità acquatica e dei servizi ecologici garantiti dai fiumi.

Per la definizione dei deflussi ecologici, in Italia, è adottato il metodo MesoHABSIM (Mesohabitat SIMulation Model) [1, Parasiewicz, 2001]. È un metodo consolidato per la modellazione dell'habitat, sviluppato per valutare la disponibilità temporale e spaziale di habitat per varie specie di pesci. Il metodo è sviluppato alla mesoscala combinando le unità idrauliche e geomorfologiche descrivendo sia caratteristiche fisiche che biologiche del fiume. I parametri usati nella metodologia sono la velocità del flusso, la profondità dell'acqua, la tipologia di substrato e la presenza di copertura o zone di rifugio all'interno del fiume. Un'altra parte essenziale del metodo MesoHABSIM è la creazione di un modello biologico tramite il metodo random forest, una tecnica di machine learning. Questi modelli definiscono l'idoneità dell'habitat fluviale nell'ospitare specie target basandosi sulle caratteristiche ambientali attuali.

L'obiettivo di questa tesi è di valutare l'impatto delle alterazioni idriche sui fiumi Aigua de Valls e Foix in Catalogna, regione della Spagna, utilizzando il metodo MesoHABSIM. Questo lavoro è parte di un progetto più ampio, commissionato dall'ACA (Agència Catalana de l'Aigua), che ha come scopo principale quello di valutare i deflussi ecologici attuali anche in funzione del prossimo ciclo di programmazione. Il progetto è stato realizzato su dieci fiumi diversi, soggetti ad alterazioni del flusso naturale, mentre i dati per lo sviluppo dei modelli biologici per specie di pesci autoctone della Catalogna sono stati raccolti in corsi d'acqua naturali.

Il lavoro di questa tesi include la raccolta di dati in campo e la successiva analisi. In particolare la raccolta dei dati per i fiumi Foix e Aigua de Valls è stata realizzata tra Giugno 2021 e Febbraio 2022. I dati necessari per sviluppare il modello biologico sono stati raccolti tra Aprile 2021 e Febbraio 2022 in diversi fiumi della Catalogna così da poter sviluppare un modello per ogni stagione.

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Chapter 1

Introduction

Water consumption increased at a rate that was more than twice that of population growth in the last century [2, Arto, 2012]. The higher demand of water led to a decrease in the local and downstream flows [3, Wada, 2013]. Thus, it is essential to develop models able to understand the impact of water diversions on the fluvial system. It will be required to manage the water flow in order to guarantee all the ecosystem services like food, drinking water, energy and flood mitigation [4, Bussettini et al., 2019]. All these services are related to an appropriate level of functionality of fluvial processes, such as appropriate flow and sediment regimes and quality of channel morphology [4, Bussettini et al., 2019].

Analysing the hydraulic infrastructures on the Catalan rivers, they are required mainly for hydropower production and irrigation. Thus, understanding the flow that is needed to maintain a certain ecological quality is mandatory to follow the European directives. The most relevant ones are the “Habitat Directive 92/43/EEC” and the “Good-quality water in Europe” (EU water directive, Directive 2000/60/EC).

The Directive 92/43/EEC aim is described in article 2 [5, Directive 92/43/EEC]:

The aim of this Directive shall be to contribute towards ensuring bio-diversity through the conservation of natural habitats and of wild fauna and flora in the European territory of the Member States to which the Treaty applies.

Measures taken pursuant to this Directive shall be designed to maintain or restore, at favourable conservation status, natural habitats and species of wild fauna and flora of Community interest.

Measures taken pursuant to this Directive shall take account of economic, social and cultural requirements and regional and local characteristics.

“Natural habitat conservation” means that the area extension is stable, the structure and functions exist and will continue to exist in the future, and the conservation

status of its typical species is favourable. To assess the conservation status of a species, their long-term distribution and abundance, as well as the dynamics, it is needed to evaluate the range of species, and the habitat availability. Another key point of this directive is that each Member State must develop the Natura 2000 network, which includes all special protection areas. This network contained both natural habitats and species habitats [5, Directive 92/43/EEC].

The goal of the Directive 2000/60/EC is to accomplish a “Good status” for European water. To achieve this [6, Directive 2000/60/EC]:

- all aquatic ecosystems must be protected, as well as the surrounding terrestrial area;
- water use should be based on long-term protection;
- protection measures should be developed, through the reduction of discharges and emissions of substances;
- pollution emissions should be reduced;
- the effects of floods and droughts should be mitigated.

Furthermore, the legislation assigns specific responsibilities to national authorities. They must identify the individual river basins on their territory; analyse the characteristics of each river basin and establish reference conditions for each type of water body to qualify their status; investigate the impact of human activity and conduct an economic assessment of water use [6, Directive 2000/60/EC]. The 2000/60/CE also includes the definition of high status of fish fauna classified as a biological quality element [6, Directive 2000/60/EC]:

Species composition and abundance correspond totally or nearly totally to undisturbed conditions. All the type-specific disturbance-sensitive species are present. The age structures of the fish communities show little sign of anthropogenic disturbance and are not indicative of a failure in the reproduction or development of any particular species.

To evaluate the fish fauna’s habitat and guarantee its good status when hydraulic infrastructures are present it is necessary to model the instream habitat. It is possible to assess the impact of hydrological and morphological changes on aquatic species by describing the channel hydro-morphology and its relationship with biota [7, Vezza, 2021]. These methods have the advantage of ignoring other factors that may affect the species and focusing only on the direct effects of the hydro-morphological alterations [7, Vezza, 2021]. Among the models that analyse the habitat, the mesoscale Habitat Suitability Models assumes a major importance. These methods operate at the mesoscale, which is one of the geomorphic units

with distinct morphological characteristics and significant size (e.g. pool, rapid, riffle, etc.). They are also based on the development for the different species of a suitability model built in relation with the hydromorphological descriptors of the river habitat. Among these methods the MesoHABSIM methodology (Meso-habitat Simulation Model) was adopted in the project. It was developed by Parasiewicz in 2000 [1, Parasiewicz, 2001] and it is widely used in Italy for river habitat modelling. It combines the hydro-morphological characteristics with fish absence-presence-abundance to develop the biological models. The model exploits random forest and it is able to define the suitability of the river habitats to host the various species.

The goal of the research is to assess the impact of flow alteration on two Catalan rivers and to understand the outflow which needs to be released in order to mitigate the effects. The MesoHABSIM methodology was adopted to create a suitability model for some native Catalan species of the rivers studied.

The thesis is divided into five chapters, the first is the introduction. The second chapter describes the research area, the MesoHABSIM methodology, the data collection procedures, and the development of the biological model. The main results are described in chapter 3. The discussion of the results is found in chapter 4, followed by the conclusion in chapter 5. The other results of the biological model are highlighted in the appendix.

Chapter 2

Material and Methods

2.1 Study area and river reaches

The research was conducted on the rivers Aigua de Valls and Foix, two of Catalonia's internal basins. These rivers are part of a larger study that was conducted on eight internal rivers throughout the region. All of the study areas are highlighted in red in figure 2.1. The number one is assigned to the Aigua de Valls River, and the number three is assigned to the Foix River.

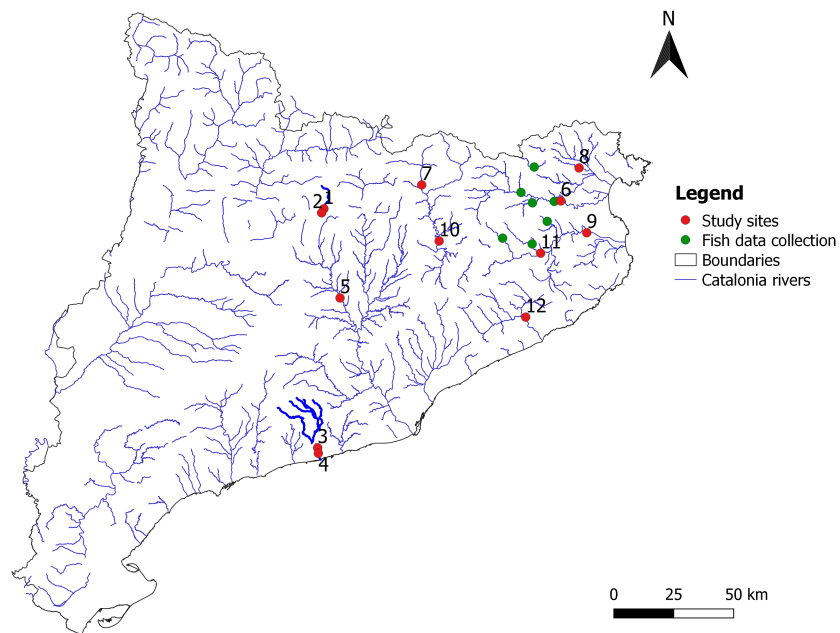


Figure 2.1: Rivers analysed in the project (numbered from 1 to 12 and marked in red) and points studied for the fish data campaign (marked in green).

The biological model was built using data from six additional rivers that did not have any form of intake constructions or dams, upstream of the chosen places. Figure 2.1 shows the measurement points in green.

Aigua de Valls is a Pre-Pyrenees water course [8, Enciclopèdia, 1996], with its spring near Gósol, Berguedà, and it is a tributary of the Cardener. The basin of Aigua de Valls is approximately 100 km² in size before it flows into the Cardener [9, Agència Catalana de l'Aigua, 2005]. The stretch of the river under consideration, as red-circled in figure 2.2, belongs to the municipality of Guixers and it is approximately 160 m in length and 8 m in width.

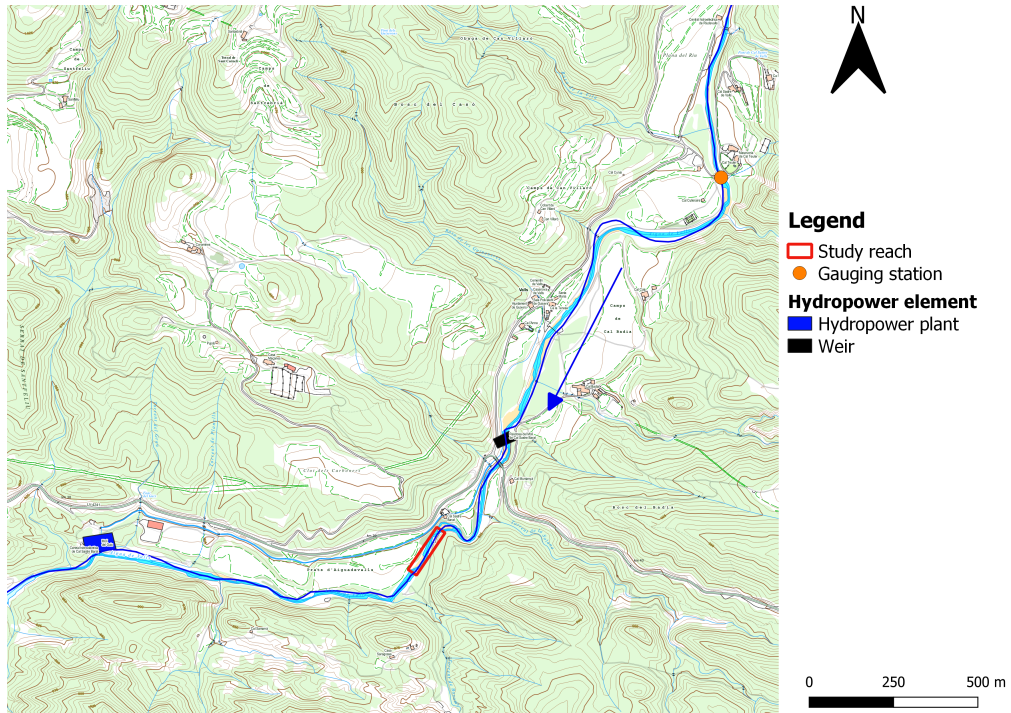


Figure 2.2: Aigua de Valls river and study reach, the territorial topographic map is in the background.

Foix is a river in Catalonia that begins in the pre-coastal region and flows into the sea near Cubelles, Garraf [10, Enciclopèdia, 1996]. Its basin is approximately 310 km² in area [9, Agència Catalana de l'Aigua, 2005] and 48.7 km long [10, Enciclopèdia, 1996]. It is worth highlighting that the Foix river is a Mediterranean temporary river, which means that there are times when it is completely dry while its flow peaks are between October and December, with a secondary peak in May [10, Enciclopèdia, 1996]. The stretch that is considered in this study is red-circled in figure 2.3, in the municipality of Castellet i la Gornal, and has a length of approximately 154 m and a width of 10 m.

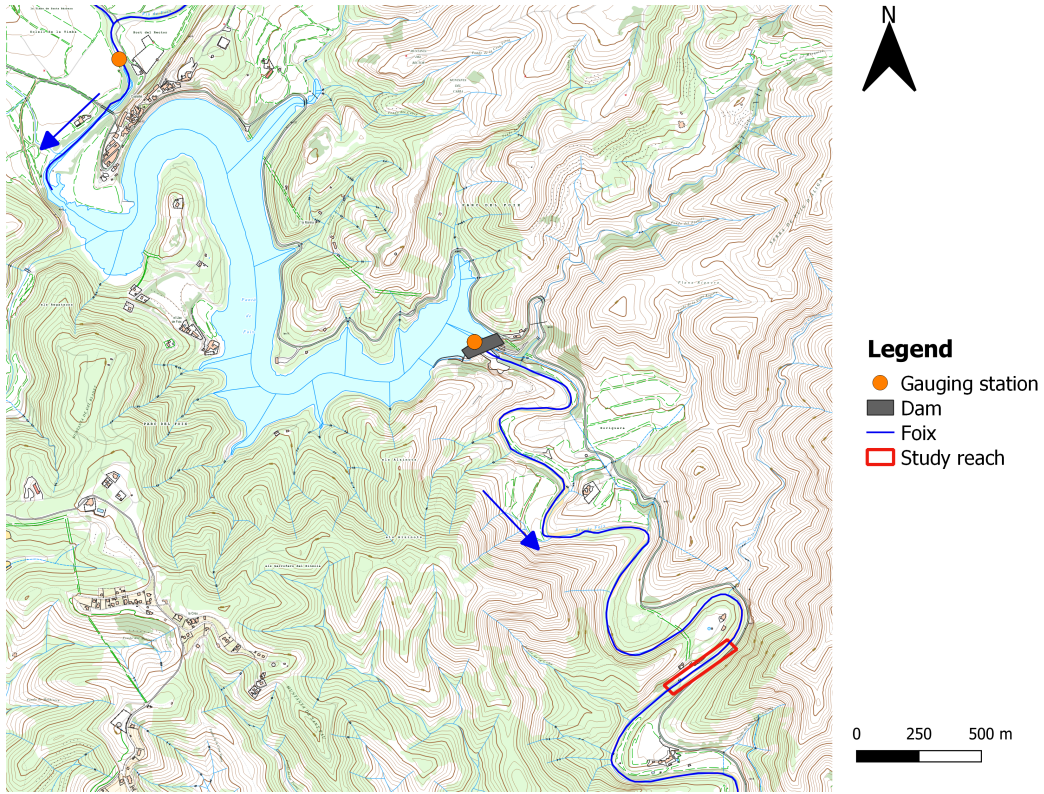


Figure 2.3: Foix river and study reach, the territorial topographic map is in the background.

In both the rivers, there are hydrological alterations that modify the natural flow and affect the whole river system including its fish population [11, Nilsson et al., 2005] even if the causes of the alteration are different. In Aigua de Valls there is a weir upstream from the study area, visible in black in figure 2.2, which diverts part of the flow to a small hydropower plant, which is represented in figure 2.2 in blue. In Foix, as it is shown in figure 2.3, upstream from the study area, there is a dam that creates a reservoir used mainly for coastal irrigation and supply [10, Enciclopèdia, 1996].

The project's goal is to find the flow that must be released during the year into the two rivers to maintain the availability of the habitat for the analysed species. This definition of flow level is one of the three points needed to determine the ecological flow for the Water Framework Directive [12, European Commission, 2016]. The second point is the achievement of good ecological status in natural surface bodies. The last item to consider is the non-deterioration of the existing status. To evaluate the e-flow and the habitat availability with different flow levels, the method that will be employed is the MesoHABSIM.

2.2 MesoHABSIM

The MesoHABSIM or MesoHABitat SIMulation system allows the physical modelling and the management of the instream habitat. It is mainly adopted when there are external elements that modify the river's flow, such as hydro-powers or wires [13, Parasiewicz et al., 2013]. It was created in 2000 by Parasiewicz to simulate the habitat at a mesoscale level rather than adopting a microscale [1, Parasiewicz, 2001]. The mesoscale is defined as a spatial scale with a relatively homogeneous flow and depth at which both research and river management objectives are reached [14, Hawkins et al., 1993].

Before 2000, to analyse the effects of flow modifications, the methods adopted required high precision measurements and habitat suitability data for fish [1, Parasiewicz, 2001]. One of this method is PHABSIM, it uses a deterministic hydraulic model. Although it is very effective with single-thread channel water course with a low gradient it has some issues [15, Vezza et al., 2017]. One of it is that measurements are often realized in just a few sampling locations, thus the representations are dependent on the choice of the sampling site. Another relevant aspect is that the resolution of the hydraulic and biological models must match. The fish's position is random if considered at a microscale level; but if the mesoscale is considered, this problem could be sorted out because it would be easier to surround the animals and catch them in order to classify them [1, Parasiewicz, 2001]. For all this reason Parasiewicz developed the MesoHABSIM model that is able to overcome these problems.

2.2.1 Description of the methodology

The MesoHABSIM model is based on the classification of the river in units called mesohabitats. The mesohabitat is an area in which an animal spends a significant percentage of its life [16, Parasiewicz, 2008]. Usually, in natural water courses, this unit coincides for dimension with the morphological unit. This is the scale of the mesoscale instead, the microscale is the one of a single element of the river, like a group of similar sediments or plants [17, Rinaldi et al., 2016]. The longitudinal dimension has the same order of magnitude of the width of the river if it is a single-thread channel. In general, the dimension of the mesohabitat could be between 10^{-1} and 10^3 m and they cannot be bigger than 10% of the stretch surface of the river under study. Elements that are smaller than this dimension are at the scale of microhabitat [15, Vezza et al., 2017].

