POLITECNICO DI TORINO

Master's Degree in Environmental and Land Engineering

Master's Degree Thesis

River restoration and ecological flows: Habitat availability for fish species in the Ticino River (Italy)

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Abstract

Climate change is affecting the water availability and the temperature of rivers, leading to modifications in their biodiversity and posing new challenges for water management. This thesis focuses on investigating the habitat availability for temperature-sensitive fishes during a low-flow period, as part of the T°Cino project aimed at identifying mitigation strategies for the arising problems in the Ticino River (Italy). This study was performed in two sections of the river (Turbigo and Vigevano), located in northern Italy, which is an area significantly impacted by flow regulation and climate change. Through field surveys and the implementation of the MesoHABSIM methodology, the habitat suitability for five different species (bullhead, Italian spring goby, Italian vairone, Po brook lamprey, and marble trout) was assessed to contribute to the T°Cino project's objectives. The results indicate that in both sections, the habitat is suitable for Italian vairone, while Po brook lamprey and Italian spring goby face unsuitable conditions due to the substrate composition. Observations of bullhead and marble trout indicated that, although they face some habitat limitations in terms of water depth, velocity, and substrate composition, other factors such as water temperature or the introduction of alien species may influence the species distribution and presence. The study suggests that factors beyond low flows and morphology, including water temperature and the presence of alien predatory species (e.g., Silurus glanis), contribute to the decline in species abundance. This thesis provides valuable insights for developing effective mitigation strategies for the river, however, further research is necessary to propose more effective environmental flows in the Ticino River.

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Acronyms

ADCP
  Acoustic Doppler Current Profiler

BC
  Boundary Conditions

CIRF
  Centro Italiano per la Riqualificazione Fluviale

DMV
  Deflusso Minimo Vitale

DEM
  Digital Elevation Model

FDC
  Flow Duration Curve

GIS
  Geographic Information System

GNSS
  Global Navigation Satellite System

HII
  Habitat Integrity Index

HMU
  Hydromorphological units

IPCC
: Intergovernmental Panel on Climate Change

ISPRA
: Istituto Superiore per la Protezione e la Ricerca Ambientale

IUCN
: International Union for Conservation of Nature

MQI
: Morphological Quality Index

PDF
: Probability Density Function

WFD
: Water Framework Directive

Chapter 1

Introduction

According to the IPCC report of 2021, greenhouse gas concentrations are at their highest point in 2 million years, reaching emissions of 59 GtCO2-eq in 2019 [1], and emissions keep rising. Because of this, the planet has warmed by around 1.1°C since the late 1800s, with the most recent decade (2011-2020) being the warmest on record [2], and this is just one of the results. Temperature, precipitation, and water flow regime changes have affected freshwater availability, modified river discharge, and heightened the severity and frequency of extreme events. There will be more severe floods, droughts, and sea level rise in the future under the climate change scenarios A2 (high CO2 emission) and B2 (medium CO2 emission) [3].

The effects of climate change are exacerbated by anthropic pressures such as the construction of barriers on rivers and water diversions for hydroelectric and agricultural purposes. These effects have a significant impact on rivers, affecting both their water availability and ecological condition. Alterations in water temperature within rivers can have profound effects on the physiology and ecology of various organisms, including fish species [4], which is a serious problem to be addressed as European watercourses are projected to experience a rise of over 2°C in the mean annual water temperature during the 21st century. [5]. In the north of Italy, the warming has been more intense with respect to the European and global average, with increments in the mean air temperature of around twice the one registered on a global level [6]. This is why it is urgent to take preventive and adaptive actions in the rivers located in this area, focusing on reducing the anthropic pressures on rivers and their consequences.

There are already a lot of initiatives in the EU that are attempting to manage these problems. For example, in 2000 the Water Framework Directive (WFD) was created, which is the main law for water protection in Europe and ensures an integrated approach to water management, respecting the integrity of whole ecosystems. In some rivers of the EU ecological flows (or e-flows) are being implemented, which are considered within the context of the WFD as “a hydrological regime consistent within the achievement of the environmental objectives of the WFD in natural surface water bodies as mentioned in Article 4(1)” [7]. The mentioned objectives consider the non-deterioration of existing status, the achievement of good ecological status, compliance with standards, and objectives for protected areas. In this context, the T°Cino project is born, as a collaboration between Centro Italiano per la Riqualificazione Fluviale (CIRF), Politecnico di Torino, and Parco Ticino, which aims to find the most adequate measures to avoid the degradation of the ecological quality of the Ticino river due to climate change.

The Ticino River is located in the north of Italy, in an area that is strongly affected by climate change and where agriculture is one of the main economic activities. In this river, it is being implemented a Deflusso Minimo Vitale (DMV) or minimum environmental flow which focuses on setting a baseline level of water to prevent harm to the aquatic ecosystem, in contrast to the e-flows, which take into account not only the minimum flow needed but also the natural variability of flow regimes, seasonal fluctuations and specific water requirements for different ecosystem components.

As the temperatures are rising, the discharge of the river has been affected, having in the last year one of the lowest flows recorded in the last two decades, and presenting longer periods of low water flow. Not only the water temperature and river discharge have changed in the last years, but also its biodiversity, which can be seen in the reduction and even extinction of some fish species, as was the case of Thymallus aeliani or in Italian Temolo italico.

This study aims to assess the habitat availability in the Ticino River in low flow conditions by applying the MesoHABSIM methodology in two of the sections analyzed by the T°Cino project, to contribute to the definition of mitigation strategies. Assessing the available habitat for a target species or community serves as a valuable and effective measure for quantifying the impact of hydromorphological changes on the biocoenosis of a watercourse. [8]. The MesoHABSIM method is a useful tool for quantitatively estimating potential changes in fish community habitats resulting from hydromorphological transformations [9].

In order to simulate the habitat availability of the river using the MesoHABSIM methodology the first activities to do were field surveys during low flows, considering topographic and hydromorphological information, and water temperature and fish sampling. With the data obtained in those surveys, it was possible to make 2D hydrodynamic simulations with the software HEC-RAS. These simulations were later used to describe the hydromorphological units of both studied reaches in ArcGIS Pro. Each HMU was described in terms of water depth, flow velocity, water surface gradient, substrate composition, and presence of cover and shelters for fish. After that, the SimStream-Web service was used to get habitat suitability maps and assess habitat availability for the studied species.

Chapter 2

Material and Methods

2.1 Meso-scale Habitat Modelling

It has been demonstrated in numerous studies that alterations in a river's morphology and natural flow regime have a significant impact on its habitat availability. Therefore, it is vital to consider the interactions between fluvial ecosystems and their local hydromorphology to accurately assess the habitat availability of the river. [8]. In this investigation, meso-scale habitat modeling is performed. The meso-habitat refers to the specific section of a river characterized by favorable conditions that support the survival and development of a particular aquatic species. These conditions arise from the homogeneity of morphological features, hydrodynamic configurations, and the presence of distinct physical attributes. [10]. The main objective of this novel approach, which is currently applicated to model habitat changes in small high-gradient streams within the Italian Alps and Apennine mountain ranges [11], is to assess habitat availability for species on a larger scale instead of linking the suitability criteria to small microhabitat units.

The difference between the models based on micro- and meso-scale is that, in the case of the first one, the distribution of the species is defined based on hydraulic variables, such as water depth and flow velocity, whereas in the meso-scale models, the use of spatial units by part of the target community is described as a function of a larger number of environmental variables [8]. The meso-scale approach has many advantages over other established micro-scale methods. For instance, the data collection is based on a robust hierarchical structure of morphological classification [12], and it can be easily carried out with light instrumentation, such as mobile mapping techniques [13] or inexpensive remote sensing [11]. Furthermore, because of the meso-scale resolution, greater stretches of watercourses can be surveyed, and a wider variety of habitat descriptors can be used in the analysis. As such, it may be used to represent and model the intricate morphology of high-gradient mountain streams [14]. Additionally, this approach has the potential to take into account the biotic interactions between the organisms selected as targets and enables, from a biological perspective, a more in-depth analysis at both the single species and community levels [8].

For this study, the procedure performed corresponds to the one defined by the MesoHABSIM methodology. This approach is a physical habitat modeling system developed for instream habitat management in applications such as hydro-power and water withdrawal mitigation as well as the planning of river channel restoration projects [15]. This methodology is an effective method for quantifying potential alterations in fish community habitats within rivers due to hydromorphological transformations. It integrates field-based habitat mapping with a computer model (Sim-Stream service) that forecasts the amount of habitat available for aquatic communities. [9]. Since 2010, the Politecnico di Torino has enhanced and adapted the MesoHABSIM methodology to the Italian rivers [16]. It currently serves as the river habitat suitability model for the entire national context, having the ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) document, written in 2017, as the application's procedural manual [8].

In the MesoHABSIM methodology, mesohabitat types are defined by the so-called hydromorphological units (HMUs), such as riffles and glides. HMUs have a spatial extension between $10^{-}1$ m and 10^{3} m, which is substantially larger compared to microscale structures, which have an extension of about 10 cm [16]. The HMUs are mapped under different flow conditions at specific representative locations along the river. Randomly distributed mesohabitats are surveyed to gather information on fish and/or invertebrates, and habitat surveys are also carried out. These collected data are utilized to develop mathematical models that determine the suitability of each mesohabitat based on the frequency of animal utilization. By employing suitable area as a metric, this approach enables the evaluation of habitat availability across various flow scenarios [15].

This methodology is dedicated to the assessment and modeling of the river habitat to quantify and modulate the *Deflusso Minimo Vitale* (DMV), define the ecological flows (or e-flows), plan and monitor projects of river restoration, preserve protected aquatic species and calculate the Habitat Integrity Index (HII), among other functionalities [8].

2.2 Study area

The study was performed on the Ticino River, which is a 248 km long river with a total catchment area of 7228 km^2, located in southern Switzerland and northern Italy [17], as it can be seen in Figure 2.1. The section in the Italian territory, which is the focus of the T°Cino project, starts in the southern part of Lake Maggiore (91 m.a.s.l.), close to Sesto Calende, and it marks the border between Lombardy and Piedmont until it reaches Abbiategrasso. After that, it flows completely in Lombardy territory until it meets with the Po River in the Pavia province, being its main tributary in terms of flow rate [18].

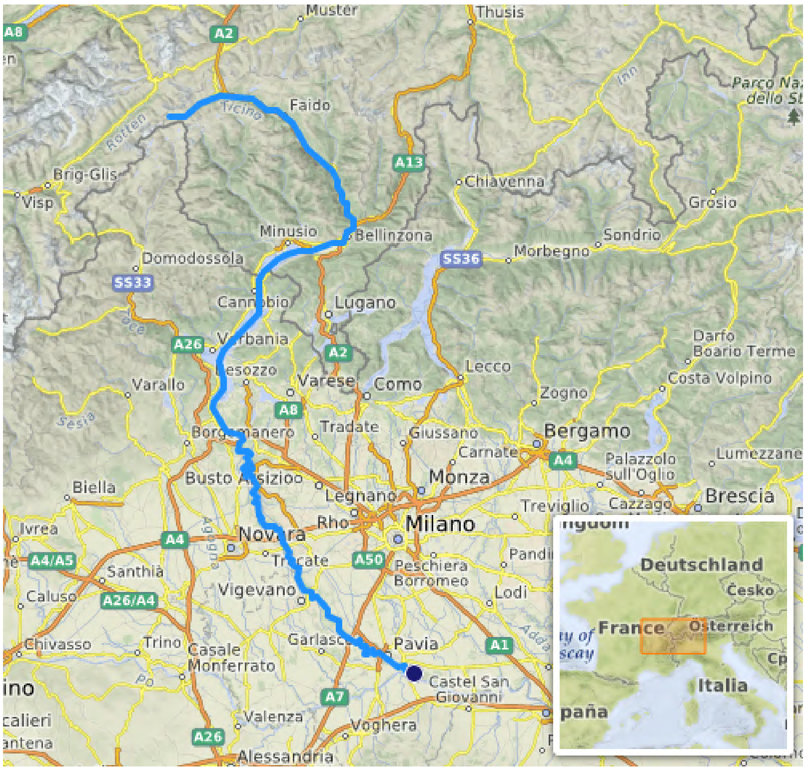

Figure 2.1: Location of Ticino River.

The Ticino River is partly protected by two Regional Parks, which cover a total area of 968.9 km^2, and it has a temperate climate with annual mean values of 13°C for air temperature and 700 mm for rainfall [19]. According to the CORINE Land Cover project [20], almost half of the extension (48%) of the Ticino River basin (considering its whole extension) is used for agricultural activities, with a predominance of rice cultivation, as shown in Figure 2.2.

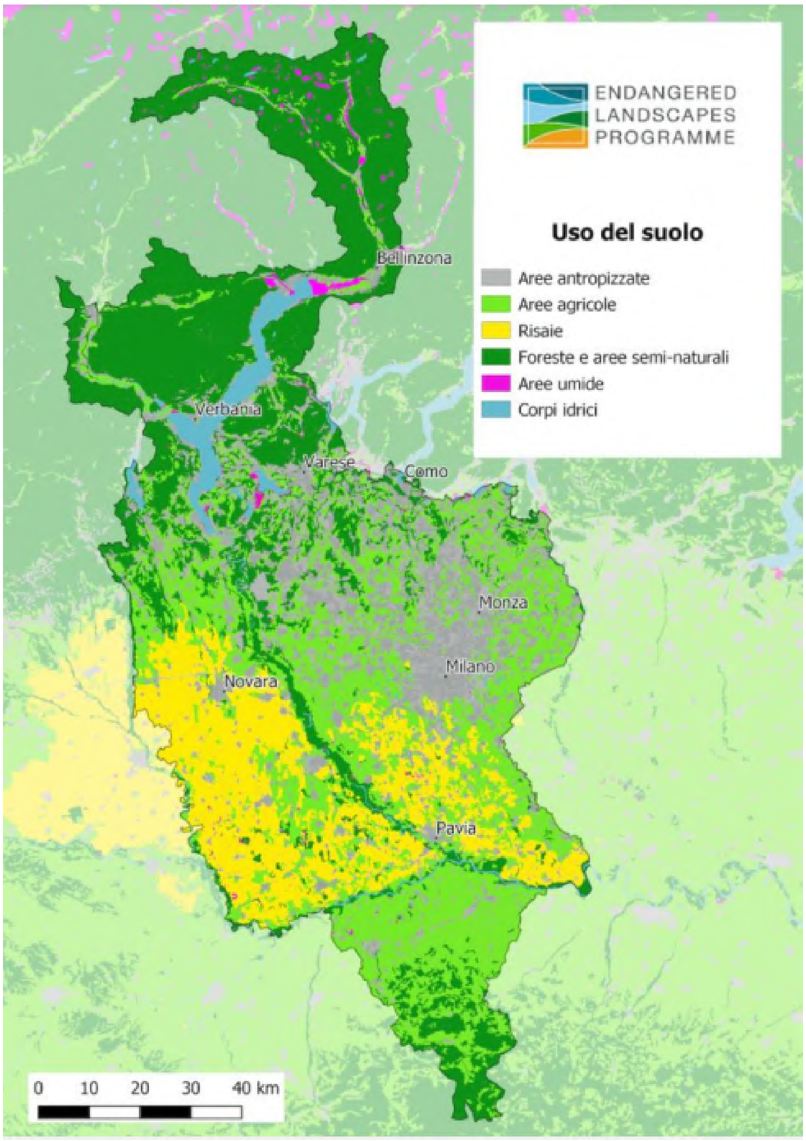

Figure 2.2: Land use of Ticino River basin [6].

