POLITECNICO DI TORINO

Master's degree in Environmental and Land Engineering

Master Thesis

HYDROPOWER GENERATION AND RIVER ECOLOGICAL STATUS: SUSTAINABLE MANAGEMENT SCENARIOS

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Ai miei Nonni, Giuseppe ed Emilia, Renato e Luigina.

ABSTRACT

River systems provide essential services to human activities, the so-called ecosystem services. However, due to anthropological activities, such as dams, water withdrawals, or defensive works, they are often subject to hydromorphological pressures. In order to preserve their ecological status and to ensure an appropriate water management, a legislative framework that considers this conflict is necessary. In Europe, the Water Framework Directive, WFD, has been introduced with this aim. Within this context, the concept of environmental flow (e-flow) has been developed and it has been defined as the hydrological regime that allows to achieve a good ecological status of the water body.
To correctly define e-flows, habitat modelling has been widely used all over the world.

In Italy the methodology used to define the e-flows is the Mesohabitat Simulation Model, which assess the river habitat suitability for target species at the morphological unit scale (or the mesohabitat scale). The methodology has been included to the Italian legal framework with the 'Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale' and the Ministry Decree DD n. 30/STA 2017.

This master thesis work consists in the application of the MesoHABSIM methodology to the Dora Baltea River in the Aosta Valley, Italy. The selected river reach is located close to Morgex, where a new, hypothetical hydropower plant is currently under design. The aim of this thesis is to simulate the water withdrawal management system that allows to optimize the power generation and, at the same time, to preserve the ecological quality of the river habitat.

The work is composed by two parts. The first one has been focused to quantifying the area suitable for some target species in different discharge conditions, obtaining the so-called Habitat – Flow Rating curve that relates the flow rate in the river with the aquatic habitat availability by using the SimStream-Web Platform.

The second part of the thesis aimed at evaluating different water management scenarios that ensure an economically sustainable power production and minimize the ecological impacts on the aquatic habitat. Also those analysis has been performed by means of SimStream-Web Platform, a web service developed by the Politecnico di Torino for the MesoHABSIM model applications. The comparison between different water management scenarios has been based on the Habitat Integrity Index (IH) as a metric that quantify the deviation between reference and hypothetical altered conditions.

It is important to highlight that both low flows and high flow occurrence should be somehow preserved to produce low impacts (IH=0.8) on the aquatic habitat availability. However, if more habitat

alterations are allowed, scenarios with an IH value between 0.6 and 0.8, can be considered for future, possible hydropower production.

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Chapter 1

1. INTRODUCTION

Fluvial systems provide many necessary services for human society. These are the so-called ecosystem services: food, drinking water, natural flood mitigation, energy and so forth. These services are linked to an appropriate level of functionality of the fluvial processes, which can be quantified with ecological objectives. The maintenance of the flow regime that allows to reach those objectives is therefore an essential element in preserving river ecosystems and the services they provide and should be included as a constraint in the legislative framework. (Bussettini & Vezza, 2019)

In the year 2000, the Water Framework Directive, WFD, (Directive 2000/60/CE) (European Commission, Directive 2000/60/ec of the European Parlament and of the Council: Water Framework Directive, 2000) has been introduced. Its main goal was to homogenize the water resource management between all the member state.

According to the Annex V of the directive, the water bodies ecological status can be classified as: ‘high’, ‘good’, ‘moderate’, ’poor’ and ‘bad’. The goal that was set for the first cycle of application of the directive was that all the river basins join at least a ‘good’ ecological status (Good Environmental Status, GES).

Before its application, a preliminary phase was planned in order to help the States to reach the goals set by the directive. In particular this phase has consisted in:

- Geographic definition of the river basin and identification of the competent authorities;
- Economic and environmental analysis;
- Definition of the River Basin Management Plans, RBMPs, and definition of the schedule to reach the goals;
- Adoption of the tariff plan for the water services.

The member states had some difficulties in reaching a GES for all the river basins. To support the achievement of the WFD environmental objectives, to provide the tools and to give some suggestions to the states, the European Commission has drawn up the 'Ecological flows in the implementation of the Water Framework Directive – Guidance Document No. 31' (European Commission, 2015).

In this document for the first time is adopted the concept of Ecological Flow which is defined as 'an hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies as mentioned in Article 4' (European Commission, 2015). The environmental objectives can be summarised as the non-worsening of the existing status and the achievement of the GES. All the procedures adopted should consider the standards of the protected areas.

The Guidance Document No. 31 identifies the models for the river habitat simulations as the appropriate tool for the assessment of the variation of the available habitat with the variation of the discharge.

The Aosta Valley region is an alpine region located in the north-western part of Italy. Its territory is peculiar because the area has a very high average altitude, an average temperature of the water quite low, high gradient of the slopes, the streams are characterized by a rapid flow fields and by a rapid pollution dispersion, large areas are covered by glaciers, the solid transports in rivers is significant, the riverbeds are recessed in rocks, natural cascades are present and also the insulation can be very low, the discharges naturally vary of orders of magnitude and the bedrock can emerge in area without vegetations and with an inefficient pollution dispersions. The hydropower generation is the main source of renewable energy in this region. The average installed power is of about 530000 kW. Even if this source has nearly any carbonic emissions, it has many impacts on the fluvial ecosystems. (ARPA VDA, 2022)

The Compagnia Valdostana Acque, CVA, which is the main hydropower energy producer of the region and one of the most relevant 'green energy' producer in Italy, would like to set a new run-of-river hydropower power plant in Morgex, Aosta

Valley (Compagnia Valdostana Acque, 2022). The main goal of this essay is to identify different scenarios of water intake and to evaluate their impacts in order to choose the appropriate environmental flow. Those scenarios have been created only for didactical purposes because the power plant is only at an hypothetical level. Moreover, the hydrological data considered have not been validated.

In order to do that, the MesoHABSIM methodology has been applied to the river reach of interest. This methodology is a mesoscale Habitat Suitability Model, it has been developed by the Rushing Rivers Institute (MA, USA) and adapted to the Italian context by the Politecnico di Torino (Vezza, Parasiewicz, Spairani, & Comoglio, 2014). Its main ecological target is the fish fauna.

This methodology has been applied following the rules set by the 'Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale'. (Vezza, Zanin, & Parasiewicz, 2017)

First, a site survey has been performed to obtain bathymetric and topographic data of the area. Then 2D hydrodynamic simulations at different discharge conditions have been carried out. With the hydro-morphological data obtained by the simulations, and after the selection of some target species, some biological models have been used to obtain the Habitat Flow Rating curves which correlate the variation of the discharge to the variation of the habitat. Moreover, to correctly determine the Environmental Flow, some possible water management scenarios and flow releases downstream the abstraction have been developed with the aim of assessing the scenario which minimizes the impacts on the river eco-system but allows to have a cost-effective hydropower generation. To quantify the impacts, the Habitat Integrity Index has been calculated for each scenario and the indices obtained have been compared. (Vezza, Zanin, & Parasiewicz, 2017).

Chapter 2

2. MATERIALS AND METHODS

2.1 STUDY AREA

The area interested by the study is a reach of the Dora Baltea River, near Morgex village in Aosta Valley region (ITALY).

The Aosta Valley is an alpine region with an average elevation of 2106 m asl. It is located in the north-western part of the alpine ridge. The main valley is crossed by the Dora Baltea River, which is the main stream of the region. It originates at the confluence of the Dora di Ferret, fed by the Pré de Bar Glacier in Val Ferret, and the Dora di Veny, fed by the Miage Glacier and Brenva Glacier in Val Veny.

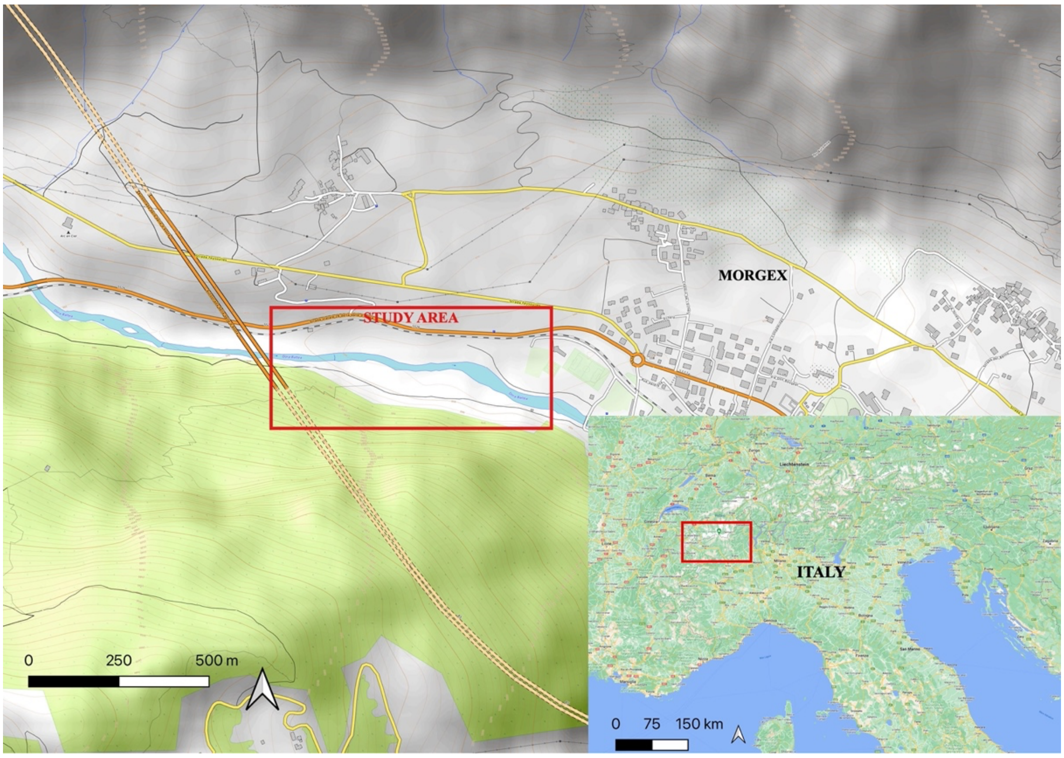

Figure 1: Detailed geographic introduction of the study area.

It is an alpine river, characterized by a peak due to snow melting in late spring and during summer, as shown in figure 2.

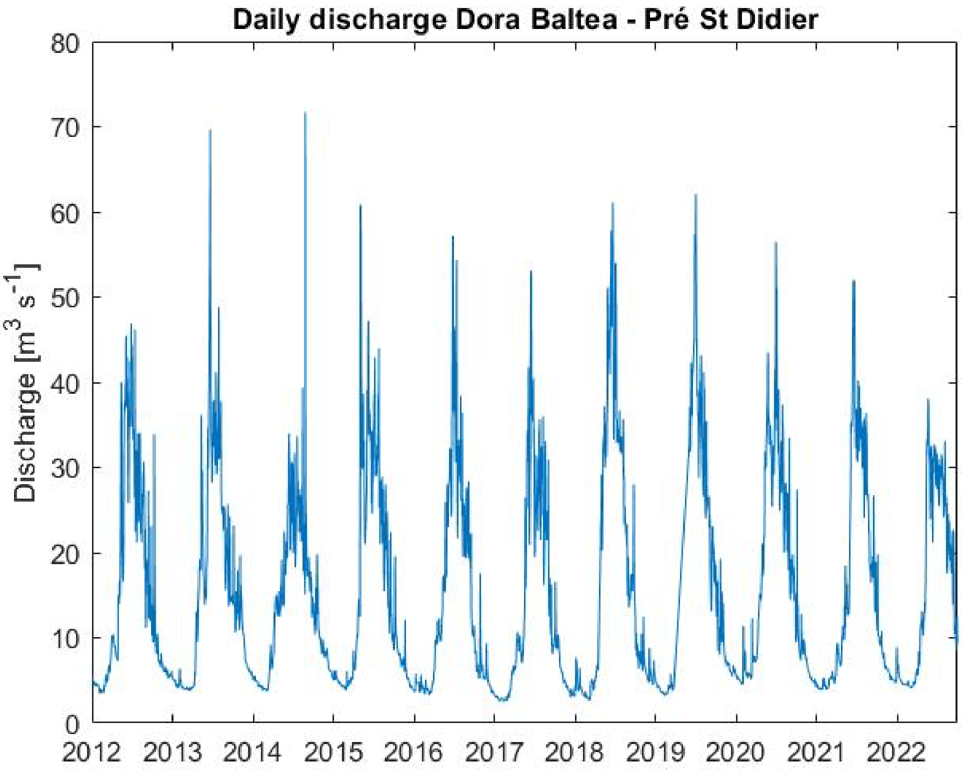

Figure 2: Daily discharge of Dora Baltea River in Pré-Saint-Didier.

The discharge varies of many orders of magnitude during the year, with a discharge below 3 $\frac{m^3}{s}$ during winter season that increases to 50 up to 70 $\frac{m^3}{s}$ during late spring.

Its tributaries ran through the minor valleys of the region. They are characterized by a torrential nature with a nivo-glacial regime.

The analysed river reach is characterized by an elevation of about 945 m asl and a length of about 450 m, while the width of the riverbed ranges from 10 to 30 m.

The area is covered by Quaternary, alluvial and river-glacial deposits. They are characterised by the presence of stratified sandy gravels, supporting clasts, with rounded pebbles. (Regione VdA, 2022)

2.2 MESOHABSIM METHODOLOGY

Models that aim to describe and simulate the river habitat are present since ‘70s. Their aim is to determine and quantify some hydro morphological parameters, such as flow velocity, depth, substrate and river bathymetry, and to relate their variations to the variations of the species distribution. (Vezza, Zanin, & Parasiewicz, 2017)

Those models differ mainly for their spatial distribution.

In fact, there are models, such as PHABSIM (Bovee, Lamb, Bartholow, Stalnaker, & Taylor, 1998), that consider a microscale approach. The unit distribution depends on the hydraulic parameters. The microscale ranges from 0.1 to 10 m spatially, and from 1 to 10 years temporally. (Rinaldi M. , et al., 2016).

Other models, such as MESO-HABSIM, consider a mesoscale approach in which the unit distribution depends on the morphological parameters. The scale varies between 0.1 and 1000 m spatially, and between 0.1 to 10 years temporally. (Rinaldi M. , et al., 2016).

The meso-habitat is that portion of the river in which, due to the homogeneity of the morphological characteristics and the hydrodynamic configurations (HMU), and the presence of physical attributes (environmental descriptors), favourable conditions for the survival and growth of a particular aquatic species or its vital stage are created. (Parasiewicz, 2007). Usually, a meso-habitat, in a natural river, spatially corresponds to a morphological unit, such as pool or a riffle, or to an hydraulic unit, so a part of the river with homogeneous flow conditions and substrate. This scale matches more easily restoration and environmental analysis needs because it provides quantitative tools for the assessment and simulation of the conditions for the whole stream. (Parasiewicz, 2001)

One of the mesoscale models is the Meso-HABSIM methodology that has been developed starting from 2000, and it has been widely applied. It is a physical habitat modelling system that can be useful for instream habitat management in applications such as the definition of the environmental flow for hydropower power production or in river restoration planning. (Parasiewicz, et al., 2013) It can be applied both to assess and monitor the habitat in current conditions, both to predict their evolution. (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017) .

The different phases of the methodology can be summarised as following:

- Habitat description through hydro morphological survey at different discharge conditions;
- Habitat suitability biological model application;
- Analysis of the spatio-temporal variation of the river habitat. (Vezza, Zanin, & Parasiewicz, 2017).

This methodology is very efficient. It is based on a data collection which follows a rigid system for the morphological classification that can be easily performed with low-cost remote sensing techniques or with light instrumentations. Moreover, the mesoscale allows to take into consideration a lot of environmental parameters that can be effective for the biological description of the habitat, whether at a community level or at a single specie level. Furthermore, it can be applied also without the usage of hydraulic modelling software which allows to consider also stream with a torrential nature that are difficult to be considered in software because the hypothesis of shallow water over which the software are generally built, hardly happens. For these reasons, it is widely applied. (Vezza, Zanin, & Parasiewicz, 2017).

When the results of the model are analysed, it must be taken into account the fact that the physical habitat is the limiting factor for the grown of the species; nevertheless, there can be other aspects such as water quality that are not considered with this method.

The methodology applied in this essay is the Meso-HABSIM methodology in particular the procedure proposed by the "Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità fluviale – 154/2017" (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017).

2.3 FIELD SURVEYS

A survey was performed the 12th April 2022 using an Unmanned Aerial Vehicle (UAV) and Acoustic Doppler Current Profiler (ADCP) (SonTek, San Diego, CA, USA, 2011).

2.3.1 TOPOGRAPHIC SURVEYS

The topographic survey was carried out by the geomatics' team of the Land and Environment department of the Turin Polytechnic using UAV. Some georeferenced ground control points (GCP) were positioned on the ground and then a drone flight was performed over the area. An ortho-mosaic of the area has been obtained and it was possible to extrapolate the orthophotos and the DSM (Digital Surface Terrain) and the DTM (Digital Terrain Model) of the reach of stream under analysis. The photogrammetric process has been performed using PIX4D software (PIX4D SA, Lausanne, Switzerland) and applying structure from motion techniques, that uses a series of 2D images to reconstruct a 3D scene.

The two orthophotos acquired have different resolutions, 0.6 cm and 2 cm. For the goal of the analysis developed during this thesis the orthophoto with a resolution of 2 cm was adequate.

2.3.2 BATHYMETRIC SURVEYS

The bathymetric survey has consisted in an echo sounder survey. It has been performed simultaneously to the topographic one, and it was conducted using a hydroboard with an highly accurate Acoustic Doppler Current Profiler (ADCP) that allows to describe bathymetry and flow field of a river section. The ADCP has two sets of velocity measurement transducers (bottom track), one used for deep water (1.0 MHz) and the other used for shallow water (3.0 MHz). They also give a rough estimation of the depth. The ADCP is equipped also with a 0.5 MHz vertical acoustic beam (echo – sounder) that allows to obtain highly accurate depth data. The depth measurements are possible from depth ranging from 0.2 m to 80 m with a resolution of 0.001 m.

This instrument is coupled with a RTK-GNSS antenna that acquires latitude, longitude and height of the sensor with a frequency of 1 Hz,from the starting point of the survey.

To analyze the output of the survey the RiverSurveyor Live software is available.

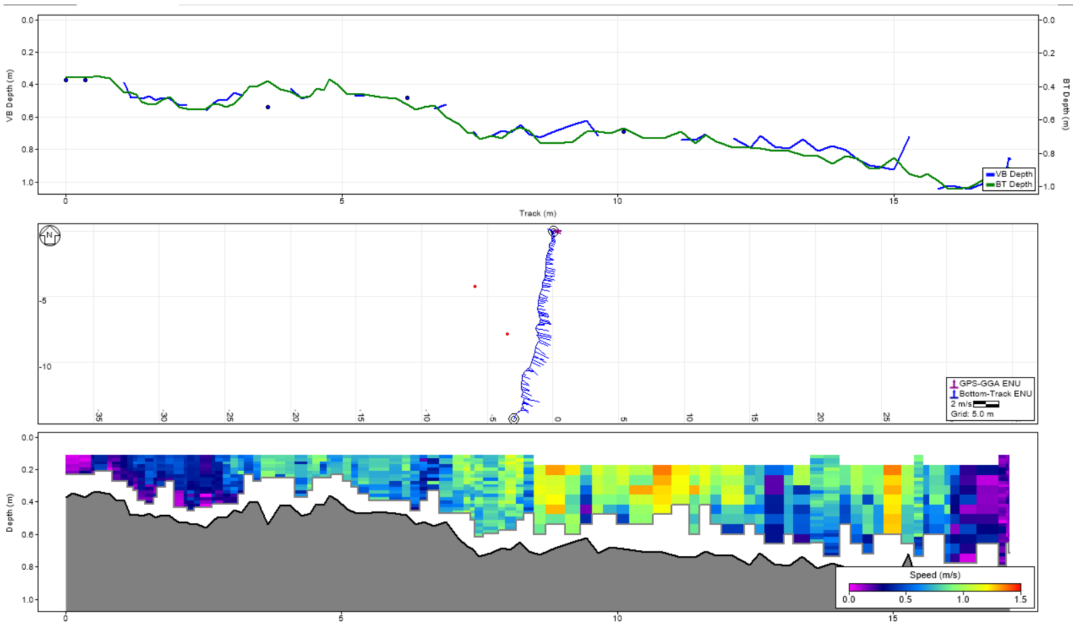

Figure 3: Example of RiverSurveyor Live output. On top there is the stream bed obtained from the measured depth values; in the middle there is the track on N-E plan;in the bottom there is the section view of current velocity grid.