The structure of hydraulic patterns in hydromorphological units (HMUs) defines Mesohabitats as well as the elements that provide shelter and produce favourable survival and development conditions [16, Parasiewicz, 2008]. In particular, the depth and the velocity of the water, the presence of cover parameters, and the type

of substrate inside each mesohabitat are considered. The MesoHABSIM model has been integrated with the SUM (survey and classification System of Morphological Units of watercourses) for the classification and identification of the HMUs [17, Rinaldi et al., 2016]. In figure 2.4 it is possible to see the different scales of the problem.

Each element has its characteristics and delimitation criteria [17, Rinaldi et al., 2016]:

- Basin: area drained by the same river, the watershed line splits different basins;
- Segment: portion of the river with similar topographic, morphological and geological characteristics;
- Stretch: portion of the segment with a homogeneous interaction between shapes and processes. The morphology is essential to delimit this area;
- Morphological unit: fluvial shape done with erosion and deposition of sediments. The differences in morphology, sedimentation, and vegetation are essential to identify the different elements.

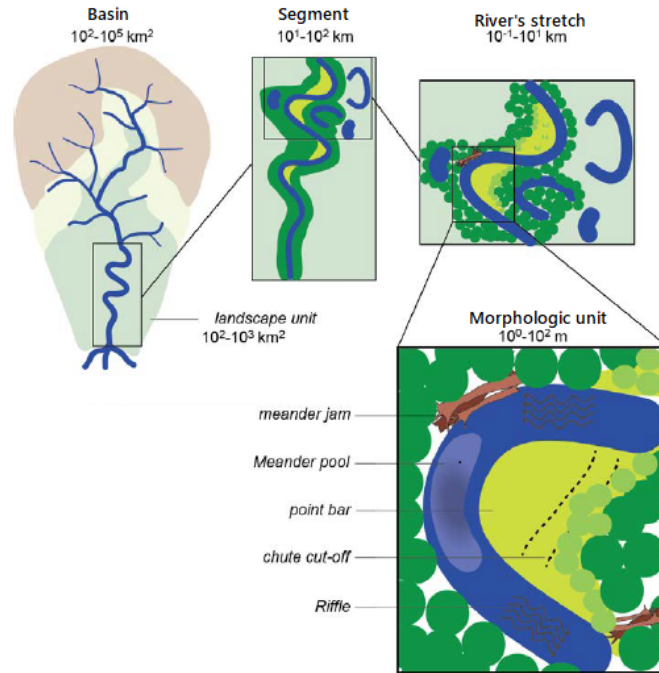


Figure 2.4: Different scales in the river system, basin, segment, river's stretch, morphologic unit. The figure is taken from [17, Rinaldi et al., 2016] with some modifications.

The morphological units taken into account in the latest version of the MesoHABSIM model are described in the following table 2.1.

The type of HMU depends on some general characteristics of the river itself in that area. These characteristics are the slope of both the bed river and the valley, the flow level and the type and quantity of the sediments. In highly sloped mountain rivers the typical units are the erosive ones and the ones made up of bigger sediments. In rivers characterized by medium slope and energy, there is a higher concentration of depositional units and the typical HMU of an alluvial plain. In rivers with low slope and energy instead, the alluvial plain is larger and the depositional units are usually lateral [15, Vezza et al., 2017].

The analysis of the mesohabitat has to be realized under different flow conditions. The habitats will change with the flow and the distribution of the HMUs will move from the riffle-pool configuration toward homogeneous run-type habitat [1, Parasiewicz, 2001].

It is possible to see the different steps of the MesoHABSIM methodology in the following figure 2.5, taken from [15, Vezza et al., 2017] and translated.

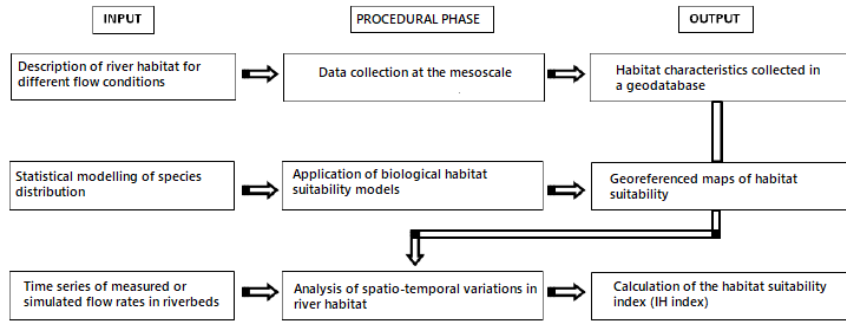


Figure 2.5: Procedure of the MesoHABSIM method [15, Vezza et al., 2017].

The different phases of the procedure could be divided into three main points:

- Description of the habitat through hydromorphological measurements at different flow levels (subsection 2.2.2);
- Production and application of biological models (section 2.3);
- Analysis of time-space variations in the river's habitat (section 2.4).

The output will be delivered by the software SimStream. This software is the technological reference for the application of the MesoHABSIM method. The input and the procedural phase in figure 2.5 will be described in this chapter and the output of the methods in chapter 3.

Type of HMU	Description
Backwater	Also called the “one-way connected branch”, is a secondary channel united at the primary one downstream or upstream. The water flows into the alluvial aquifer if the connection is upstream or comes from there for the downstream connection.
Isolated pool	Also called a “pond” is a part of the secondary channel separated from the flow of the river.
Pothole	It is a deep fracture, made from erosion in the bedrock channel if the flow energy is concentrated.
Cascade	It is a geomorphic unit alluvial or semi-alluvial. It is formed by boulders but the sediments are disorganized and brought by large floods. The flow is very turbulent.
Rapid	Also, this one is made of boulders but they are very stable and organized into lines perpendicular to the channel. It is visible only at low flows. The flow is turbulent with high air concentration.
Riffle	It is defined by shallow and fast flow with uniform sediments that occasionally stick out from the water. The waves often are unbroken.
Step	It is distinguished by nearly vertical drops in the channel bed. The steps are made of sediment but this shape can be produced by bedrock or woods.
Glide	Glides have a regular longitudinal profile, with a smooth surface almost parallel to the bed.
Pool	It is characterized by a depression in the channel bed. They are characterized by slow velocity and high depth. Usually, the sediments could be finer than the ones in the other units.
Dune system	It is typical in sand-bed rivers, the surface is determined by the presence of a dune on the bed channel. The presence of this unit can be assumed if it is known the material of the bed and the surface is undulating and homogeneous.
Aquatic vegetation	It can be assumed as a unit if its extension is greater than 5 m^2 and induce sediment retention.
Artificial element	This unit is composed of all the artificial elements that can be found in a river as a dam, check dam, weir, retention basin, diversion, spillway, culvert, ford, bridge, bed revetment, bed sill, ramp, bank protection, embankment.

Table 2.1: Type of HMU of the MesoHABSIM methodology. The definitions are taken from [18, Rinaldi et al., 2015].

2.2.2 Habitat parameters and data collection procedure

The first step of the MesoHABSIM method is the description of the habitat through hydromorphological measurements at different flow levels. To fulfil this objective, it is essential to find the right section of the river to analyse.

One of the protocols entails trekking or rowing the length of the river in the project analysed region to assess the proportion between the different types of HMUs [13, Parasiewicz et al., 2013]. After this estimation, it is possible to choose a part of the river that will have a similar proportion.

Following the selection of the stretch, it is required to determine the flow level at which the surveys must be conducted. The minimum number of surveyed flows is three, and they should be strategically dispersed, with more surveys at the more crucial conditions (the lowest) [13, Parasiewicz et al., 2013]. Another aspect that should be evaluated is the maximum flow level at which there is a survey, in relation to the flow time series. Usually, the maximum flow during the day of the survey corresponds to the river's highest summer low flows, while the lowest flow corresponds to the river's yearly minimum flow during the rearing season as well as the time of growth [13, Parasiewicz et al., 2013]. The flow must stay stable during the one-day survey, otherwise, there would be difficulties in the post-processing of field data [13, Parasiewicz et al., 2013]. It is necessary to calculate the flow level each day of the surveys.

The necessary successive steps are:

- the identification of the HMUs and the drawing of these units in QGIS;
- the realization of measurements of velocity and depth and the identification of the different types of substrates for each HMU.

To identify the HMU it is required to walk in the river and focus on the river bottom morphology, on the water surface and on the shore characteristics [13, Parasiewicz et al., 2013]. Then, it is possible to realise the drawing on MapStream, a plugin of QGIS. When the HMUs are drawn, it is necessary to record some other characteristics that are described in table 2.2.

Then, there is the need to record the velocity, the depth, and the substrate for each HMU. The different classes of the three parameters are in table 2.3.

Name	Description and classes
river	Name of the river
dd	Day
mm	Month
yyyy	Year
site	Name of the site
HMU number	Progressive number for the HMU of a specific site
HMU type	Backwater, Isolated pool, Pothole, Cascade, Rapid, Riffle, Step, Glide, Pool, Dune, Aquatic vegetation, Artificial element
Covers	Presence or absence of refuges, for each type of refuge it is possible to add true/false. The refuges are Boulders, Canopy shading, Overhanging vegetation, Roots, Submerged vegetation, Emerged vegetation, Undercut banks, Woody debris, Rip-rap, Shallow margins
Comments	Other information that could be necessary

Table 2.2: QGIS input parameters.

Name	Description and classes
Depth	9 classes of intervals of 15 cm until the last class ">120 cm"
Velocity	9 classes of intervals of 15 cm/s until the last class ">120 cm/s"
Substrate	12 classes of substrate: Gigalithal, Megalithal, Macrolithal, Mesolithal, Microlithal, Akal, Psammal, Pelal, Detritus, Xylal, Sapropel, Phytal

Table 2.3: Parameters needed for the analysis of each HMU.

Each point of measurement is representative of 1 m² of the river. The points of measurement inside the unit should be homogeneously distributed. There should be at least 15 points for each unit or at least a density of 2 points/m². The points taken for depth, velocity, and substrate must be representative of the unit in terms of percentage. It could be useful to theoretically divide a unit with various characteristics into sub-units and quantify the extension of the sub-unit in percentage. Then it would be necessary to take the correct number of measurements

in each sub-unit in order to maintain these percentages [15, Vezza et al., 2017].

The differences between the classes of the substrate of the river are listed in the following table 2.4.

<i>Substrate</i>	<i>Size range</i>
<i>Gigalithal</i>	<i>(bedrock)</i>
<i>Megalithal</i>	<i>>40 cm</i>
<i>Macrolithal</i>	<i>20 - 40 cm</i>
<i>Mesolithal</i>	<i>6 - 20 cm</i>
<i>Microlithal</i>	<i>2 - 6 cm</i>
<i>Akal</i>	<i>0.2 - 2 cm (gravel)</i>
<i>Psammal</i>	<i>0.06 - 0.2 cm (sand)</i>
<i>Pelal</i>	<i><0.06 cm (clay)</i>
<i>Detritus</i>	<i>(organic matter)</i>
<i>Xylal</i>	<i>(woody debris)</i>
<i>Sapropel</i>	<i>(anoxic mud)</i>
<i>Phytal</i>	<i>(submerged plants)</i>

Table 2.4: Sediment classification according to Hauer et al. [19, Pinna, 2019/20].

To realize these measurements it is necessary to have the following instruments with the right resolution.

Equipment

The required equipment for the MesoHABSIM procedure is:

- telemeter with Bluetooth technology;
- field tablet with the software QGIS on it;
- flowmeter acoustic or electromagnetic;
- tripod;
- compass;
- wading rod.

One of the advantages of this procedure is that the equipment is really light and also low-cost [15, Vezza et al., 2017].

The telemeter is used to compute distances and heights. It uses an infrared laser and measures the time that the signal takes to arrive at the target and to go back. It is also possible to obtain the position of a point in the space thanks to

the measurement of the inclination angle and the azimuth angle [15, Vezza et al., 2017]. The telemeter used in this project is a TruPulse 360°R in figure 2.6. The specifications of the telemeter are reported in the following table 2.5 .



Figure 2.6: Telemeter TruPulse 360°R used in the project.

Measurement Range

<i>Maximum distance for reflective targets</i>	<i>2000 m</i>
<i>Maximum distance for non-reflective targets</i>	<i>1000 m</i>
<i>Inclination</i>	<i>$\pm 90^\circ$</i>
<i>Azimuth</i>	<i>0-359.9°</i>

Accuracy

<i>Distance accuracy to weak targets</i>	<i>$\pm 1 m$</i>
<i>Distance accuracy to typical targets</i>	<i>$\pm 0.2 m$</i>
<i>Inclination accuracy</i>	<i>$\pm 0.25^\circ$</i>
<i>Azimuth accuracy</i>	<i>$\pm 0.5^\circ RMS$</i>

Table 2.5: Specific of the TruPulse 360°R [20, LTI, 2018].

The calibration is a fundamental step before using the telemeter. It is necessary a compass for the position of the north and follows the step of the manual for the correct calibration. It is also useful to have a tripod to set the telemeter. Furthermore, the tripod should be non-magnetic to avoid a higher error of the azimuth angle [15, Vezza et al., 2017].

The field tablet uses QGIS and its plugin, MapStream, to acquire the points taken thanks to the telemeter. The typologies of points that we have in the software are “station”, “vertex” and “meas”. The stations are the points in which there will

be the telemeter, the vertices are the ones of the HMU instead the meas are the layer of the measurements inside the HMU that include the substrate, the velocity, and the depth. It is better to use the “rugged” typology of the tablet that allows collect data also in tough conditions e.g. if the temperature is below zero, if it rains or snows, and if the instrument falls in the water [15, Vezza et al., 2017]. The typology of the tablet used in this project is a Handheld ALGIZ 8X and it is a rugged tablet.

The flowmeter used in the field is a portable electromagnetic model. It calculates the river’s velocity using the Faraday law of electromagnetism induction. It has to be perpendicular to the flow direction to calculate the velocity of the water. The flow meter used in this project is a Valeport 801 EM, with a flat sensor that is suitable for shallow applications due to the small sensing volume, but this sensor is also really sensitive to turbulence. The range of measurements is between -5 m/s and +5 m/s, the minimum depth at which it evaluates the speed is 5 cm and the accuracy is $\pm 0.5\%$ of reading plus 5 mm/s [21, Valeport, 2020]. To use the flowmeter it is necessary to have a wading rod on which putting the sensor that will take the measurement shown in figure 2.7.

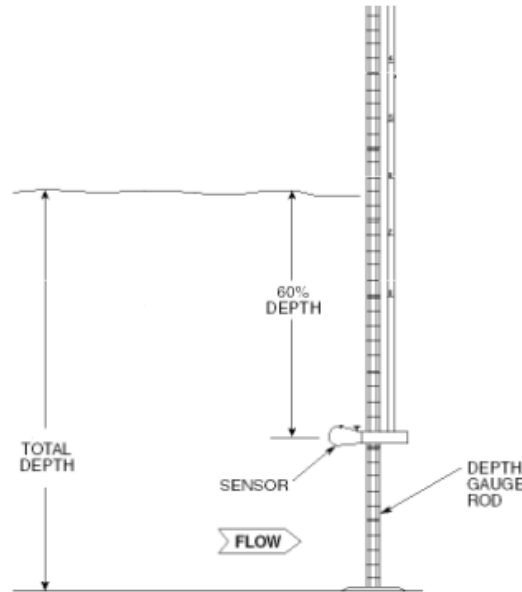


Figure 2.7: Point in which the measure of the velocity has to be calculated [22, Marsh-McBirney, INC., 1990].

The standard wading rod has a base, a bottom section, and three intermediate sections. The intermediate sections are long 0.5 m and the bottom section with the base is 0.5 m long. Each section is divided every 5 cm. It is possible to move

the position of the sensor in function of the water depth, in particular the mean velocity is measured at the 60% of the depth from the top.

Calculation of the flow level

To calculate the flow level it is necessary the use of the flowmeter, the wading rod, and a graduated tape, if it is possible to cross the river [15, Vezza et al., 2017]. There are some requirements to choose the site inside the river to measure the flow. The river have to be straight and having a homogeneous cross-section and slope, the bed and margins should be stable and well defined, the section should not have vortices or dead water and it have to be free of trees or obstacles. The procedure requires the use of a graduated tape to measure the horizontal width of the river. The depth and the velocity are measured at the same points [23, ISO 748:2007].

The method used to calculate the velocity is the one-point. This method established that the velocity is taken only at the 60% of the depth below the surface and this value represents the mean velocity in the vertical.

The approach to calculate the flow level divides the section of the river into a number of segments as shown in figure 2.8. The velocity (v_{n+1} , v_n) and the depth (d_{n+1} , d_n) are measured at each vertical line at the distance (b_{n+1} , b_n).

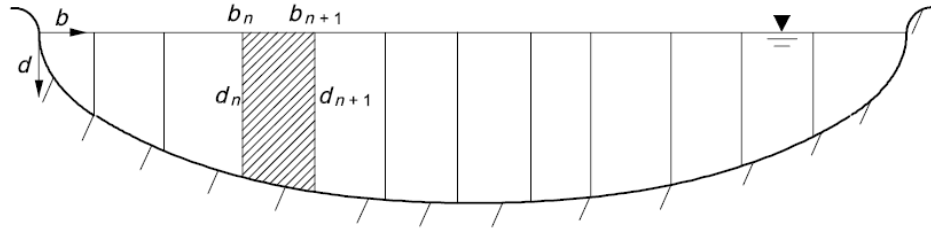


Figure 2.8: Diagram that illustrates the methodology for the flow calculation [23, ISO 748:2007].

The mathematical formula to calculate the flow is the following:

$$Q = \sum (b_{n+1} - b_n) \left(\frac{d_{n+1} + d_n}{2} \right) \left(\frac{v_{n+1} + v_n}{2} \right)$$

in which the summation is done for each section.

The description of the habitat and the calculation of the flow level will give as a result the collection of the habitat characteristics in a geodatabase. The result, for the analysed rivers, is described in section 3.1. The next step, in applying the MesoHABSIM method, is the development of the biological model described in the following section 2.3. In particular, there is the need to develop a biological model for the species that are not yet loaded in the SimStream database.