The Ticino River was selected because it is one of the best-preserved rivers in northern Italy, even though it flows through the urbanized and industrialized Po Plain. It has very good longitudinal connectivity and, in general, it has a lot of space in natural conditions along its banks, free of urbanization or agricultural activities. Based on the collected information for the T°Cino project about the water temperature and biotic communities of Ticino, and on the need to concentrate project resources on the most significant sections to determine the potential effects of thermal alteration on biotic communities, 6 reaches of the main channel and

6 corresponding secondary channels of Ticino were selected to concentrate the 2-year monitoring efforts planned for the project (Ticino at Turbigo – Roggia Fagiolo; Ticino in front of La Fagiana - Ramo Delizia; Ticino upstream of Vigevano – Ramo dei Prati; Ticino downstream of Lanca Ayala – Canale Nasino; Ticino at the confluence with the Scavizzolo – Scavizzolo channel; Ticino at the confluence with Lanca Piave - Lanca Piave). In particular, the following characteristics were taken into account for the selection of the studied areas:

- The recent presence of fish species potentially more sensitive to thermal alteration, which are described in Section 2.3,
- the different levels of hydromorphological pressures of the Ticino stretches (identified in the classification through the MQI),
- the opportunity to focus attention on the section of Ticino downstream of the main barriers and where the interaction with groundwater is more significant, excluding the section closer to Lake Maggiore and the one close to the confluence with the Po river.

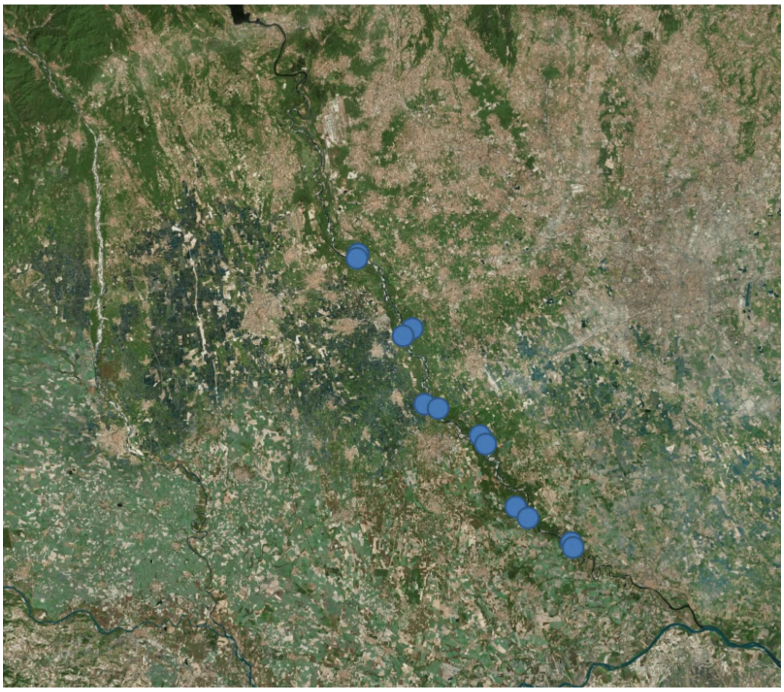

Figure 2.3: The 12 biological monitoring sites in Ticino and its connected channels [21].

The analysis of this study will be concentrated on just two sections of the main channel: Ticino at Turbigo and Ticino at Vigevano. The first one is located a bit south of the town of Turbigo, measuring approximately 1.1 km long and 90 m wide, while the second one is located north of the town of Vigevano, and it measures approximately 930 meters long and 620 meters wide. The location of the study areas can be seen in Figure 2.4. In the extension of the investigated areas, there is a variety of hydromorphological characteristics, like the presence of wood, the presence of backwaters, and the existence of different water depths, velocities, and substrate classes, which means that there is a variety of habitats that will allow us to make a more complete and representative biological analysis.

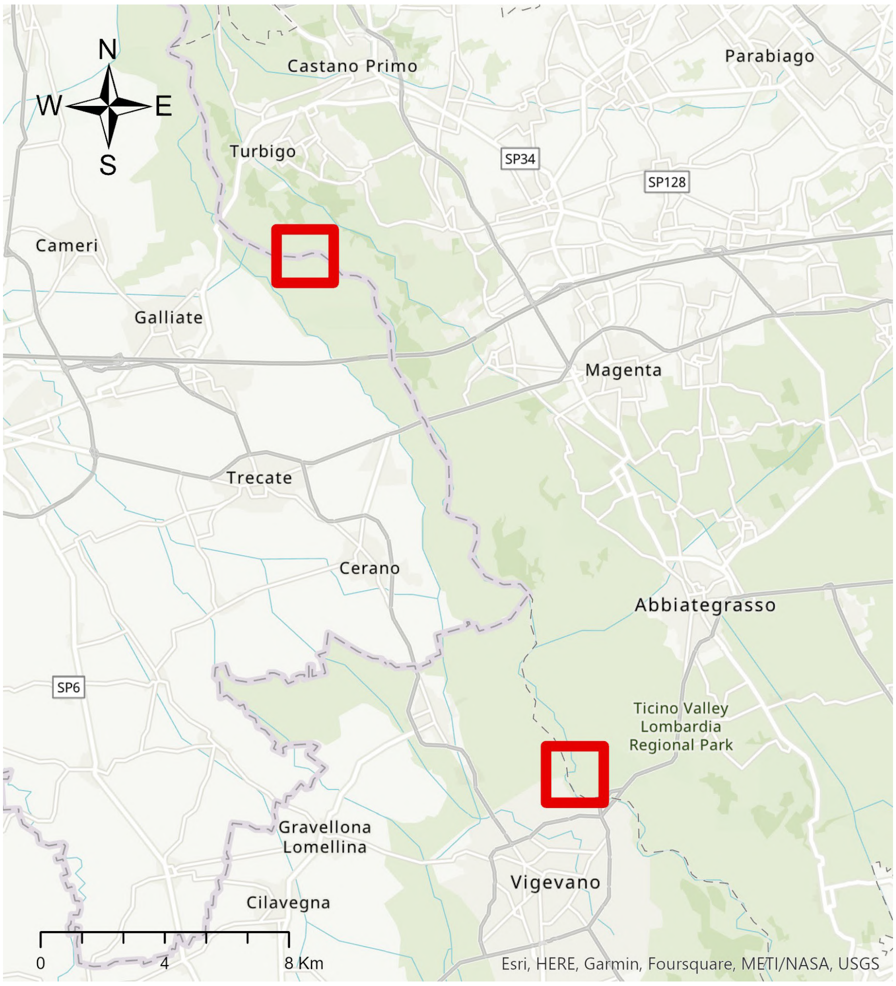

Figure 2.4: Location of study areas on Ticino River.

Figure 2.5: Studied river reach close to Turbigo.

Figure 2.6: Studied river reach upstream of Vigevano.

2.2.1 Hydrologycal description

The hydrological regime of the Ticino River is conditioned by different water sources. The main channel is mostly fed by Lake Maggiore, from where the water flows into the river regulated by the Miorina dam, with contributions that go from 35 to

1000–1500 m^3/s, with minimum flows in summer (August) and winter (February), and maximum flows in the intermediate seasons, during the rainy periods [6]. The river also exchanges flow with a complex network of artificial derivations, tributary channels, and groundwater.

The outflow of Lake Maggiore to Ticino has been regulated by the Miorina Dam since 1942, and the water releases depend mainly on the water level of the lake, according to limits established by the current laws [5]. The maximum capacity of the dam is 420 million m^3, and its maximum flow capacity is 2000 m^3/s [6]. Downstream of the Miorina Dam, approximately 60% of the mean annual discharge is diverted for irrigation and hydro-power energy production, which results in strong flow depletion, especially during the coldest and warmest months of the year [5]. Downstream of Lake Maggiore, the authorized maximum cumulative water diversion is almost equal to the mean annual outflow of the lake, which has a value of 280 m^3/s [18].

Figure 2.7 shows a sketch of the main water diversions from the Ticino River for irrigation and energy generation in each of its banks. The green and yellow lines correspond to extractions for irrigation, while the orange ones correspond to derivations for industrial purposes. On the web page of the regulatory authorities for large lakes (`www.laghi.net`) it is possible to see the flows that have been derived from the river every day by different entities.

During the hydromorphological surveys (4th August 2022), it was possible to measure the flows in both studied areas, where flows of 17.5 m^3/s and 23.33 m^3/s were measured in the Turbigo and Vigevano reaches respectively. Besides, along the Ticino River, some gauging stations are continuously monitoring the water level and the river discharge. In Vigevano, very close to the studied section in the confluence with the secondary channel Ramo dei Prati, there is a station monitoring the water level since 2000 and the discharge since 2004. Thanks to the data from that station it was possible to build a hydrograph using the data from the last 3 years to understand the discharge behavior during the years and how it has been changing lately. Also, a Flow Duration Curve (FDC) was plotted with the data of all the available years to see how low the flows measured in the field surveys were. Furthermore, the flow's Probability Density Function (PDF) was built using the available data to see the probability of low flows. The behavior in time of the flow obtained in the monitoring station in Vigevano can be considered representative of the conditions in the Vigevano section.

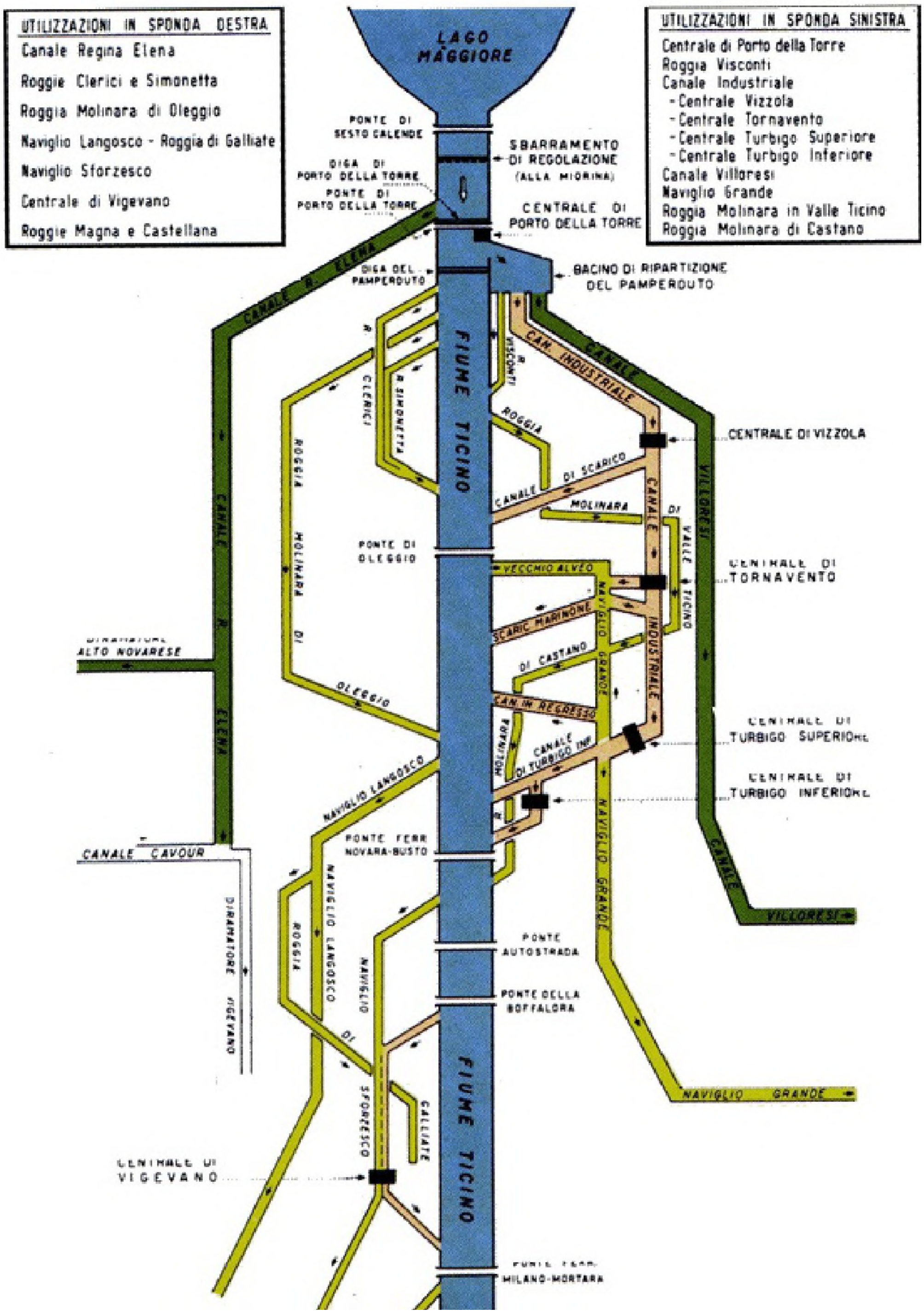

Figure 2.7: Main water diversions from the Ticino river [22].

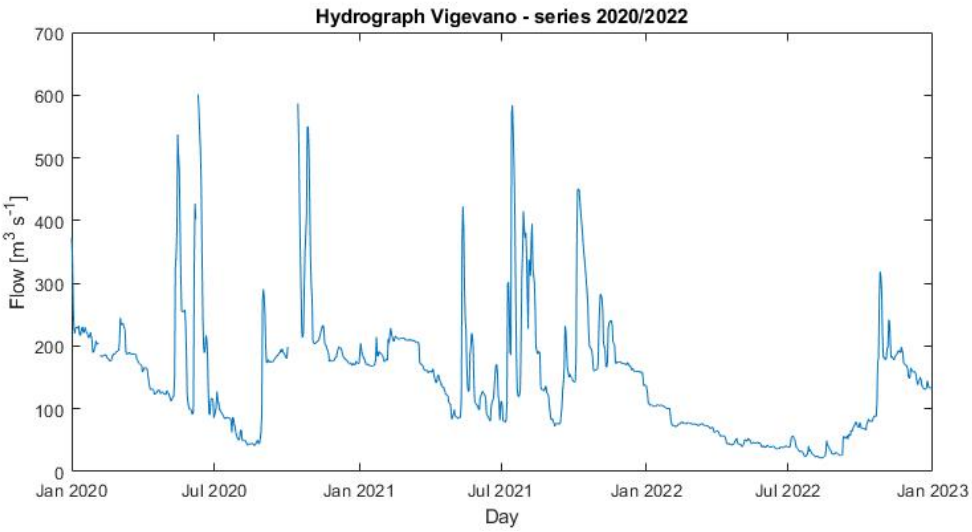

Figure 2.8: Hydrograph of the Ticino River in Vigevano from 2020 to 2022.