2.4 HYDROMORPHOLOGICAL DATA ANALYSIS

2.4.1 BATHYMETRIC MODEL

After the bathymetric survey, three different datasets were obtained:

- One containing the measurements from the GNSS antenna mounted on top of the watercraft. This file contains the position of the Acoustic Doppler Current Profiler, so it is composed by a series of coordinates acquired during the acquisition;
- One containing the measurements from the Acoustic Doppler Current Profiler (ADCP), that were acquired in a relative positioning system.
- The digital terrain model (DTM) and the orthophoto coming from the UAV survey;

All these information must be gathered together to obtain the real bathymetry of the river that is necessary for the hydrodynamic simulation.

Moreover, the bathymetry acquired by the UAV system is affected by an error due to the water refraction. This error is governed by the Snell's law:

$$\frac{sin\theta_1}{sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1},$$

Where:

- v_1 : velocity of the incident ray in the first medium , so in this case in air;
- v_2 : velocity of the incident ray in the second medium, in this case in water;
- θ_1: angle of incidence;
- θ_2: angle of refraction;
- n_1: refraction coefficient of the first medium;
- n_2: incident coefficient of the second medium.

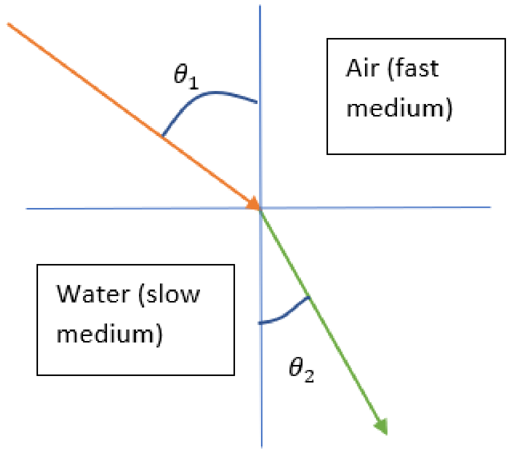

Figure 4: Representation of the refraction effect. The ray passing from one faster medium, as the air, to a slower medium, as the water, is deviated towards the normal.

The velocity of the ray in water, denser medium, is lower than in the air, less dense medium, so the ray will be refracted towards the normal and consequently the depth seen by the UAV is lower than the real one. The refraction depends on the velocity of the ray into the two media, which is quite well known, but also on the incident angle that vary during the acquisition process. Considering the light velocity in the air and in the water, the theoretical coefficient should be 1.33. The coefficient considered in this analysis is found considering the slope of the line that better interpolate, in a least square sense, the scatter plot made with the real depth versus the depth found by the UAV. In this case the depths calculated by the watercraft are considered the correct ones (ground truth). The fictitious depth was found as the difference between the free surface of the river, calculated with a spatial interpolation performed in GIS environment, and the bathymetry given by the DTM obtained after the drone flight.

Once all the values were corrected the equation can be found. Theoretically the equation is:

$$D_f = D_r * \frac{n_{air}}{n_{water}},$$

for which the error increases with the depth. In a real case, not only the refraction coefficient affects the error but also other variables, such as water torbidity or resolution of the instrument . For this reason, the equation of the bathymetric model used is: $D_r = 1.388D_f + 0.022$.

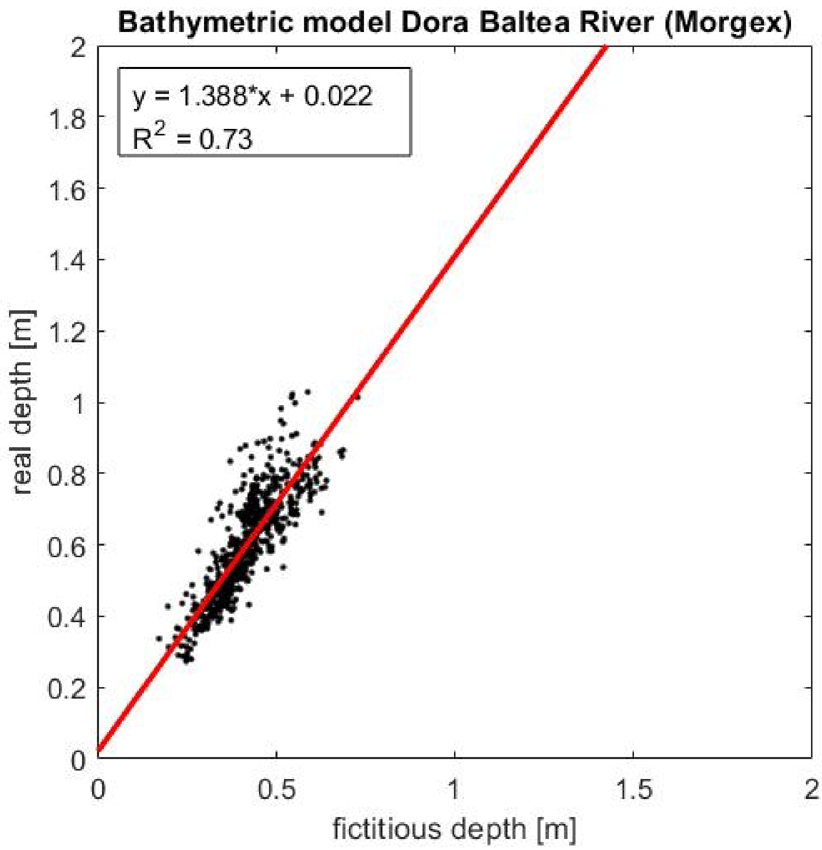

Figure 5: Bathymetric model used to correct the fictitious depth obtained from the UAV survey with the real depth obtained from the bathymetric survey.

The value of the coefficient of determination, R^2 ,that is a measure of the correctness of the statistical model used, is 0.73, that indicates that the variables are well correlated.

Using the values found with the bathymetric model, the depths found by the drone are corrected. Using those depths, a new bathymetric surface is found by subtracting the new depth to the free surface previously found, all this procedure is performed using GIS tools.

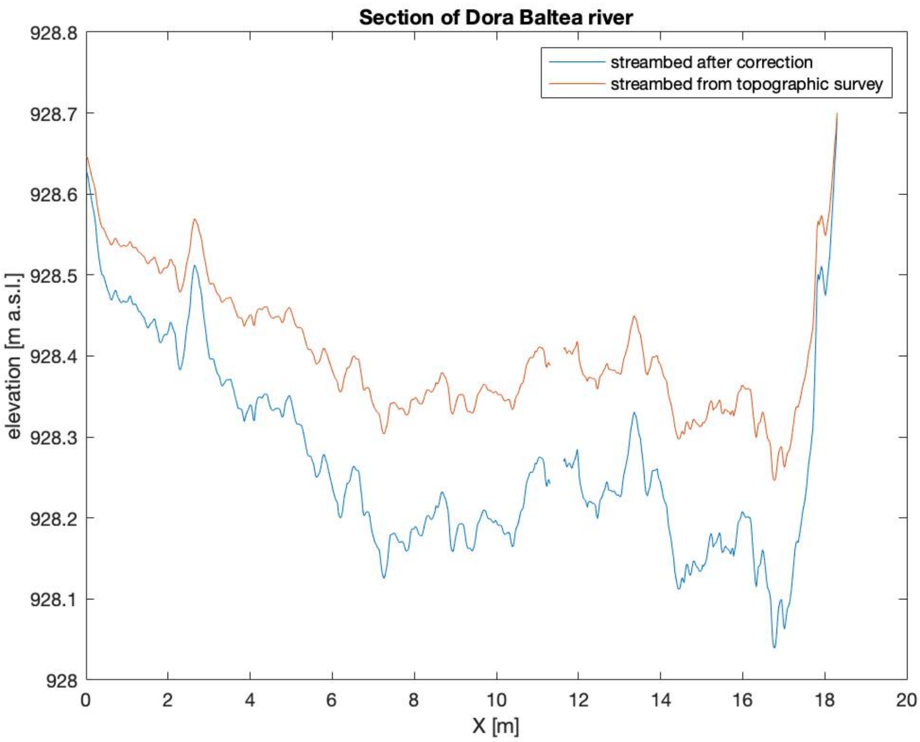

Figure 6: Section of the streambed before and after the correction performed using the bathymetric model, the streambed after the correction is lower than the one obtained from the topographic survey as the real depths are greater than the fictitious ones.

Once the correct DTM has been found, the hydrodynamic simulation can be performed.

2.4.2 2D HYDRODYNAMIC MODELING

GENERAL ASPECTS AND SIMULATION

The MesoHABSIM methodology has been applied on a Dora Baltea River reach with the aim of studying the variation of the biological habitat at different discharge values.

The Manuale MLG ISPRA 154/2017 (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017) indicates the need of at least three surveys with the purpose of a better hydraulic characterization of the section. With the aim of avoiding problems related to the on-site survey and the presence of high discharges and also to optimize and fasten the process, it has been chosen to perform only one on-site survey and to simulate the other discharge conditions by using the DTM obtained to carry out an 2D hydrodynamic simulation.

The software used to perform such simulation is HEC-RAS (US Army Corps of Engineers, Hydrology Engineering Center, Davis, California). This software allows to carry out 1D, 2D, and combined 1D and 2D modeling. The analysis can be implemented considering steady (constant flow) or unsteady flow models. (Brunner G. , 2016)

For the purpose of this work, a 2D unsteady flow modeling has been considered.

The software can perform the simulation with either Full Saint Venant equations for shallow flow or with the Diffusion wave equations. The former has been used.

The Navier-Stokes equations describe the 3D motion of fluids. The Saint Venant equations derived from them by a depth-integration. They are used when it is possible to assume that the horizontal length scale is much greater than the vertical length scale. With this hypothesis verified, by considering the mass conservation equation it is possible to consider that the vertical velocity of the fluid is negligible in comparison to its horizontal one. Other hypothesis that must be valid are incompressible flow, uniform density and hydrostatic pressure. Turbulent motion is approximated with eddy viscosity. (Brunner G. , 2016)

To fasten the computation the bathymetry is subdivided in a grid allowing to consider the discretized form of the equations with finite volume.

The Saint Venant equations are the following ones:

- CONTINUITY EQUATION (or Mass Conservation equation)
  In its unsteady differential form is
  $$\frac{\partial H}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}+q=0$$
  Where H is the water surface elevation, h is the water depth, t is time, u and v represent the velocity respectively along x and y direction and q is the source/sink flux term.
  In its integral form it becomes
  $$\frac{\partial}{\partial t}\iiint_{\Omega} d\Omega+\iint_{S} V\cdot n ds+Q=0$$
  Where Ω is the 3D volumetric region occupied by the fluid, S represents the side boundaries of the region and Q represents any flow that crosses the bottom or the top water surface of the volume.
  This form of the equation is very opportune when a gridded bathymetry approach is considered, as in this case. The volume Ω will represents the finite volume of the cell.
- MOMENTUM CONSERVATION EQUATIONS
  They derive from the Newton's second law, Force = mass x acceleration, and they can be written as
  $$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial H}{\partial x}+v_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-c_f u+fv$$
  $$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial H}{\partial y}+v_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-c_f v+fu$$

Where u and v are the velocities along x and y respectively, g is the gravitational acceleration, v_t is the horizontal eddy viscosity coefficient, c_f is the bottom friction coefficient, R is the hydraulic radius, f is the Coriolis parameter and $\frac{\partial H}{\partial x}$ and $\frac{\partial H}{\partial y}$ represents the change in static pressure. Those equations keep into account the Coriolis effect and the turbulence which is modeled as a gradient diffusion process with an emipirical mixing coefficient. (Brunner G. , 2016)

To carry out the simulation, along with the above-mentioned equations, the boundary conditions are necessary. They are the water surface elevation that must be known at one of the boundary limits, the slope of the water surface in the direction normal to the boundary, and the flow that crosses the boundary.

The hydrodynamic simulation is based on the DTM obtained with the procedure mentioned in chapter 2.4.1.

In order to obtain accurate results, an appropriate mesh grid and time step must be chosen. The DTM must be subdivided in a computational mesh with cell dimension appropriate for modeling both the water flow surface slope and its changes and the underlying terrain.

The cells in HEC-RAS can have multiple faces, and each of them represents a cross section which describe the details of the underlying terrain by an elevation versus area relationship, a wetted perimeter and the roughness. To obtain a good model the cells must capture the high points of the barriers to the flow. Furthermore, in the center of each face, a water surface slope is calculated and thus, if the edges of the slope are further apart, then the slope is averaged over long distances and so it will be less precise.

A mesh of one meter over one meter has been considered adequate. The computational grid used in the model is represented in figure 7.

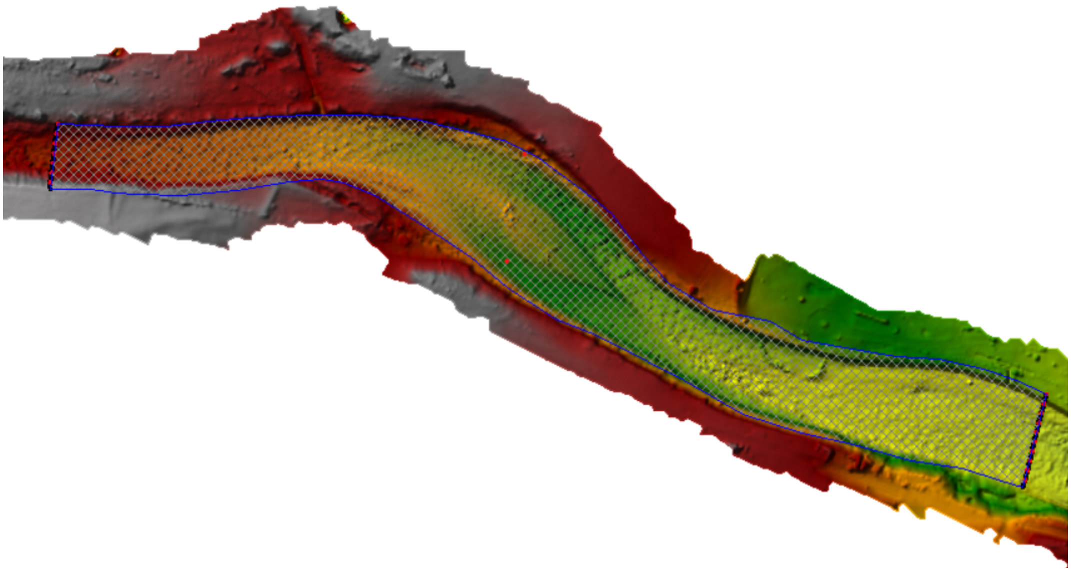

Figure 7: DTM and mesh used to perform the hydrodynamic simulations.

The cell size, the Courant number and the flow velocity influence the time step. It has been chosen to carry out the analysis considering the Saint-Venant Equations and thus, the relation between the flood wave velocity V, the time step ΔT, the Courant number C and the average cell size ΔX is the following:

$$C = \frac{V * \Delta T}{\Delta X} \leq 1.0$$

The Courant number should be kept lower than one to avoid instabilities. Depending on the discharges and so on the velocities, an appropriate time step has been chosen in order to maintain valid this condition. (Brunner G. W., 2016)

DISCHARGE AND MANNING COEFFICIENT CALIBRATION

Once the time step and the cell size have been decided, the Manning coefficient and the discharge should be validated to have a good correspondence between the real situation and the simulated one.

Given that Dora Baltea River can be considered a mountain stream, it has no vegetation in channel and the bottom is characterized by the presence of cobbles and large boulders, the Manning coefficient should vary between 0.040 and 0.070. (Chow, 1959)

The discharge has been measured with the ADCP and show some oscillations around 6.6 $\frac{m^3}{s}$.

To obtain good results, the two data must be validated. The validation is done through the same procedure as for the bathymetric model, and in particular, considering the least square method and so a scatter plot with measured depth data, which are set as the correct data, and the simulated depths. Different combination of discharge and Manning coefficient has been examined.

Once an acceptable correspondence between the real and simulated case has been found, the validated Manning coefficient can be used to develop further hydrodynamic simulations at different discharges. Through those simulations, for each discharge considered, flow velocity and water depth distributions are obtained.

Those distributions will be used to define the correlation between the variation of the habitats along with the discharges. The choice has been based on the hydrograph curve based on the hydrometer placed in Pré – Saint – Didier, even if the data of the hydrometer shows some imprecisions at the low discharges.

In particular the discharges considered are:

- $2.5 \frac{m^3}{s}$;
- $6.6 \frac{m^3}{s}$, which is the discharge measured on site;
- $15 \frac{m^3}{s}$;
- $20 \frac{m^3}{s}$;
- $30 \frac{m^3}{s}$, which corresponds approximately to the Q_{15}.

2.4.3 MESO-HABSIM DATA EXTRACTION

HMU DESIGN AND ATTRIBUTES DEFINITION)

For the five discharge conditions selected, the hydrodynamic simulations are available and so it is possible to identify the mosaics of HMU, with homogeneous characteristics.

The type of HMU that have been found in this case study are the following:

- Rapids: They are characterized by very turbulent flow, with tumbling flow dominant only at low and medium flows. The substrate is characterized by boulders and large cobbles that are submerged at high flow;
- Pools: They are characterized by a depression in the channel bed, with a reversed bed slope at the downstream end. They have deep but slow velocity flow, usually with complex hydrodynamic patterns. The substrate is finer than in the adjacent units;
- Glides: They are characterized by a regular longitudinal bed profile. The water surface is roughly parallel to the bed. Some coarse grains can be present but unlikely protrude out of the flow. They are more turbulent than pool units at low flow conditions;
- Riffles: They are characterized by shallow and fast flow. The substrate is composed by uniform sediment that range from gravel to small cobbles, rarely the substrate protrudes out of the flow. They are less turbulent than the rapid units and they have an accelerated flow velocity in comparison to the glide. This acceleration produces an undulated but unbroken flow surface;
- Backwaters: They are located at the margins of the baseflow channel as a consequence of local erosion or of the presence of some elements which create local low flow conditions. They often represent a refugee for aquatic organisms at high flow. (Rinaldi M. , et al., 2015)

All the above mentioned HMU have been identified in every discharge simulations, with the exception of backwater unit which is present only at higher discharges, in particular $30\frac{m^3}{s}, 20\frac{m^3}{s}, 15\frac{m^3}{s}$, where some rocks create an area of low flow.

After the identification of the units, a shapefile must be defined for each discharge condition in a way that follows a rigid standard to be recognizable by the software which will elaborate the data. In particular it must be organized as following.

First of all, it is assigned a number to the unit and it is specified the type of the unit considered. Then the maximum and minimum elevation of the water surface it is calculated for each unit as the sum of the DTM elevation and of the water depth. Those two values will be used to define the gradient of the unit that is a factor influencing the suitability of the mesohabitat for a specific specie. Afterwards there the hydraulic connectivity between the units is evaluated and summarized with a categorical variable (True/False). For all the units it has been set as 'True', meaning that all the units are connected to the nearby ones.

The last variables used for the description of the mesohabitats indicate the presence or not of certain covers or refugees, their value can be 'True' or 'False':

- Boulders: indicates the presence or absence of boulders, the dimensions of the substrate considered as boulders are related to the target species considered. As an example, if the target species is the trout which have a dimension of approximately 40 cm, then are considered as boulders only the substrate larger than 40 cm.
- Canopy shade: indicates the presence of vegetation at the borders of the unit that can create shade over the unit.
- Overhanging vegetation: indicates the presence of vegetation that touches the water surface.
- Roots: indicate the presence of roots into the unit.
- Submerged vegetations: indicates the presence of submerged vegetation into the water.
- Emerged vegetations: indicates the presence of emerged vegetation.

- Undercut banks: indicates if the banks are eroded in their lower part by the passage of water. The presence of this erosion structure can represent an habitat for some species.
- Woody debris: indicates the presence of woody debris into the unit.
- Riprap: indicates the presence of graded stones or crushed rocks for the stabilization of the streambanks (Fischenich, 2003).
- Shallow margins: indicates the presence of area with shallow water and slow water flow at the border of the unit. To be set as true, those area must be consistent.

Once this shapefile is correctly compiled, the substrate composition must be defined for each HMU. This is performed in GIS environment from remote by the mean of the orthophoto collected by the UAV, integrated by observations on site. The Manuale LG ISPRA 154/2017 sets a minimum of points that are necessary for each unit in order to correctly define their substrate. For unit with a surface greater than 5 m^2 at least 15 points are necessary, for the other units at least 7 points must be identified.