2.3 Biological models

The biological model is essential in the MesoHABSIM procedure to understand the availability of the habitat in the river and the hydromorphological characteristics that each species choose. It is proven in many studies that fishes are precise indicators of flow alterations [24, Poff et al., 2010]. In particular, the abundance of specimens and the number of different species answer in a negative way to the alteration of the natural flow [15, Vezza et al., 2017]. This effect is a consequence of the dependence of the fishes on habitat availability. Fishes are one of the most important indicators to analyse the quality of the environment because of the ease to identify the specimens, the number of different species, and the relative simplicity to identify stress answers [15, Vezza et al., 2017].

In this project, the sampling sites to build the biological models are different from the rivers in which the MesoHABSIM method is applied. The main reason is that the rivers used to build a biological model have some requirements. The area should not have hydrological and morphological alterations, the presence of fish population should be natural and the alien species should not be present [15, Vezza et al., 2017].

2.3.1 Species and life stages

The species analysed throughout the project are:

- adult and juvenile brown trout;
- adult and juvenile Mediterranean barbel;
- adult Catalan reptiles;
- adult and juvenile European eel;
- adult and juvenile Catalan chub;
- adult and juvenile freshwater bivalve;
- adult freshwater blenny;
- adult European stickleback.

This work focuses on the first four above-mentioned species. In Aigua de Valls the species taken as a target are the Catalanian barbel, the brown trout and the viperine water snake. The Catalanian barbel (or *Barbus haasi*) is an autochthonous species that is extinguished in the reach but present in other parts of the river. Since the Catalanian barbel is really similar to the Mediterranean barbel, in this work

the biological model of Mediterranean barbel is adopted to model the Catalanian barbel. The brown trout already have a biological model, and it is used in this thesis. The viperine water snake is an autochthonous species which lives in the reach, and it will be used to build the suitability model of reptiles.

In Foix the target species are Catalanian barbel, European eel, Mediterranean turtle and viperine water snake. The Mediterranean turtle is an autochthonous species and the suitability model of the reptiles will be adopted to analyse it and the viperine water snake.

Each species examined will be described here.

The brown trout (or *Salmo trutta*) belongs to the Salmonidae family. A picture of it is shown in figure 2.9 [25, Britannica, 2020]. It is a diurnal carnivores and is native to many areas including Spain and Italy. Adult brown trouts are between 18 to 56 cm, the juvenile trout has fewer spots than the adults and it has “Parr marks” that disappear as they age. The brown trout spawns during autumn and winter [26, Ryan, C.]. The model for the brown trout was already developed by the Politecnico di Torino and uploaded in SimStream.



Figure 2.9: Picture of a brown trout [26, Ryan, C.].

The Mediterranean barbel (or *Barbus meridionalis*) belongs to the Cyprinidae family. It is visible in figure 2.10. The fish is considered a near threatened species by IUCN and it is associated with freshwater habitat [27, EOL]. It is native of Mediterranean rivers in northeastern Spain and southeastern France [28, FishBase]. The difference between the adult and juvenile fish was done in terms of length not in terms of fertility, in particular, the length considered to distinguish the two elements is 45 mm.



Figure 2.10: Picture of a Mediterranean barbel [27, EOL].

The Catalan reptiles include two different species the Mediterranean turtle and the viperine water snake, that are both shown in figure 2.11.

The Mediterranean turtle (or *Mauremys leprosa*) is a small to medium-sized freshwater turtle diffused in the Iberian Peninsula, Southern France and North Africa. It is an oviparous that tolerates salt water, polluted freshwater habitats and also reduced water levels [29, Bartolero, 2017].

The viperine water snake (or *Natrix maura*) is a snake proper of aquatic environments. It is distributed in Western Europe and North Africa. An element necessary to its presence is enough vegetable coverage and thermoregulation sites[30, Zucchi].



Figure 2.11: Pictures of the Catalan reptiles studied in this project, in figure A there is a Mediterranean turtle [29, Bartolero, 2017], in figure B there is a Viperine Water Snake [30, Zucchi].

The European eel (or *Anguilla anguilla*) is a species in the family of freshwater eels. It is shown in figure 2.12.



Figure 2.12: Picture of a European eel [31, FishBase].

It is considered critically endangered by the IUCN. It is a solitary, diurnal carnivore native to the Mediterranean Sea and Atlantic and Pacific Oceans [32, EOL]. Usually, the spawning migrations occur during the second half of the year [31, FishBase]. In the early spring months, European eels migrate to the sea for breeding. The silver eel is the juvenile and it lives in tributaries along with the European coast, to distinguish the juvenile from the adult a length of 250 mm is adopted .

To realise the sampling for the species it is necessary to work at the mesoscale.

It is required to sample the fishes in the different types of HMU identified and to collect all the information about the HMU already described. To capture the fishes it was used backpack electrofishing, then each fish was classified and measured to divide into juvenile and adult. It was not needed to sample all the width of the river but only some HMU.

The sampling period in this project is divided into the different seasons, in this way, it is possible to develop a biological model for each season:

- Spring: 26 of April 2021 - 7 of May 2021;
- Summer: 12 of July - 23 of July 2021;
- Autumn: 5 of October - 22 of October 2021;
- Winter: 17 of January - 7 of February 2022.

Starting with this data it is possible to build the biological model with random forest.

2.3.2 Random forest

To develop the species distribution model a commonly used technique is random forest (RF). It is a supervised machine learning algorithm built with a combination of decision trees [33, Vezza et al., 2012].

A decision tree can be used to express a map from attribute values, that represents a list of properties, to classes that are mutually exclusive labels [34, Quinland, 1996]. In the biological models that are developed for this thesis the attribute values are depth, velocity, substrate and refugees instead the classes are presence/absence or presence/abundance. A decision tree is made up of a leaf node with a class or a structure with a test node linked with two sub-trees [34, Quinland, 1996]. It is possible to see an example in figure 2.13. There is the structure of the test node that has the output “No” on the right arrow, and “Yes” on the left arrow. The successive node could be a sub-node or a terminal node, in this case, they are “Absent” or “Present”.

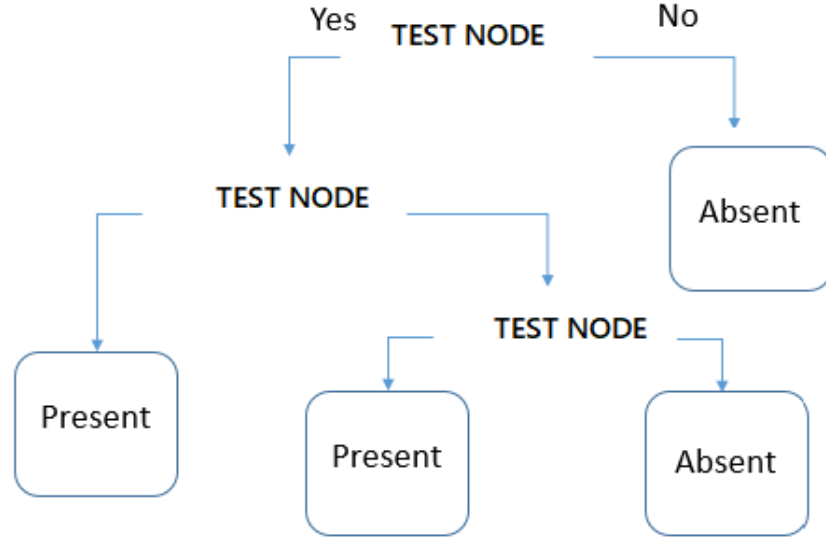


Figure 2.13: Example of a decision tree.

It is used random forest because it achieves the best performance in creating predictive habitat models for the distribution of species [35, Liaw et al., 2007]. Random forest is based on the bagging method but adds another layer of randomness. In Bagging each tree is independent and uses a bootstrap sample of the dataset. In this way, it would reduce the variance of the simple classification and regression trees. Furthermore, in RF each node is split using the best splitting between a sub-set of them randomly chosen at that node [35, Liaw et al., 2007].

It was used R studio and its library package random forest to apply the method. The needed parameters are the original dataset X , the number of trees in the forest t and the number of variables in the random subset at each node m . The method is developed with the following series of steps [33, Vezza et al., 2012]:

- drawing t bootstrap samples X_i , one for each tree, that are equal to the two third of the original dataset. The remaining elements are called OOB data (out-of-bag data);
- at each node of each tree there is a random selection of m variables and then there is a choice of the best splitting between them;
- development of the tree and prediction of the OOB observations to validate the method.

Because the OOB observations are not used in the development of the RF model, the estimation of these values is the cross-validation [33, Vezza et al., 2012]. The

cross-validation is performed by computing the EOOB (out of bag error) for each tree. The final error is the mean of the errors in each decision tree [15, Vezza et al., 2017]. Random forest chooses the most parsimonious model to define the lowest number of required variables. Another important result is the order of relative importance of variables [33, Vezza et al., 2012]. To evaluate the relevance of each variable it is possible to estimate the increase of the prediction error when the OOB data for these values are permuted and the others are unaltered, this activity is performed tree by tree. The final results are obtained by dividing the difference between the two errors by the standard errors [33, Vezza et al., 2012].

In the following list there is a brief overview of the main advantages of the methodology adopted [15, Vezza et al., 2017]:

- the prevision is done considering all the variables at the same time;
- it is not needed to modify the data before applying the methodology;
- outliers do not impact the analysis and it is easy to identify and eventually remove them;
- there is no over-fitting and over-training;
- a procedure of cross-validation is already developed in the method;
- the algorithm has a reasonable speed also with a huge dataset due to the use of a small sample of variables at the same time.

In this project the random forest model was applied twice, one for the binary presence/absence model and another one for the presence/abundance model. The threshold for the presence in the first model is a density of specimens above zero, instead, for the abundance the threshold is species specific and is obtained using the inflexion points in the density histogram done with direct observation in the field [15, Vezza et al., 2017]. The development of the biological model is a fundamental step to obtain the georeferenced maps of habitat availability in the river analysed, as it is shown in section 3.2. In the following section, the description of the next step of the MesoHABSIM method is explained.

2.4 Habitat-flow relationships

To assess the influence of hydro-morphological changes on the fish community [36, Vezza et al., 2015] the first step is the realization of the habitat-flow rating curve [15, Vezza et al., 2017]. The minimal number of hydromorphological surveys needed to establish the habitat-flow relationship is three [4, Bussettini et al., 2019]. The digital mesohabitat maps and the biological suitability model allow understanding

if each mesohabitat is optimal, suitable or not suitable for the different species [37, Parasiewicz, 2007]. It should be highlighted that if a mesohabitat is not suitable it means that the fishes do not live in this area in their daily routine but still they could cross it [15, Vezza et al., 2017]. It is possible to summarize the habitat classified as suitable (H_i) and optimal (H_o) into the available habitat with the use of the following formula [36, Vezza et al., 2015].

$$H_d = H_i * 0.25 + H_o * 0.75$$

Weighted factors are used to provide a higher contribution of the optimal habitat [37, Parasiewicz, 2007]. After this calculation, the result will be the available habitat in relation to the flow level during the sampling. A mathematical spline function is used to interpolate the habitat-flow rating curve for each target species [36, Vezza et al., 2015]. Hence, these curves with habitat expressed in m^2 and flow level in m^3/s are plotted also with the extension of the wetted area [37, Parasiewicz, 2007] whereas the available habitat is expressed in the percentage of the wetted area at the highest sampled flow [36, Vezza et al., 2015]. It has to be considered that these curves are realized up to the maximum sampling flow [37, Parasiewicz, 2007]. Thus it is fundamental that the maximum flow level in the sampling days is higher enough in the flow time series of the reference condition. It is defined as the flow level without any alterations. The flow-time series are a tool to develop the habitat-time series that will forecast the size and length of stressful events for river fauna [38, Koutrakis et al., 2019].

Another fundamental consideration is that the Foix is a temporary river. For this reason there are some other information that are necessary to build the habitat-flow-time curve. In particular the Foix is a river that dries up during the year without permanent ponding case. Another fundamental information is “the number of days to have a dry riverbed after flow ceased”, that are five for the Foix [39, Simstream, 2021]. The curve that will be obtained is characterized by the relation between the flow and the habitat when there is flow, but also the relationship between the habitat and the time in days of non-flow conditions [39, Simstream, 2021].

In the project, six different flow conditions have been analysed.

- Altered 1-4: actual conditions if there are gauging measurements downstream (Foix) or the worst possible conditions (Aigua de Valls) (BAU).
- Altered 2-5: legal flow level that should be applied in all the existent infrastructure in Catalonia according to the “Pla de gestió” (PdG) [40, Generalitat de Catalunya, 2017]. It represents the 60% of the flows in the Sectoral Plan for Maintenance Flows.
- Altered 3-6: flow written in the Sectoral Plan for Maintenance Flows (PSCM) and it applies to all the new concessions [9, ACA, 2005].

The difference between the scenarios 1 and 4, 2 and 5, 3 and 6 is that in the scenarios 4, 5 and 6 it will be considered the 15% less flow to analyse possible future impacts of climate change.

For the river Aigua de Valls, the reference condition has been taken from the gauging station “Guixeres (Aigua de Valls)”. This station is upstream of the wire for which it is necessary to evaluate the effects. The position of the station in relation to the study area is shown in figure 2.2. The turbine is a Francis and it could turn a minimum amount of flow equal to $0.400 \text{ m}^3/\text{s}$ and the concession value is equal to $0.670 \text{ m}^3/\text{s}$. The data collected from the gauging station starts from 15/02/2008 until 21/12/2021. In table 2.6 are written the flow level that should be maintained for the “Pla de gestió” (scenarios 2-5) [40, Generalitat de Catalunya, 2017] and for the “Pla Sectorial de Cabals de Manteniment de les conques internes de Catalunya” (scenarios 3-6) [9, ACA, 2005], instead for scenarios 1-4, it is considered a value of minimum flow level equal to 0.1 of the Q_{50} . Figure 2.14 shows the values of the reference flow-time series and the one in the scenario Altered 1.

Month	Pla de gestió	Sectoral plan
Jul-Aug-Sep-Oct-Nov-Dec	0.270	0.450
Jan-Feb	0.216	0.360
Mar	0.270	0.450
Apr-May-Jun	0.405	0.675

Table 2.6: Flow level that should be maintained (m^3/s) for two different plans for the Aigua de Valls river.

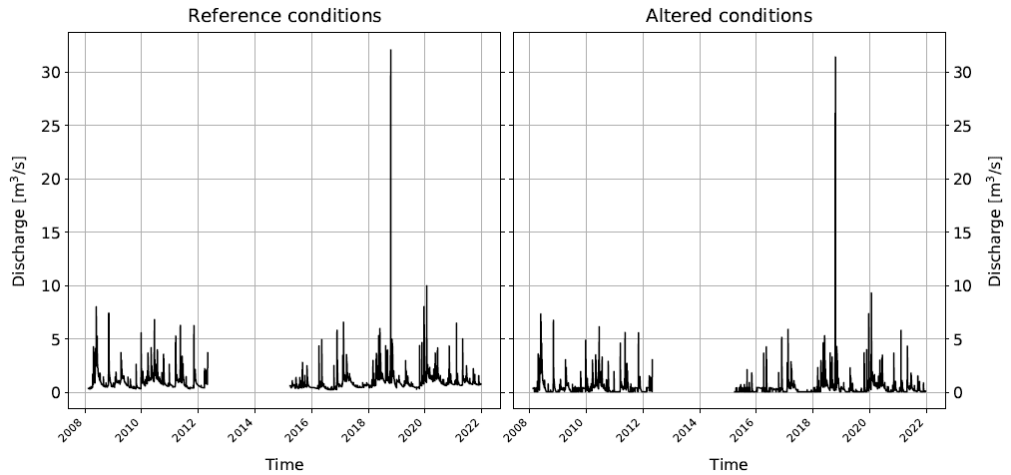


Figure 2.14: Flow-time series for the river Aigua de Valls, the reference condition and the altered condition. The graphs are obtained with the software SimStream.

Instead for the river Foix, the flow level both upstream and downstream the dam is taken from “Castellet i la Gornal” and “Sortida d’Embassament de Foix (Castellet i la Gornal)”. The data collected from upstream of the dam are the reference flow-time series instead the downstream one are the scenarios 1-4. The data collected from the gauging station is relative to the period between 7/5/2019 and 21/12/2021. In table 2.7 are written the flow levels that have to be maintained according to “Pla de gestió” (scenarios 2-5) [40, Generalitat de Catalunya, 2017] and “Pla Sectorial de Cabals de Manteniment de les conques internes de Catalunya” (scenarios 3-6) regulations [9, ACA, 2005].

Month	Pla de gestió	Sectoral plan
Oct-Nov-Dec-Jan-Feb-Mar-Apr-May	0.053	0.088
Jun	0.048	0.08
Jul-Aug-Sep	0.038	0.064

Table 2.7: Flow level that should be maintained (m^3/s) for two different plans for the Foix river.

Figure 2.15 shows the values of the reference flow-time series and the one in the scenario Altered 1.

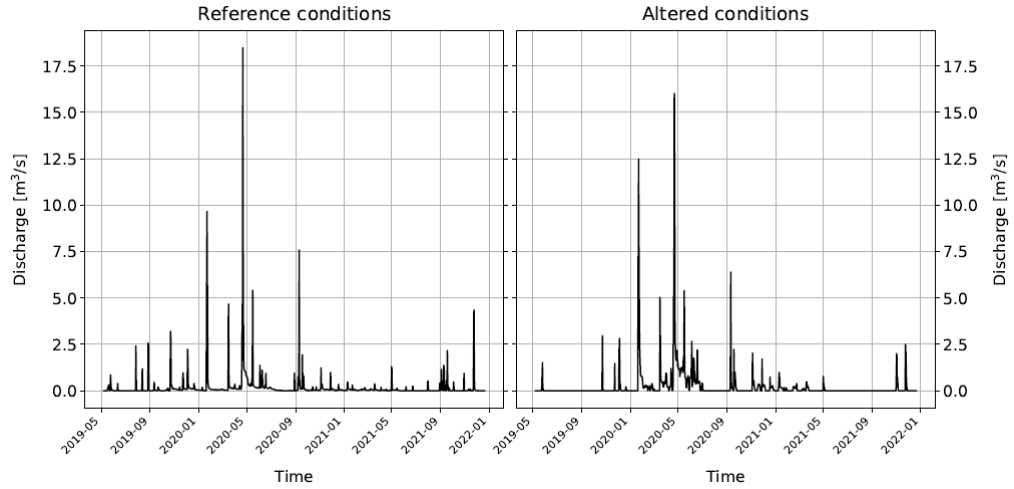


Figure 2.15: Flow-time series for the river Foix, the reference condition and the altered condition. The graphs are obtained with the software SimStream.