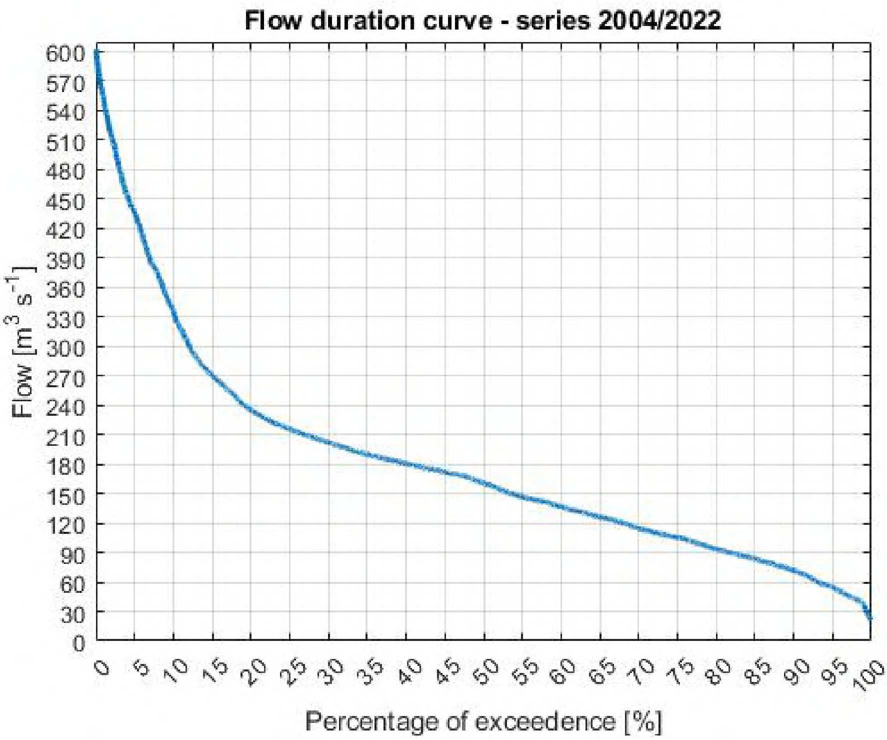

Figure 2.9: Flow duration curve of the Ticino River (2004-2022).

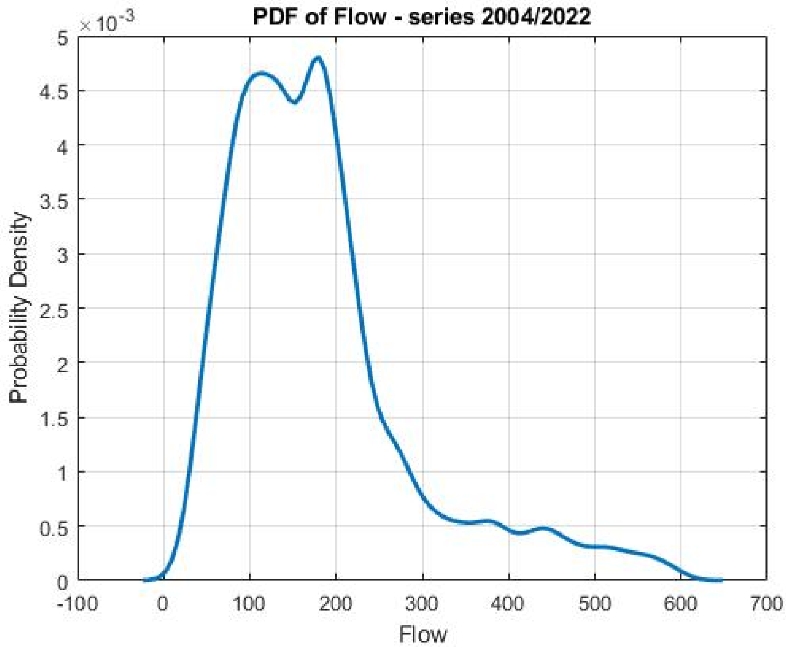

Figure 2.10: Probability Density Function of the flow of Ticino River in Vigevano (2004-2022).

2.2.2 Thermal regime

It is important to understand the thermal regime of the river since it is a fundamental feature of river ecology [23]. The thermal regime is influenced by several factors, including the river discharge, which determines heat load; the topography and streambed morphology, which determine heat exchange at the streambed/water interface; and the atmospheric conditions and shading by riparian vegetation, which determine heat exchange at the air-water interface [5]. Also, the interaction with groundwater plays a significant role since it ensures the presence of patches of cool water for aquatic organisms [5].

In the case of Ticino, the river discharge is influenced by the releases coming from the dam, which results in a thermal regime alteration. Depending on the dam structure, the water released can come from the epilimnetic (warmer) or hypolimnetic (colder) reservoir layers [24]. In the case of Miorina Dam, the water that flows into the river comes from the epilimnetic layer [5], which produces an increase in the water temperature downstream of the dam.

Another factor that influences the river's temperature is the amount of water flowing in the river. In low flow conditions, the reduced thermal capacity translates into an increase in summer maxima and a decrease in winter minima and widens the daily range of variability [23]. In the case of low flows, river temperature along a section ranges between a maximum that is higher than the water temperature at the lake outlet, due to shallow water warming, and a minimum that is lower than the water temperature at the lake outlet, due to the groundwater contribution [5]. In the Ticino River, the lateral channels of the river are mainly fed by groundwater, while the water in the main channel comes mostly from Lake Maggiore. As part of the T°Cino project, water temperature surveys are being performed, as explained in Section 2.4.3, to better characterize the thermal regime of the river and understand how it is influencing the habitat suitability of each area for the studied species.

2.3 Species of interest

In order to comprehend the behavior of the studied species when facing changes in their habitat, it is important to understand their habitat preferences, considering not only hydromorphological characteristics but also their thermal tolerance. The MesoHABSIM method takes into account only hydromorphological parameters for the prediction of habitat suitability and biological models, which is why it is necessary to also study the thermal preferences for a more complete analysis. The upper thermal limit of a species provides insight into its relative sensitivity to high temperatures, which is especially important in river systems exposed to severe water stress and relatively high water temperatures, such as the Ticino River [5]. This section aims to introduce each of the studied species, which as said before were chosen because they are potentially more sensitive to thermal alteration, and to briefly describe their habitat preferences.

Bullhead – *Cottus gobio*

The bullhead, known in Italy as scazzone, is widely distributed in Europe, ranging from North Spain to Scandinavia, excluding only Scotland and Ireland [25]. The bullhead generally inhabits unpolluted, clear, and oxygen-rich streams, with water temperatures non-superior to 14–16 °C [26]. During the day, bullheads are inactive and seek shelter underneath loose stones, whereas stones are also important for successful reproduction because they are used as spawning substrates [25]. Riffles have been mentioned as their preferred habitat with low water depth, high velocity, and coarse substrate [27]. The upper thermal tolerance for C. gobio was found to be 27.7 °C [4].

Figure 2.11: Cottus gobio.

Italian golden loach - *Sabanejewia larvata*

This fish, known in Italy as Cobite mascherato, is endemic to the Padua-Venetian regions. Its habitat corresponds to clear and almost still waters [28], in the lowland and hill zones with sandy or muddy bottoms rich in vegetation [29]. There is not much information about the habitat and temperature preferences of this species available in the literature.

Figure 2.12: Sabanejewia larvata.

Italian spring goby - *Knipowitschia punctatissima*

The Knipowitchia punctatissima, or panzarolo in Italian, is endemic to north-eastern Italy and it lives in springs and cold clean streams on the plain, with water temperatures that go from 11°C to 16°C [30]. The species is endangered by habitat destruction, especially that caused by the lowering of the water table [29]. Its habitat corresponds to streams with slow flow and sandy or graveled bottoms, rich in vegetation [30].

Figure 2.13: Knipowitschia punctatissima.

Italian Vairone - *Telestes muticellus*

The Telestes muticellus, commonly known in Italy as vairone italico, is endemic to Northern and Central Italy [31] and it inhabits cold running waters with high levels of dissolved oxygen [32]. According to D'Amen et al. (2017) [33], T. muticellus is mainly distributed in the upper part of the watercourses and its presence is negatively influenced by fine substrate (that is, silt and clay).

Data about its temperature preferences was not found specifically for Telestes muticellus, but there are studies for Telestes souffia (western vairone) and for other species of the Cyprinidae family [34]. For western Vairone the optimum temperature for the juvenile stage appears to lie between 13 °C and 15 °C [35], while for the adult stage, the optimum is between 10 °C and 18 °C, with an extreme maximum of 27 °C [36].

Figure 2.14: Telestes muticellus.

Marble trout - *Salmo marmoratus*

Salmo marmoratus, or in Italian trota marmorata, is an endemic species of the foothills reaches of the alpine affluents of the Po River and it belongs to the family of Salmonidae. This species needs an extremely heterogeneous habitat for its different life stages. The adults prefer deep areas with slow flows where they can find shelter, while the juveniles prefer zones with shallow and fast flows [37].

This species prefers cool and oxygenated water with sandy or gravelly bottoms [29], with water temperatures lower than 16-18°C [37]. No studies were found in the literature about the maximum temperature limit for Salmo marmoratus, but a study by Pankhurst and King (2010) [38] provides this value for other species of the same family. For example, Salmo salar L. and S. alpinus have an approximate upper limit of thermal tolerance of 22–24°C, while O. mykiss has an upper threshold of 26,5°C [39].

Figure 2.15: Salmo marmoratus.

Po Brook lamprey - *Lampetra zanandreai*

The Po Brook lamprey, or in Italian Lampreda padana, lives in clean and cold water, with a bottom that may be muddy or sandy, usually near springs in the foot-hill zone, with water temperatures ranging from 5°C in winter to 19,5°C in the summer [40]. It belongs to the family Petromyzontidae, and it can be found in the Po Plain in northern Italy.

No study was found in literature concerning the upper thermal tolerance of the

Lampetra zanandreai, but according to Potter (1980), who performed studies on lethal temperatures on ammocoetes of different species of Petromyzontidae in the laboratory, the ultimate incipient lethal value for Lampetra planeri is of 29.2°C, and it has been found that this species has an affinity with Lampetra zanandreai [41].

Figure 2.16: Lampetra zanandreai.

To develop quantitative relationships between physical habitat conditions and the distribution of autochthonous Italian fish species, Negro et al (2021) [42] reviewed 250 bibliography sources published over the last 8 decades, describing habitat preferences of 34 Italian autochthonous freshwater species, which included all the species of interest for this study, except for the Knipowitschia punctatissima. Figure 7 shows the results obtained in the bibliographic investigation for the species of interest for this study. In the figure, the orientation of the arrows suggests the preferred category of habitat parameters for each species, life stage (A=adult, J=juvenile), and bioperiod (S=spawning), and the size expresses the corresponding number of sources reporting the same information. Background colors are used to highlight the three groups of species: species with quite copious information (yellow), species with limited available data (orange), and species with very poor information (red). Water depth, current velocity, substrate composition, and cover are represented by the categories described in the Mesohabsim methodology. For a better understanding, sample diagrams are given at the bottom of the Figure.

Table 2.1 summarizes the studied species, showing the family to which they belong, if they were historically present in Ticino (before 2012), and if they were recently present in the main or secondary channels (since 2017). In the table it can also be seen the status of each species in the IUCN Red List, where VU stands for Vulnerable, LC is Least Concern and CR means Critically Endangered.

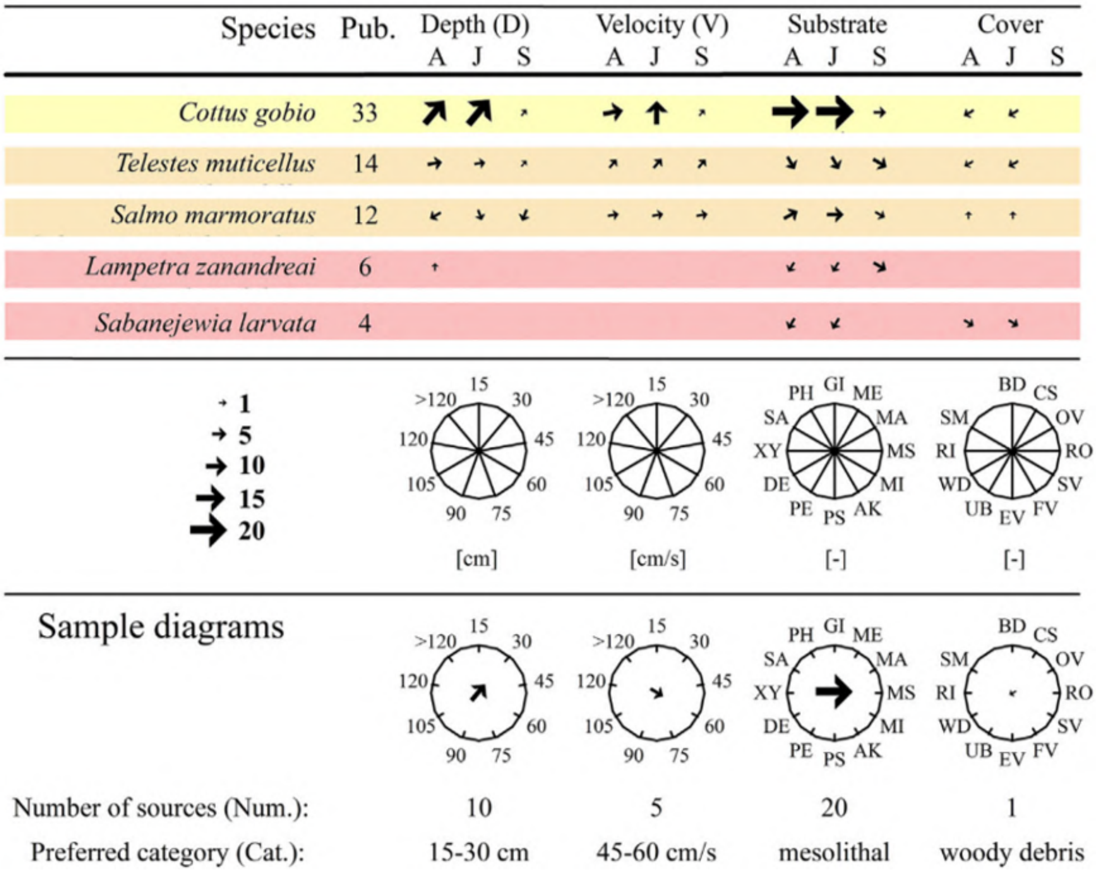

Figure 2.17: Habitat preferences of the studied species. Substrate categories codes: GI, gigalithal; ME, megalithal; MA, macrolithal; MS, mesolithal; MI, microlithal; AK, akal; PS, psammal; PE, pelal; DE, detritus; XY, xylal; SA, sapropel; PH, phytal. Cover categories codes: BD, boulder; CS, canopy shading; OV, overhanging vegetation; RO, roots; SV, submerged vegetation; FV, floating vegetation; EV, emerging vegetation; UB, undercut bank; WD, woody debris; RI, riprap; SM, shallow margins. Source: Adapted from Negro et al, 2021 [42].