There are 12 classes of substrate depending on their size. The sediment classification according to the 'Manuale tecnico-operativo per la modellazione e la valutazione dell'habitat fluviale' (Vezza, Zanin, & Parasiewicz, 2017) is summarized in the following table.

Table 1: 12 classes of substrates and their correspondent size range, they have been used to characterized the substrates of the area.

Substrate	***Size range***
Gigalithal	*(Bedrock)*
Megalithal	*>40 cm*
Macrolithal	*20-40 cm*
Mesolithal	*6-20 cm*
Microlithal	*2-6 cm*
Akal	*0.2-2 cm*
Psammal	*0.06-2 cm*

Pelal	*< 0.06 cm*
Detritus	*(organic matter)*
Xylal	*(woody debris)*
Sapropel	*(anoxic mud)*
Phytal	*(submerged plants)*

In the mesohabitats analyzed in this essay, only substrates ranging from megalithal to psammal have been identified.

The data about substrates will be used together with the data on depth and velocity extracted from the simulations, to define the hydro-morphological punctual dataset that characterize the HMUs and that is necessary for the elaboration.

To perform this procedure, the rules set by the Manuale LG ISPRA 154/2017 (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017) are followed.

The depth values are classified in nine classes, with an interval of 15 cm until depths greater than 120 cm. The same is done for the velocity values which are divided in classes of 15 cm/s until velocities greater than 120 cm/s. The substrates are classified in 12 classes, as mentioned above. Therefore, to each HMU a frequency of presence of each class of velocity, depth and substrate has been assigned by using GIS tools. An example which reports the frequency distribution of water depth, flow velocity and substrate for the HMU 1, extracted from the simulation at 6.6 $\frac{m^3}{s}$ is reported in the following figures.

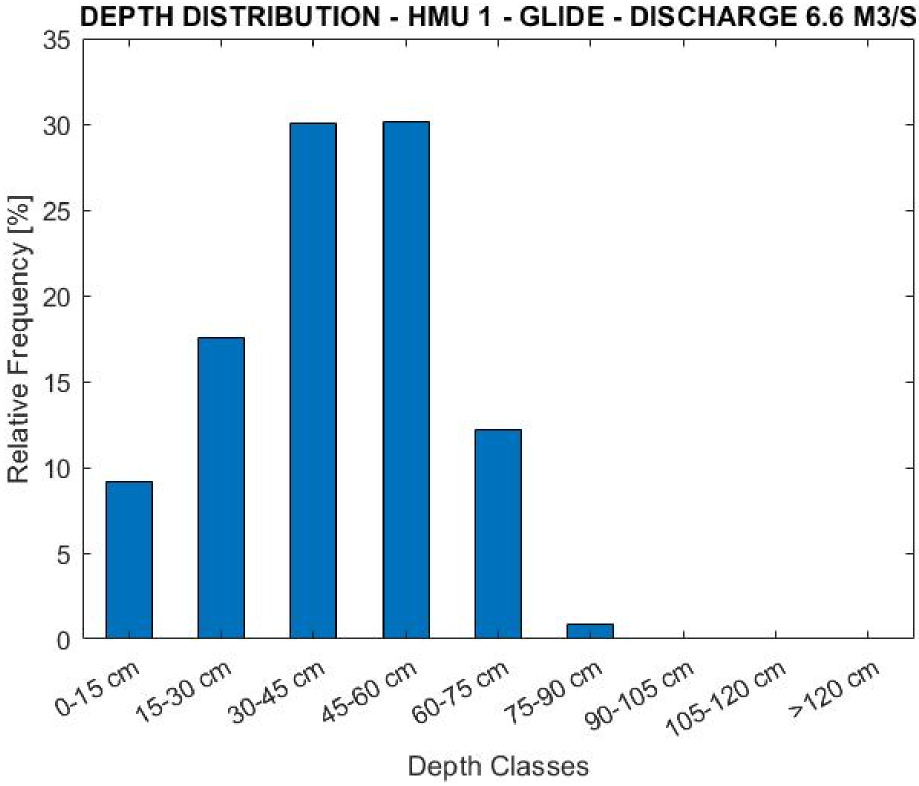

Figure 8: Histogram reporting the relative frequency of each depth class for the HMU 1, glide, for the simulation performed with a discharge of 6.6 m3/s.

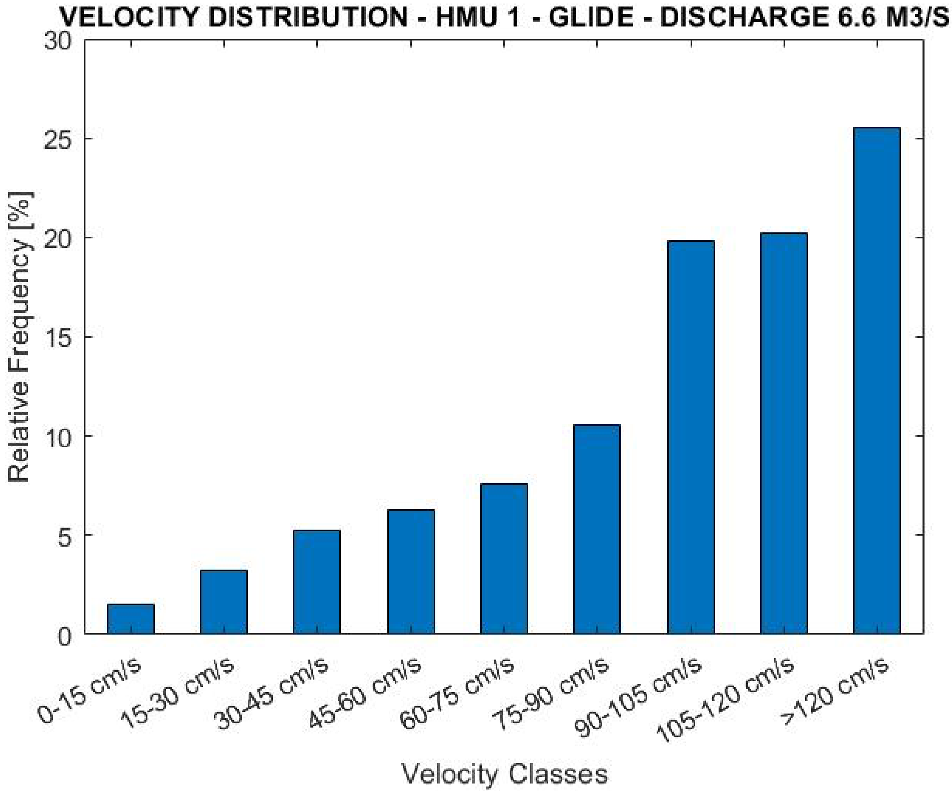

Figure 9: Histogram reporting the relative frequency of each velocity class for the HMU 1, glide, for the simulation per-formed with a discharge of 6.6 m3/s.

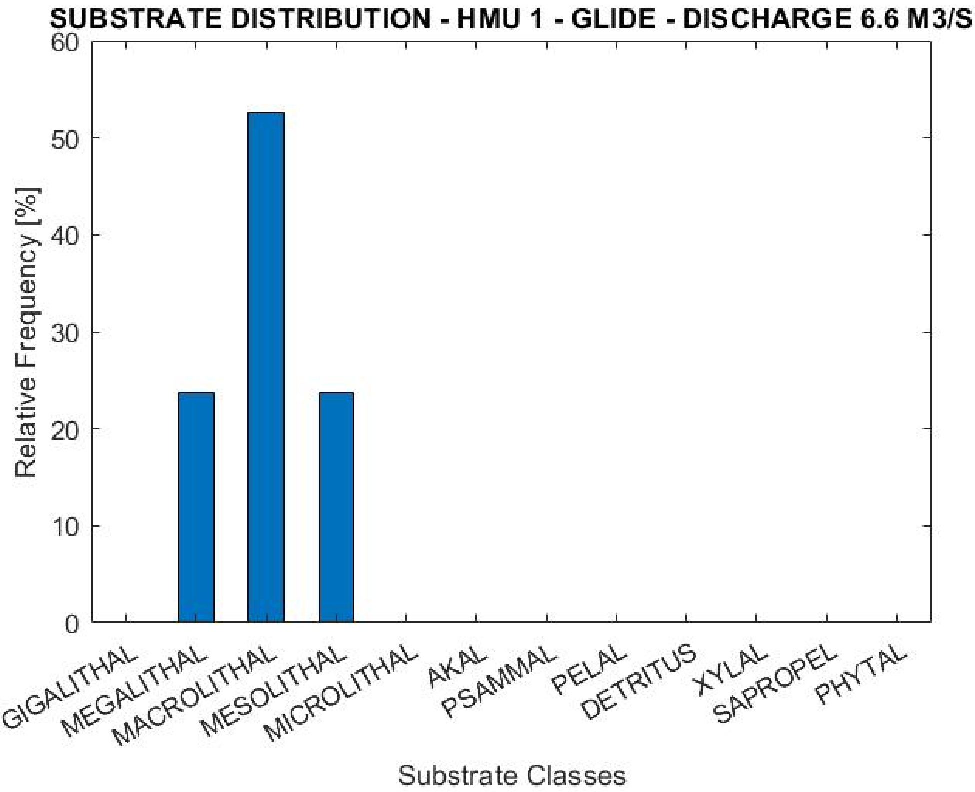

Figure 10: Histogram reporting the relative frequency of substrate class for the HMU 1, glide, for the simulation performed with a discharge of 6.6 m3/s

Once the frequency distributions have been organized, a text file containing the hydro morphological data can be built in a format acceptable by the software.

2.5 HABITAT AVAILABILITY ANALYSIS

SIM-STREAM WEB PLATFORM: functioning and possible applications

SIM-STREAM WEB is a web platform released in September 2021 by ISPRA. It has been developed by Riccardo Pellicanò, Andrea Zanin, Erik Tiengo, Paolo Vezza and Piotr Parasiewicz. It is the web platform used to apply the Meso-HABSIM methodology.

Figure 11: SimStream Web logo.

The data are uploaded and sent to a server that perform the calculation on GIS and R environment. The server belongs to ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale).

The steps that characterize the process are the following:

- The user uploads the input file;
- The input must be validated by the software;
- The server performs the calculations;
- The output files are created;
- The user can download the files.

The input necessary for the procedure are the shapefile and the text file that contains the depth, velocity and substrate data organized in relative frequency of presence of each class, described in chapter 2.4.3. The input format must follow rigid rules otherwise an error message appears. A file containing the reference series of discharges and the altered series of discharges can be optionally uploaded too.

An example of the correct shapefile header is reported in table N° 2.

Table 2: Example of the shapefile that must be uploaded on SimStream Web with data about covers and elevation.

HMU_NUM	HMU_TYPE	Z_MAX	Z_MIN	CONNECTIV	BOULDER	CANOP_SHAD	OVERHA_VEG	ROOTS	SUBMER_VEG	EMERG_VEG	UNDERC_BAN	WOODY_DEBR	RIPRAP	SHALL_MARG
1	RIFFLE	934.887	934.319	True	True	True	False	False	False	False	False	False	False	False
2	RIFFLE	934.308	933.586	True	True	True	False	False	False	False	False	False	False	False
3	RIFFLE	933.552	932.728	True	True	True	False	False	False	False	False	False	False	False
4	POOL	932.734	932.516	True	True	False	False	False	False	False	False	False	False	False
5	GLIDE	932.762	932.397	True	True	False	False	False	False	False	False	False	False	True
6	RIFFLE	932.497	932.174	True	True	False	False	False	False	False	False	False	False	False
7	RAPID	932.239	931.416	True	True	False	False	False	False	False	False	False	False	False
8	RIFFLE	932.427	931.327	True	True	True	False	False	False	False	False	False	False	False

For what concern the text file containing data on depth, velocity and substrates, it must be designed as shown in table N° 3.

Table 3:Example of the table that must be uploaded of SimStream with data about depth, velocity and substrate.

HMU_NUM	HMU_TYPE	PNTNUM	DEPTH	VELOCITY	SUBSTRATE
1	RIFFLE	1	0.14	0.14	MEGALITHAL
1	RIFFLE	2	0.14	0.14	MEGALITHAL
1	RIFFLE	3	0.14	0.28	MEGALITHAL
1	RIFFLE	4	0.14	0.28	MEGALITHAL
1	RIFFLE	5	0.14	0.28	MEGALITHAL
1	RIFFLE	6	0.14	0.42	MEGALITHAL

The altered discharge series file must have the format represented in table N° 4.

Table 4: Example of the table that has to be uploaded on SimStream Web with the reference and altered discharge series.

DATE	REFERENCE	ALTERED_1	ALTERED_2	ALTERED_3
1/1/2012	5.2	0.87	0.87	0.87
2/1/2012	5.2	0.87	0.87	0.87
3/1/2012	5	0.87	0.87	0.87
4/1/2012	5.2	0.87	0.87	0.87
5/1/2012	5.3	0.87	0.87	0.87
6/1/2012	5	0.87	0.87	0.87
7/1/2012	4.9	0.87	0.87	0.87
8/1/2012	4.8	0.87	0.87	0.87
9/1/2012	4.7	0.87	0.87	0.87

Sim-Stream allows to select between seven different outputs which are:

- Hydro-morphological unit data;
- Biological model results;
- Habitat suitability;
- Habitat-flow rating curve;
- Streamflow-habitat time series;
- UCUT curves;
- Habitat integrity index.

The last three outputs are available only when an altered series is uploaded. The user can choose the files of interest that can be downloaded and analyzed. (Pellicanò, Zanin, Tiengo, Vezza, & Parasiewicz, 2021)

TARGET SPECIES DEFINITION

The target species have been chosen among the species described on the D.Lgs 152/2006, ‘Testo Unico Ambientale’, that naturally characterize the Dora Baltea River.

The species selected are:

- Brown Trout (Salmo Trutta), at adult and juvenile life stage;
- Marble Trout (Salmo Marmoratus), at adult life stage.

The juvenile stage of the Brown Trout is modeled in the same way as for the Marble Trout, so only one of the two has been chosen.

The Brown Trout belongs to the Salmonidae Family and it is a freshwater fish. Originally, it was present on the North side of the Apennines Ridge, but in XX century has been introduced in the rest of Italy. It can grow up to 35-50 cm, depending on the environment. It lives in streams characterized by rapid current flows, with good oxygenation, and with a coarse substrate. It is typical of the mountainous streams. At the juvenile stage, this species prefers to stay in low depth areas, while at their adult stage they search quiet area. The reproduction occurs in late autumn or in winter, when the female ascends the stream to search low depth areas. (Regione Autonoma Valle d'Aosta, 2022)

It is considered at ‘Rischio Minimo’ in the ‘Lista Rossa dei Vertebrati italiani’ (Rondinini, Battistoni, Peronace, & Teofinili, 2013).

Figure 12: Brown Trout.

The Marble Trout belongs to the Salmonidae Family and it is a freshwater fish. It is bigger than the Brown Trout, and can reach a length of one meter. They live in stream with a medium to high discharges, and with well oxygenated water. They find refugee between the streambed boulders. The reproduction occurs in late autumn or in winter, when the female ascends the stream to search low depth areas. (Regione Autonoma Valle d'Aosta, 2022)

It is considered at 'Rischio Critico' in the 'Lista Rossa dei Vertebrati italiani' (Rondinini, Battistoni, Peronace, & Teofinili, 2013).

Figure 13: Marble Trout.

2.5.1 HABITAT FLOW RATING CURVE

To analyze the relation between the habitat and the discharge, not only hydro morphological data are necessary, but they must be coupled with the biological model.

The biological models are statistical models that describe the distribution of the species. They are species specific and they are built with on-site survey performed

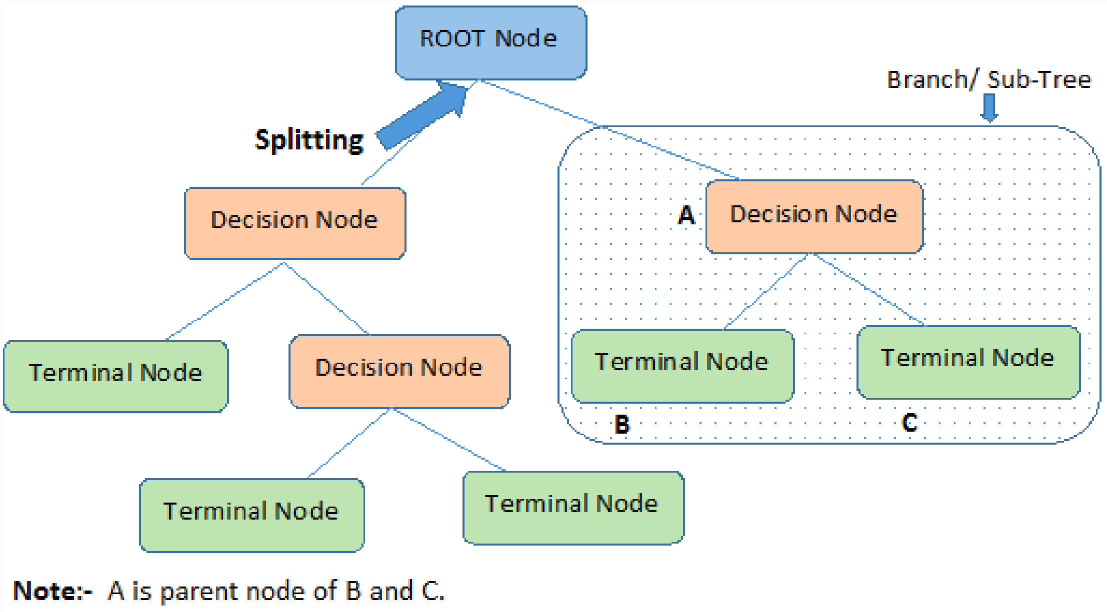

Figure 14: Example of a decision tree, with decision and terminal node(Choundary, 2022)

in reference conditions, which means without artificial alterations of the stream. The machine learning technique that is applied to build the biological models is called *Random Forests* (RF). It is based on the combination of decision trees. An example of functioning of a decision tree is reported in the figure N° 14.

At each *decision node* of the tree, there is an if-else condition that allows to choose between two or more sub-nodes. When a node cannot be split anymore, the process ends and the node is called *terminal node*.

The independent variables present at each node are determined with a technique that consists in the redistribution of the dataset through a cross-validation which involves the subdivision of the dataset in two parts. The first parts of the data is called calibration dataset, and it includes the two third of the dataset. The remaining one third of the data are called validation dataset. In this way, the validation of the model is performed using data which are independent to the data used for the model construction. This procedure must be repeated for each tree of the 'forest', and it allows to obtain the dependent variable, which, for the MesoHABSIM methodology, can assume three values, absence, presence or abundance. (Vezza, Zanin, & Parasiewicz, 2017)

A set of biological statistical models, constructed in this way, is implemented into SimStream-Web.

In order to graphically represent the trees forest, the technique of '*Partial Dependance Plot*' PDP is used. Each PDP is a graph in which the relation between the presence, or abundance, probability and the dependent variable is explicit. An example of the PDP curves for the presence probability of the Brown Trout is represented in figure N° 15.

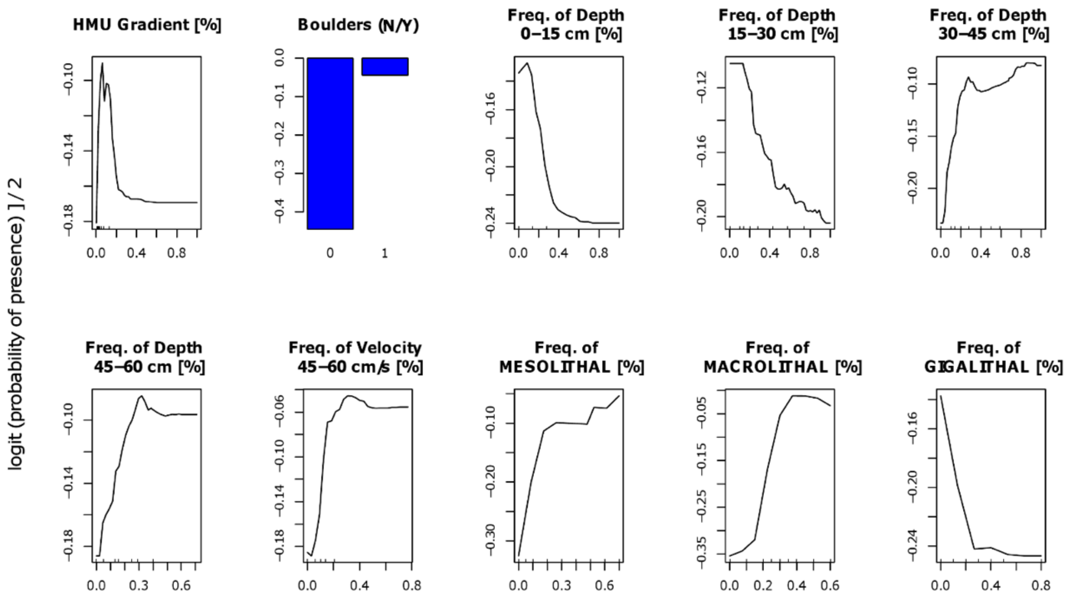

Figure 15: Example of suitability, presence/absence, model for Brown Trout built with RF technique and represented through PDP.