Thus it is possible to obtain for both the rivers the habitat-flow-time rating curve using the relation

$$HA(t) = PH(Q(t))$$

in which PH is the physical habitat-stream flow function for a given fish species, $Q(t)$ is the streamflow at the time t and $HA(t)$ is the available habitat area at the time t [41, Vezza et al., 2014]. It allows estimating the quantity of habitat that would be present at a certain flow level [13, Parasiewicz et al., 2013]. The habitat time series show also how the habitat varies over time, and statistical analysis of them can be used to spot stress conditions brought on by ongoing habitat availability restrictions [36, Vezza et al., 2015]. Statistical analysis is then used to depict how habitat changes over time and to pinpoint stressful situations, adopting the Uniform Continuous Under Threshold methodology (UCUT) [4, Bussettini et al., 2019]. Each UCUT curve depicts the cumulative duration of events that occur when the habitat is less than a defined quantity for a continuous period of days and describes the magnitude, frequency, and duration of events [36, Vezza et al., 2015]. This methodology is predicated on the idea that habitat is a limiting element, and that unusual natural occurrences stress aquatic species and influence the community [36, Vezza et al., 2015]. In particular fish densities are immediately altered by a pulse stressor, whereas species composition is persistently altered by a press [13, Parasiewicz et al., 2013].

To express the integrity of the habitat between the reference and altered condition is used the integrity index that depends on both temporal and spatial variation. The average habitat modification during a specified period is represented by the Index of Spatial Habitat Availability (ISH) [36, Vezza et al., 2015]. The following formula explains how to obtain the index:

$$ISH = \min \left(\left\{ \begin{array}{ll} 1 - \frac{|A_{H,r} - A_H|}{A_{H,r}} & \text{se } \frac{|A_{H,r} - A_H|}{A_{H,r}} \leq 1; \\ 0 & \text{se } \frac{|A_{H,r} - A_H|}{A_{H,r}} > 1 \end{array} \right. \right)_{species}$$

where A_H is the habitat area in an altered condition, $A_{H,r}$ is the habitat area in the reference conditions, both expressed in m^2 [36, Vezza et al., 2015]. Another fundamental index is the Index of Temporal Habitat availability (ITH). It compared under-threshold event duration under reference and modified settings. The threshold used is related to low flow and it is the flow value exceeds 97% of the time Q_{97} [36, Vezza et al., 2015]. For obtaining this index is calculated the i_{SDA} which is the indicator of stress days alteration. This index reported the mean distance between two UCUT curves indicating the cumulative duration of habitat under-threshold events under reference $d_{c,r,AQ97}$ and changed $d_{c,AQ97}$ circumstances [36, Vezza et al., 2015].

$$i_{SDA} = \frac{1}{d_{max,r}} \cdot \sum_{k=1}^{k=d_{max,r}} \left(\frac{|d_{c,AQ97} - d_{c,r,AQ97}|}{d_{c,r,AQ97}} \right)$$

Then it is possible to obtain the ITH index using an exponential function in order

to give more weight to low stress days alteration [36, Vezza et al., 2015].

$$ITH = \min \left(e^{-0.38i_{SDA}} \right)_{species}$$

Finally is possible to obtain the IH index as the minimum value between the ISH and ITH [4, Bussettini et al., 2019]. The results of this study are shown in section 3.3.

Chapter 3

Results

3.1 Hydro-morphological surveys

The field surveys uploaded on Simstream provide as output georeferenced maps and the relative flow level. It is possible to see the georeferenced map of the river Aigua de Valls in figure 3.1, whereas figure 3.2 is relative to Foix.

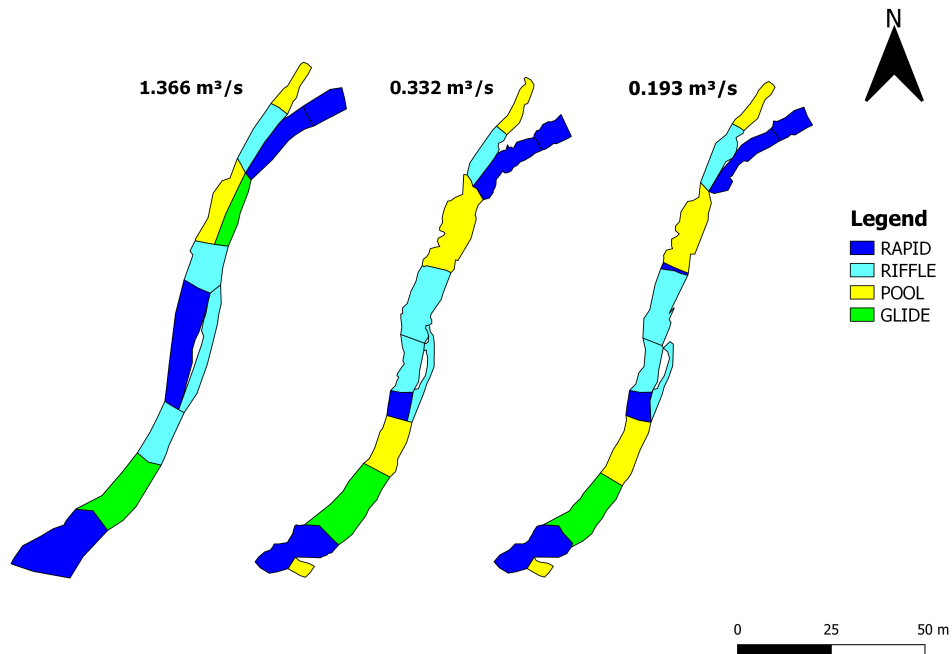


Figure 3.1: Georeferenced maps of the Aigua de Valls river. Representation of the types of HMUs.

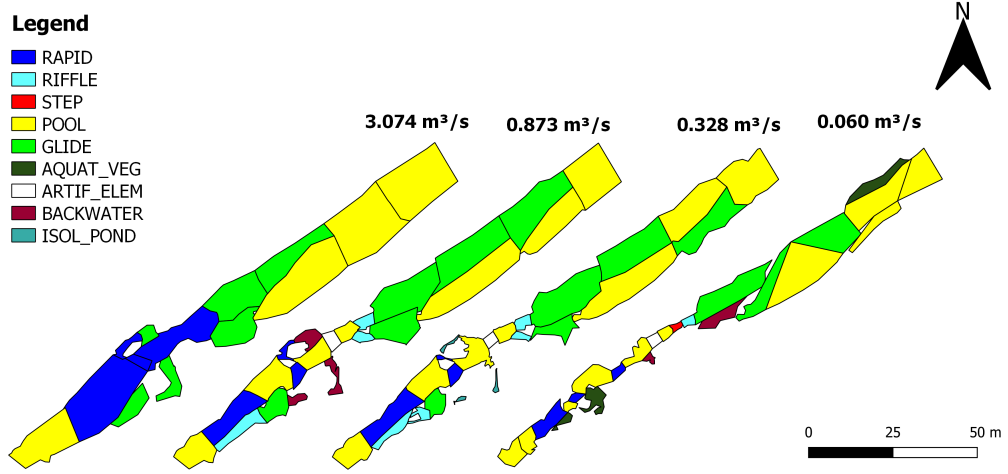


Figure 3.2: Simstream output relative to the the Foix river. Representation of HMUs.

Furthermore, a unified text file with the following information for each HMU is provided.

- The number, type, area, and slope of each HMU.
- The refugees that are 1 if the relative shelter form is available, 0 otherwise.
- The respective frequency distribution of depth, velocity, and substrate for each HMU.
- The standard deviation and the Froude number are computed from depth and velocity.

3.1.1 Data consistency

Data consistency has to be analysed across the various flow conditions in the subsequent phase [42, Negro G., 2021]. The points that should be examined are the following [42, Negro G., 2021]:

1. the wetted area should increase with the flow;
2. the type of HMUs through different flow levels should be consistent;
3. depth and velocity values should rise with the flow level;
4. the flow level measured in the field should be comparable with the one estimated using the mean value of depth, velocity and width;

5. the type of substrate should be consistent with different flow levels;
6. the prediction of the biological model should be consistent.

The following tables are the framework to perform the consistency analysis of the point one and four, for the rivers studied.

$Q[m^3/s]$	$Area[m^3]$	$\bar{p}[m]$	$\bar{v}[m/s]$	$\bar{L}[m]$	$Q_{calc}[m^3/s]$	$variation\%$
0.193	1110.8	0.20	0.221	7.03	0.31	+60
0.332	1243.32	0.23	0.364	8.27	0.69	+109
1.366	1406.07	0.32	0.576	8.20	1.50	+10

Table 3.1: Table for checking the consistency of the river Aiuga de Valls. Q is the flow obtained in the field, \bar{p} is the average depth, \bar{v} the average velocity, and \bar{L} the average width. Q_{calc} is the one obtained by multiplying width, depth and velocity. Finally, the variation is relative to the value of the flow obtained in the field, in relation with the one calculated.

Analysing the table 3.1, it is possible to see that the area increases with the flow, thus the first point is consistent. When the two flow levels are compared, it is clear that they have the same order of magnitude while being quite different. It is relevant that the calculated flow is always greater than the measured flow in the field.

$Q[m^3/s]$	$Area[m^3]$	$\bar{p}[m]$	$\bar{v}[m/s]$	$\bar{L}[m]$	$Q_{calc}[m^3/s]$	$variation\%$
0.06	1274.91	0.29	0.076	7.59	0.17	+177
0.328	1618.2	0.31	0.140	9.68	0.43	+30
0.873	1842.46	0.39	0.247	10.53	1.01	+15
3.074	2109.22	0.587	0.441	12.18	3.15	+3

Table 3.2: Table to check the consistency of the river Foix.

The conclusions that are valid for the river Aigua de Valls are valid also for the river Foix. The area increases with the flow, thus the data is consistent; instead, the two flow levels are different, particularly with the lowest flow. Also for this river, the flow calculated is higher than the one measured in the field.

To check the point two, it is possible to observe the figure 3.1 for the river Aigua de Valls. It is shown that the typologies of HMUs are very similar. The main difference is the loss of HMU classified as pool toward riffle, rapid and glide. For the river Foix in figure 3.2, the changes are more evident but coherent with the flow increase. With the lowest flow level, there are many small HMUs as step,

backwater, and aquatic vegetation that disappear with higher flows. Also, the artificial element is no longer detectable with the highest flow.

To analyse the point three for the river Aigua de Valls, the graphs in figure 3.3 and 3.4 have been used. The cumulative frequency for the classes of depth and velocity is shown in relation to the different flow levels. Given that the lowest flow curves are always above the other curves, the data is consistent. Thus, the classes with the lowest values are bigger in terms of percentage.

Also for the river Foix, the corresponding graphs are shown in figures 3.5 and 3.6. In this river, the data are consistent because both the depth and the velocity increase with the flow.

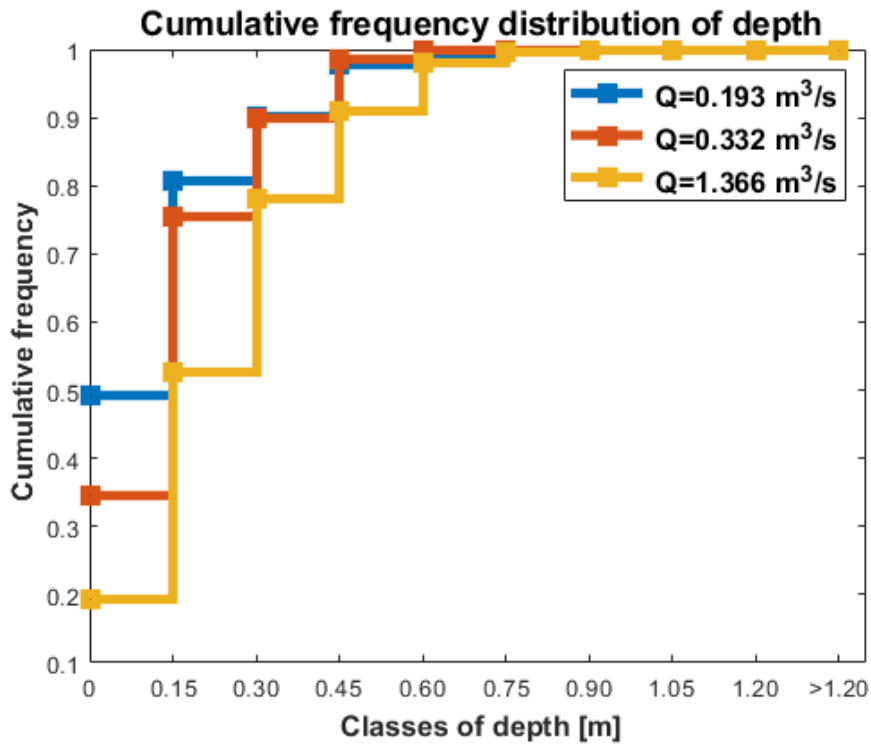


Figure 3.3: Cumulative frequency graph realised to evaluate the consistency of the depth for Aigua de Valls River.

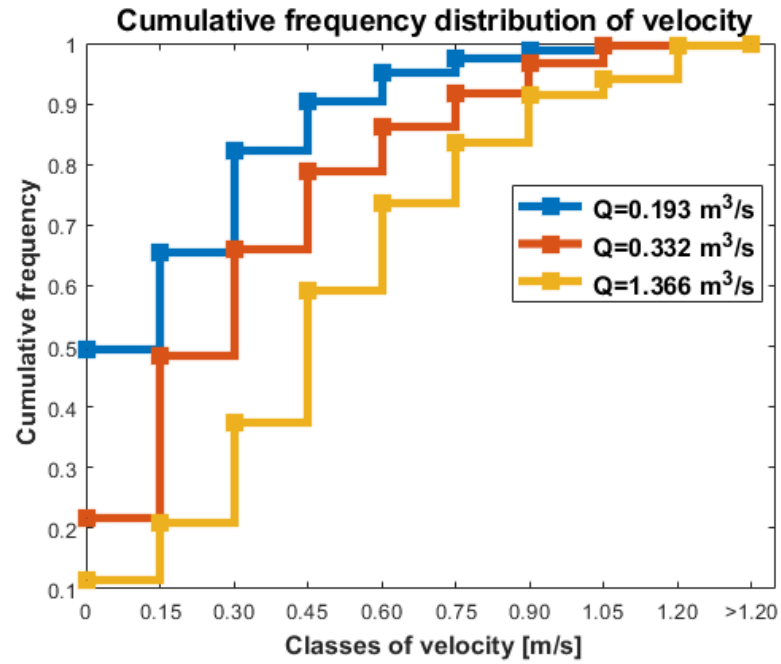


Figure 3.4: Cumulative frequency of velocity for Aigua de Valls river.

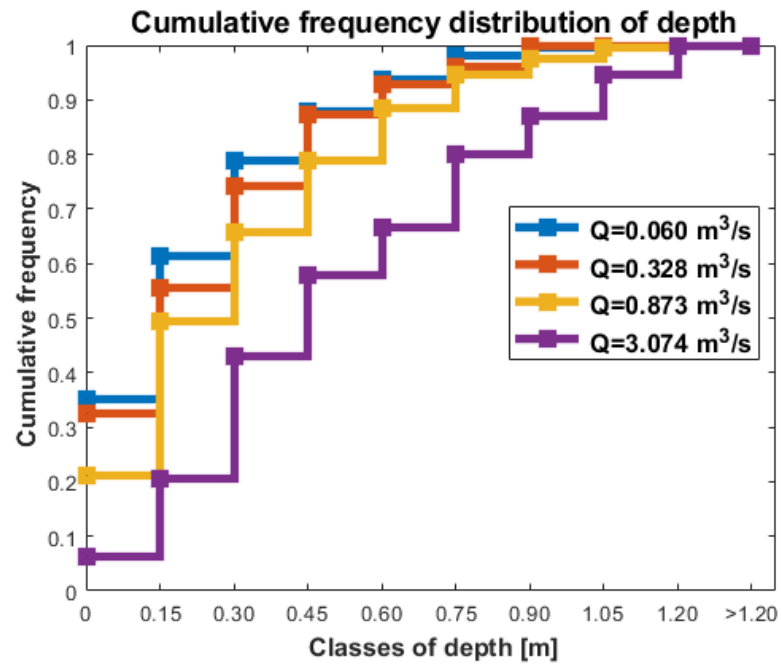


Figure 3.5: Cumulative frequency of depth for Foix river.

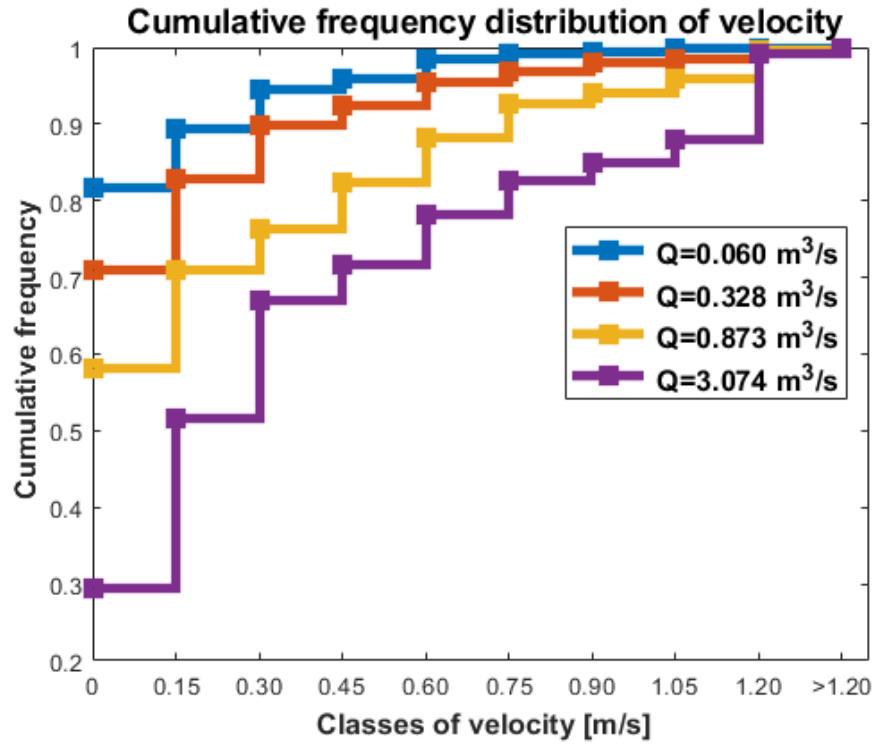


Figure 3.6: Cumulative frequency of velocity for Foix river.