Table 2.1: Historical presence in Ticino and IUCN Red List status of the studied species

Family	**Species**	**Common name**	**Historic presence in Ticino**	**Recent presence in Ticino**	**Recent presence in secondary channels**	**Red List status [43]**
Cottidae	*Cottus gobio*	Bullhead	YES	YES	YES	LC
Cobitidae	*Sabanejewia larvata*	Italian golden loach	YES		YES	VU
Gobiidae	*Knipowitschia punctatissima*	Italian spring goby	YES		YES	CR
Cyprinidae	*Telestes muticellus*	Italian Vairone	YES	YES	YES	LC
Salmonidae	*Salmo marmoratus*	Marble trout	YES		YES	CR
Petromyzontidae	*Lampetra zanandreai*	Po brook lamprey	YES		YES	VU

2.4 Field survey

Before the field surveys were performed, previous monitoring data of the study area were collected as part of the T°Cino project during the period of March–May 2022. In particular, the searched information corresponded to water temperature data recorded at already existing measurement stations as well as data concerning the fish fauna (Figure 2.18) and benthic macroinvertebrates. After the previous research was done and the studied areas were selected, the following surveys were programmed for each section [21]:

- In the first 5 reaches of the main channel: Bathymetric and flow field surveys and water temperature measurements,
- spatial measurements of water surface temperature via a drone-mounted thermal camera and acquisition of orthophotos with 2.5 cm and 10 cm resolution,
- continuous measurement of the water temperature through probes, some of them already present in the area and others installed for the project,
- 4 biological surveys for fish fauna and benthic macroinvertebrates.

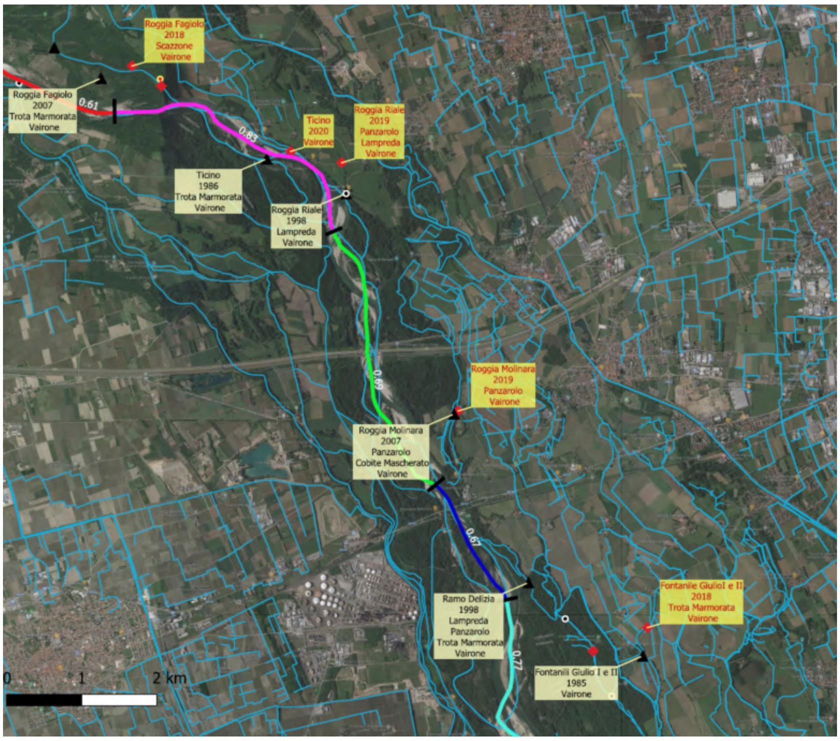

Figure 2.18: Extract of the mapping of the preexisting monitoring data of the fish fauna in a section of the Ticino River [21].

2.4.1 Topographic surveys

The data collection process involved gathering information about the physical habitat through the integration of a drone survey, and it took place only in the stretches depicted in Figure 2.19, with an average length of 1.5 km, focusing on sections within the main channel. The survey comprised two main steps: Firstly, a consistent number of Ground Control Points were strategically placed throughout the entire area of interest for each section to ensure precise georeferencing of the orthophoto obtained from the drone footage. Secondly, a drone flight was conducted to capture the necessary images [16]. The equipment utilized for this survey included a dual-frequency GNSS (Global Navigation Satellite System) antenna and a DJI Mavic 2 Pro remote-piloted aircraft, as illustrated in Figure 2.20.

Figure 2.19: The 6 polygons of the sites of biological monitoring in Ticino, where the thermal and bathymetric surveys were performed [21].

Figure 2.20: DJI Mavic 2 Pro drone used in the surveys in August 2022 on Ticino River.

The recorded images were processed using PIX4D software (PIX4D SA, Lausanne, Switzerland) and employing *structure from motion*, which utilizes a sequence of 2D images to reconstruct a 3D scene. Through this post-processing procedure, an RGB orthomosaic of the designated area was generated [16]. Two orthophotos were obtained, with resolutions of 2.5 cm and 10 cm, respectively, along with the corresponding Digital Elevation Model (DEM). The DEM is of utmost importance for the development of hydrodynamic models.

2.4.2 Hydromorphological surveys

Hydromorphological and bathymetric surveys were conducted between August 1st and 4th, 2022 to gather essential data for assessing habitat availability for the target fish species using the MesoHABSIM methodology. The surveys were limited to the first five monitoring sections of the main channel of the Ticino River due to safety concerns and inadequate transparency conditions in the downstream reach, which hindered the accurate assessment of flow rate, speed, riverbed reconstruction, and substrate composition [21].

The bathymetric survey and flow field mapping were conducted concurrently using the RiverSurveyor M9 system (Sontek, San Diego, CA, USA), which consists of an ADCP sensor (Acoustic Doppler Current Profiler) and a multi-beam precision depth sounder mounted on a floating platform, as depicted in Figure 2.21. To ensure georeferenced data for water depth and velocity measurements, a dual-frequency GNSS antenna was integrated into the system [16].

Figure 2.21: Bathymetric survey in the Turbigo reach using the ADCP on the floating platform.

The acquisition of depth data is facilitated by the multi-beam precision depth sounder, which measures two types of water depth: Bottom Track and Vertical Beam. Bottom Track provides rough depth data and records the vessel's speed over the ground, particularly in GPS loss situations. However, the Vertical Beam method is preferred when ultra-precise positioning is available, as it yields more accurate depth values. Additionally, the ADCP calculates velocity profiles along the water column at a frequency of 1 Hz by utilizing the Doppler effect resulting from the interaction between emitted sound waves and water waves. These velocity profiles form a grid of mean velocity for the entire section [16].

The RiverSurveyor Live software enables both post-processing data analysis and real-time data monitoring. It facilitates the extraction of acquired water depth and velocity data, providing visualization of the vessel's georeferenced track, bathymetric profile, and the grid of calculated current velocity in each section. Furthermore, the software allows for the determination of flow rate values by selecting the appropriate section of the river [16]. Figure 2.22 illustrates an example of the software's output.

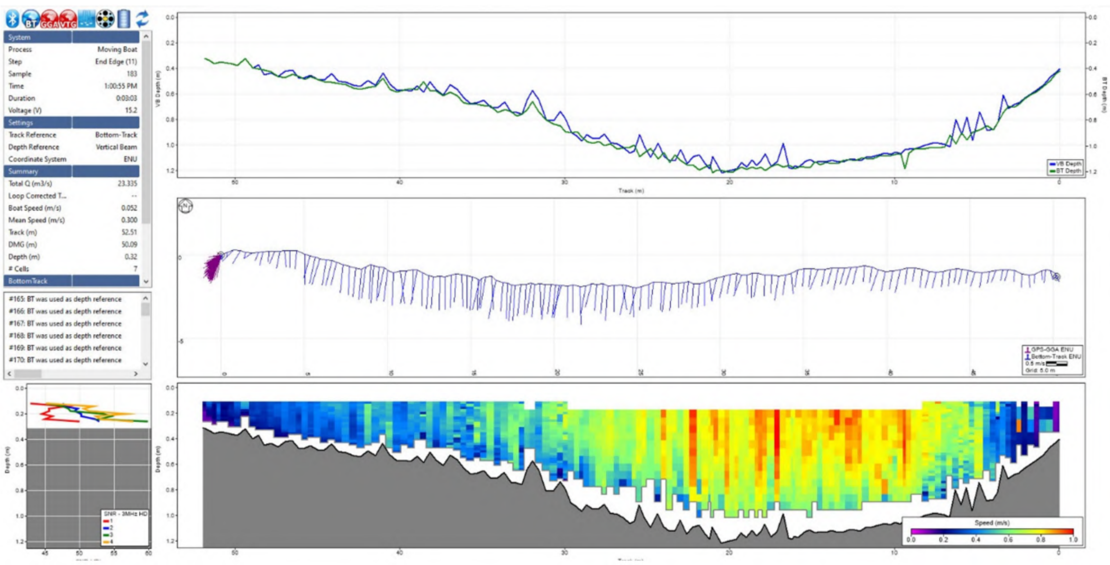

Figure 2.22: Example of the visualization of the use of the RiverSurveyor software along a section of the river. The top view displays the riverbed, indicating water depth values obtained from the Bottom Track and Vertical Beam measurements. The middle view shows the vessel's track on an N-E plan, and the bottom view presents the grid depicting the calculation of mean current velocity [16]. The calculated flow rate is 23.33 m^3/s.

The use of this instrumentation has allowed the collection of a large number of measurement points of water depth and current velocity, which were later used as ground truth for both the construction of bathymetric models and the validation of the corresponding hydrodynamic models. In particular, concerning the local hydromorphological conditions (flow rate, wet area extension, average riverbed width, number of channels) of each analyzed stretch of the watercourse, it was possible to obtain a total number of measurement points of the hydrodynamic variables equal to 17520 [21]. In the case of the Turbigo reach, the water depth and velocity measures covered a surface of approximately 815 m long and 30 m wide, with almost 3500 sample points, while in the Vigevano section, the measures covered a surface of about 990 m long and 60 meters wide, with nearly 6000 sample points.

A limitation of this data acquisition method is its inability to record data in areas with water depths below approximately 20 cm. To overcome this limitation, electromagnetic current meter acquisition (MF PRO, OTT Loveland, CO, USA) was used in those zones to fill in the missing data. Although the spatial frequency of sampling is lower compared to the boat method, this approach enables the acquisition of a more comprehensive dataset [16].

2.4.3 Temperature surveys

For the temperature measurements, two techniques were employed. The first one consisted of the installation of temperature loggers in each of the studied sections. The temperature loggers used were waterproof and they use Bluetooth to deliver high-accuracy data to mobile devices or Windows computers. In addition to this, in each of the surveys (biological and bathymetric), the water temperature was measured in every section using a dissolved oxygen meter, along with the oxygen content, to record the environmental conditions at the moment of the survey [21].

Figure 2.23: Example of data logger used in the filed.

Unfortunately, the installation of the data loggers could not be carried out at all sites from the start of the project as initially planned due to an unexpected and extremely long delay in the delivery by the distributor. Therefore, starting from the beginning of May 2022, 5 probes already owned by the project partners were installed, awaiting those ordered by the Parco Ticino Lombardo's authority, which were delivered only in November, while those with remote data transmission received with technical problems are currently not yet available. Therefore, in November, the installation of the new data loggers was done, replacing the previous ones [21]. The location of the data loggers is illustrated in Figure 2.24.

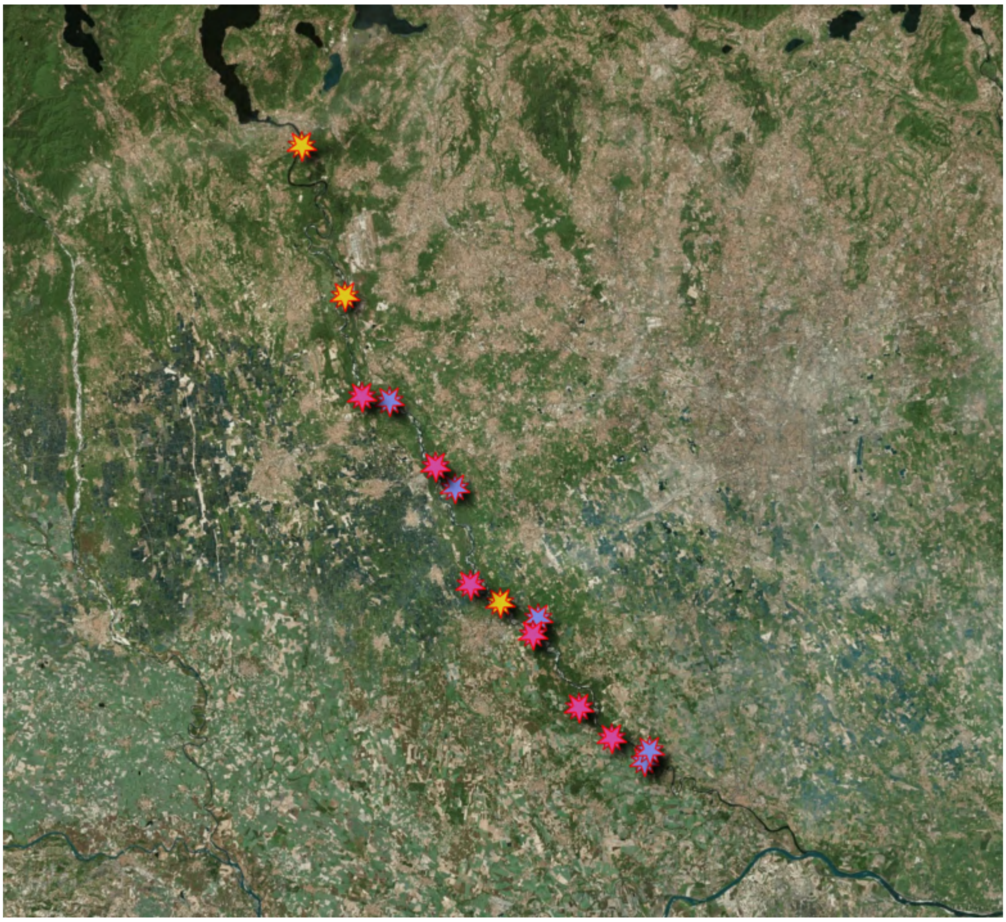

Figure 2.24: Temperature measurement sites currently available for the project (in yellow: probes present before this project in the context of the project Interreg Parchi Verbano Ticino; in violet: installed in March 2022 for the T°Cino project; in pink: installed in November 2022 for the T°Cino project) [21].