From the PDP it is possible to evidence that the relations between the habitat features and the habitat distribution are generally not linear. (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017)

In the following table the parameters that influence the presence and abundance of the species considered are summarized. The other parameters set as input are used to define the boundary conditions of the model.

Table 5: Parameters that influence the presence and abundance of the different species.

		Presence			Abundance		
		Adult Brown Trout	Adult Marble Trout	Juvenile Trout	Adult Brown Trout	Adult Marble Trout	Juvenile Trout
Gradient of the HMU area		X	X	X	X	X	
Presence of boulders		X		X			
Frequency of depth	0 – 15 cm	X	X	X			
	15 – 30 cm	X		X			

	30 – 45 cm	X	X			X	
	45 – 60 cm	X	X				X
	60 – 75 cm		X		X		X
	75 – 90 cm		X				X
	– 105 cm				X	X	
	105 – 120 cm					X	
Fre-quency of veloc-ity	15 – 30 cm/s				X		X
	30 – 45 cm/s					X	X
	45 – 60 cm/s	X	X		X		X
	75 – 90 cm/s					X	X
	90 – 105 cm/s					X	
	105 – 120 cm/s				X		
Fre-quency of pres-ence	Gigalithal	X					
	Mega-lithal		X		X		X
	Macro-lithal	X	X	X			
	Meso-lithal	X		X			

Those models are applied by the software during its analysis and downstream of their implementation the HMUs are classified into three categories that are:

- Not Suitable, if the presence probability is lower than 0.5;
- Suitable, if the presence probability is higher than 0.5;
- Optimal, if the habitat is suitable and it has an abundance probability greater than 0.5.

Once the HMUs have been classified in those categories, it is possible to quantify the area available to host the fauna at each discharge value selected. For each discharge value, in particular, it is determined the area, in m^2, that can be considered **Suitable Habitat** (H_i) and the area which can be considered **Optimal Habitat** (H_o).

Then it is possible to construct the relation that connect the habitat, expressed in m^2 or as a percentage of the wet area measured at the higher discharge, to the discharge, expressed in $\frac{l}{s}$ or $\frac{m^3}{s}$.

The **Total Available Habitat** (H_d) is obtained, through the H_i and H_o area, with the following expression:

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

(1)

Looking to this expression, it is clear that the H_d calculated in that way gives more importance to the area considered optimal compared to the area considered only suitable.

With this expression the Habitat-Flow rating curve is built. This curve is a cartesian diagram with, on the abscissa axes, the discharges and, on the vertical axes, the available area expressed in m^2 or as a percentage of the wet area measured at the higher discharge.

The non-suitability of an area should not be considered as an interruption of the river continuity, but it is only related to the possibility for the species to use the area under discussion during their daily routine. (Vezza, Zanin, & Parasiewicz, 2017)

2.5.2 ALTERATION SCENARIOS

The main goal of the MesoHABSIM methodology application is the quantification of the available habitat at certain hydro morphological conditions of interest compared to the available habitat at reference conditions. To perform this comparison, some indices have been developed and implemented on SimStream-Web. An index, called ‘Spatial Habitat Availability Index (ISH)’ assess the spatial alteration of the available habitat comparing reference and altered conditions. The other index, called ‘Temporal Habitat Availability Index (ITH), assess the duration of stress period for the fauna. A stress period is defined as the persistence of scarce habitat availability conditions and it is described by the number of day during which the available habitat is lower than a certain threshold. The two indices are merged together in an index called ‘Habitat Integrity Index (IH)’. The minimum values between ITH and ISH is assigned to the IH. All those indices can vary between 0 and 1.

To obtain them it is necessary to transform the discharge temporal series in habitat temporal series. This conversion is performed with a relation of the type:

$$H_d(t) = H\big(Q(t)\big)$$

(2)

Where H is the habitat discharge relation, which can be the Habitat-Flow rating curve, $Q(t)$ is the discharge flowing at time t and $H_d(t)$ is the available habitat at time t.

The habitat temporal series can be helpful to analyze the duration and frequency of certain hydrological events which correspond to habitat conditions which are under a certain threshold. Furthermore, they can be used to analyze the current habitat situation compared to the reference one or to simulate future or hypothetical scenarios.

To obtain this series, and so the assessment of the habitat availability, usually, at least one year of data is requested.

When the series are obtained the indices can be calculated.

The ISH is calculated as the comparison of the available habitat during the period of interest between reference biological conditions ($A_{Hd,r}$) and the altered ones (A_{Hd}).

$$ISH = \min\left(\begin{cases} 1 - \dfrac{\left|A_{Hd,r} - A_{Hd}\right|}{A_{Hd,r}}, \dfrac{\left|A_{Hd,r} - A_{Hd}\right|}{A_{Hd,r}} \leq 1 \\ 0, \dfrac{\left|A_{Hd,r} - A_{Hd}\right|}{A_{Hd,r}} > 1 \end{cases}\right)$$

This index is calculated for all the species of interest and, for the segment of the interest, the global one will assume the minimum value between all the indices calculated.

To calculate the ITH, the stress threshold is considered to be, according to the MesoHABSIM methodology, as the discharge that is exceeded for the 97% of the time in reference conditions. This threshold is called AQ_{97}. The duration of the under-threshold events is calculated through the UCUT curves(Uniform Continuous Under-Threshold curves). (Vezza, Zanin, & Parasiewicz, 2017) They are constructed considering the duration of the under-threshold events for different cases, reference and altered. For each case, the durations are ordered from the longest to the shortest and they are represented in a graph that, on X-axes, has the cumulative under-threshold duration, and on Y-axes, it has the continuous under-threshold duration. An example of UCUT curves is represented in figure N.16.

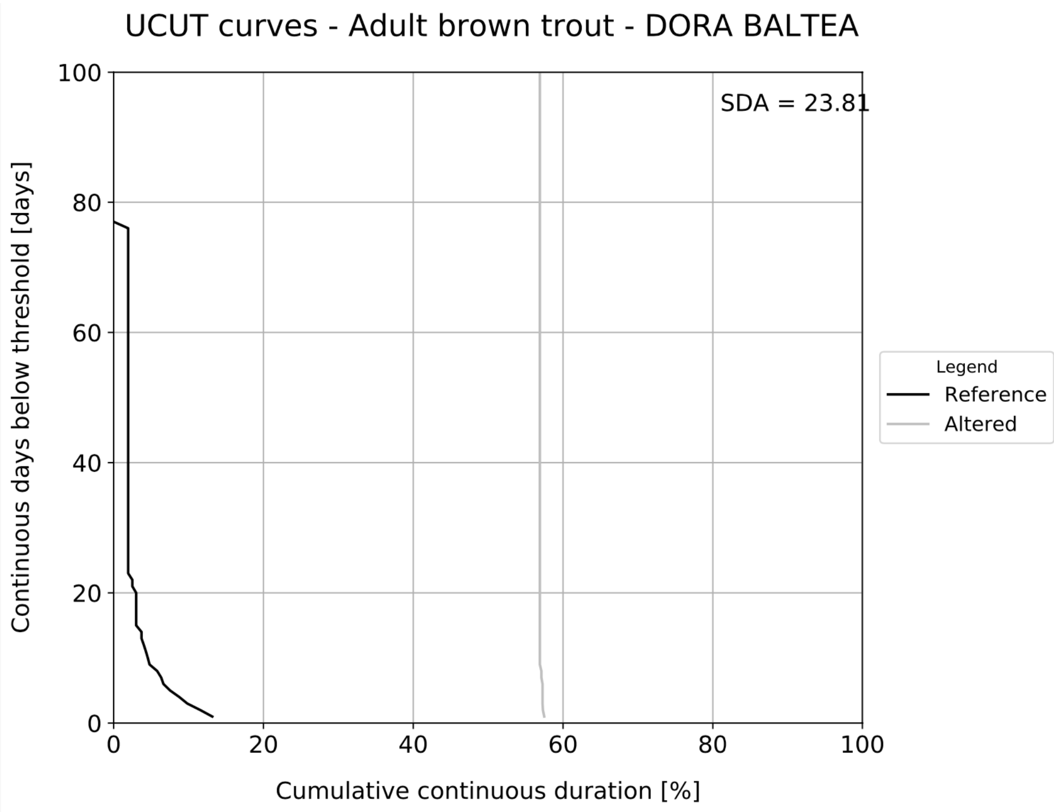

Figure 16: Example of UCUT curves for a reference and an altered scenario The altered scenario shifts towards right, the greatest is the distance between the reference and altered curves and the greatest is the alteration.

The average distance between curves represents the average increase of habitat stress days. For each value of the Y-axes of the UCUT curves, the relative difference, in absolute value, between the number of days of cumulative under-threshold duration of the reference and of the altered conditions.

Therefore, the variation of the stress day, called SDA, Stress Days Alteration, is calculated as:

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

Where:

- $d_{max,r}$ is the maximum duration under-threshold at reference conditions;

- $d_{C,AQ97}$ is the number of days of cumulative continuous duration under-threshold at altered conditions;
- $d_{C,r,AQ97}$is the number of days of cumulative continuous duration under-threshold at altered conditions.

The index ITH is calculated starting from the SDA as:

$$ITH = (e^{-0.38SDA})$$

Thanks to the negative exponential, a great weight is given also to the little alteration of the stress event, as it is well described in figure N°17. (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017)

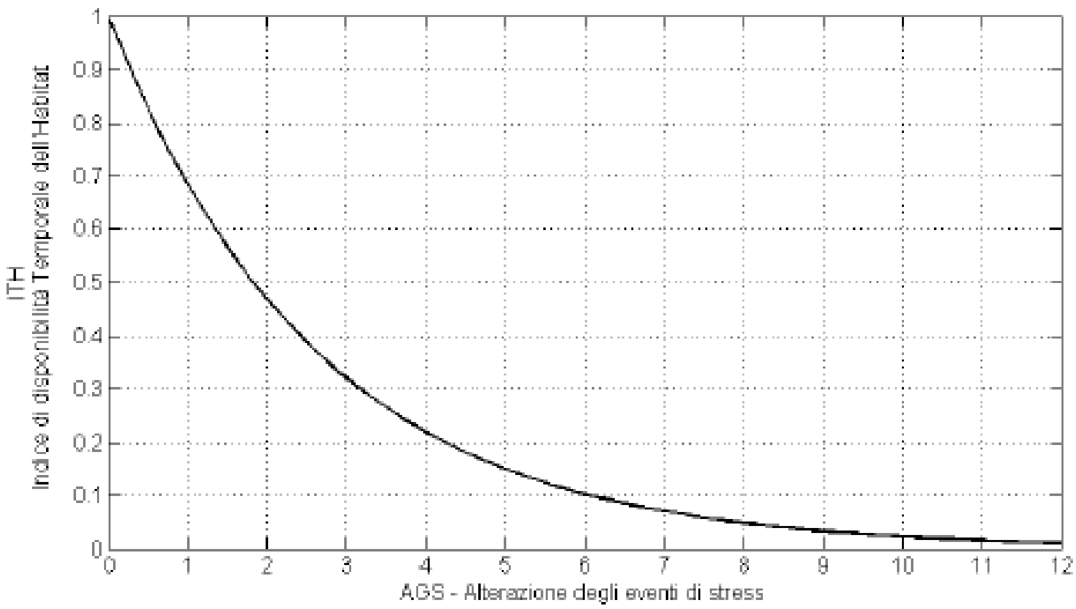

Figure 17: ITH variation as a function of the SDA value, the negative exponential allows to give a weight also to the lower alterations (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017).

Also for the ITH, the general value is taken as the lower between all the values obtained for the species considered.

When the values of ITH and ISH have been obtained, the IH index is calculated as the minimum between them:

$$IH = \min(ISH, ITH)$$

Considering the IH value, it is possible to assess the habitat quality considering the classification reported in Table N.6. (Vezza, Zanin, & Parasiewicz, Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale, 2017).

Table 6: Classification of the habitat of a given scenario of alteration depending on the IH index value obtained from SimStream Web.

IH	CLASSE
$IH \geq 0.80$	ELEVATO
$0.60 \leq IH < 0.80$	BUONO
$0.40 \leq IH < 0.60$	SUFFICIENTE
$0.20 \leq IH < 0.40$	SCADENTE
$IH < 0.20$	PESSIMO

The threshold that divides the classes has been determined through simulations of case study with temporal series that have data for at least 15 years and observing the natural variability, at reference conditions, of the two index ITH and ISH. The subdivision is linear because the non-linearity has been already considered in the calculation of ITH and ISH. (Vezza, Zanin, & Parasiewicz, 2017)

Using the IH index, it is possible to compare different withdrawal scenarios and choose the most appropriate one in term of habitat status.

The aim of this work is to produce and compare different hypothetical scenarios and understand which one can allow an economically satisfactory power production and, at the same time, preserve the habitat. To do so, six scenarios have been developed.

The first scenario considers the traditional approach proposed by the legislative framework to define the monthly base flow modulation. In particular, the base flows are calculated by comparing the flows proposed by the first and second criteria present in 'Allegato G' of the 'Piano Tutela delle Acque della Regione Autonoma Valle d'Aosta'. (Regione Autonoma Valle d'Aosta, 2006)

The first criteria proposed is based on the calculation of the q_{meda} at a monthly rate as proposed in the following formula:

$$q_{meda} = 0.004204856 * H + 0.02302933 * A_{MA}$$

Where A_{MA} is the mean annual inflow over the basin [mm] obtained using the data from the mean annual isohyet map present on the 'Allegato G' and H is the mean elevation of the basin [m a.s.l.]. (Regione Autonoma Valle d'Aosta, 2006).

The values of q_{meda} used for those analysis are summarized in table N.7.

Table 7: Table reporting the q_meda values used to determine the EF with the first criteria proposed by the PTA of the Aosta Valley region.

Month	$q_{meda}\ [\frac{m^3}{s}]$
Gennaio	3.59
Febbraio	3.28
Marzo	3.81
Aprile	7.10
Maggio	22.90
Giugno	40.33
Luglio	30.75
Agosto	22.61
Settembre	15.06
Ottobre	10.91
Novembre	6.74
Dicembre	4.45

Once the values of discharges are available, the monthly base flow is determined as:

$$BF = k * q_{meda} * S * M * Z * A * T$$

Where:

- S is the basin surface of 372 km^2;
- k is an experimental parameter estimated for each hydrographic area. The values proposed are summarized in the following table.

Table 8: k values depending on the surface of the basin considered.

k	S [km^2]
0.06	$S < 10\ km^2$
0.08	$10 < S < 100\ km^2$
$-2 * 10^{-5}S + 0.14$	$100 < S < 1000\ km^2$
0.12	$S > 1000\ km^2$

In this case the value adopted is $k = -2 * 10^{-5}S + 0.14 = 0.133$.

- M is a morphological parameter which is assumed to 1.2 for the entire Dora Baltea River basin.
- Z is a parameter which takes into account the environmental conditions of the river section under consideration. If it is available, it is assumed equal to the fluvial functionality index (IFF), otherwise it can be assumed equal to 1.3 as in this case.
- A is a parameter that quantify the relation between the surface water and the groundwater. It is assumed equal to 1 for every surface river.
- T is the parameter that consider the time modulation of the environmental flow. The values are summarized in the table N.9.

Table 9: Values of the T parameter correspondent to each month of the year. This is the method used by the first criteria of the PTA of Aosta Valley Region to modulate the BF during the year.

Month	T
January	1
February	1
March	1
April	1.05

May	1.05
June	1.15
July	1.15
August	1.15
September	1.05
October	1
November	1
December	1

The values of minimum flow obtained with this criterion, must be compared with the values obtained by the second criterion presented into the 'Allegato G'.

The second criterion is based on the calculation of the q_{meda} at an annual scale and not at a monthly scale. The q_{meda} used here is 15.49 $\frac{m^3}{s}$.

Once the q_{meda} is obtained, the values for each month of $q_{mediamensile}$ are calculated as shown in the table N°9.

Table 10:Relation used to obtain the values of q_mediamensile, this method is used to obtain a modulation of the BF during the year by the second criteria proposed by the PTA of the Aosta Valley Region.

$\boldsymbol{q_{january}}$	$\boldsymbol{0.231656449 * q_{meda}}$	$\boldsymbol{q_{july}}$	$\boldsymbol{0.034169591 * q_{meda}}$
$\boldsymbol{q_{february}}$	$0.211382342 * q_{meda}$	q_{august}	$0.025126331 * q_{meda}$
$\boldsymbol{q_{march}}$	$0.245702885 * q_{meda}$	$q_{september}$	$0.01019068 * H + 0.380281169 * q_{meda}$
$\boldsymbol{q_{april}}$	$0.457959942 * q_{meda}$	$q_{october}$	$0.703911596 * q_{meda}$
$\boldsymbol{q_{may}}$	$1.478190999 * q_{meda}$	$q_{november}$	$0.434878021 * q_{meda}$
$\boldsymbol{q_{june}}$	$0.012059623 * H + 1.92348292 * q_{meda}$	$q_{december}$	$0.286993259 * q_{meda}$

The base flow is then calculated as:

$$BF = q_{mediamensile} * S * Z_{DECIMALE}$$

Where S is basin surface in km^2 and $Z_{DECIMALE}$ is the decimal part of the Z parameter mentioned above.

Those flows are compared with the flows obtained with the other methodology. If the ones obtained with the second criteria are lower than the ones obtained by the first criteria, then they must be incremented of the 20% and adopted as the base flows curve. They can be augmented, until the average monthly discharge, or diminished, until the 50% at maximum, if some specific exigences are present.

The values of BF considered in this case are:

Table 11: Values of BF considered after the application of the methodology present into the allegato G of the PTA of the Aosta Valley region.

Month	BF $[\frac{m^3}{s}]$	Month	BF $[\frac{m^3}{s}]$
January	0.87	**July**	6.15
February	0.80	**August**	4.53
March	0.93	**September**	3.63
April	1.71	**October**	2.63
May	4.59	**November**	1.62
June	8.07	**December**	1.07

The modulation of the flows is implemented as shown in table N.12.

Table 12: Criteria used to modulate the BF. In the left column three different conditions are reported, while on the right the corresponding Qalt (Q in the altered scenarios) are shown..

$\boldsymbol{IF}$	$\boldsymbol{Q_{alt}}$
$\boldsymbol{Q_{ref} < BF}$	$Q_{alt} = Q_{ref}$
$\boldsymbol{BF < Q_{ref} < BF + Q_{max}}$	$Q_{alt} = BF$
$\boldsymbol{Q_{ref} > Q_{max} + BF}$	$Q_{alt} = Q_{ref} - Q_{max}$

Q_{ref} is the daily discharge in $\frac{m^3}{s}$ naturally present into the river, Q_{alt} is the discharge left on the river after the water withdrawal, so under altered conditions, in $\frac{m^3}{s}$, Q_{max} corresponds to the plant capacity flow of the hydro installation, so that it is the maximum discharge which can be diverted to the hydropower plant in $\frac{m^3}{s}$.

In particular, the value choses as Q_{max} is $30\,\frac{m^3}{s}$ .This value corresponds to the discharge exceeded, on average, the 15% of time ($Q_{15} = 30\,\frac{m^3}{s}$).

The hydrographs of the reference and altered conditions for the first scenario are shown in the following figure.