To examine the point 5, the graphs 3.7 and 3.8 shows the percentage of the different types of substrate in Aigua de Valls and Foix rivers, respectively.

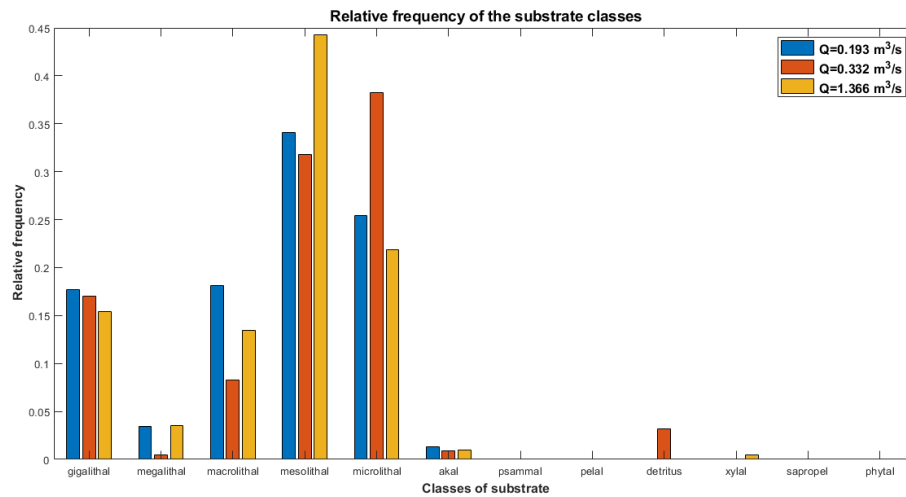


Figure 3.7: Substrate for Aigua de Valls river.

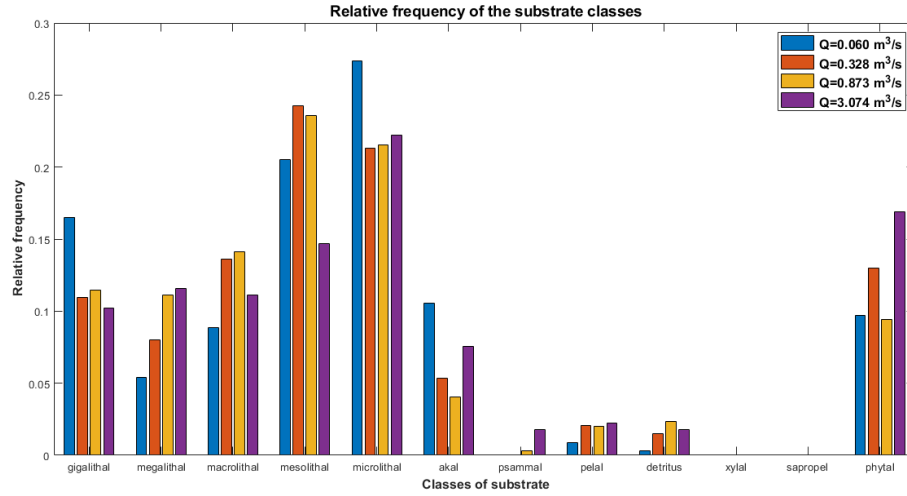


Figure 3.8: Substrate for Foix river.

Analysing the two graphs is possible to appreciate that the typologies of substrate is almost constant between the different sampling days in both the rivers. The point six concerns the biological model, and it is analysed in the following section.

3.2 Biological modelling

Using the random forest technique, the suitability model was developed. The main outputs that allow to understand how the model predicts the results are:

- the correlation matrix;
- the visualization of the variable importance;
- the partial dependence plot that represents the relationship between the predicted values and the habitat descriptors [19, Pinna, 2020];
- the TSS or true skill statistic.

Between the different biological models realized, this section describes only the biological model for the juvenile Mediterranean barbel; but the same procedure is followed also for the other models. This species is common to both rivers. The outputs of the other models, instead, are reported in appendix A.

The development of the biological model for each species is divided into two secondary models. The first one classifies the absence or presence of the species, and the “presence” indicates when, in a specified HMU, there is at least one fish. The second model is only applied in the HMU previously classified as “presence”,

and the threshold between abundance and presence is obtained using the inflection point of the envelope curve of the fish density histograms [43, Vezza et al., 2013].

One of the first obtained outputs is the correlation matrix shown in figure 3.9.

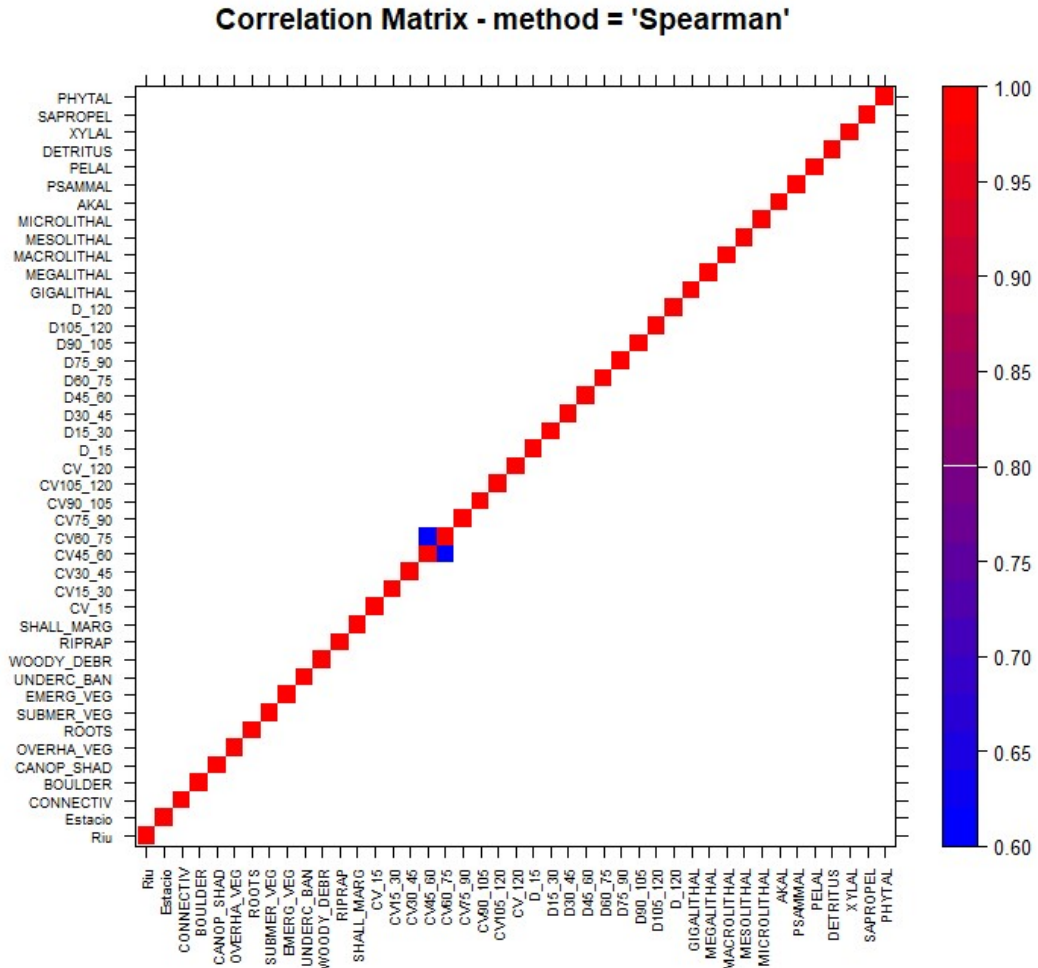


Figure 3.9: Correlation matrix of all the variables for the biological model of the juvenile Mediterranean barbel (presence/absence). It is obtained with the Spearman method.

It is necessary to avoid collinearity effects on the model [43, Vezza et al., 2013]. This matrix is built using the Spearman method for the calculation of the correlation coefficient. The chart shows that the variables are not correlated in general, with the exception of flow velocity between 45 and 60 cm/s and flow velocity between 60 and 75 cm/s.

The next step is the creation of the ranking visualization of the variable importance. To do so, the MDA (Mean Decrease in Accuracy) metric was used. This value shows the variable's contribution to overall prediction accuracy; consequently, the greater the value, the greater the variable's relevance [43, Vezza et al., 2013]. Starting with this classification, the Boruta algorithm is then applied that can progressively eliminate the irrelevant variables. The result of the final ranking of the variable importance is shown in figure 3.10. In this case, almost all the variables are classified as important, except for the riprap for which the result was not conclusive.

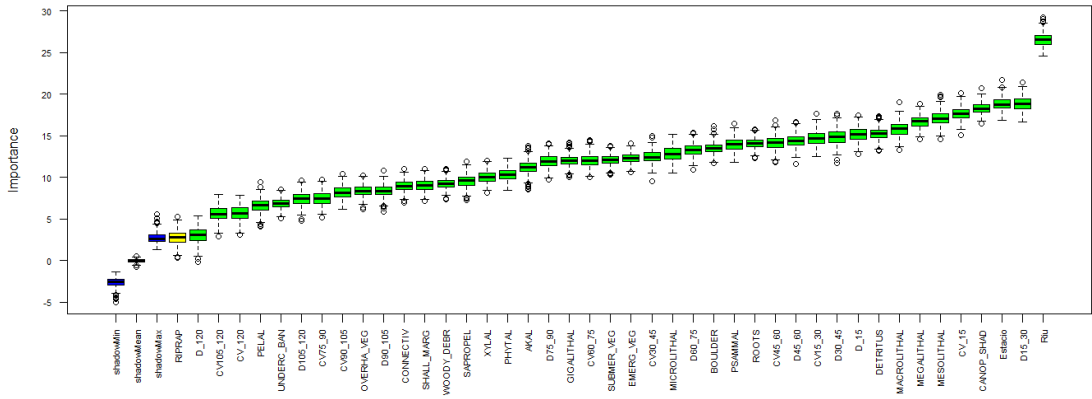


Figure 3.10: Ranking of the statistical importance of independent variables for the juvenile Mediterranean barbel for the presence/absence model.

The PDP (partial dependence plot) is another important output. These curves are shown in figure 3.11 only for the most significant variables that are the ones used in the final model. They allow to see how the independent variables affect the predicted results [33, Vezza et al., 2012], and they were designed for each variable with the other variables constant [19, Pinna, 2020]. These curves are used to visualize the RF results as well as to interpret their ecological significance [43, Vezza et al., 2013].

The outputs of the presence/abundance model are shown in figures 3.12, 3.13, 3.14.

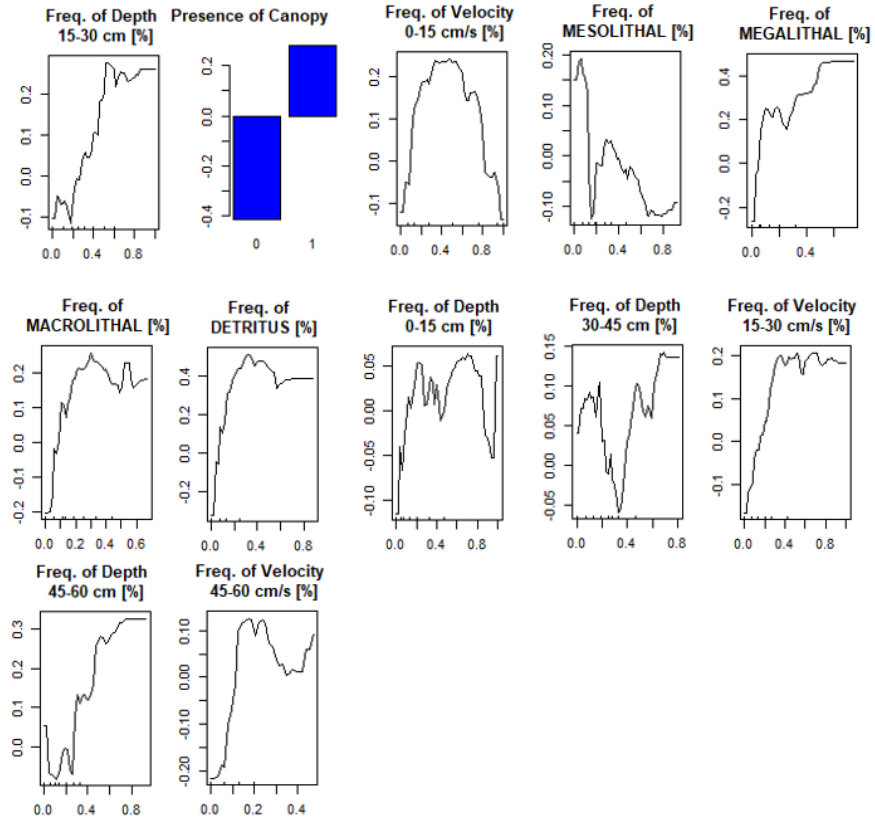


Figure 3.11: Partial Dependence Plots of the variables that have greater importance for the presence/absence model of the juvenile Mediterranean barbel. They are in order of importance.

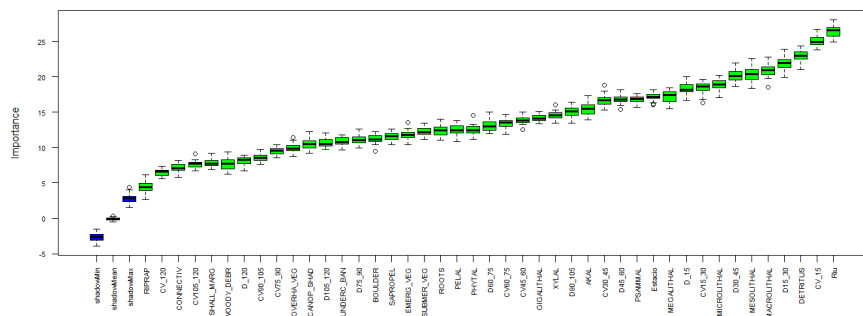


Figure 3.12: Ranking of the statistical importance of independent variables for the presence/abundance model of juvenile Mediterranean barbel.

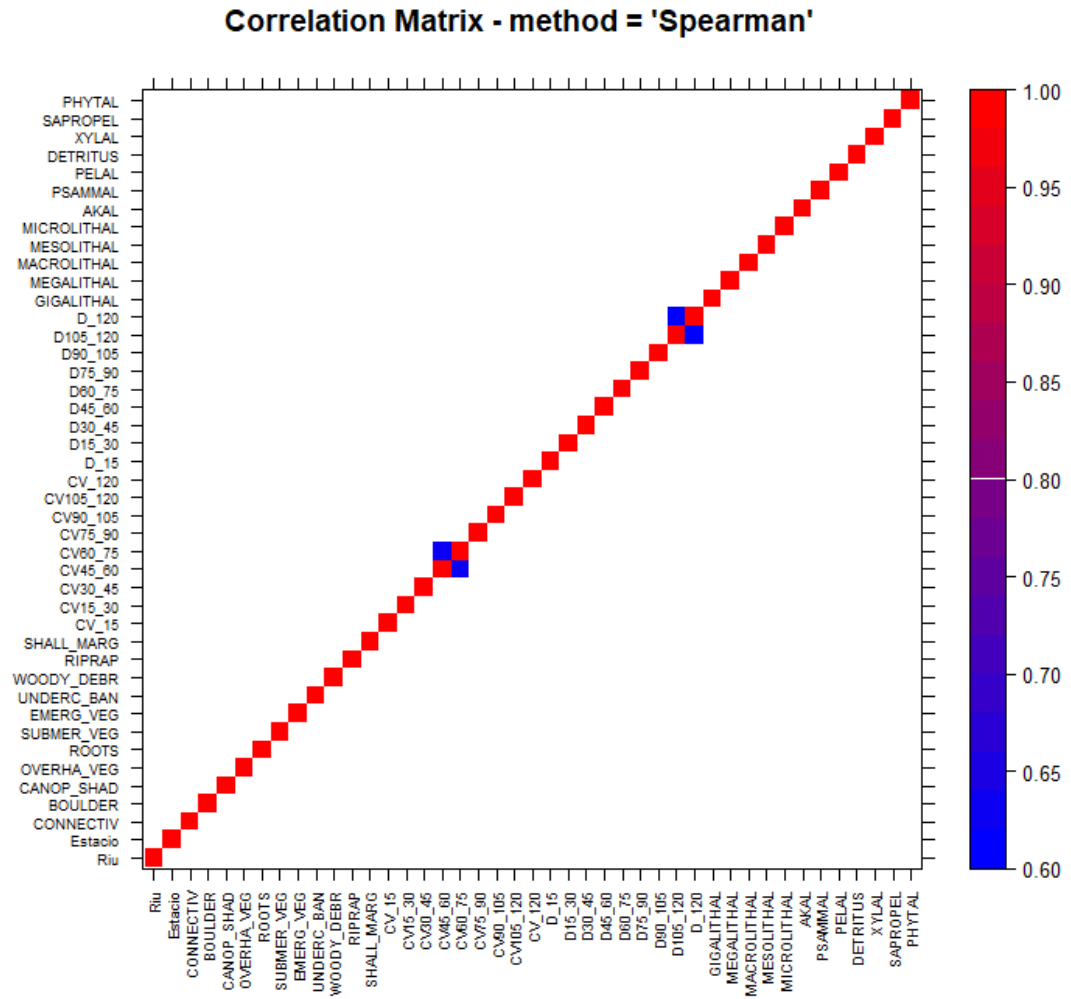


Figure 3.13: Correlation matrix of all the variables for the biological model of the juvenile Mediterranean barbel (presence/abundance).