The second technique adopted for the measurement of water temperature was the use of a drone-mounted thermal camera. The radiant temperature measurement campaign by drone, carried out as planned during the longest period of high ambient temperature (August 1–5, 2022), did not provide the expected results. The extension of the monitored sections and the high temperatures in the field have led to excessive overheating of the thermal camera (although it corresponded to the state of the art in the field of drone measurements). This has led to a frequent automatic recalibration of the instrument, with an overall "thermal drift" of the measurement, which is therefore not reliable as it suffers from an uncorrectable error. However, the lack of an aerial survey of the water temperature was, at least partially, compensated by the linear measurements carried out during the bathymetric survey [21].

The limitations encountered in the used technology led to a change in the monitoring plan, which now considers a similar survey for August 2023, but with a different type of thermal camera, which is larger and is mounted on an ultralight drone. On the basis of previous experience in the river sector, this technique ensures accuracy and reliability even in the foreseen temperature conditions [21].

2.4.4 Biological surveys

The fish samplings were carried out in the periods 9-12 May 2022, 1-5 August 2022, and 17-21 April 2023, and the last one is planned for August 2023. The samplings were carried out at all 12 monitoring sites (Figure 2.3) for the fish and lamprey species shown in Table 2.1, which were selected because they are potentially more sensitive to thermal alteration.

The surveys consisted of semi-quantitative sampling by electro-fishing, mostly from boats for the reaches of the Ticino main channel and on foot for the secondary channels. After the fish were collected, each of them was weighed and measured and then returned to the river. With this inspection, it is possible to get an idea of the number of individuals of each species that are present in the studied sections, and with this information, it is also possible to build length-weight curves for each species. The Figures below show some of the procedures for the survey.

Figure 2.25: Electro-fishing in one of the secondary channels.

Figure 2.26: Electro-fishing in the main channel.

2.5 Hydromorphological data analysis

2.5.1 Bathymetric correction

The software used for the correction of the DEM obtained in the field was ArcGIS Pro (version 3.1.0) from Esri. ArcGIS Pro is a desktop GIS (Geographic Information System) application that can make full use of modern computer hardware while at the same time presenting users with an easy-to-use and intuitive interface [44]. It can be used to explore, visualize and analyze data, create 2D maps and 3D scenes, automate and standardize processes and share the work through ArcGIS Online and ArcGIS Enterprise portal.

It is essential to correct the DEM to ensure an accurate representation of the riverbed's topographic surface. This correction is necessary because the current DEM creation process does not account for water refraction effects. As a consequence, the recorded elevation of the submerged area appears higher than its actual value due to the refraction effect. When the beam passes from air to water, its direction is altered, as water is a denser medium. Consequently, the calculated water depth, determined by comparing the DEM with the free water surface raster, underestimates the true depth [16]. Figure 2.27 shows an example of the refraction effect in a section of the Vigevano reach.

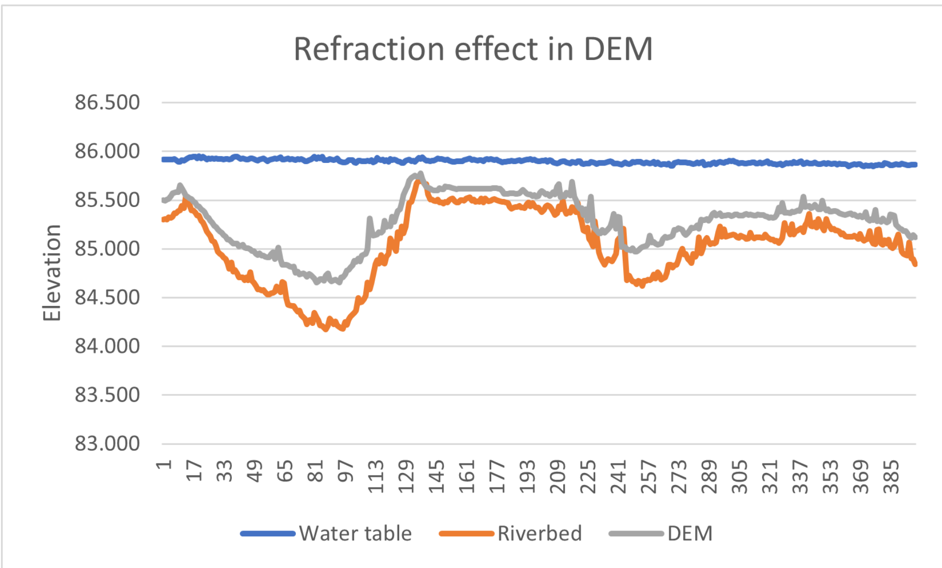

Figure 2.27: Refraction effect: The orange profile represents the stream bed elevation provided by the bathymetric survey (considered the real one). The gray one is the stream bed elevation measured during the topographical survey.

To address this issue, a calibration process was conducted to refine the bathymetric model by integrating data from both the photogrammetric survey and the bathymetric acquisition. Through photogrammetric analysis, fictitious water depth points were estimated and compared with the measured water depth points (actual water depth). This comparison allowed the establishment of a linear regression model that accurately describes the relationship between the real and fictitious points. This calibration process resulted in a correction equation that can be applied to adjust the DEM, serving as the geometric foundation for the hydrodynamic model [16].

2.5.2 Hydrodynamic simulation

For the hydrodynamic simulation, the software HEC-RAS (U.S. Army Corps of Engineers River Analysis System) version 6.3.1 was used. The use of this program allows the performance of 1D steady flow hydraulics, 1D and 2D unsteady flow river hydraulics calculations, quasi-unsteady and full unsteady flow sediment transport-mobile bed modeling, water temperature analysis and generalized water quality modeling [45]. HEC-RAS can provide detailed 2D channel and floodplain modeling, combine 1D channels with 2D floodplain areas, directly connect 1D reaches into and out of 2D flow areas, connect multiple 2D flow areas in the same geometry, and allows to work with mixed flow regimes, among other functions.

In this study, a 2D unsteady flow simulation was performed for both reaches to get simulated rasters of water depth and velocity, which were then compared with the on-field measurements of these parameters to ensure their validity. The necessary inputs for the simulation were the corrected DEMs of the river reaches, whose creation was explained in the previous section, and the river flow hydrographs, which corresponded to the flow values measured in the field. The Mannings number, which was obtained from literature using the observed properties of the river bed, was also one of the data inputs needed.

To get the simulation, the first step is utilizing the RAS Mapper window to set the desired Projection and to create the Terrain using the corrected DEM, which has a 10 cm resolution. An accuracy of 1/128 was employed in the generation of the Terrain. After this, the creation of the geometry is done, also in RAS Mapper, with the aim of defining the boundaries within which the 2D computations will happen. A computational grid is created inside the defined area and subsequently, the Boundary Condition Lines are defined in the inflow and outflow sections of the flow area. Figure 2.28 shows the Terrain, the 2D Flow Area (black feature), and the Boundary Condition (BC) Lines (cyan lines) used for the Vigevano section, along with a water depth simulation.

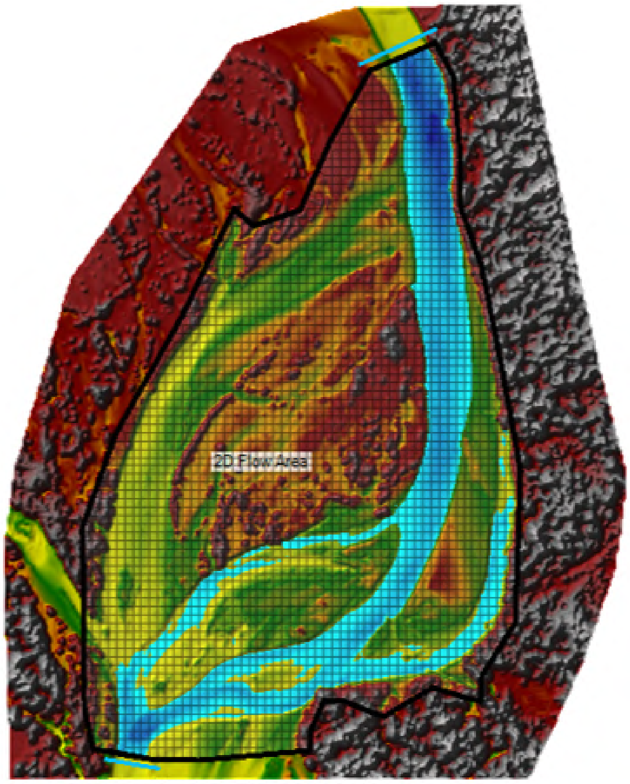

Figure 2.28: Grid built in HEC-RAS for the 2D hydrodynamic simulation of the Vigevano reach.

The external 2D flow area boundary conditions are defined in the Unsteady Flow Data window following the definition of the geometry. For the inflow BC Line, the Flow Hydrograph was chosen, using the constant value obtained from the field survey. In the case of the outflow BC Line, the Normal Depth condition was selected. Afterward, the parameters for the planned simulation were chosen in the Unsteady Flow Analysis window, where a Simulation Time window of 3 hours was defined with a computation interval of 0.5 s, obtaining thus the rasters of simulated water depth and flow velocity. These results were later validated using data taken from the field surveys and extracted for their posterior use in ArcGIS Pro to define the Hydromorphological Units (HMUs).

These simulations allow us to have raster files with data covering the whole studied river reach, in contrast to the data obtained directly in terrain, which gives us more precise data but only in some points of the interest area. These rasters are subsequently used to create the HMUs using ArcGIS Pro.

Some of the advantages of using HEC-RAS are that it is a noncommercial software, so anybody can use it, and it is easy to implement. Nevertheless, there are some limitations to this software. For example, some studies show that when the wind and atmospheric pressure are not negligible, it is better to use a software that allows 3D modeling, because 2D HEC-RAS can not simulate atmospheric forcing, leading to errors in the simulations [46].

2.5.3 HMUs delineation and parameter extrapolation

After the HEC-RAS results are obtained, it is possible to use the water depth and velocity simulations to define the HMUs. In order to create the HMUs, the polygon of the wetted area is exported from HEC-RAS and imported into ArcGIS Pro. This polygon is separated into HMUs considering areas where the water depth and velocity are more or less homogeneous, and they are classified taking into account the values of these parameters and the characteristics of the surroundings. According to the MesoHABSIM methodology, there are 13 possible classifications for the HMUs: pothole, cascade, rapid, riffle, step, glide, pool, dune system, aquatic vegetation, backwater, lowland lake, wetland, and artificial element [12]. The details of the characteristics that define each HMU type can be seen in Manual 132/2016 from ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale).

After defining the HMUs, the next step is describing the riverbed cover by detailing its physical characteristics. This is achieved by assigning the attributes of connectivity, boulder, canopy shadow, overhanging vegetation, roots, submerged vegetation, emerging vegetation, woody debris, riprap, and shallow margin with either "True" (indicating presence) or "False" (indicating absence). This description will be important for the biological model since it says, for example, whether there is connectivity for the passage of the analyzed fauna or if there is a refuge from physical stress or predators. The description of the cover can be done by using orthophotos and with observation in the field. Additionally, it is necessary to record the maximum and minimum elevation values for each HMU. These values can be determined by considering the DEM values and water depth at the highest and lowest points within each HMU.

Finally, the last process executed with ArcGIS Pro was a substrate description, which is required as input for the SimStream platform to perform the biological model. The identification of sampled substrates from the riverbed was accomplished using a random technique at the HMU level. Approximately 250 samples were collected to describe the riverbed in the Turbigo reach, while around 900 samples were taken for the Vigevano reach. These samples were classified according to the MesoHABSIM methodology, as outlined in the table presented below. This classification depends on the scale and type of substrate present at the sample point. It is important to keep in mind that the measurement of the size of the pebbles is performed by measuring the intermediate axis of the pebble, as illustrated in Figure 2.29.

Table 2.2: Substrate types according to MesoHABSIM

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 (gravel)*
Psammal	*0.06 - 0.2 cm (sand)*
Pelal	*<0.06 cm (clay)*
Detritus	*(organic matter)*
Xylal	*(woody debris)*
Sapropel	*(anoxic mud)*
Phytal	*(submerged plants)*

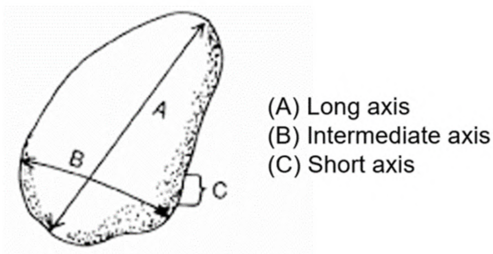

Figure 2.29: Axis of a Pebble [47].

A histogram of the substrate composition is produced after some samples are collected and classified in each HMU, and this data, along with the histograms of the simulated water depth and velocity, is processed using a MatLab script to produce a file with 100 points per HMU, each of which has a value for water depth, velocity, and substrate type. This process is done in a way that allows one to obtain a representative description of each HMU, which is presented in the form of a text file that can be uploaded to the SimStream-Web service to get the habitat availability maps.

2.6 Habitat suitability models

For creating the habitat suitability maps, the SimStream-Web platform was used. This is a web service that allows one to obtain the following outputs for both perennial and temporary rivers [48]:

- Habitat availability, considering spatial and temporal aspects, for the species of interest. Specifically, the service creates geo-referenced habitat maps in a shapefile format, habitat time series data, and habitat-flow rating curves.

- The Habitat Integrity Index (HII) associated with one or multiple hydrological or morphological management scenarios considering the reach, segment, or catchment scale.

For perennial rivers, which is the case of Ticino, the inputs needed are the date of the survey, the discharge, the shapefile containing the information of the HMUs, and a text file containing the point measurements with the data of water depth, velocity, and substrate type. It is also necessary to select the species and life stage that will be studied, which are known from the fish samplings in the field.

With the SimStream-Web service, it is also possible to obtain Habitat-flow rating curves, Habitat Time Series, Uniform Continuous Under Threshold (UCUT) curves, and Habitat Integrity Index (HII), for which it is necessary to enter data from Streamflow Time Series. For this study, the simulation is performed for just one discharge condition, so only the biological model outputs will be obtained, which correspond to hydromorphological unit data, biological models, and habitat suitability maps.

The software works based on the available biological models of the fish species, which relate the parameters of each HMU with a presence probability. If the presence probability is lower than 0.5, the HMU is classified as not suitable, while if the probability is between 0.5 and 0.75 is defined as suitable. The HMUs with presence probabilities higher than 0.75 will be classified as optimal.