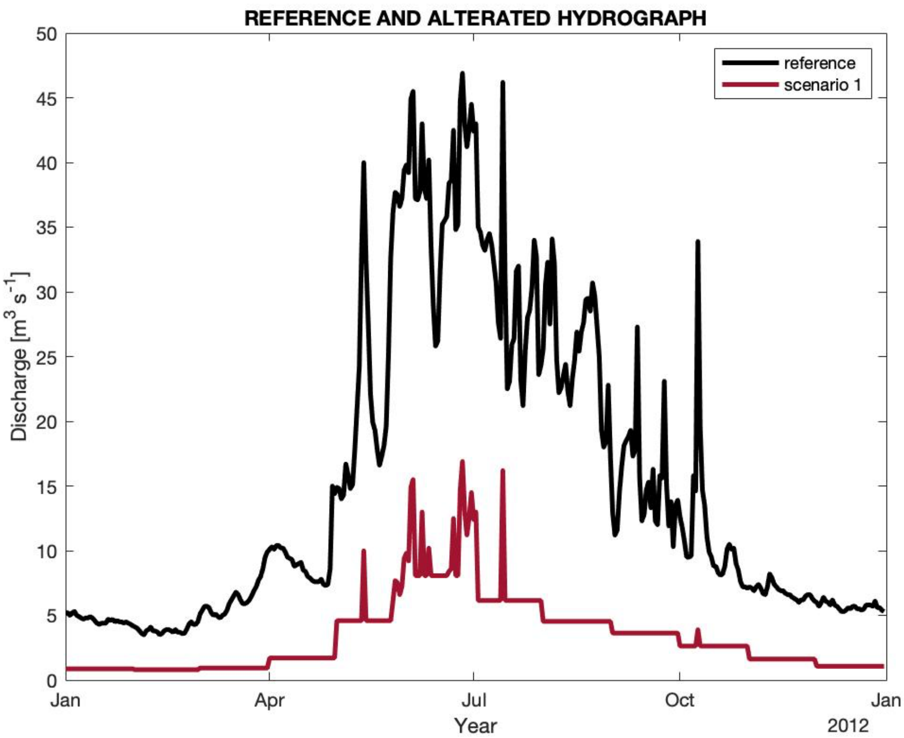

Figure 18: Reference and altered hydrographs, scenario 1.

The other five scenarios, instead, have been created following another approach.

As in the previous case, they differ for what concerning the monthly base flow modulation curve but, also some different Q_{max} values have been chosen to verify if a significant alteration of the flow in period of high discharges is relevant or if the most remarkable consequences on the habitat are present when the withdrawal occurs at low flow periods. The Q_{max} chosen are, besides $30\frac{m^3}{s}$, $Q_{40} = 15\frac{m^3}{s}$ which is exceeded the 40% of time on average, and the $Q_{60} = 7\frac{m^3}{s}$ which is exceeded the 60 % of time on an average year.

Regarding the BF modulation, it has been decided to consider for all of them again a monthly scale.

The strategy besides the choice of these five scenarios is that an alteration of the flows during period of high discharges is supposed to have a lower impact on the habitat since a consistent amount of water will be kept on the river. On the contrary, during low flow periods, when the discharge is lower than the Q_{97} which is equal to 3.4 $\frac{m^3}{s}$, it has been supposed that the river ecosystems are already under stress and thus, a further pressure is more likely to cause significant negative effects.

To apply this, it has been decided to consider the average monthly discharge and to set a base flow for each month a percentage of this value. The average monthly discharge is calculated from the data of the hydrometer located in Pré-Saint-Didier, the data are available from 1/1/2012 to 30/9/2022. Those data are not validated and can be considered only for didactical purposes.

The modulation of the flow is implemented in the same way explained by table N° 12 for all the scenarios.

The scenario N° 2 is characterized by a $Q_{max} = 30\frac{m^3}{s}$, which corresponds to high values of water withdrawal during high flow period, as it is shown in figure N.19.

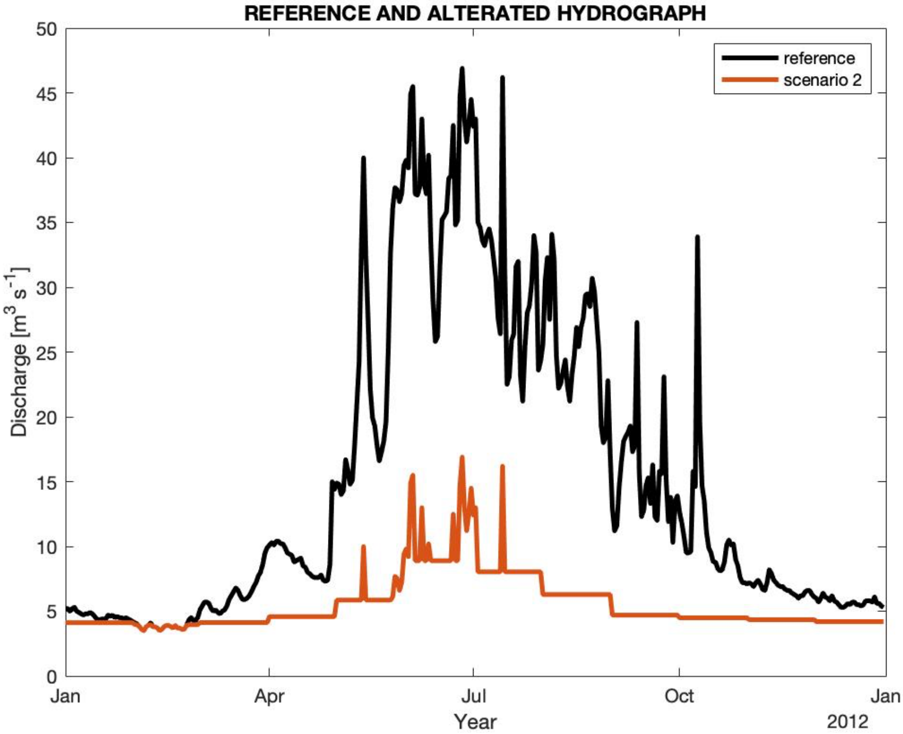

Figure 19: Reference and altered hydrographs, scenario 2.

On the contrary the base flow never goes under the Q_{97} threshold. The lower value is 3.96 $\frac{m^3}{s}$ during the month of February, which corresponds to the 95% of the natural river discharge measured on average on the site during this month.

The idea beyond this choice is to verify the impact on the IH index value of water withdrawal that never goes below the Q_{97} threshold but at the same time during high flow periods the withdrawal are consistent because of high base flow values and a high Q_{max}.

The values of base flow chosen, the natural monthly average discharges and the percentage that relates the two are reported in the following table.

Table 13: base flow values for scenario 2.

Month	Base Flow $[\frac{m^3}{s}]$	Average discharge $[\frac{m^3}{s}]$	%

January	4.11	4.57	90
February	3.96	4.17	95
March	4.12	5.15	80
April	4.58	10.66	43
May	5.85	23.42	25
June	8.90	35.60	25
July	8.03	32.14	25
August	6.28	25.13	25
September	4.70	15.65	30
October	4.49	10.44	43
November	4.34	7.24	60
December	4.20	5.25	80

The scenario N°3 have again a $Q_{max} = 30\frac{m^3}{s}$ but, on the contrary to the previous case, the month of February has a base flow that is under threshold while the minimum flow during period of high flow is greater than in all the other scenario.

This allows to understand if a higher base flow is necessary in period which in natural conditions have high discharges and if a period under threshold is sustainable.

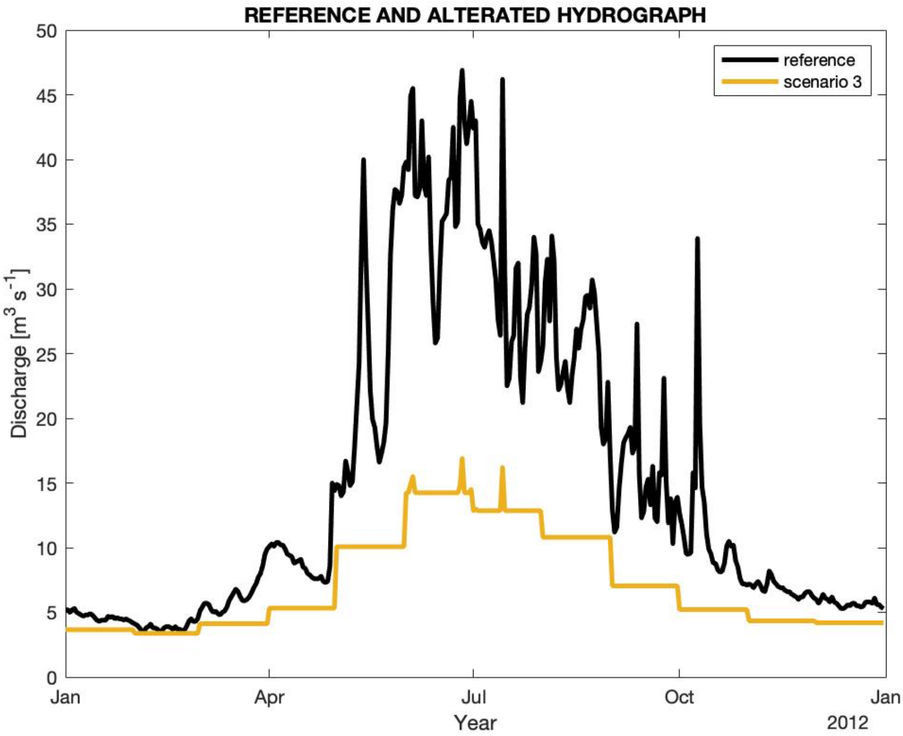

Figure 20: Reference and altered hydrographs, scenario 3.

In the table below the base flows are reported for each month.

Table 14: Values of base flow for the scenario 3.

Month	Base Flow [$\frac{m^3}{s}$]	Average discharge [$\frac{m^3}{s}$]	%
January	3.66	4.57	80
February	3.38	4.17	81
March	4.12	5.15	80
April	5.33	10.66	50
May	10.07	23.42	43
June	14.24	35.60	40
July	12.85	32.14	40
August	10.80	25.13	43
September	7.04	15.65	45

October	5.22	10.44	50
November	4.34	7.24	60
December	4.20	5.25	80

The scenario N° 4 has been defined as follow. For the months characterized by high discharges, around 30 $\frac{m^3}{s}$, the percentage of water left on the river is about the 25 % of the natural discharge allowing a significant water withdrawal and consequently an important power production. This percentage proportionally increases with the decrease of the discharge present into the river. The months with a natural average discharge which is around the Q_{97} have the lower withdrawal flow, with an e-flow of around the 80% of the average discharge. Only the month of February, which on average is the one characterized by the lower flows, has a base flow lower than the Q_{97}.

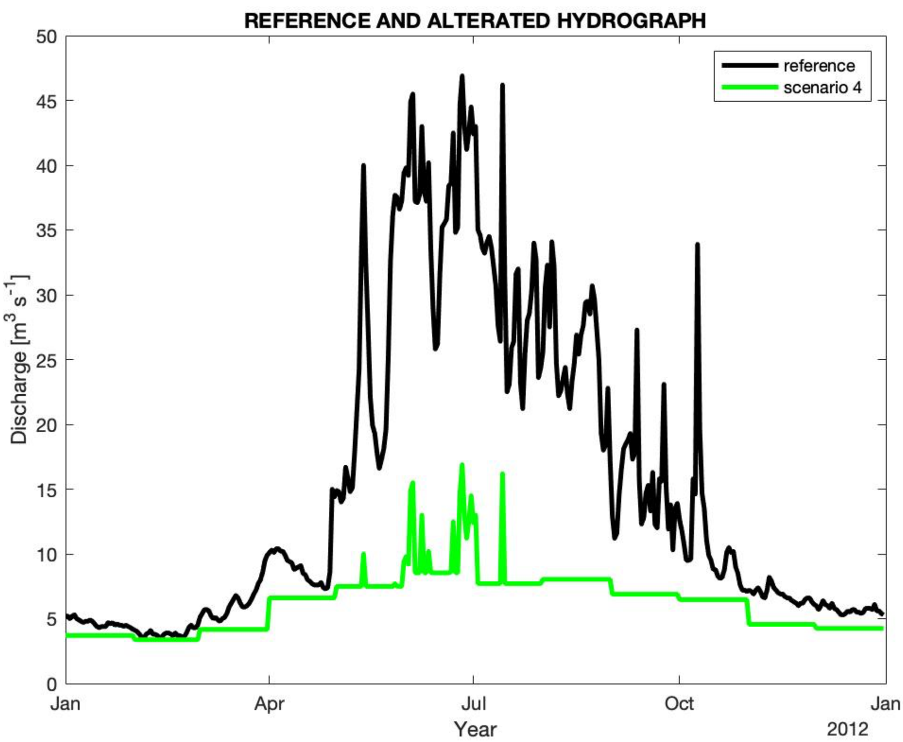

Figure 21: Reference and altered hydrographs, scenario 4.

The altered and reference hydrographs for one year are reported in the following figure.

The base flow values for each month, the naturally monthly average discharges and the percentage which relates those two values are summarized in the following table.

Table 15: Values of base flow considered for the scenario 4.

Month	Base Flow $[\frac{m^3}{s}]$	Average discharge $[\frac{m^3}{s}]$	%
January	3.70	4.57	81
February	3.38	4.17	81
March	4.17	5.15	81
April	6.61	10.66	62
May	7.49	23.42	32
June	8.54	35.60	24
July	7.71	32.14	24
August	8.04	25.13	32
September	6.89	15.65	44
October	6.47	10.44	62
November	4.56	7.24	63
December	4.25	5.25	81

From this table it is clear to note that the month of January has a BF lower than the Q_{97} even if it corresponds to more than the 80% of the discharge present during non altered period on the river. This choice allows to quantify the impacts of periods under threshold on the ecosystems.

The scenario 5 is built in a similar way that the scenario 4 for what concerning the base flow curve. Only during summer months, which usually have a higher discharge, the base flow is slightly lower. Also in this case the month of February has a minimum flow under threshold. The biggest difference consists in the Q_{max} chosen, which is much lower and it is $Q_{max} = 15\frac{m^3}{s}$. The hydrograph obtained is reported in figure below.

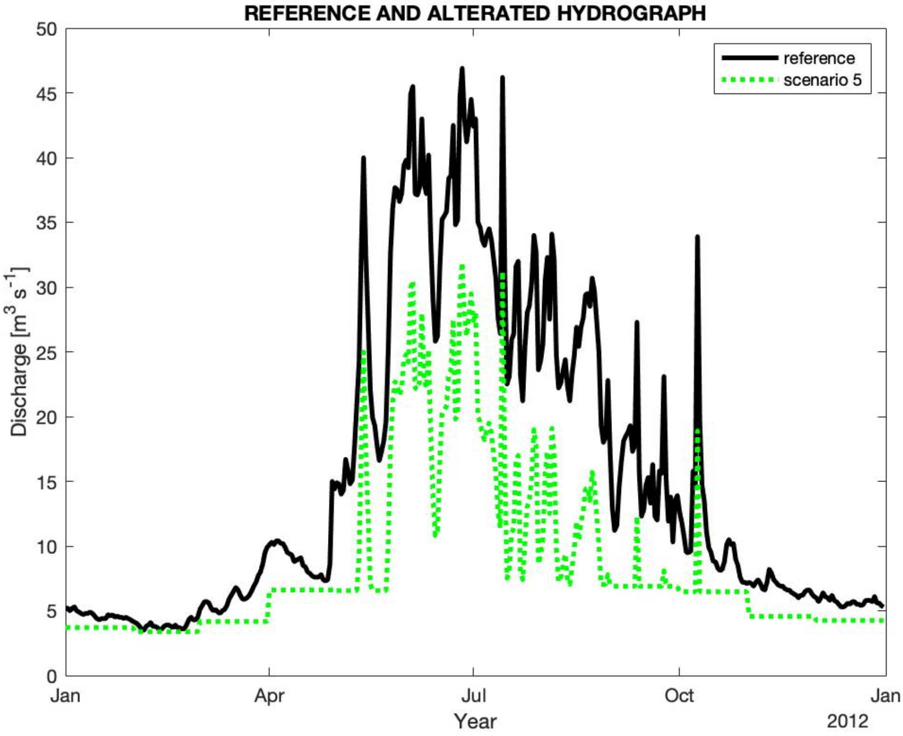

Figure 22: Reference and altered hydrographs, scenario 5.

It is evident that the altered hydrograph is the same as in the previous scenario from October to May, while in the summer months it is less altered with the high discharges maintained.

The base flow values for each month are reported in the following table.

Table 16: Base flow values for scenario 5.

Month	Base Flow $[\frac{m^3}{s}]$	Average discharge $[\frac{m^3}{s}]$	%
January	3.70	4.57	81
February	3.38	4.17	81
March	4.17	5.15	81
April	6.61	10.66	62
May	6.56	23.42	28

June	8.19	35.60	23
July	7.39	32.14	23
August	7.04	25.13	28
September	6.89	15.65	44
October	6.47	10.44	62
November	4.56	7.24	63
December	4.25	5.25	81

The last scenario, the number 6, it is the more conservative one. It has a very low maximum usable flow, $7\frac{m^3}{s}$, and the base flow never goes beyond the threshold. However, the minimum flow for the month characterized by high discharges is comparable than the scenario 2, 4 and 5. The goal of this scenario is to obtain an IH index greater than 0.8 and thus, an elevated habitat quality.

The following figure reports the hydrographs for the reference and altered conditions for this last scenario.

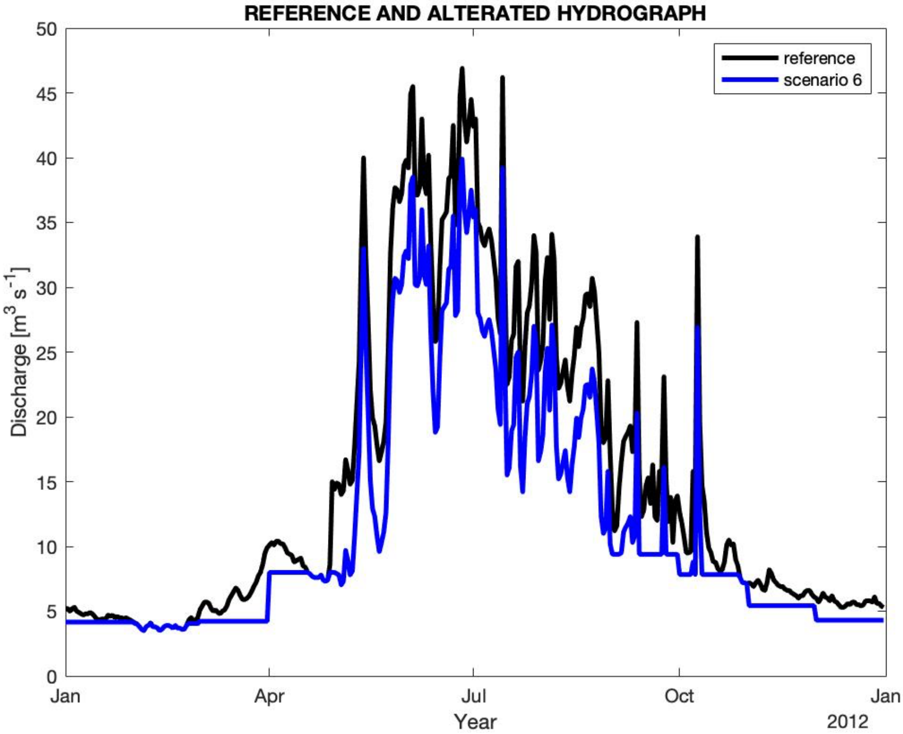

Figure 23: Reference and altered hydrographs, scenario 6.

Those six scenarios are uploaded on SimStream following the procedure explained in Chapter 2.5 and the web platform returned the results which quantify the impacts of the alterations and the IH indices for each of them allowing to perform a comparison.

The scenarios are summarized in the following table.

Table 17: Summary of the six scenarios considered in this analysis with their EF and Qmax values.

Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
BF $[\frac{m^3}{s}]$	Q_{max} $[\frac{m^3}{s}]$	BF $[\frac{m^3}{s}]$	Q_{max} $[\frac{m^3}{s}]$	BF $[\frac{m^3}{s}]$	Q_{max} $[\frac{m^3}{s}]$	BF $[\frac{m^3}{s}]$	Q_{max} $[\frac{m^3}{s}]$	BF $[\frac{m^3}{s}]$	Q_{max} $[\frac{m^3}{s}]$	BF $[\frac{m^3}{s}]$	Q_{max} $[\frac{m^3}{s}]$
0.87	30	4.11	30	3.66	30	3.70	30	3.70	15	4.16	7
0.80		3.96		3.38		3.38		3.38		4.05	
0.93		4.12		4.12		4.17		4.17		4.22	

1.71		4.58		5.33		6.61		6.61		7.99	
4.59		5.85		10.07		7.49		6.56		7.03	
8.07		8.90		14.24		8.54		8.19		8.90	
6.15		8.03		12.85		7.71		7.39		8.03	
4.53		6.28		10.80		8.04		7.04		7.54	
3.63		4.70		7.04		6.89		6.89		9.39	
2.63		4.49		5.22		6.47		6.47		7.83	
1.62		4.34		4.34		4.56		4.56		5.43	
1.07		4.20		4.20		4.25		4.25		4.30	

In order to perform a comparison of the productivity of the different scenarios, the turbined flow has been calculated as $Q_{ref} - Q_{alt}$ and summed up over one year of flow.