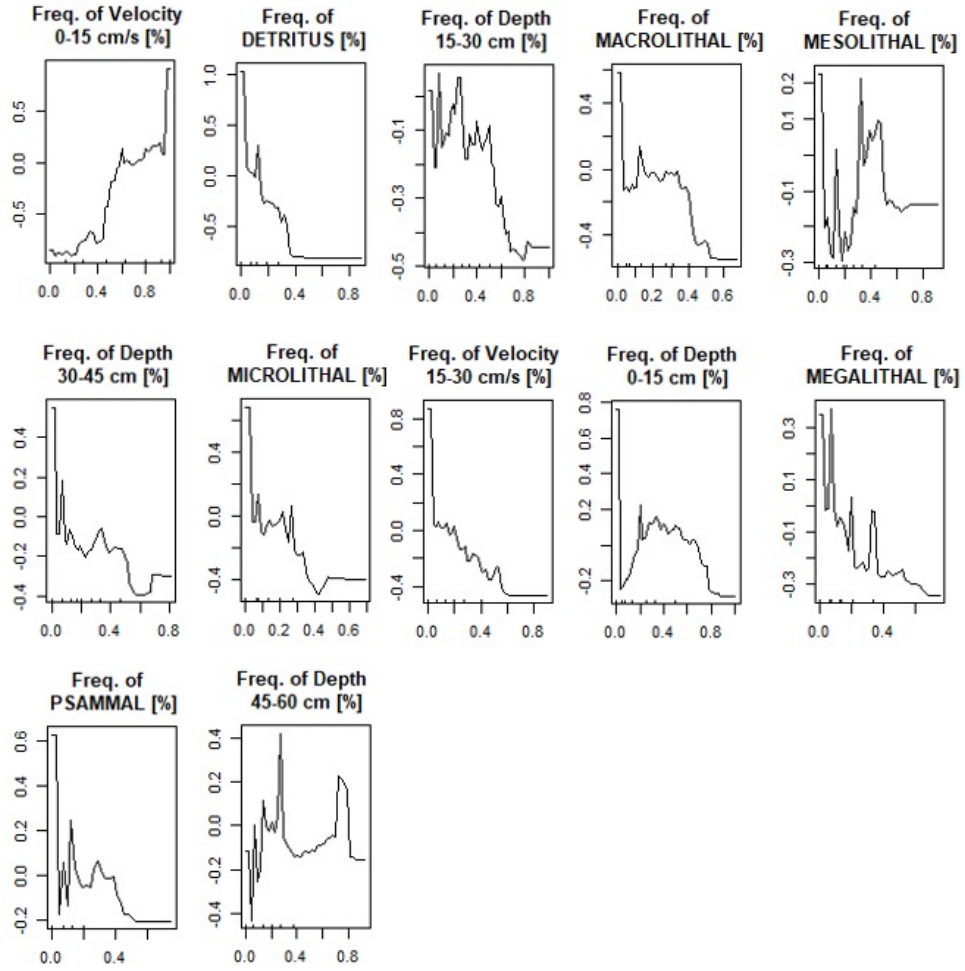


Figure 3.14: Partial Dependence Plots of the variables that have greater importance for the presence/abundance model of the juvenile Mediterranean barbel.

Table 3.3 shows accuracy, sensitivity, specificity, and TSS values for the two models of the juvenile Mediterranean barbel. These values are obtained by a comparison between the predicted values and the field data of absence/presence/abundance. The fraction of properly categorized observations is known as accuracy, whilst the proportion of real accurately detected positives and negatives are known as sensitivity and specificity, respectively [43, Vezza et al., 2013]. The TSS is calculated by subtracting one from the sum of sensitivity and specificity. The TSS is an index that represents the general goodness of a model. The better this parameter is, the more accurate the model is. In this case, the values of TSS are very good, especially for the presence/abundance model.

Model	Accuracy	Sensitivity	Specificity	TSS
Absence-presence	0.898	0.848	0.949	0.796
Presence-abundance	0.970	0.998	0.942	0.939

Table 3.3: The values obtained with the validation of the model, through the comparison between the predicted values and the measured ones for the juvenile Mediterranean barbel.

3.3 Habitat-flow series

The result of the software is the habitat-flow rating curve figure 3.15.

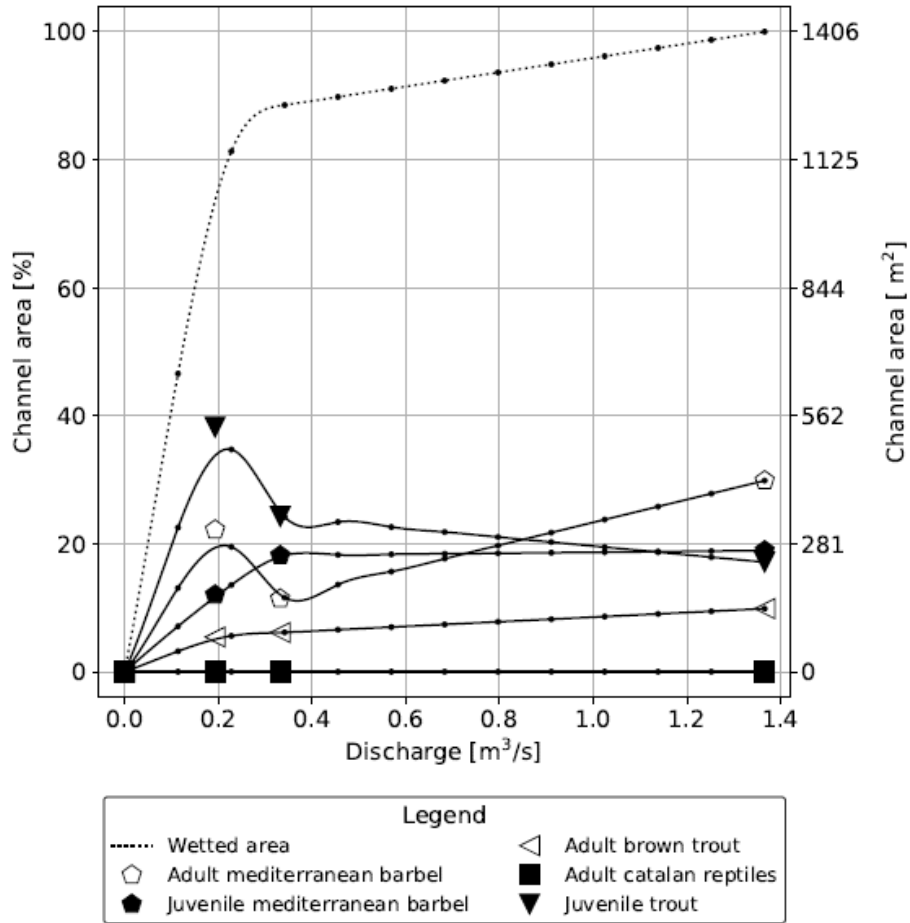


Figure 3.15: The output of the habitat-flow rating curve for the river Aigua de Valls in autumn.

For the river Aigua de Valls, there are three different relationships because the model for the Mediterranean barbel was developed for three different seasons (winter, summer and spring together, and autumn). Figure 3.15 shows the habitat-flow rating curve for autumn.

In the following list, some considerations are possible thanks to the comparison between this graph, the one in the previous chapter and the ones in the appendix A.

- Adult Mediterranean barbel: after a pattern that shows up and down in the initial phase, due to the dependence of the probability of presence on the higher velocities, the proportion of habitat that is available will rise.
- Juvenile Mediterranean barbel: after the flow of $0.3 \text{ m}^3/\text{s}$, the channel area is more or less constant.
- Adult brown trout: the channel area % increases with the discharge. This is explained by looking at the PDP of the adult brown trout. With a depth between 30 and 60 cm, the probability of presence is increased, and as a result, the area is higher with larger flow rates.
- Juvenile trout: the channel area increases until $0.2 \text{ m}^3/\text{s}$ and then starts to decrease. The depth is between 15 and 60 cm, and this pattern results from a high probability of presence coupled with a high percentage of low values of velocity.
- Adult Catalan reptiles: it is always 0.

The successive outputs that are obtained are the curves habitat-time series for each species for each of the 6 scenarios. Figure 3.16 shows the habitat-time series of the juvenile Mediterranean barbel in reference and altered conditions. Another element present in the graph is the mean and the AQ97. The former is the average value of habitat availability which is represented in blue, and it is the one used for the calculation of the ISH. The latter is the minimum habitat threshold during low flows, and it is represented in blue and is used to generate the UCUT and calculate the ITH [4, Bussettini et al., 2019]. Q97 was chosen as the threshold for rare habitat events, representing the minimum ecological flow rate required to keep fish populations in the river [38, Kutrakis et al., 2019].

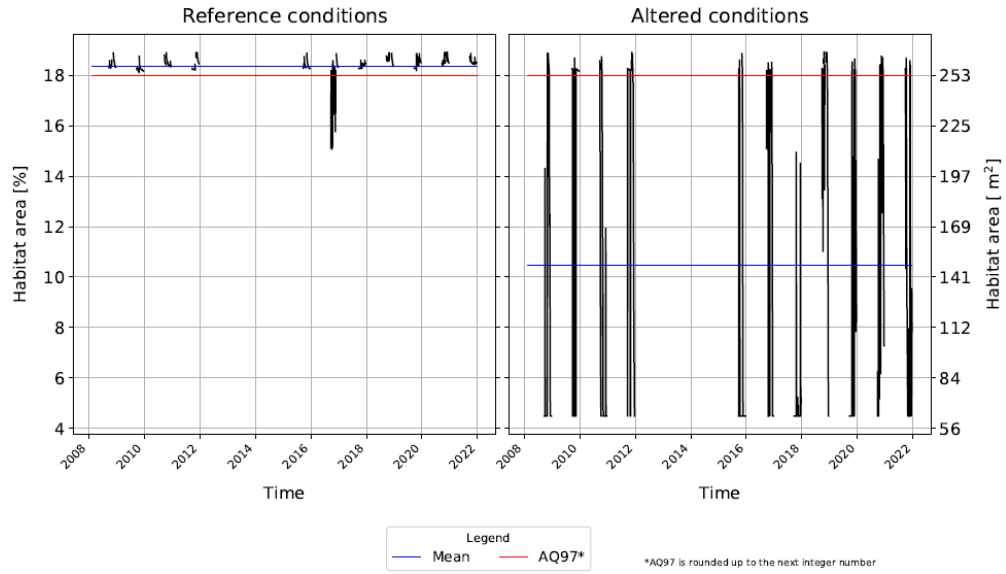


Figure 3.16: Habitat-time series of the juvenile Mediterranean barbel in reference and altered (scenario 1) conditions for the autumn.

Starting from this graph, it is possible to obtain figure 3.17 which shows the Uniform Continuous Under-Threshold (UCUT).

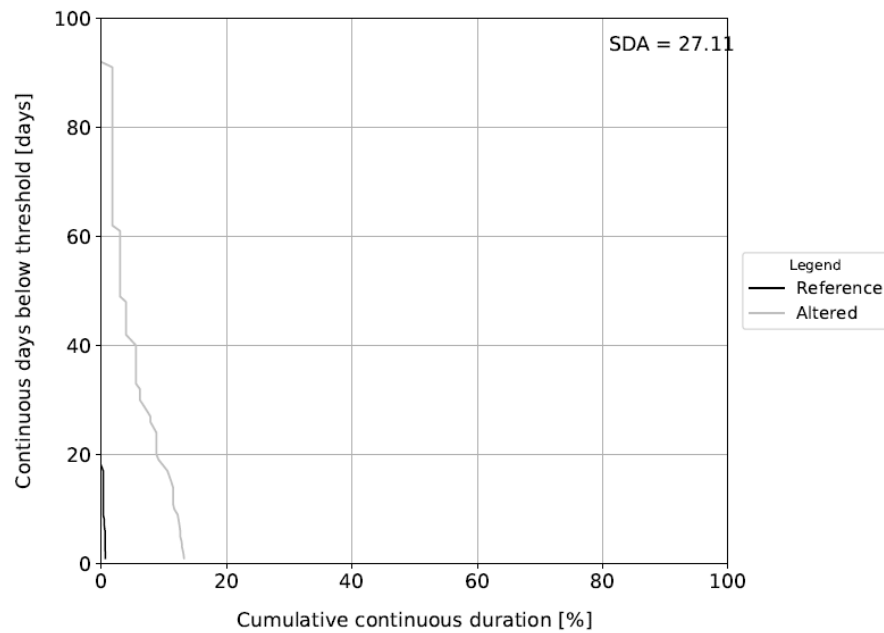


Figure 3.17: Uniform continuous under threshold curve for the juvenile Mediterranean barbel, in autumn in the river Aigua de Valls for the scenario 1.

These curves give the result of the Stress Days Alteration index (iSDA), in this case, it is 27.11 [38, Kutrakis et al., 2019].

Then the following table reports, for this case, the values of:

- ISH measures the average amount of habitat loss;
- ITH measures the increase of continuous duration of events when there is stress for the fauna;
- IH is the minimum between the ISH and ITH.

ISH	ITH	IH
0.57	0	0

Table 3.4: Values obtained with Simstream for the index IH in the river Aigua de Valls, during the Autumn, for the juvenile Mediterranean barbel.

In the next chapter all the more important results are described and compared between them.

Chapter 4

Discussion

Looking at the many results obtained, it is necessary to find differences and similarities. It is needed to understand the phenomenon and try to find the best solution to manage the rivers analysed.

4.1 Biological model

Through the comparison between the habitat-flow rating curve of the river Foix and Aigua de Valls and their analysis, it is possible to do some general considerations.

In both the rivers, the Catalan reptiles have almost always 0% of habitat availability area. The maximum value of habitat availability percentage for the Foix is 2.5% of the total habitat. But there should be species of Catalan reptiles in these rivers. This result can be explained if we observe the biological model in figure A.5.

It is possible to see that the presence of canopy shading is an exclusive factor because the reptiles need the presence of the sun. The only problem is that when the presence of canopy shading was checked in the different HMUs, it was intended as a refuge. When the units are characterized by more than 20% of shadows, the canopy shading is classified as “present”. Therefore, many units were excluded.

Another noticeable element is the behaviour of the brown trout in the river Aigua de Valls. In particular, the behaviours of the adult and the juvenile brown trouts are different. This can be explained with the biological model in the appendix. In particular, figure A.1 shows the dependence of a high probability of presence with a low percentage of low-water depth. Instead, in the model presence/abundance of the juvenile brown trout, figure A.4 shows that the highest probabilities are associated with a low percentage of high velocities.

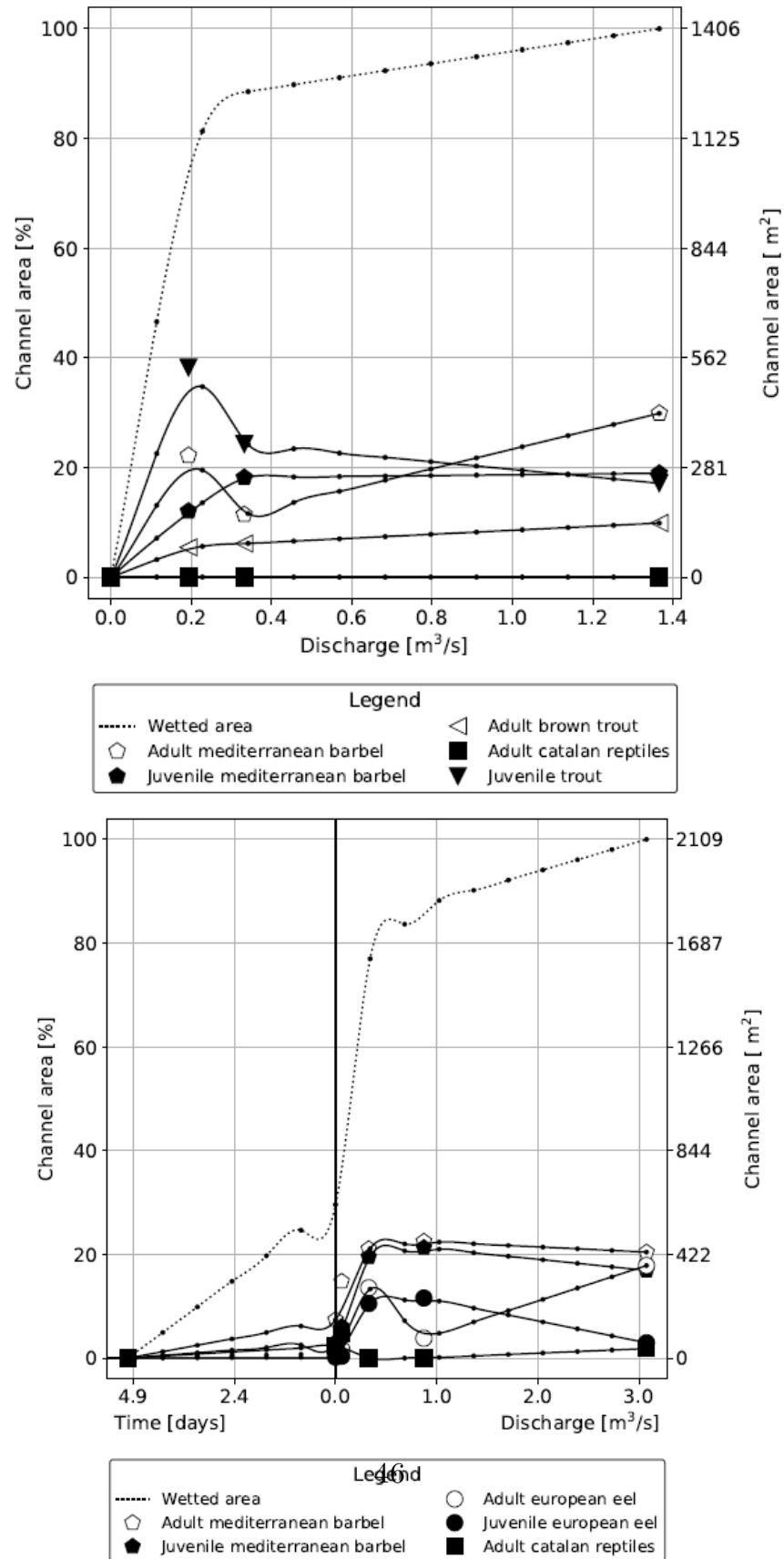


Figure 4.1: Habitat-flow rating curves for the river Aigua de Valls and Foix, respectively. The graph reported is for Autumn, but for the other seasons the only differences are the curves of the adult Mediterranean barbel.