For each species, there are 2 biological models, one for adults and one for juveniles. Unfortunately, not all the biological models are available. In the case of bullhead and Italian spring goby, only the model for adults was obtained, while for the Po brook lamprey only the model for juveniles was available. The model of the Italian golden loach was not needed in this study. The available biological models can be seen in the following figures:

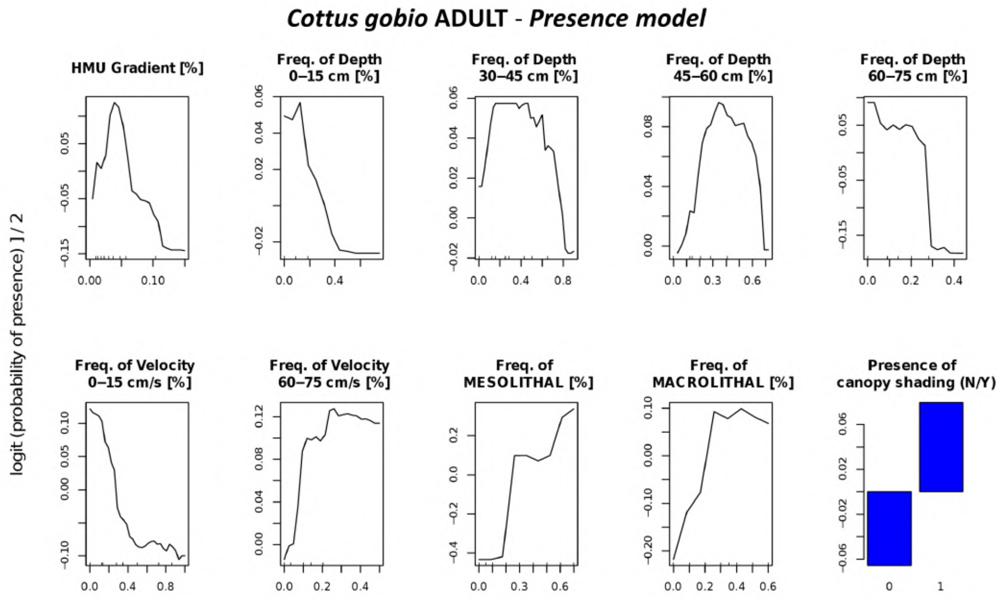

Figure 2.30: Biological model for bullhead, adult

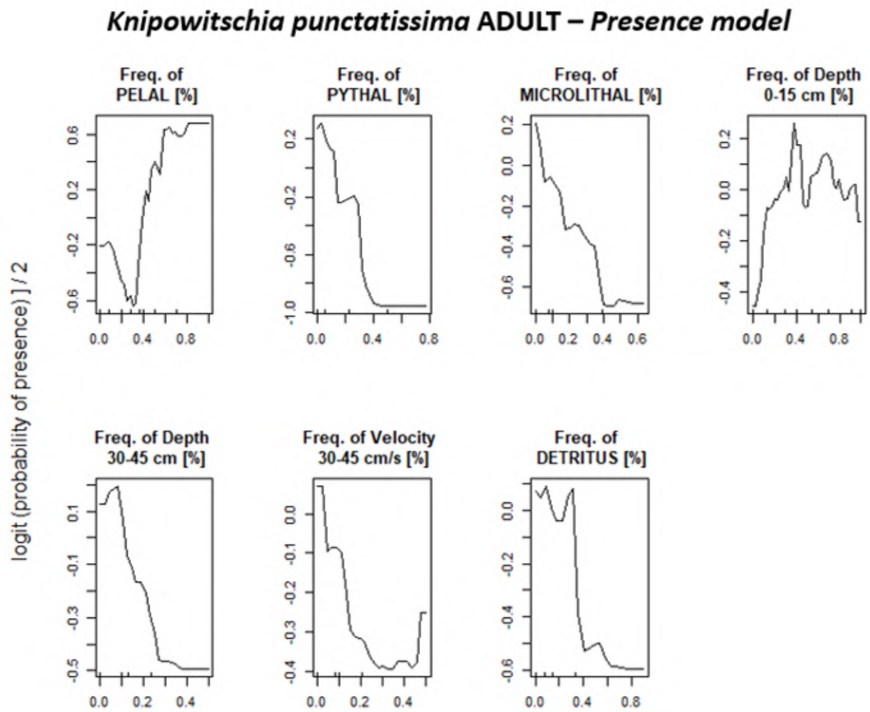

Figure 2.31: Biological model for Italian spring goby, adult

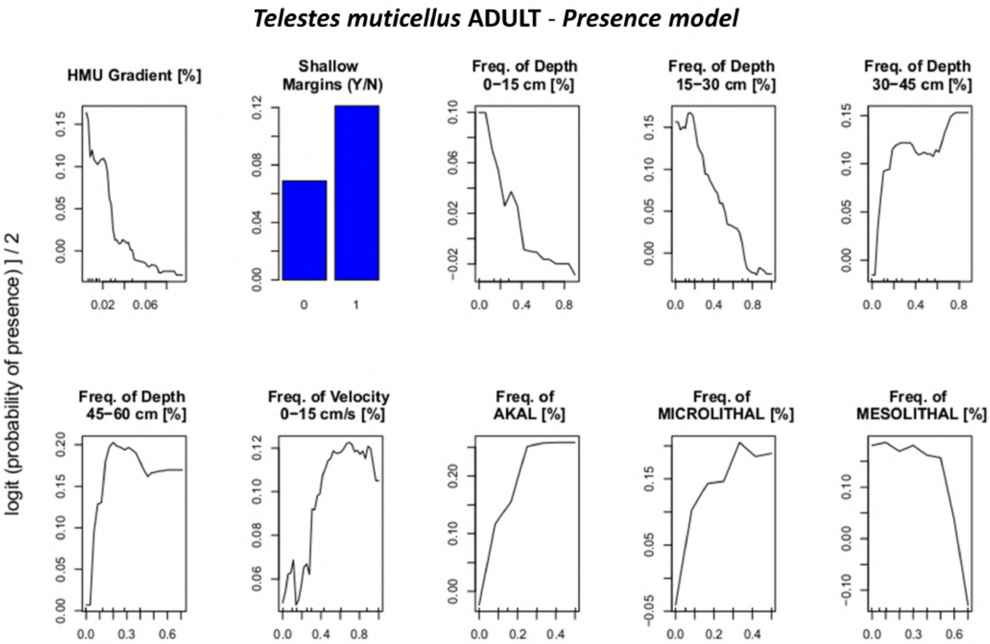

Figure 2.32: Biological model for Italian vairone, adult

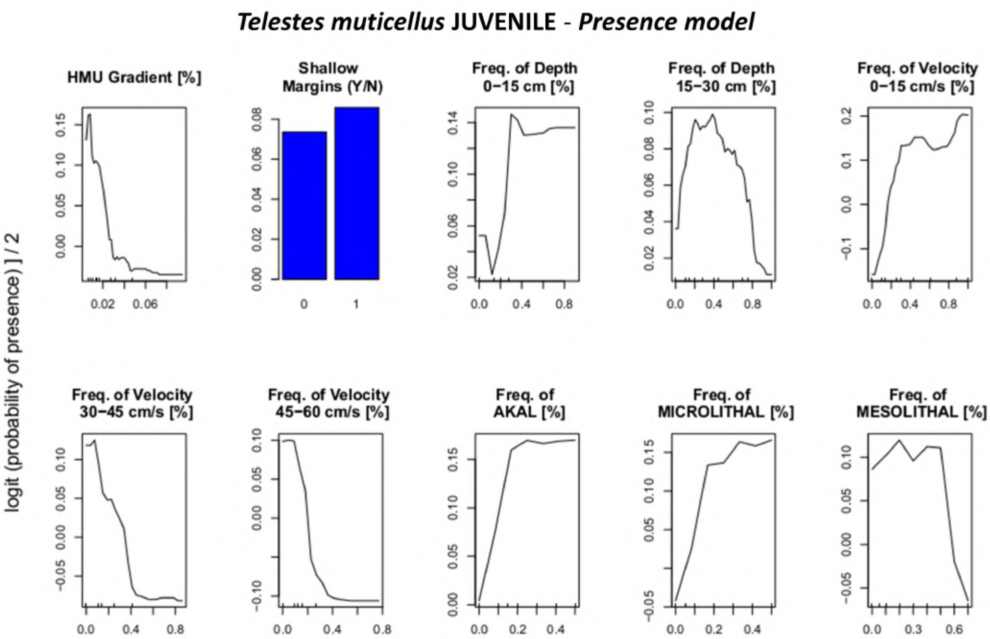

Figure 2.33: Biological model for Italian vairone, juvenile

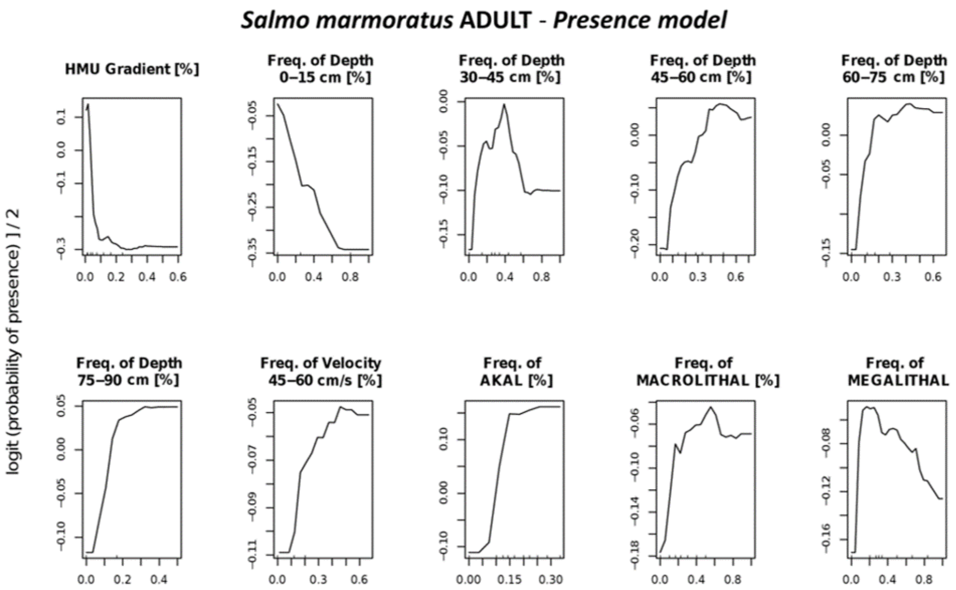

Figure 2.34: Biological model for marble trout, adult

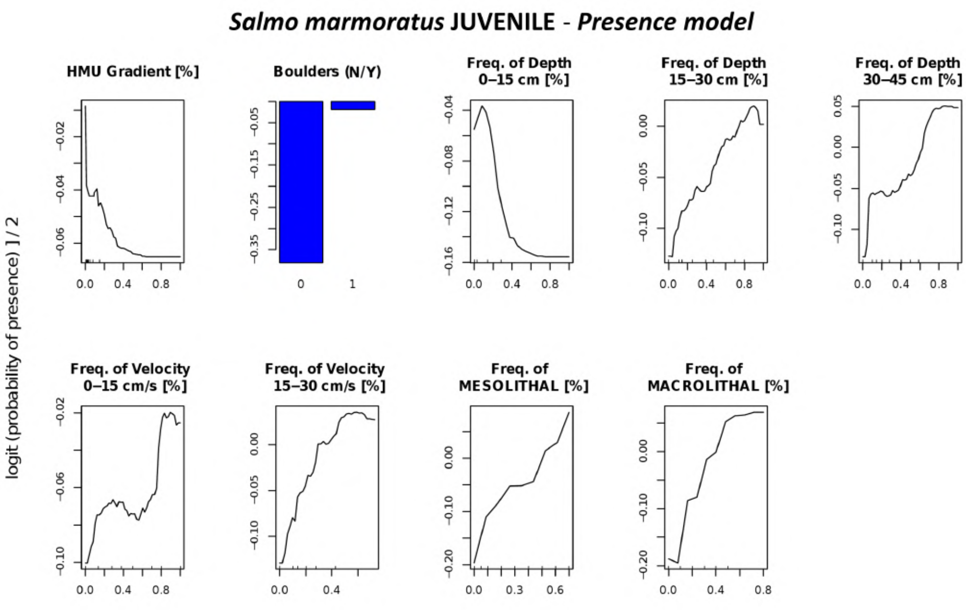

Figure 2.35: Biological model for marble trout, juvenile

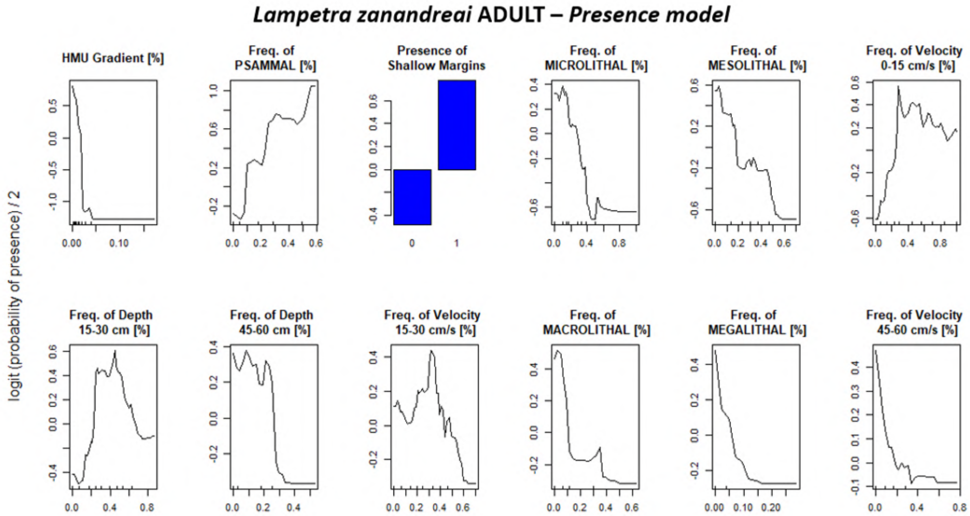

Figure 2.36: Biological model for Po brook lamprey, juvenile

Chapter 3

Results

3.1 Surveys outputs

As a result of the Topographic surveys explained in Section 2.4.1, a raw DEM and two orthophotos of different resolutions were obtained for each of the studied areas, which later were used in the elaboration of the HMUs. The orthophotos with a resolution of 2.5 cm of Turbigo and Vigevano reaches are shown in Figure 3.1 and Figure 3.2 respectively.

Figure 3.1: Orthophoto of the study area in Turbigo (August, 2022).