Chapter 3

3. RESULTS

3.1 TOPOGRAPHIC AND BATHYMETRIC SURVEY

The results of the topographic survey are the orthophoto and the DTM.

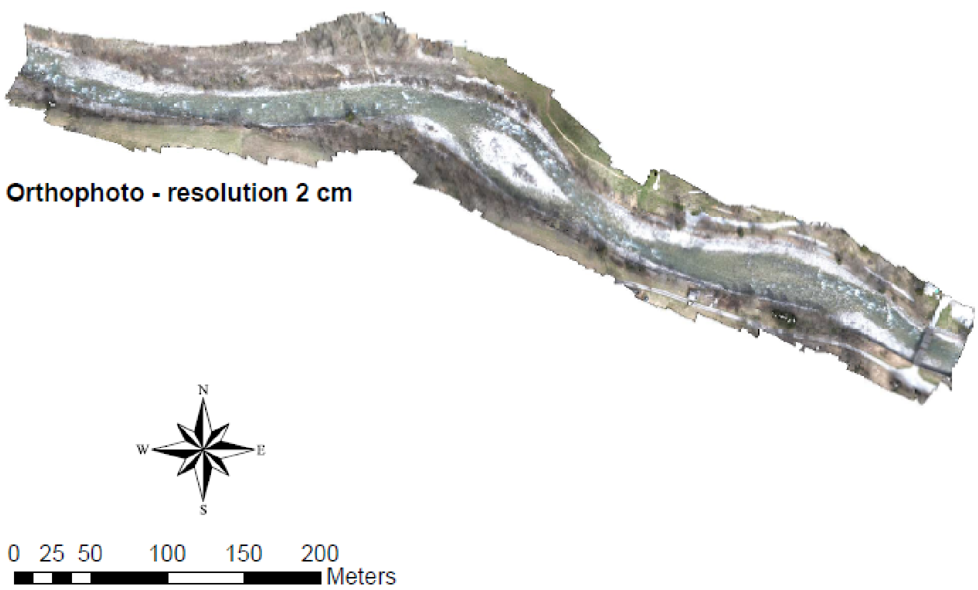

Figure 24: The orthophoto obtained after the topographic survey. It has a resolution of 2 cm.

The correct DTM is reported in the following figure. It has been obtained by the DTM produced by the topographic survey and then adjusted considering the bathymetric model.

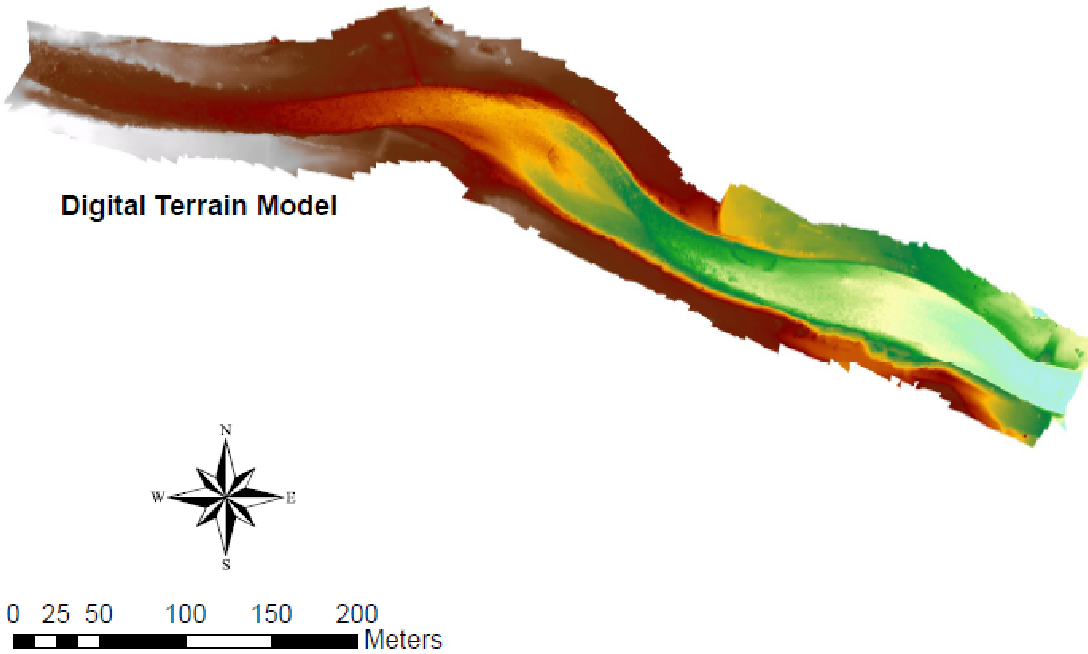

Figure 25: DTM obtained from the topographic survey and corrected with the bathymetric model.

3.2 HYDROMORPHOLOGICAL DESCRIPTION

The hydrodynamic simulation provides a set of current velocity and water depth distributions. Those datasets have been used as the input for the subsequent analysis.

A validation of the Manning coefficient and the discharge was necessary in order to consider correct input data for carrying out the hydrodynamic simulation. The value for the Manning coefficient was set at 0.047 and the discharge was set at 6.6 m^3. The resulting scatter plot is shown in the following figure. It is possible to notice that the two datasets, the real and simulated one, show a good correlation and this is further proven by the high value, 0.89, of the determination coefficient, R^2 and 0.05 of RMSE.

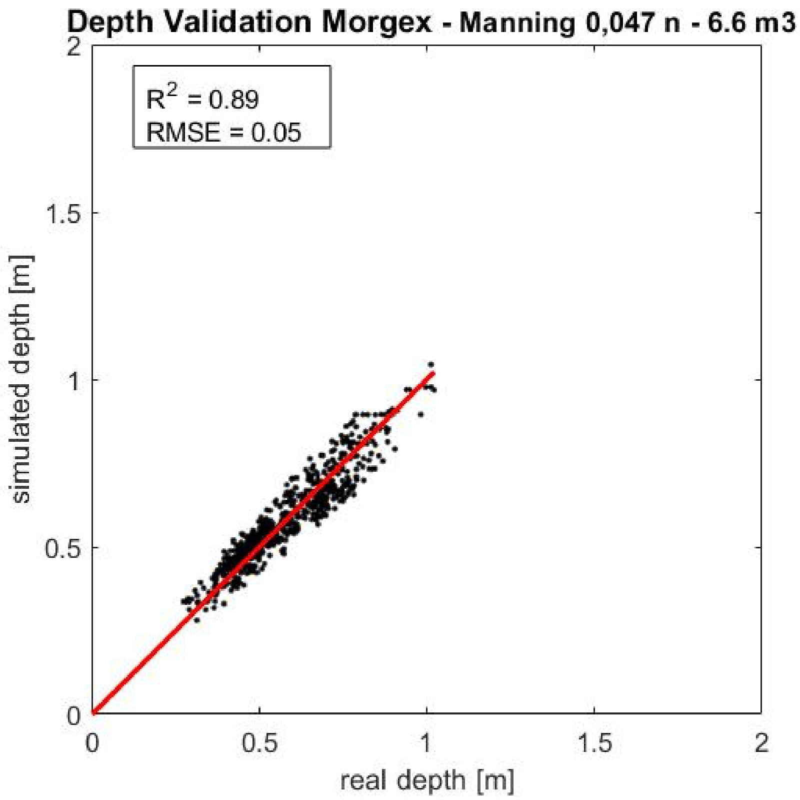

Figure 26: Scatter plot reporting the real and simulated depths. The latter are obtained from the hydrodynamic simulation. The correlation between the two variable seems to be good.

The results of the simulations for the lower and greater discharges and for the on-site measured discharge follow. The depth and velocity distributions are subdivided in classes following the indication of Manuale LG ISPRA 154/2007 (Vezza, Zanin, & Parasiewicz, 2017).

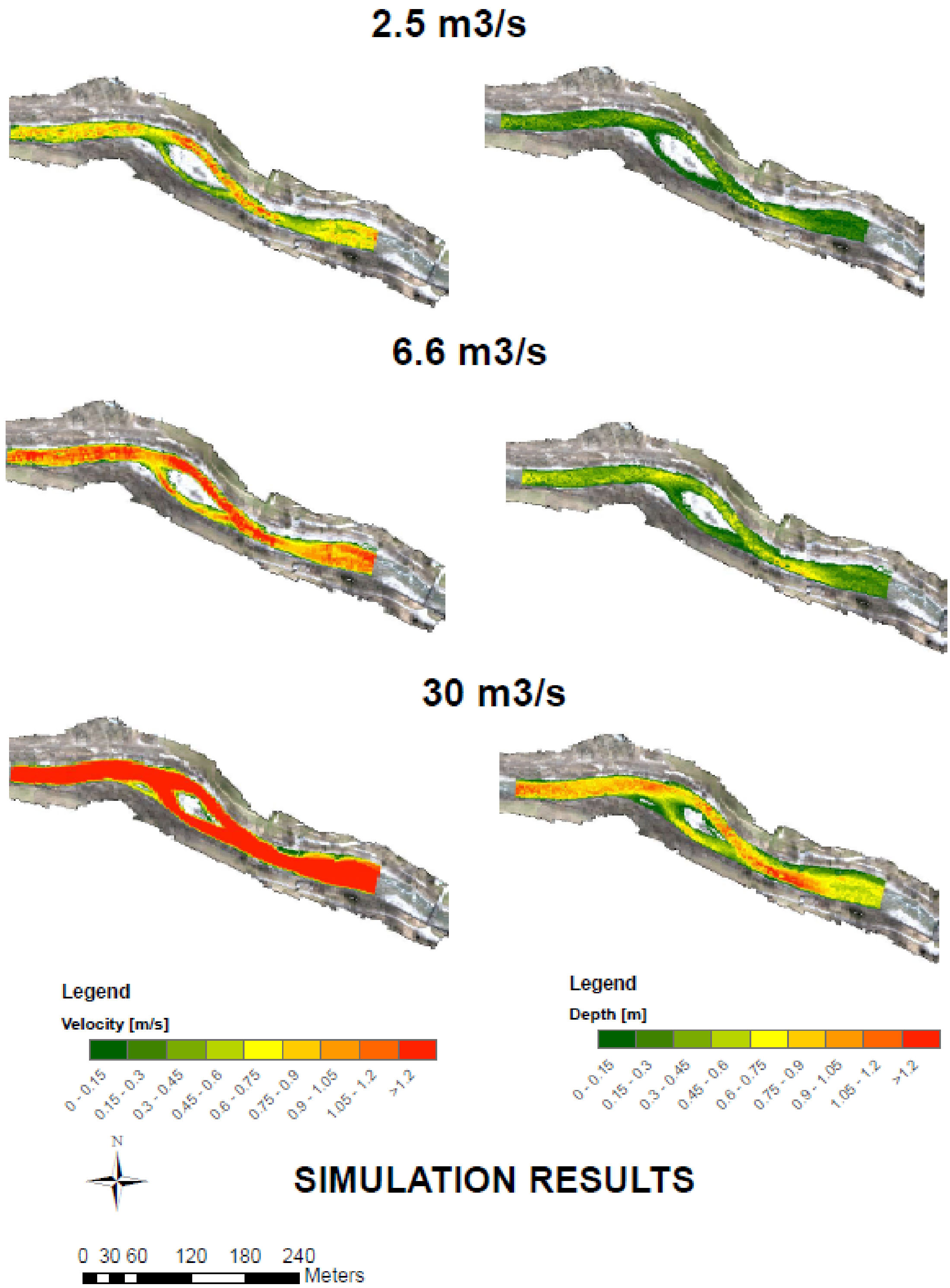

Figure 27: Results of the hydrodynamic simulations, on the left side of the figure the velocity maps obtained are reported for different discharge values, on the right side the depth map are reported for the same discharge values.

When the results of the simulations have been available, starting from the velocity and depth distributions, the HMU areas have been identified. As an example, the HMU identified at $2.5\frac{m^3}{s}, 6.6\frac{m^3}{s}, 30\frac{m^3}{s}$ are reported in the following figure.

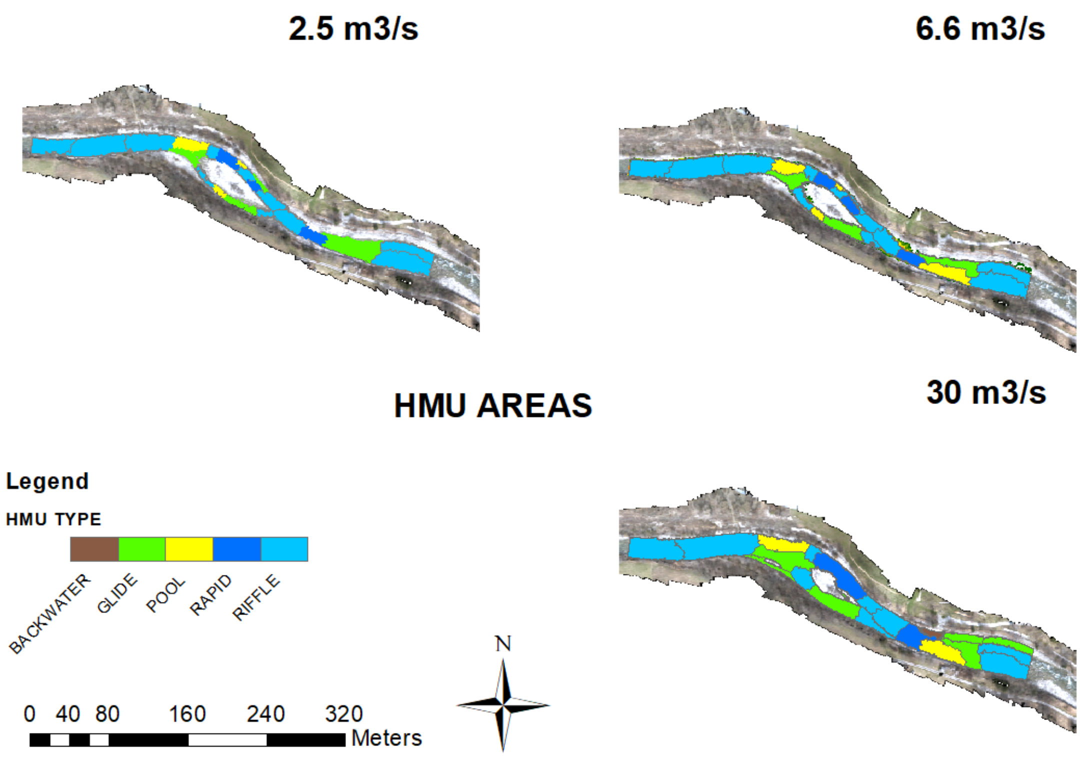

Figure 28: Three maps of the HMU areas are reported for three different discharge values.

3.3 HABITAT AVAILABILITY

The results provided by SimStream-Web can be downloaded from the download session of the web site.

SimStream-Web assigns to each HMU a color depending on the suitability, red for the not suitable areas, yellow for the suitable and green for the area that represent an optimal habitat for the species.

In the figure below the results obtained at different discharges for the Trout at juvenile stage and for the Brown Trout are reported as an example.

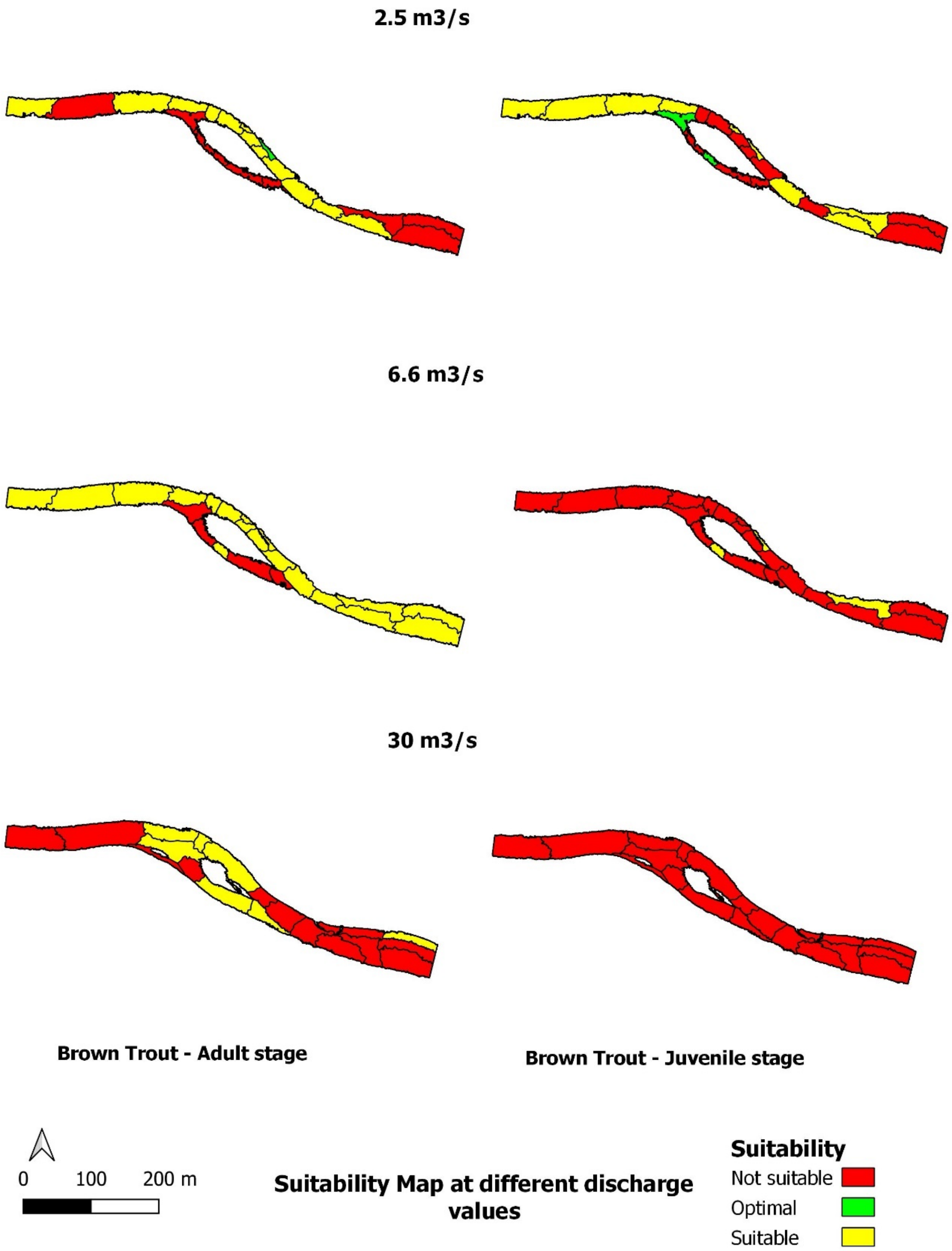

Figure 29: Suitability Map obtained from SimStream Web. On the left side the maps for the Adult Brown Trout are reported, on the right the maps for the Juvenile Trout are presented.

Once a suitability class has been assigned to each unit, the **Total Available Habitat** (H_d) is assigned through the equation (1).

Finally, the Habitat – Flow Rating Curve is obtained. The result follows.