4.2 Integrity index

The integrity index is the final output of all the MesoHABSIM methodology. It allows us to define whether the status of a river is high, good, sufficient, poor or bad. All the results are analysed in relation with the different rivers.

4.2.1 Aigua de Valls

In this river, the species of fishes analysed are the adult and juvenile Mediterranean barbel, the adult and juvenile brown trout, and the Catalan reptiles. The river was analysed in three different seasons because the model of the adult Mediterranean barbel is divided into one for the summer and spring, one for the autumn, and one for the winter. Also, six different scenarios were analysed in relation to the reference conditions. The scenarios are:

- BAU: lowest flow level
- PdG: intermediate flow level
- PSCM: flow level that tries to guarantee more amount of water.
- BAU+cc, PdG+cc, PSCM+cc: are the corresponding values but without the 15% of flow.

If the indices ITH and ISH are analysed, it is possible to see that the ITH is the more problematic one. The problem is the continuous duration of events below AQ97. In particular, the minimum value of ITH reached is 0 for both the spring and summer period and for the autumn. Instead, the minimum value of ISH is 0.57 obtained in autumn. Another core idea is that the differences between the scenarios BAU, PdG and PSCM are more important than the differences between them and the corresponding flow without the 15%.

The different changes affect mostly the Mediterranean barbel, both the adult and the juvenile. The index that is analysed is the ITH because the minimum value of the ISH for this species is 0.57 for the juvenile in the autumn. For the adult Mediterranean Barbel the worst period is the spring and summer, instead for the juvenile is the autumn.

If the graphs of the juvenile barbel in autumn for the PdG and the PSCM are compared, figure 4.2, it is noticeable that the part of the curves under the threshold AQ97 is much bigger in the PdG scenario. Instead, the difference between the means is not so relevant; in fact, the ISH index is very high also in the PdG scenario. However, the BAU scenario is even worse than that of the PdG.

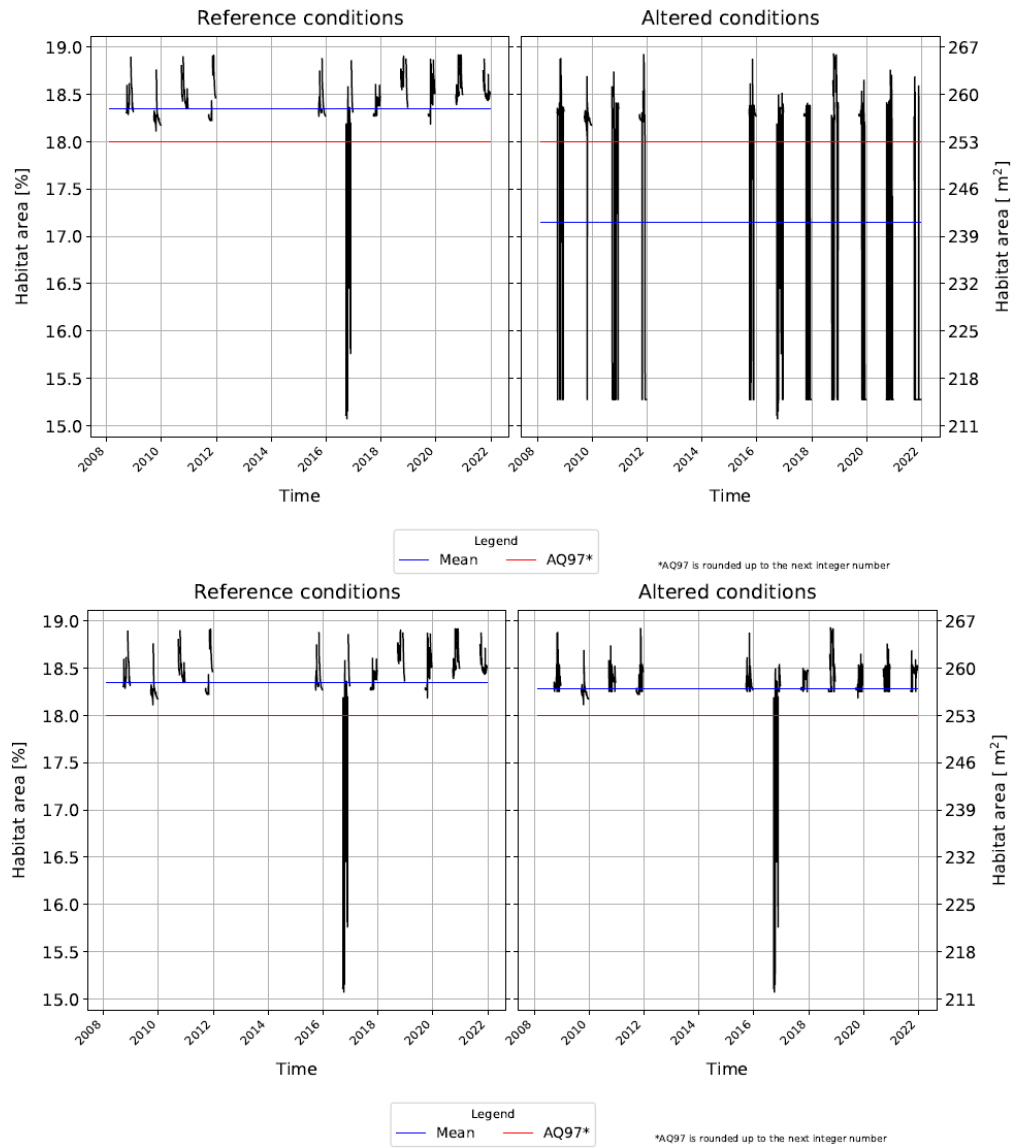


Figure 4.2: Habitat-time series for the juvenile Mediterranean barbel in the two scenarios, namely PdG and PSCM, during the autumn.

In the following figure, PdG and PSCM scenarios are shown for the adult Mediterranean barbel. The PdG yields a low ITH in this instance as well because of the frequent periods below the threshold. It is important to note the different scales between this figure and the one before.

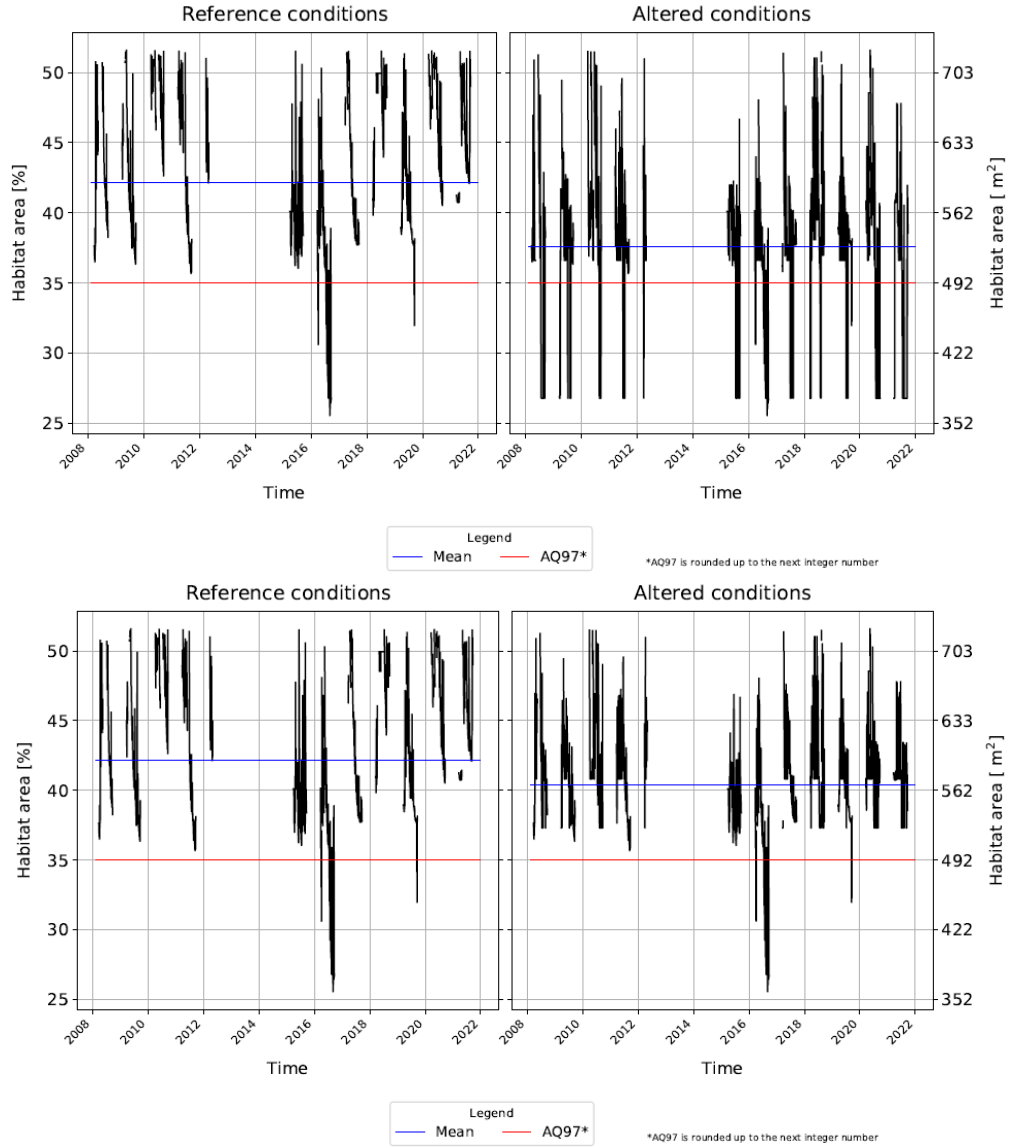


Figure 4.3: Habitat-time series for the adult Mediterranean barbel in the two scenarios, namely PdG and PSCM during the spring-summer period.

In conclusion, it is possible to analyse the IH index between the periods and have some final considerations.

Analysing the table, it is clear that the habitat condition for the spring-summer and autumn periods are sufficient only for the PSCM scenario. This is mainly due to the Mediterranean barbel. In winter, however, PdG might give good results as well.

	spring-summer	autumn	winter
BAU	0	0	0.43
PdG	0.22	0.01	0.67
PSCM	0.57	0.82	0.81
BAU + CC	0	0	0.41
PdG + CC	0.19	0.04	0.64
PSCM + CC	0.62	0.52	0.7

Table 4.1: Table of the IH index for the different periods and scenarios of the river Aigua de Valls. The colors represent the classification of the IH. Cyan is classified as high, green as good, yellow as sufficient, orange as poor, and red as bad.

4.2.2 Foix

In this river, the species of fishes analysed are the adult and juvenile Mediterranean barbel, the adult and juvenile European eel and the Catalan reptiles. The river was analysed in three different seasons because of the model of the adult Mediterranean barbel. Also, six different scenarios were analysed in relation to the reference conditions. The scenarios are the same as for Aigua de Valls.

By analyzing the indices, it is easy to see that the disparities between the three scenarios in this case are similarly more than the difference between them and the similar scenario constructed with a flow that is 15% smaller.

Looking at the IH indices in relation to the habitat-flow rating curves, it is possible to understand that there is a problem with the input data of the flow-time series. In particular, from May 2019 to November 2020, the sum of the entrance flow in the reservoir is lower than the sum of the exit flow. Even though this difference is present in all the seasons, it is more evident in the winter period, figure 4.4

Some considerations are necessary, in particular the entrance flow is not the natural flow but, it is already modified by upstream alteration. Possibly, the reason behind the difference in the flow is the infiltration that is befitting for this river.

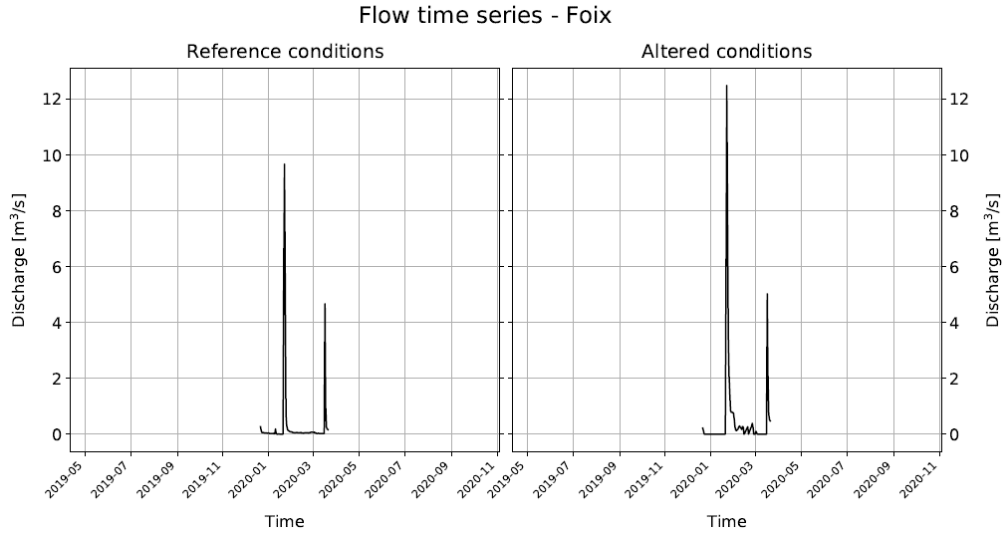


Figure 4.4: Flow-time series in winter of the BAU scenario in relation with the reference conditions.

The importance of the infiltration can also be highlighted if the habitat-flow relation of the river Foix is analysed in figure 4.1b. In fact, the habitat of all the species is almost zero when the flow is equal to zero, thus the pool quickly dries up entirely. To comprehend the phenomena and how it impacts the river, a thorough examination of the infiltration in the river should be performed.

In order to evaluate the habitat loss, it is not possible to use the index obtained with Simstream. It is necessary to compare the different scenarios. The comparisons were executed only for the first three scenarios. In particular, to evaluate the spatial habitat loss for each species of fishes, the values of A_{Hd} are evaluated. In the case of the highest value, the rating 1 was assigned. The ratio between other values and the maximum one is the rating of the other scenarios. The only substantial spatial habitat loss is in the BAU scenario for the Catalan reptile during the spring-summer period and for all the species in autumn.

To evaluate the temporal spatial loss, it is necessary to compare the graph of the habitat-time series. Through this comparison, it is possible to appreciate that ITH in the spring-summer and autumn periods is the one calculated with respect to the reference condition. In fact, the curve between the reference condition and the PdG and PSCM are the same under the threshold AQ97. Instead, for the winter, the ITH is always comparable with the one already calculated by the software. Indeed, the curve is equal to the PSCM under the threshold. An example of this comparison is visible in figure

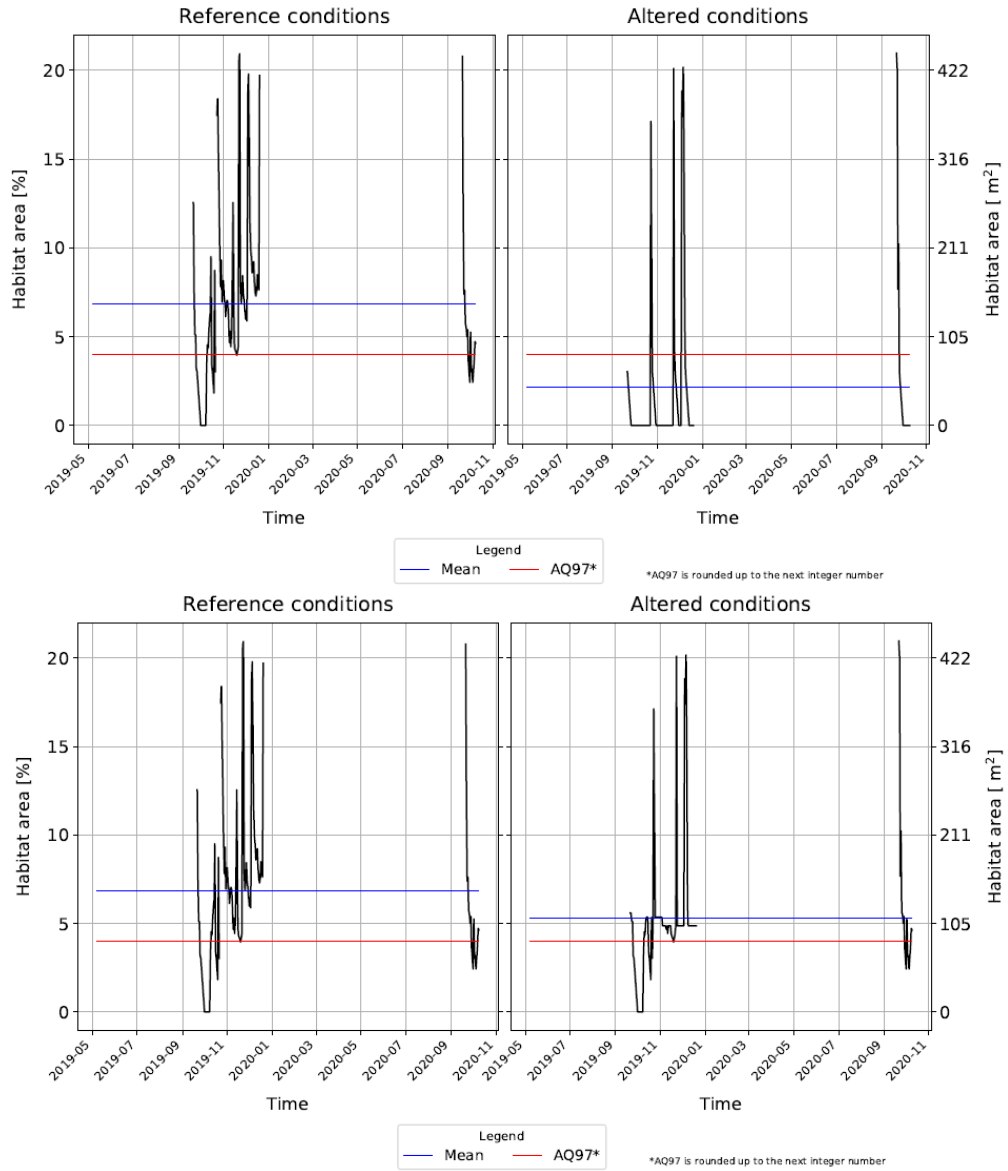


Figure 4.5: Graphs of the juvenile Mediterranean barbel, respectively the BAU scenario and the PdG in autumn.