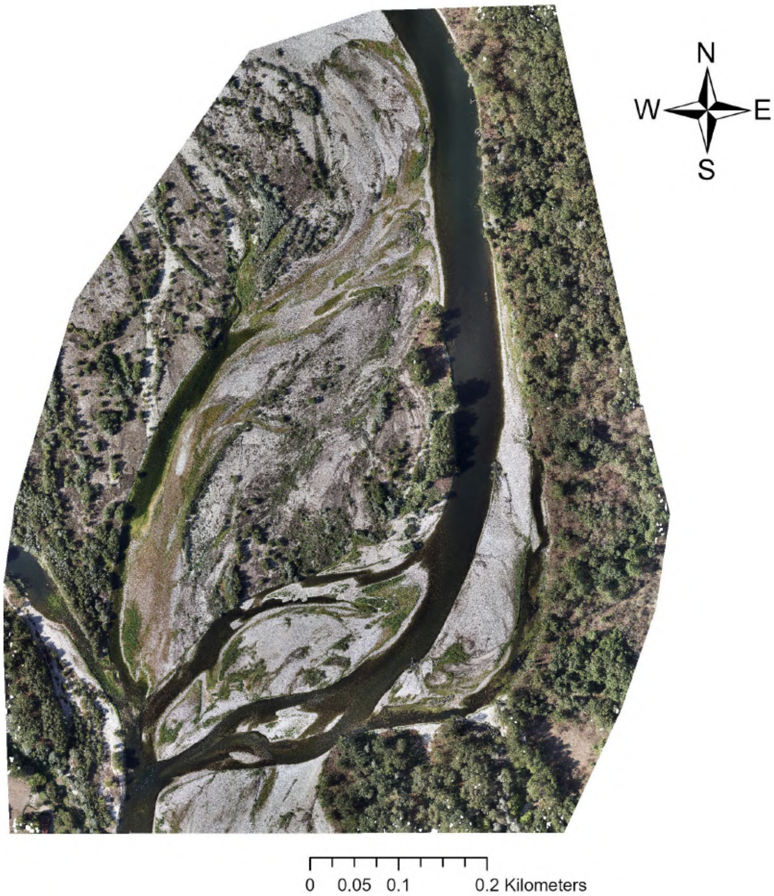

Figure 3.2: Orthophoto of the study area in Vigevano (August, 2022).

Figures 3.3 and 3.4 show the water depth and velocity measured in each of the stretches with the ADCP during the hydromorphological surveys, as described in Section 2.4.2. Moreover, Tables 3.1 and 3.2 show the results of the three fish samplings that have been carried out to date. Table 3.3 explains the symbology used to describe the results of the biological monitoring.

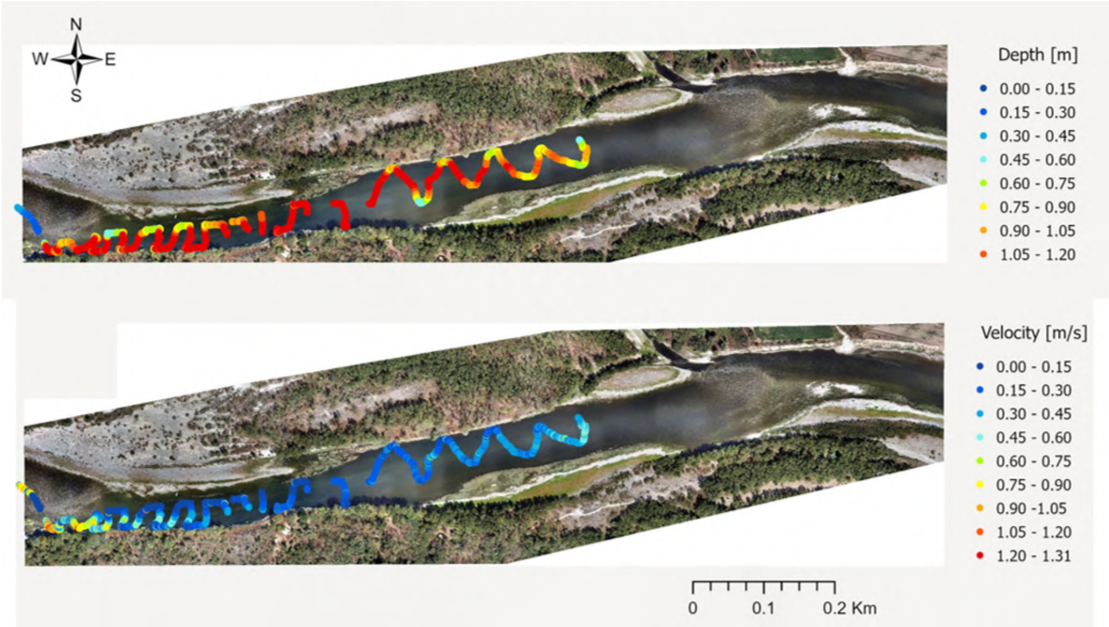

Figure 3.3: Water depth distribution acquired with the ADCP and current meter for the Turbigo stretch.

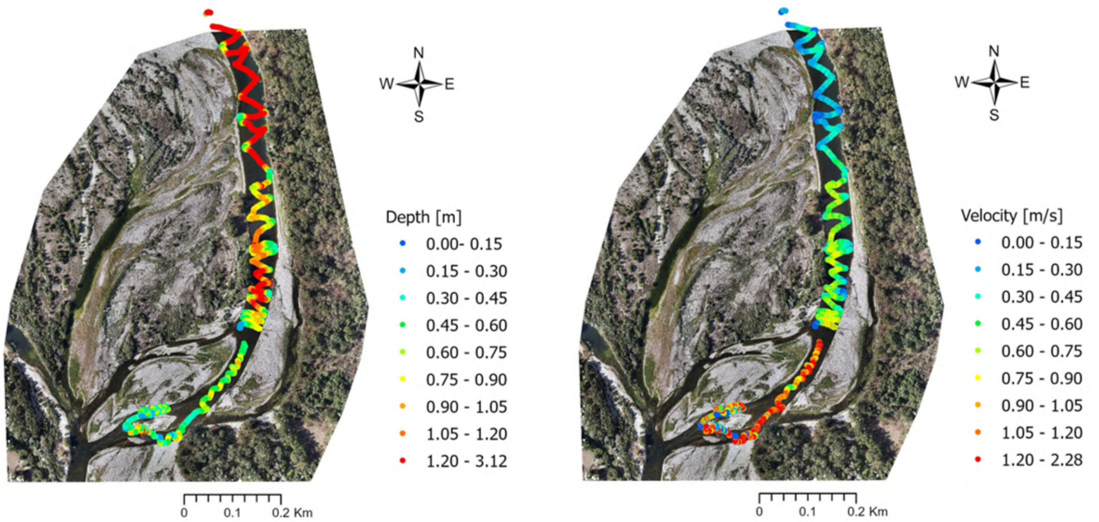

Figure 3.4: Water depth distribution acquired with the ADCP and current meter for the Vigevano stretch.

Table 3.1: Results of the biological surveys in the Turbigo reach

	Ticino Turbigo		
Date	**11/5/2022**	**4/8/2022**	**17/4/2023**
Time	**9:15-10:15**	**9:00-10:30**	**8:30-10:00**
Temp. [°C]	**16-6-17.2**	**24.4-25**	**12.3-13.7**
Bullhead	4S (H)	2S (H)	(H)
Italian golden loach			
Italian spring goby	(H)	(H)	(H)
Italian vairone	4S (H,R)	4S (H,R)	4S (H,R)
Marble trout	(H)	(H)	(H)
Po brook lamprey			

Table 3.2: Results of the biological surveys in the Vigevano reach

	Ticino Vigevano		
Date	**11/5/2022**	**4/8/2022**	**17/4/2023**
Time	**16:00-17:00**	**16:40-17:40**	**16:00-17:00**
Temp. [°C]	**15.4-16.9**	**25.9-28.4**	**15.4-16.9**
Bullhead			
Italian golden loach			
Italian spring goby	(H)	(H)	(H)
Italian vairone	3S (H, R)	2S (H,R)	3S (H, R)
Marble trout	(H)	(H)	(H)
Po brook lamprey	(H)	(H)	(H)

Table 3.3: Symbology of the results of the biological surveys

1	Occasional
2	Present
3	Abundant
4	Very abundant
(H, R)	Historical presence (till 2012), Recent presence (after 2017)
S	Structured (adults and juveniles)

3.2 Hydromorphological characterization

Figures 3.5 and 3.6 illustrate the DEMs that were obtained after correcting the error produced due to the refraction effect. These DEMs represent the riverbed elevation more accurately and, as a result, the water depth value distribution within the submerged zones. These representations of the terrain were afterward used as input to generate the simulations of water depth and velocity in HEC-RAS.

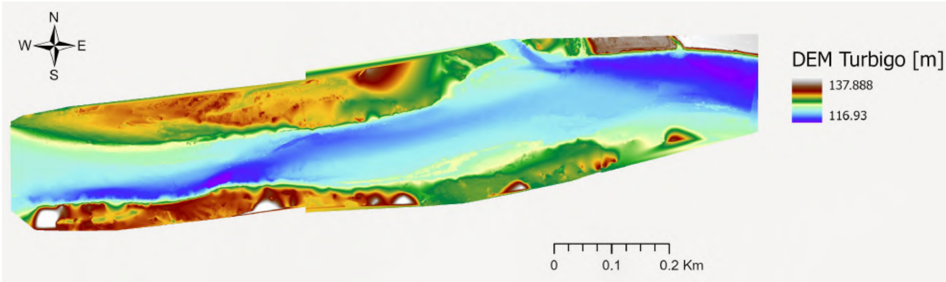

Figure 3.5: Corrected DEM Turbigo.

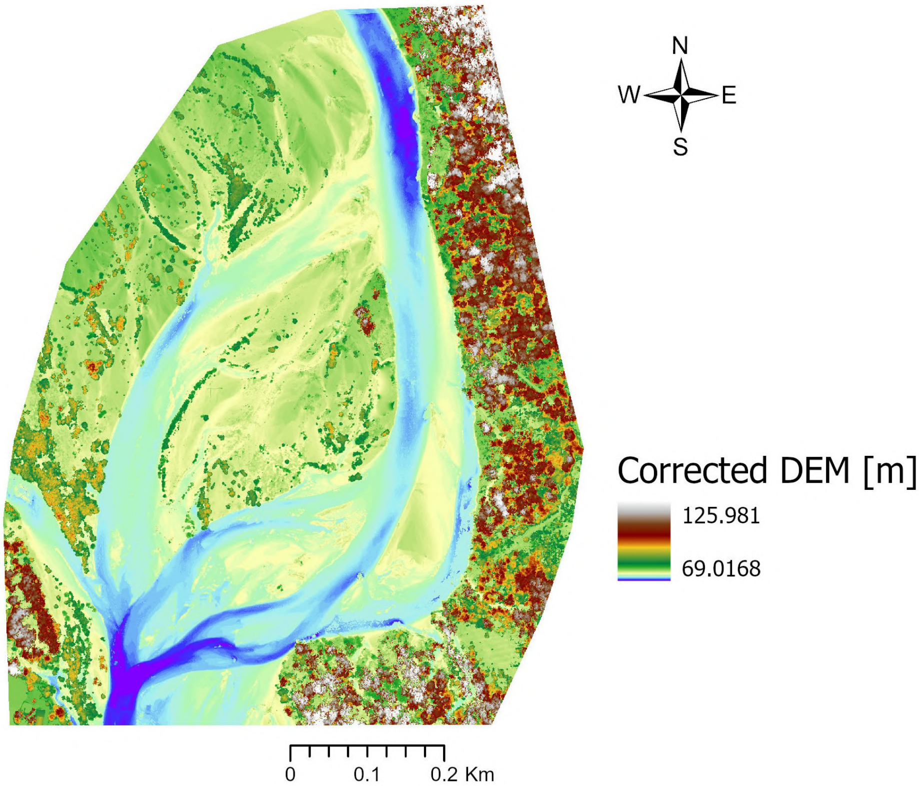

Figure 3.6: Corrected DEM Vigevano.

As explained in Section 2.5.1, the DEM correction process is performed by comparing the estimated water depth points with measured ones to obtain a linear regression model, which produces a correction equation. The obtained correction equations for Turbigo and Vigevano correspond to Equations 3.1 and 3.2 respectively. In the equations, Df represents the fictitious water depth and Dr represents the real one. Furthermore, Figure 3.7 shows the scatter plot of the bathymetric models of both reaches.

$$D_r = 1.432 * D_f \tag{3.1}$$

$$D_r = 1.358 * D_f \tag{3.2}$$

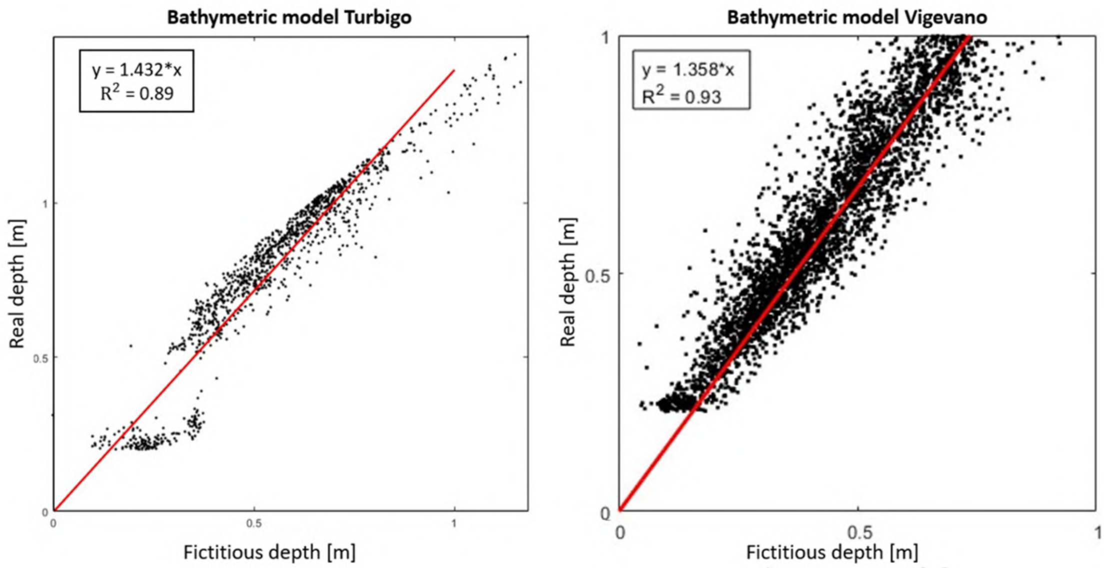

Figure 3.7: Bathymetric models for the Turbigo (left) and Vigevano (right) reaches.

To do the simulations of water depth and velocity, a Mannings number equal to 0.035 was used, since this is the normal value for clean, straight, full-stage channels [49]. After following the procedure in HEC-RAS described in Section 2.5.2, simulations of water depth and flow velocity were obtained for the studied reaches, which are shown in Figure 3.8 and 3.9, respectively, along with the orthophotos. For the display of the results, nine classes were used for both the water depth and the velocity, as indicated by the MesoHabsim methodology.