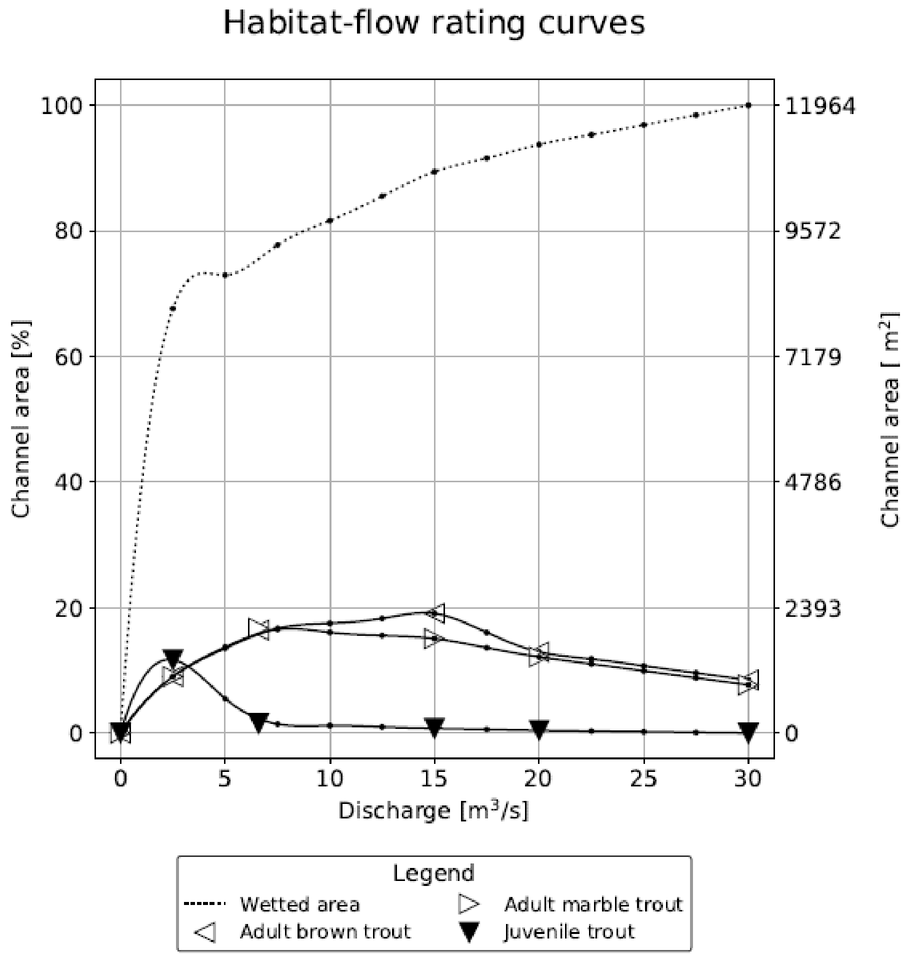

Figure 30: Habitat-flow rating curves for the three species considered. On the x-axes the discharge values are reported, while the channel area is on the y-axes. The area is reported both as percentage of the total wet area and both as in m2.

3.4 ALTERATION SCENARIOS

Once the alteration scenarios have been defined and the altered discharges calculated, SimStream-Web performs some analysis on the habitat impacts of the hydropower plant.

The IH index summarizes those analysis. The values obtained for each scenario are represented in the following figure. The first three scenarios have an IH index lower than 0.6, in particular they have obtained 0, 0.24 and 0.52 as IH index, while the other three scenarios are associated to a value greatest than 0.6 , in fact they have obtained 0.6, 0.6 and 0.8 .

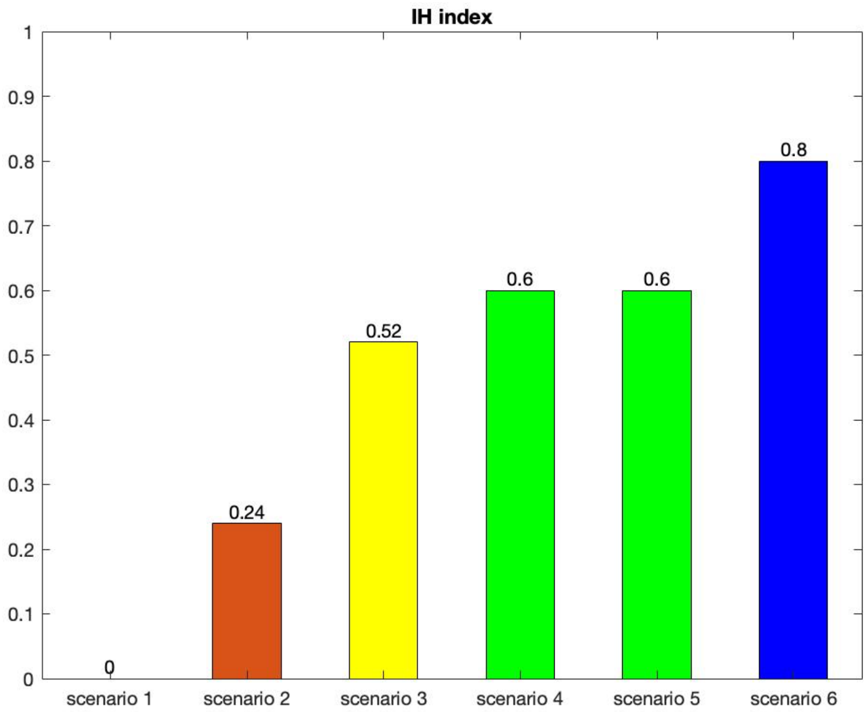

Figure 31: Bar chart reporting the IH index values for the six different scenarios considered. On the top of each bar the exact value is shown.

The IH index is set as the minimum value between the ITH and ISH indices, so in order to understand which of them has mostly influenced the IH index their values must be known. They are summed up for each species in the following table.

Table 18: Table reporting the ITH, ISH and IH values obtained for each scenario for the different species.

	Species	ITH	ISH	IH
Scenario 1	Adult Brown Trout	0	0.61	0
	Juvenile Brown Trout	0.78	0.21	
	Adult Marble Trout	0	0.64	
Scenario 2	Adult Brown Trout	0.98	0.95	0.24
	Juvenile Brown Trout	0.62	0.24	
	Adult Marble Trout	0.95	1	
Scenario 3	Adult Brown Trout	0.74	0.98	0.52
	Juvenile Brown Trout	0.62	0.52	
	Adult Marble Trout	0.69	0.98	
Scenario 4	Adult Brown Trout	0.74	0.99	0.6
	Juvenile Brown Trout	0.62	0.6	
	Adult Marble Trout	0.69	0.94	
Scenario 5	Adult Brown Trout	0.74	0.99	0.6
	Juvenile Brown Trout	0.7	0.6	
	Adult Marble Trout	0.69	0.99	
Scenario 6	Adult Brown Trout	0.96	0.98	0.8
	Juvenile Brown Trout	0.8	0.83	
	Adult Marble Trout	0.95	0.99	

The ISH value, and so the spatial variation of the available habitat is calculated considering the Habitat – Flow rating curve which relate the discharge with the available habitat.

Instead, the ITH, and so the temporal variability of the habitat available, is obtained from the habitat time series curve which is obtained from a relation between the discharge at time t and the available habitat H_d at time t, (equation (2)).

In this way the discharge time series can be transformed in habitat time series and statistically analyzed to know the frequency and the duration of events under a certain threshold, relevant from the ecological point of view. The habitat time series are obtained for an hydrological year.

As an example, the flow time series and the correspondent habitat time series, in reference and altered conditions, are reported for the Adult Brown Trout for the scenario 1. On the habitat time series graph, the habitat available is expressed on the y-axes, as percentage of the total wet area and as area in $[m^2]$.

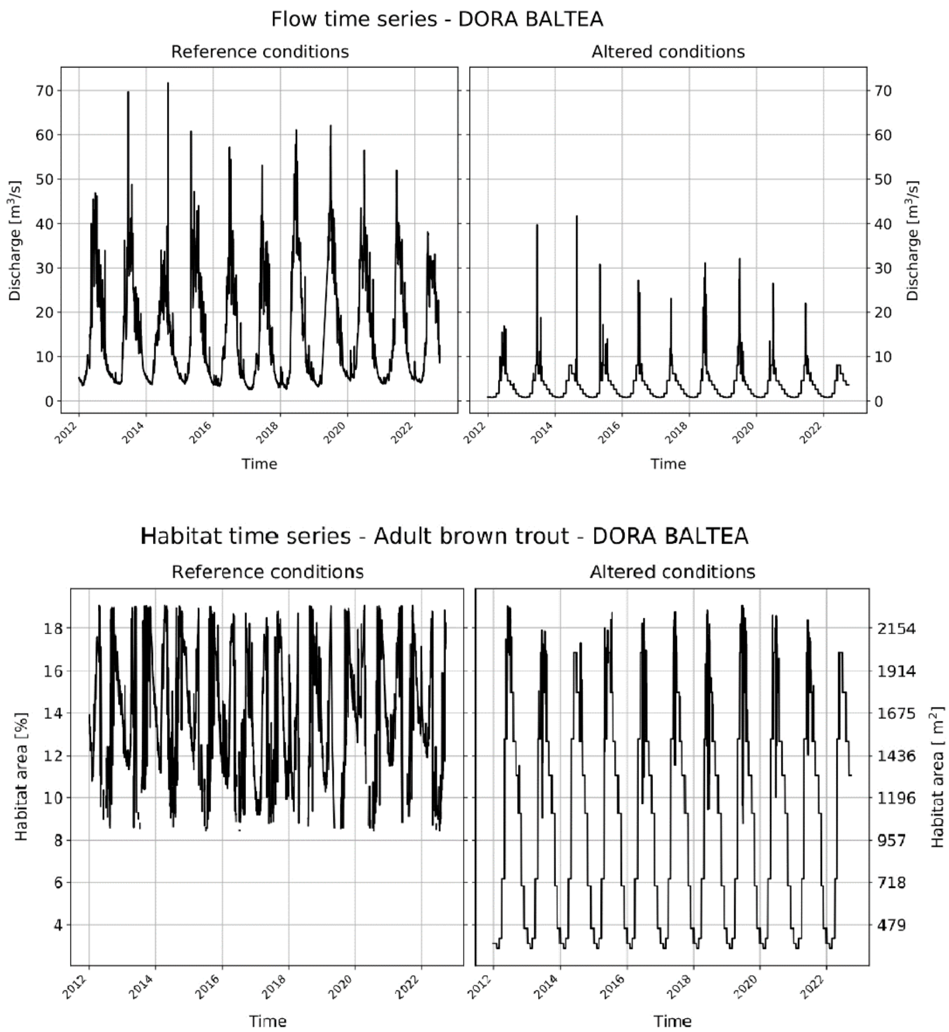

Figure 32: The figure on top reports on the left the flow time series at reference conditions and on the right at altered conditions. The flow time series are transformed into habitat time series which are shown below.

Over the habitat time series, a blue line representing the average habitat available for the series is reported, this value is used to calculate the ISH index.

To calculate the ITH index the AQ_{97}threshold is considered, and so a red line depicting this threshold is marked in order to visualize the duration and frequency of the under-threshold events.

As an example the habitat time series obtained for the Juvenile Trout and for the Adult Brown Trout are reported with the mean available habitat and the AQ_{97}threshold. Scenarios 1 and 4 have been reported.

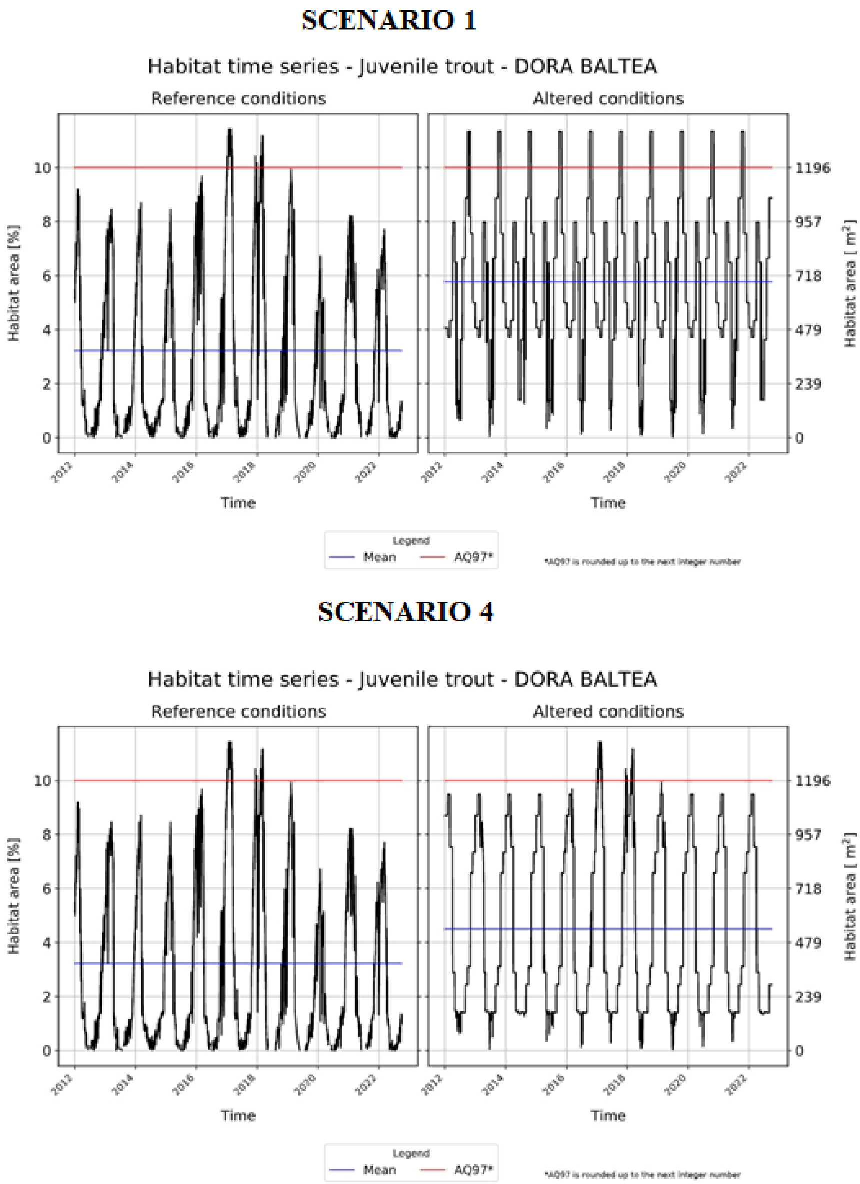

Figure 33: Habitat time series at reference and altered conditions, scenario 1 and 4, for the Juvenile trout. The red line represents the AQ97 threshold while the blue the mean habitat available.

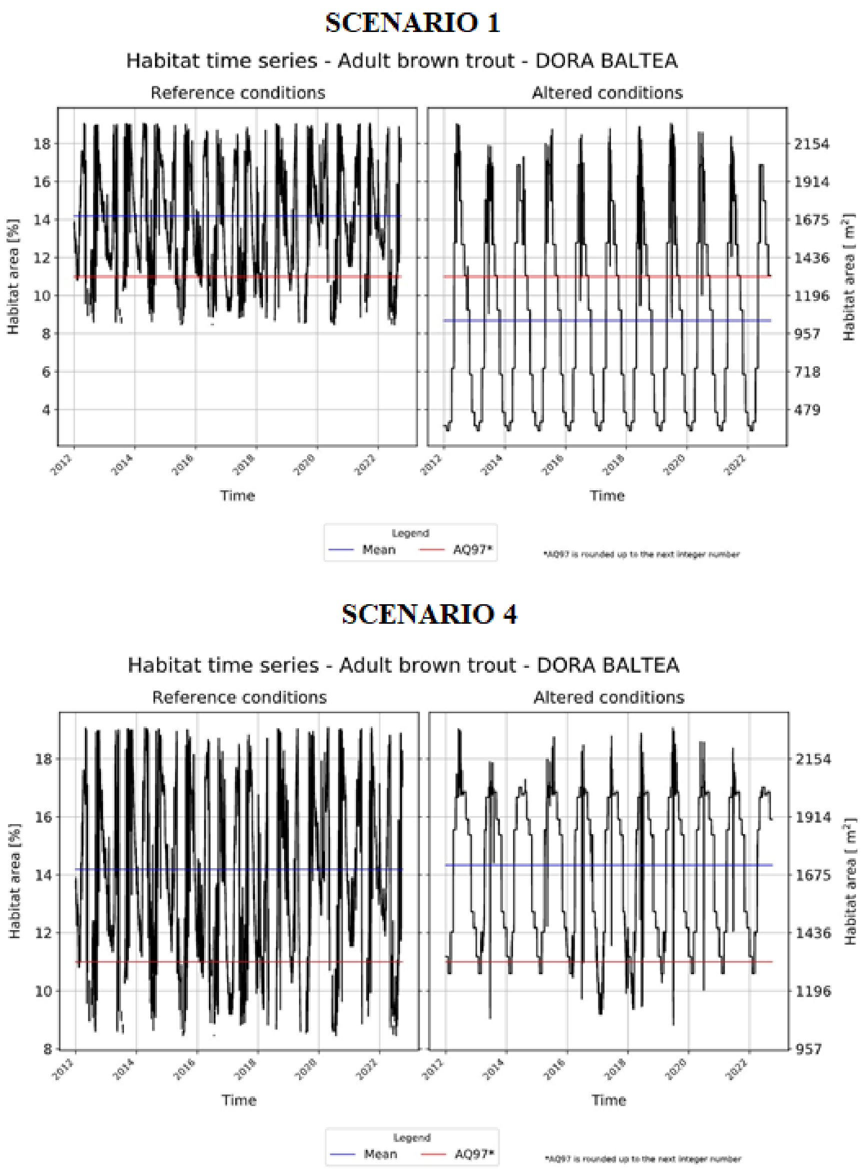

Figure 34: Habitat time series at reference and altered conditions, scenario 1 and 4, for the Adult Brown trout. The red line represents the AQ97 threshold while the blue the mean habitat available.

Once those curves are obtained, considering the AQ_{97} threshold, the UCUT curves are built for the reference and altered conditions. The results obtained for the Juvenile Trout and for the Adult Brown Trout are reported as an example.

The graphs have the cumulative continue under threshold duration in $[\frac{day}{year}]$ on the x-axes and the cumulative duration under threshold in [day] on the y-axes. The distance between the reference and altered curve is used to calculate the ITH, greater is the distance and greater will be the alteration from the reference conditions.

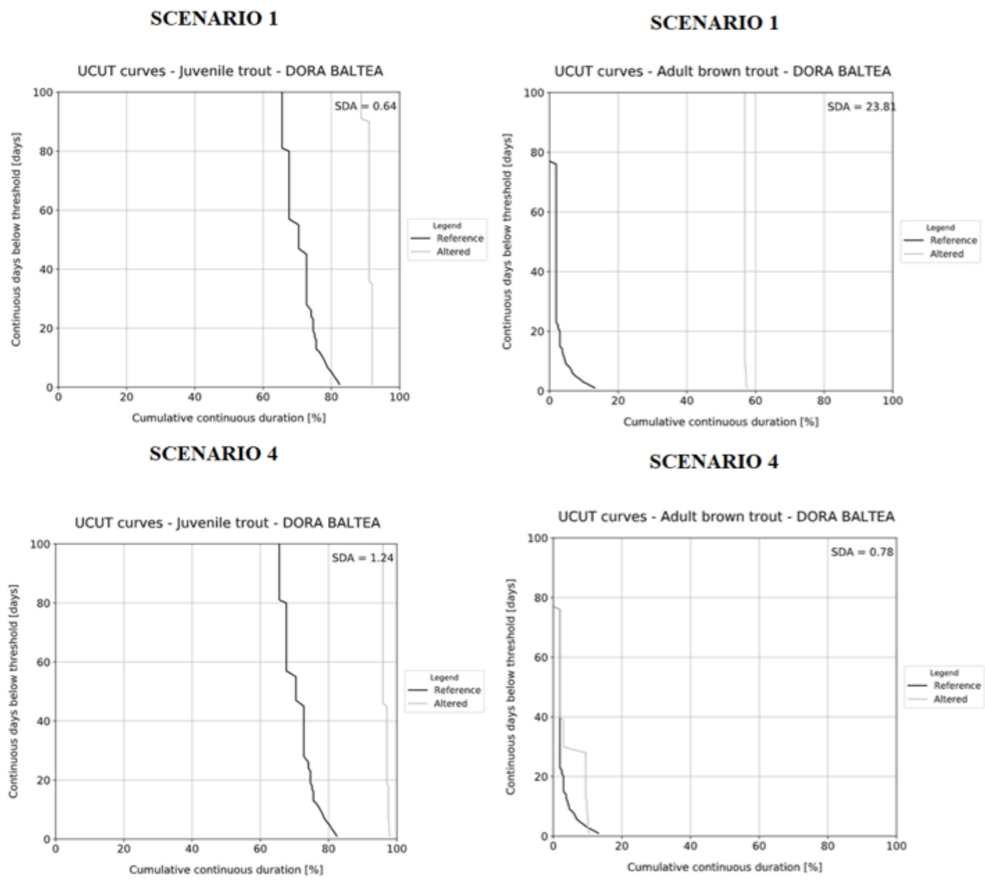

Figure 35: UCUT curves comparison for the scenario1 and 4 for the Juvenile and Adult Brown Trout. The UCUT are reported in reference and altered conditions.