In these graphs, it can be highlighted that the curves under the threshold are the same for the PdG and for the reference scenario.

After the analysis of all the scenarios, the only critical case is the BAU both for spatial and temporal habitat loss. On the other hand, the PdG and the PSCM scenarios are very similar in terms of habitat loss.

Chapter 5

Conclusion

The thesis goal was to evaluate the impact of flow changes on the habitat of native species in the rivers Aigua de Valls and Foix. Furthermore, the research had the aim of understanding the outflow required to minimize the effects on native species. The MesoHABSIM methodology was adopted to realise the objective.

Hydromorphological and biological data were collected, analysed, and interpreted. In particular, it was necessary to develop the biological suitability model for the native Catalan species proper of these rivers. It was realised using Random Forest which is a machine learning technique.

The interpretation of the data provided relevant results which allowed to manage properly the flow and find a solution that could handle all the conflict interests.

Focusing on the river Aigua de Valls, it should be guaranteed a major amount of water than the one that is mandatory nowadays. In fact, according to the actual flow management, results are classified as unsatisfactory during the periods of spring-summer and autumn. Instead, the results relative to the winter season are classified as satisfactory.

For the river Foix instead, the actual plan management should be enough. Unfortunately, the river is subject to infiltration problems and the results are not definitive. It should be performed a further detailed study to assess whether the causes of such infiltrations are natural or anthropic.

Finally, two possible further investigations could be evaluated to get a broader understanding of the problem. One possible development should be the validation of the suitability model of the Catalan reptiles. And the other refers to the overall project, carried out by the company ACA, should collect additional data on rivers where the maximum flows have been not enough due to rainfall scarcity of the current year. In particular, this flow is considered in relation to the flow-time series of the river.

Appendix A

Results of the biological models

Adult Brown Trout

This model was already developed by the Politecnico of Turin (Department of land, environment and infrastructure, DIATI) and uploaded on Simstream. The following figures show the partial dependence plot for the presence/absence model and the presence/abundance.

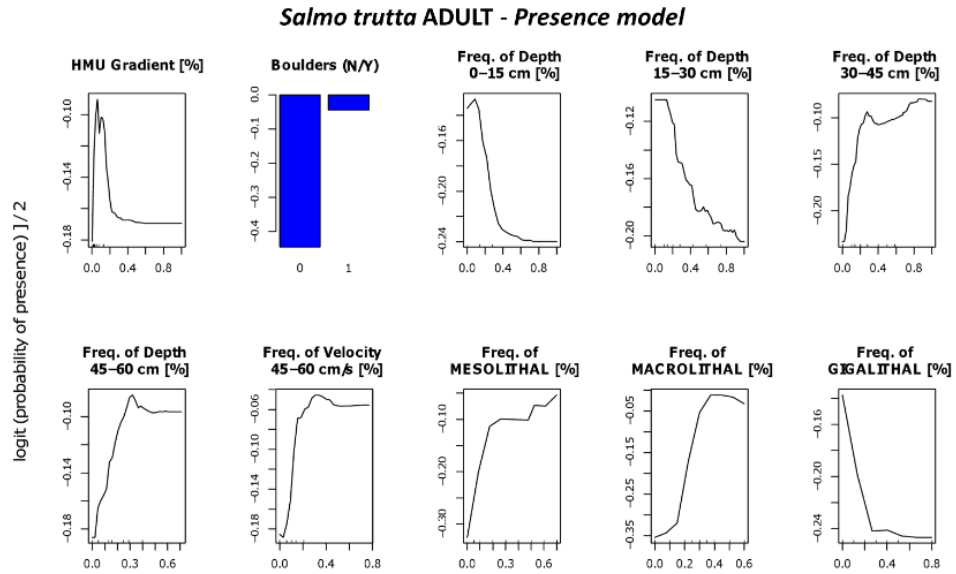


Figure A.1: Partial Dependence Plots of the variables that have greater importance for the presence/absence model of the Brown trout adult.

Partial dependence plots: Abundance model

Salmo trutta ADULT - Abundance model

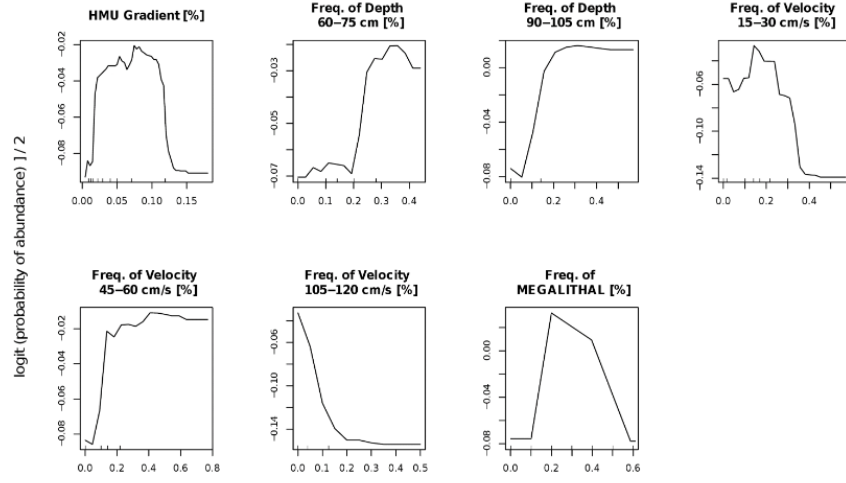


Figure A.2: Partial Dependence Plots of the variables that have greater importance for the abundance/presence model of the Brown trout adult.

Juvenile Brown Trout

Also this model was already developed.

Salmo trutta JUVENILE - Presence model

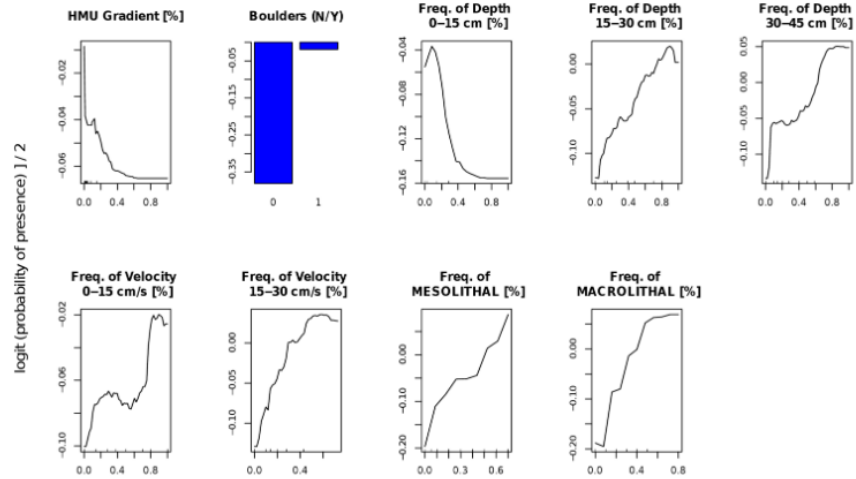


Figure A.3: Partial Dependence Plots for the presence/absence model of the juvenile Brown trout.

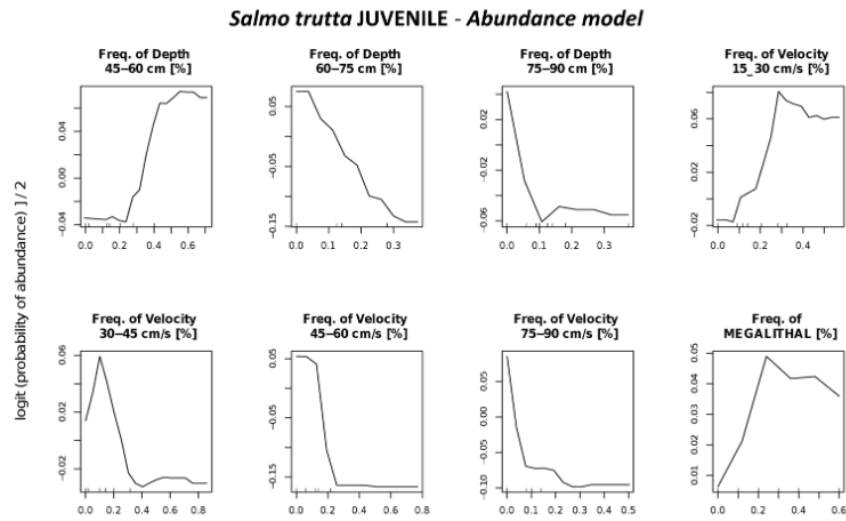


Figure A.4: Partial Dependence Plots for the abundance/presence model of the juvenile Brown trout.

Adult Catalan Reptiles

The decision tree of the adult Catalan reptiles was developed based on data coming from previous studies. Also this model was developed without random forest and only the model absence/presence was realized.

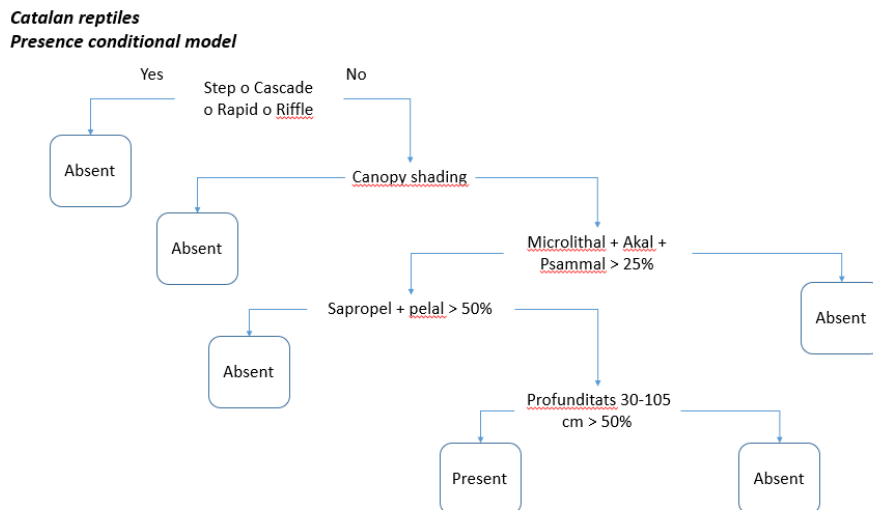


Figure A.5: Decision tree of the Catalan Reptiles for the presence/absence.

Adult European Eel

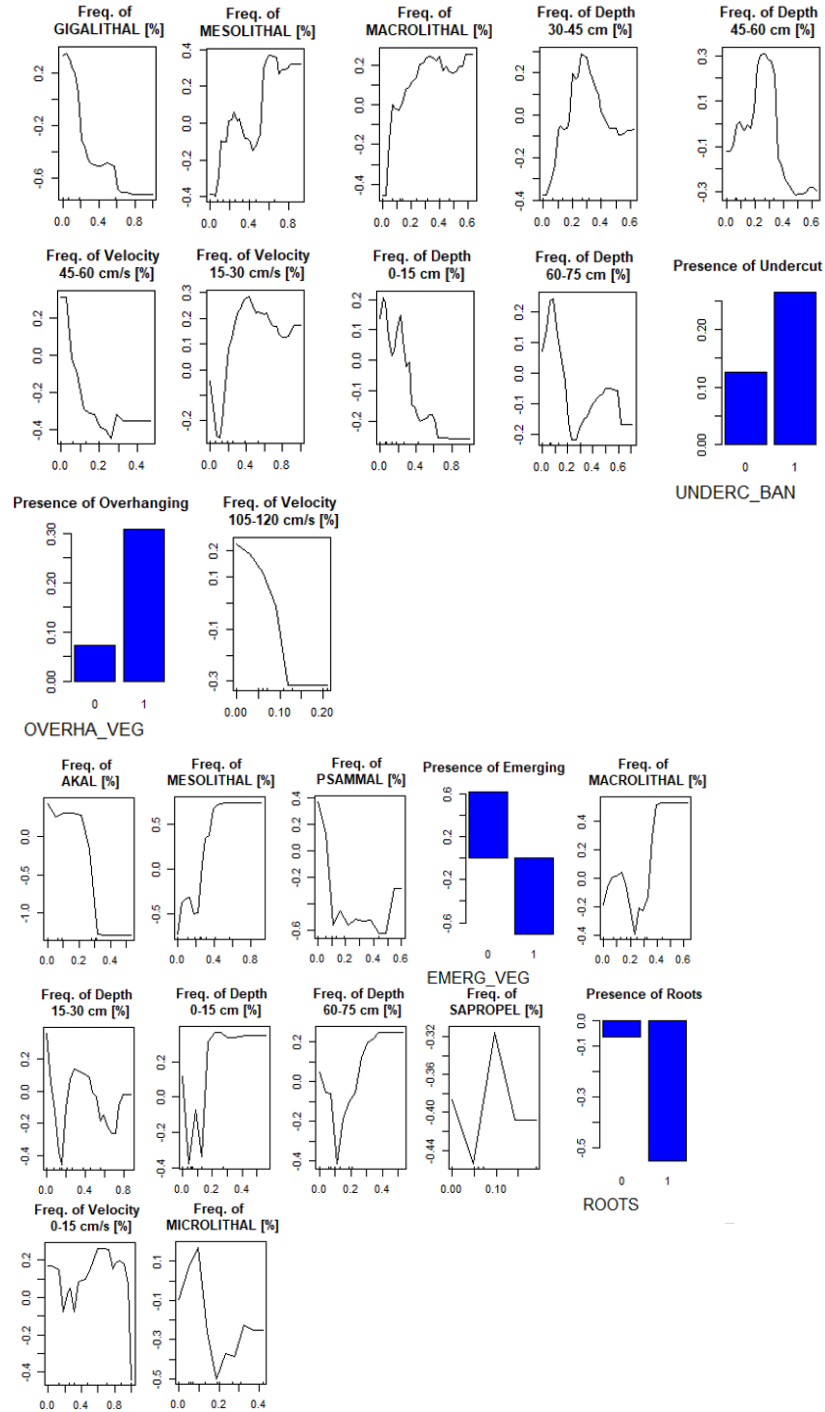


Figure A.6: Partial dependence plot of the adult European eel for the presence/absence and abundance/presence.

Juvenile European Eel

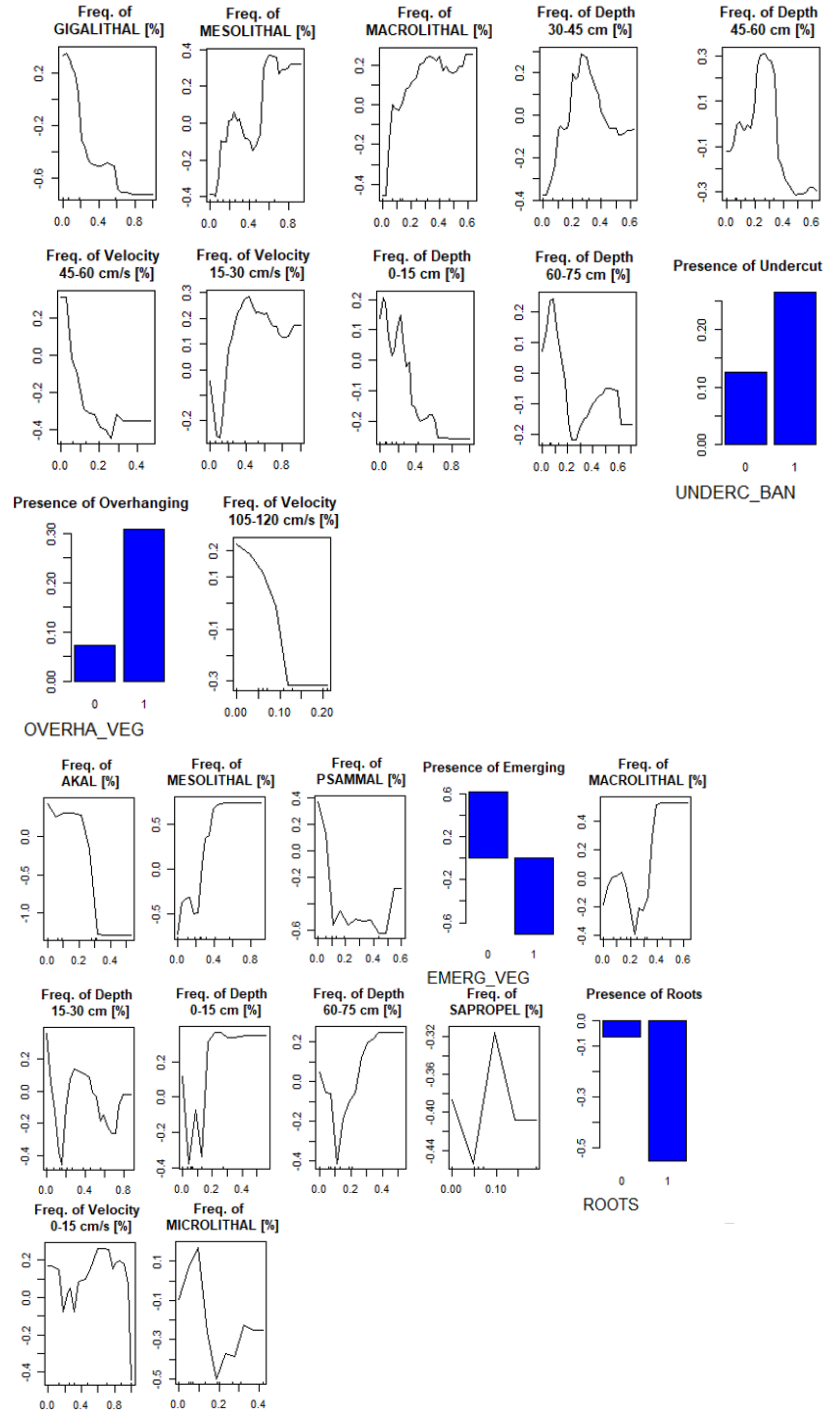


Figure A.7: Partial dependence plot of the juvenile European eel for the presence/absence and abundance/presence.

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