Another results which is helpful to understand the magnitude of the alteration is given by the UCUT curves obtained for different percentage of the total wetted area. For each percentage of a considered wetted area, the correspondent continuous days under this threshold are calculated.

As an example, the curves obtained in scenario 1 and 4 for the Adult Brown Trout are reported. On the left graph, the reference conditions are represented with different UCUT curves for different percentage of available wet area. On the right, the altered conditions are reported with the same percentage. Also in this case, the distance between correspondent curves quantifies the temporal impacts of the alteration considered. Greater is the distance and greater are the temporal alterations on the physical habitat.

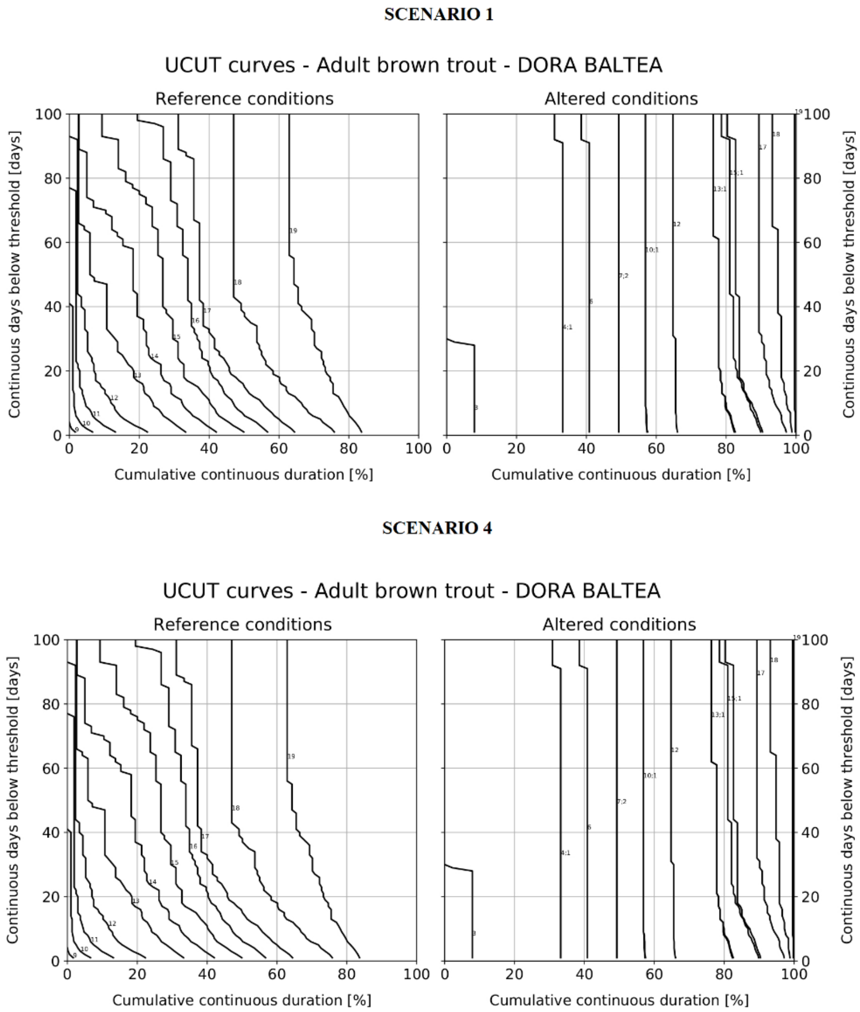

Figure 36: UCUT curves for the first and fourth scenario for the Adult Brown Trout at different percentage of available area.

Another important result obtained is the calculation of the possible annual inflow volume for hydropower production, that can be calculated for each scenario. It is important to underline that it represents only an estimation of the possible production because it is based on hypothetical flow time series not subjected to validation.

The values of the eventual annual inflow volume for hydropower production are reported in the following table.

Table 19: Estimated Inflow Volume for the six scenarios considered.

	Inflow Volume $[10^8\ m^3]$		**Inflow Volume** $[10^8\ m^3]$
Scenario 1	3.66	**Scenario 4**	2.77
Scenario 2	2.99	**Scenario 5**	2.1
Scenario 3	2.47	**Scenario 6**	1.13

Chapter 4

4. DISCUSSION

4.1 HYDROMORPHOLOGICAL DESCRIPTION

The results from the hydrodynamic simulation show an increase in water depth and in velocity with an increase of the considered discharge. In particular, at the higher discharges, greater than 15 $\frac{m^3}{s}$, nearly the entire wetted area belongs to the higher class of velocity (greater than $120\frac{cm}{s}$). This aspect is less relevant but still present for what concerns the water depth distribution.

The following histograms explicate this aspect. They represent for each discharge condition, the cumulative frequency of occurrence of the classes reported on the X-axes.

As shown by the histograms the depth and velocity values tend to increase with an increase of the discharge.

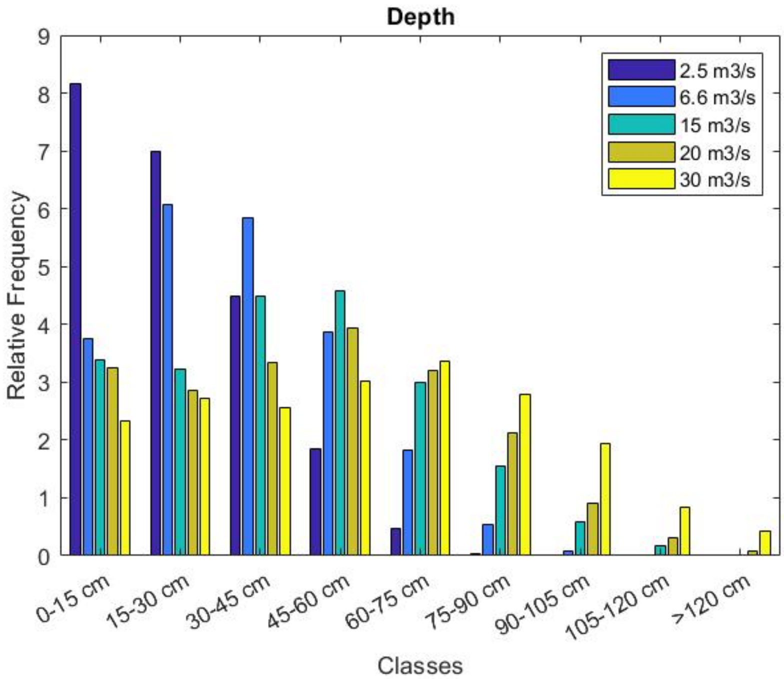

Figure 37: Bar chart reporting the relative frequency of the different depth classes at the discharge values considered. The distribution should shifts towards right as the discharge increases.

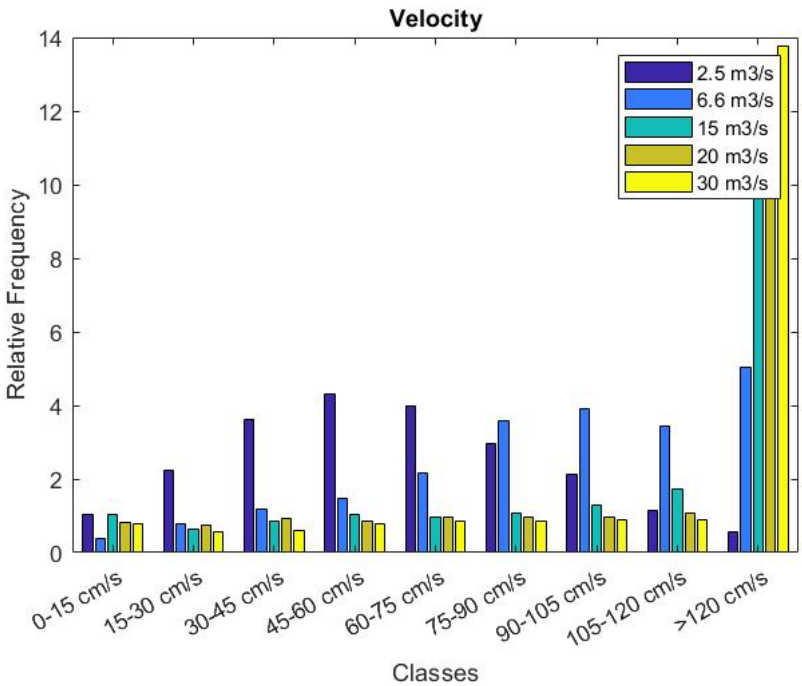

Figure 38: Bar chart reporting the relative frequency of the different velocity classes at the discharge values considered. The distribution should shifts towards right as the discharge increases.

For what concerns the validation of the simulation at the measured discharge in terms of water depth, the R^2 value is very high meaning of a good correlation between the measured and simulated depth. The qualitative accuracy of the model can be also observed in the correspondence of the wetted area extension in both the orthophoto and the results of the simulation itself.

4.2 HABITAT AVAILABILITY

For what concerns the habitat availability and so the results of the data processing peformed by SimStream-Web, the suitability maps and the flow rating curve, highlight some behavior of the selected species.

The juvenile stage of the Brown and Marble trout is present almost only at the lowest discharge, $2.5\frac{m^3}{s}$. All the glides of the first and last segment and of the main branch of the river are suitable. In the secondary branch, some area are also considered as optimal habitat. At higher discharges, almost every habitats are not suitable for the species. This behavior is confirmed also by the rating curve, that for the juvenile stage, shows a maximum of the availability habitat at the lowest discharge. The trout at the juvenile stage in fact prefers water depths of about 45-60 cm and velocities in a range of $45\frac{cm}{s}$ (Negro, et al., 2021) which seems to be coherent with the obtained results.

Regarding the adult Marble Trout instead, the shape of the rating curve is different. In fact the maximum habitat availability is present at higher values of discharge, in particular the maximum is at $6.6\frac{m^3}{s}$ where almost all the habitats are considered suitable, with the exception of the secondary branch of the river, characterized by lower water depth and flow velocity. At the lower flow conditions, an area of the main branch, is considered optimal. It is a glide area sheltered by many big blocks of rock and with depth values of about 80 cm and velocity values around 45 $\frac{cm}{s}$, which are values coherent with the necessity of this specie (Negro, et al., 2021). At greater discharges, the two branches of the ramified part of the river reach are considered suitable while the upstream and downstream sub-reaches are not.

For what concerns the adult Brown Trout, the greatest available area is, as for the Marble Trout, at an average discharge but in this case it is at 15 $\frac{cm}{s}$. In this condition almost all the areas are considered suitable apart from the downstream sub-reach which turns out to be classified as not suitable. Only a lateral meso-habitat is considered optimal . It is characterized by lower depths and velocities in comparison to the areas surrounding it. Another optimal area is present at the lowest discharge value and it is again the glide lateral area sheltered by big rocks. At 2.5 $\frac{m^3}{s}$ the secondary branch is not suitable as well as some glides in the upstream and downstream parts.. The Brown Trout habitat is characterized by slightly lower values of discharge and depth in comparison to the Marble one.

The rating curve for the two adult Trouts are comparable with the only difference of the maximum which is at a lower discharge for the Marble Trout. The juvenile Trout, instead, has a very different curve which is characterized by a lower area available and only at very low discharge values.

4.3 ALTERATION SCENARIOS

The results obtained from the alteration scenarios are particularly significant, because of the comparison of the traditional method for the definition of the e-flows,, to a novel approach, based on the habitat availability analysis.. The first one, does not allow to reach a good habitat quality, while other ways do. This finding underlines the necessity of overcoming the pure hydrological approach.

The following figure reports the hydrograph for one year, in reference and altered conditions. The colors of the altered hydrographs are the same as the IH classes to which they belong.

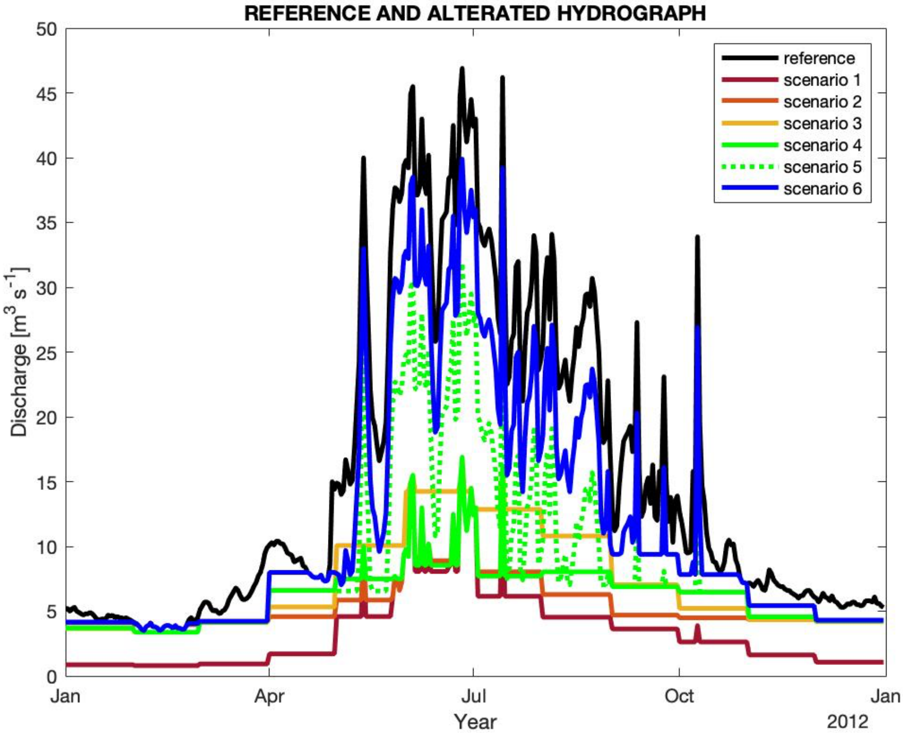

Figure 39: Reference and altered hydrographs for all the scenarios proposed. The colors of the hydrographs correspond to the IH index class of the scenario.

From this graph it is clear that to obtain a good habitat quality is crucial to preserve a consistent discharge during the low flow periods, and eventually incrementing the withdrawal during the periods of higher flows.

The second scenario, for example, always imposes a base flow higher than the Q_{97} but this is not sufficient to reach a good IH index. The fixed base flow slightly exceeds the threshold for a prolonged period. In fact, by this way, there are months, such as May or November, characterized by a significant discharge, during which the minimum flow imposed is too lower than the average reference discharge. This seems to create an issue for the Juvenile Trout habitat spatial availability, ISH index, which negatively impact the IH of this scenario.

The third scenario has a month characterized by habitat availability under threshold but it has very high base flow during high flow periods. However, those high base flow seems not to be relevant for the achievement of a good IH index. Again, the limiting factor is the ISH value of the Juvenile Trout, that determines the IH value. This issue seems to be related again to the base flow values too low during the intermediate months, as in the previous scenario.

The fourth and fifth scenarios both reach an IH index of 0.6. The scenario 4 has base flow slightly higher during the months of May, June, July and August. Both have a month under threshold. The main difference between them is their Q_{max} values which is much lower in the scenario 5. This difference seems not to be relevant for the habitat quality. In fact, only the variation of the Q_{max}, which affect the higher discharges, seems to be not sufficient for the habitat maintenance.

To obtain much higher values of the IH index, it is necessary to have all the base flows over threshold, to have a very low Q_{max} and to keep quite high base flow values during months characterized by intermediate discharges, similar to the average annual discharge of the river in this section. This happens in the scenario N°6, which reaches an IH equal to 0.8. It really follows the original hydrograph, both at the low discharges where the threshold is always exceeded, and both at high discharges where the low Q_{max}value allows to obtain a curve very similar to the original one.

This high rate is obtained even if in some months the minimum flows proposed are lower than the ones proposed for other scenarios which have a much lower IH index, as the scenario 3 which have an IH index of 0.52.

The IH index is determined from the ITH and ISH index which are summarized in table N.18.

Analyzing those results, it is evident that, with the exception of the first scenario, the final value of IH is determined by the ISH index of the Juvenile Trout which has an habitat-flow rating curve that indicates optimal habitat at lower discharges than for the Adult species. Thus, the last five scenarios that propose higher base flows need to be carefully modulated in order to create optimal conditions also for the juvenile stage.

Another important aspect to notice, for what concerns the juvenile stage of the species, is that, conversely to the other stages considered, the ITH values are much higher than the ISH values, meaning that the continuous duration of under threshold events is not significative for them while the spatial availability of the habitat affects more their environment. The difference between the ITH and ISH values is more significant for the first three cases, while it is much less evident for the other scenarios.

In order to better understand the results, it can be helpful to analyze the habitat-time series obtained in reference and altered conditions for the Juvenile Trout (figure N.33) and for the Adult Trout (figure N.34).

For what concerns the Juvenile Trout it can be noticed that in all the scenarios proposed, and also in reference conditions, the mean available habitat (blue line) is lower than the AQ_{97} habitat.

Instead, for the Adult Trout this happens only in the first scenario.

Another fundamental point, that probably determined the fact that for the Juvenile Trout in all the scenarios the ITH is higher than 0.6, is that the periods under threshold are very frequent and very long also at reference conditions. This is also confirmed by the UCUT curves (figure N.35) , where it is easy to notice the very high occurrence of continue under threshold periods in reference conditions. Therefore the reference UCUT is shifted towards right, making the average distance between the reference and altered curve not too significant and thus determining a higher value of ITH.

This phenomenon does not occur for the Adult Trout for which the UCUT curve at reference conditions indicates the presence of very short period under threshold. Consequently the scenario 1, which has a correspondent UCUT curve shifted on the left side, produce a very low ITH index because the average distance between the curves is remarkable.

Finally, in order to choose the best scenario from an ecological and economical point of view, some considerations can be done for what concerns the volume of water turbined, which strongly affects the power production. It is obvious that the greatest production is obtained in scenario 1, table N.19, because it has very low base flow values but a very high maximum usable flow that can be turbined. The increase in minimum flow in the other scenarios determined a drastic reduction of the productivity. As would be expected, the scenario 5 and 6 which reduce the Q_{max} further reduce their productivity.

However, a very interesting aspect to be noticed is that not always an increase of the IH index means a reduction of the productivity. In fact, the scenario 3 has a lower IH index than the scenario 4 even if characterized by a higher productivity in terms of the annual inflow volume for hydropower. This underline the need of a careful management method, in order to find the best trade-off between power production and natural environment preservation.

The scenario which seems to be the best compromise between productivity and habitat maintenance seems to be the scenario 4 which allows to maintain a considerable production and, at the same time, a good IH index. Instead, if lower habitat alterations are allowed then the best scenario is the number 6 which allows to reach an IH index of 0.8.

Chapter 5

5. CONCLUSIONS

The aim of the present work is to find a sustainable management scenario for the base flows that must be released after a river diversion that bring water to an hypothetical hydropower plant.

The Italian legislative framework proposes an approach which consist on the determination of the base flows curve based on an hydrological perspective, starting from the isohyet map or, if available, the mean discharges.

In this analysis this traditional perspective has been overcome and the MesoHABSIM methodology has been applied in order to assess the spatial and temporal habitat availability. Once this analysis was performed for the specific site considered, some scenarios have been developed and their impacts have been quantified by means of the IH index, referring to specific fish species.

The results obtained are quite satisfactory, especially compared to the results obtained from the scenario proposed by the application of the hydrological approach. In fact many scenarios proposed allow to obtain a good habitat quality of the river despite the presence of the alterations and also they allow to get an annual inflow for hydropower which is good enough for a convenient hydropower production. On the contrary, the scenario 1, which follows the legislative guidelines, does not allow to achieve conditions good enough for the fish health and prosperity.

It is important to highlight that both low flows and high flow occurrence should be somehow preserved to produce low impacts (IH=0.8) on the aquatic habitat availability (see Scenario 6, Fig. 23 for details). However, if more habitat alteration is allowed, Scenario 4 and 5 can be considered for future, possible hydropower production.

Those outcomes lead to some reflections in relation to the hydrological approach proposed by the Italian legislative framework because its application can bring to the depletion of the river habitat, as demonstrated by the results obtained from the scenario 1.

The approach proposed in this work resulted in a good achievement, trying to be one the first attempts to define a sustainable management of hydropower production, even if much more deep analysis need to be performed.

However, these first results can encourage further developments in order to evaluate the effectiveness of the method, from both an ecological and productive point of view.

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