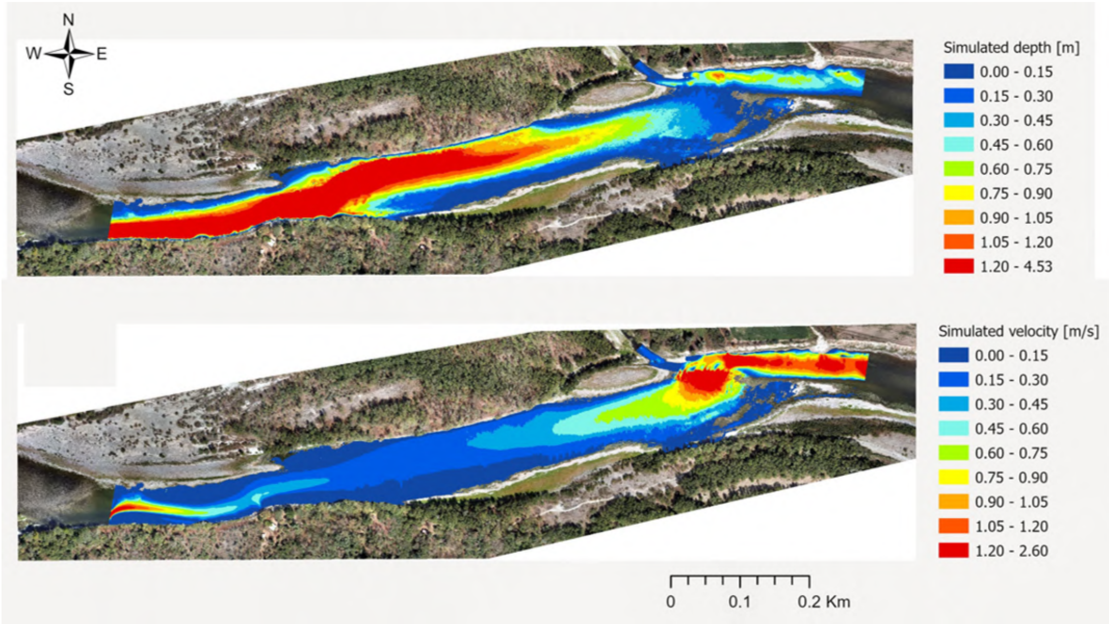

Figure 3.8: Water depth and velocity raster obtained from the HEC-RAS simulation for Turbigo.

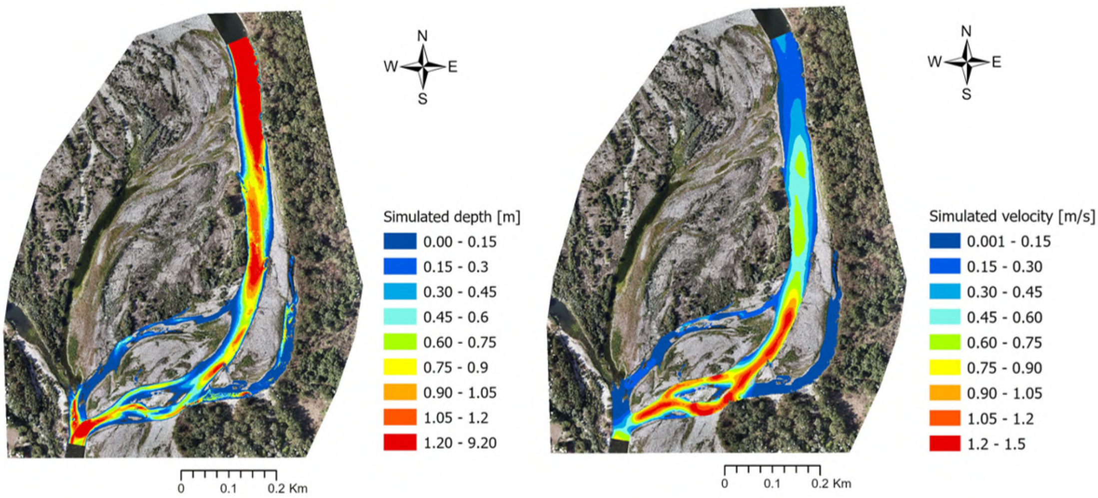

Figure 3.9: Water depth and velocity raster obtained from the HEC-RAS simulation for Vigevano.

After performing the hydrodynamic simulations in HEC-RAS and checking their quality using the data collected in the field, the generated water depth and velocity rasters and the orthophoto were used to delineate the HMUs. As shown in Figures 3.10 and 3.11, 13 HMUs were defined for Turbigo, and 44 were defined for Vigevano. In both sections, there are 4 types of HMU: Backwater, Glide, Pool, and Riffle.

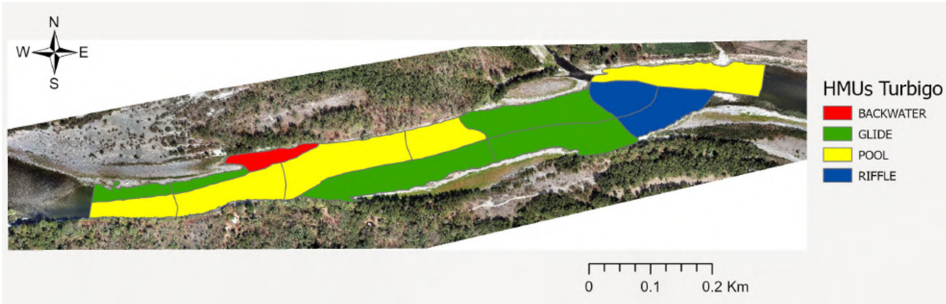

Figure 3.10: Hydromorphological Units defined in Turbigo.

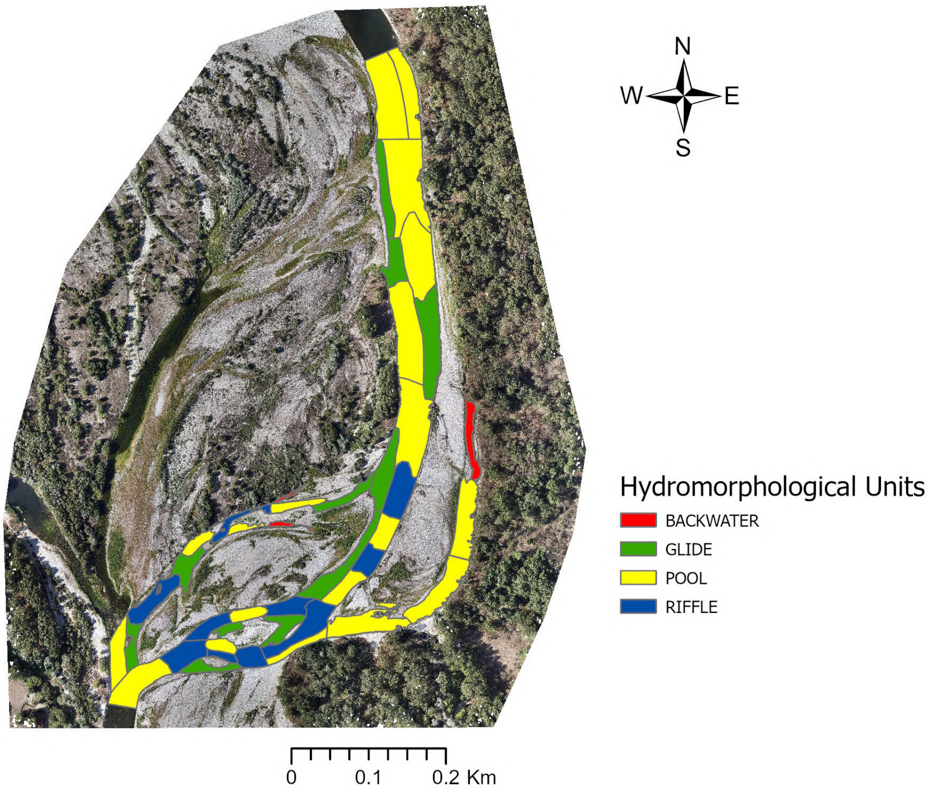

Figure 3.11: Hydromorphological Units defined in Vigevano.

The riverbed composition depicted in Figure 3.12 was created after choosing random samples from the riverbed and employing a Matlab script that generates 100 points for each HMU, as explained in Section 2.5.3. Here it can be seen that in both sections about 80% of the substrates of the riverbed correspond to Mesolithal and Microlithal. There is also presence of Phytal and Akal, as well as a little amount of Psammal and Pelal, and in the case of Turbigo, there is also some Megalithal (2%) and Sapropel (0.4%).

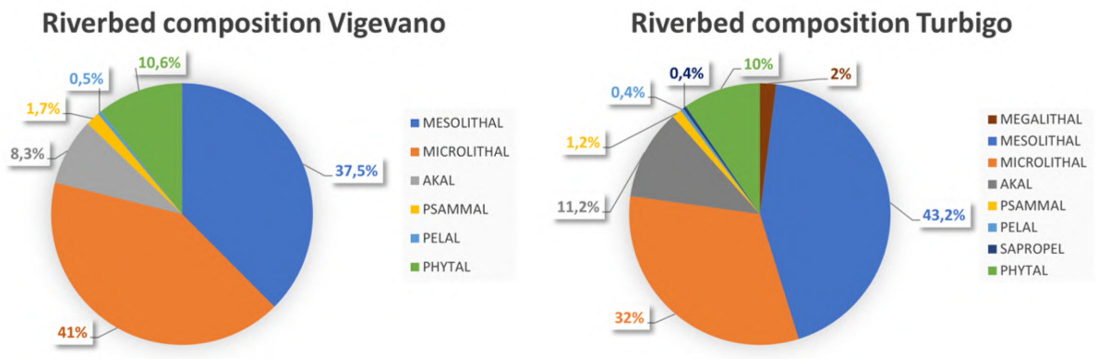

Figure 3.12: Proportion of the substrate classes present in the riverbed.

The SimStream-Web service gives as an output not only the Habitat suitability maps but also HMUs data, which include the frequency distributions of water depth, velocity, and substrate composition for the entire studied stretches. The histograms obtained for the Turbigo and Vigevano reaches are shown in Figures 3.13 and 3.14 respectively.

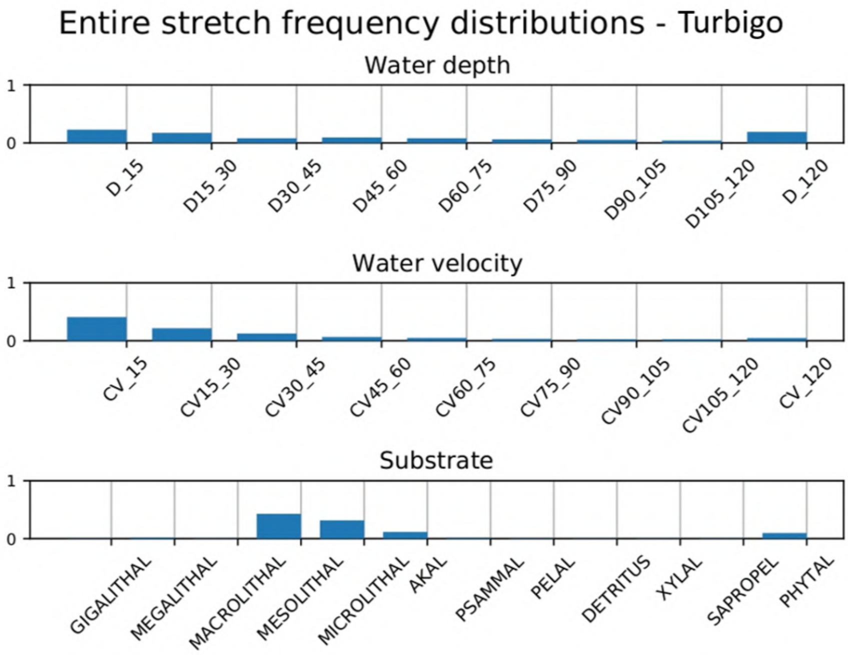

Figure 3.13: Frequency distributions for the Turbigo reach.

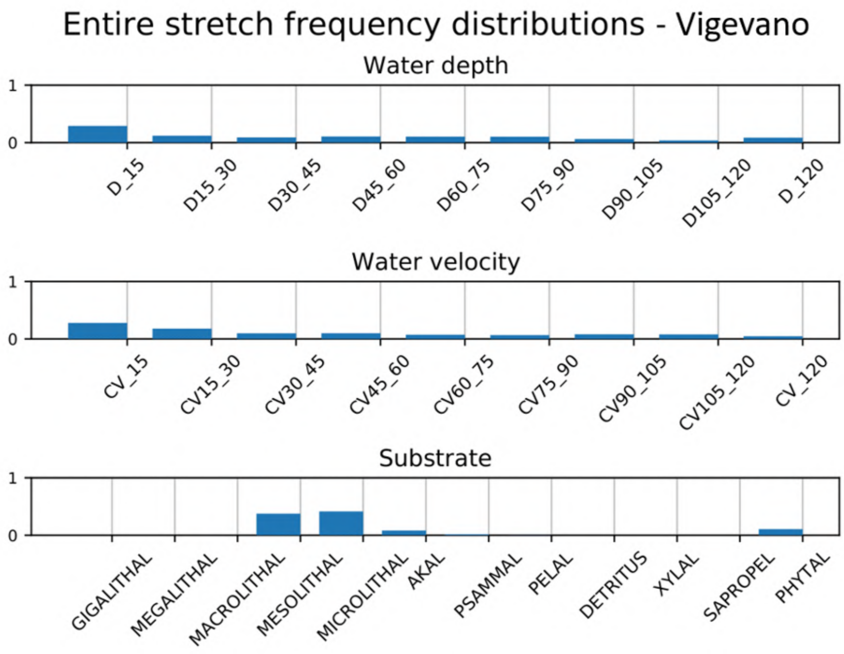

Figure 3.14: Frequency distributions for the Vigevano reach.

3.3 Habitat suitability maps

Once all the previous results were obtained, it was possible to get the habitat suitability maps for each of the studied species in both river sections using the SimStream-Web service, which considers just the hydromorphological parameters. Figures 3.15 to 3.25 show maps where each HMU is classified according to its suitability for the studied species on two of their life stages (adults and juveniles). In the case of the bullhead and Italian spring goby, only the models for adults were available, and for lampreda just the model for juveniles was available. In the maps, red means not suitable, yellow is suitable and green stands for optimal. The habitat suitability maps were obtained just for the species that are or were present in each section, which in the case of Turbigo correspond to bullhead, Italian spring goby, Italian vairone, and marble trout, while for Vigevano they correspond to the Italian spring goby, Italian vairone, marble trout, and Po brook lamprey.

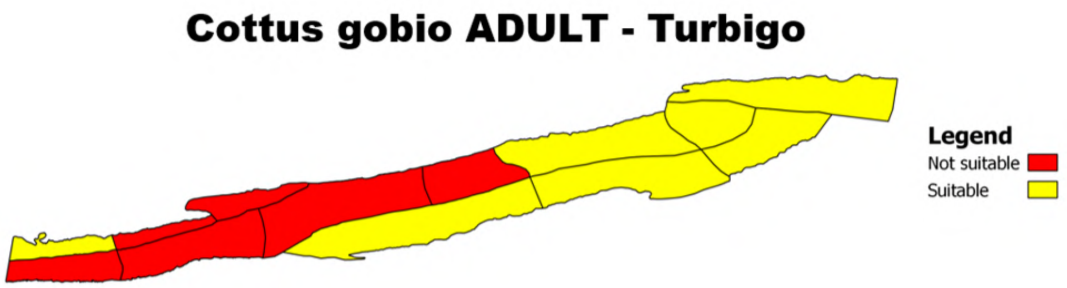

Figure 3.15: Habitat suitability for bullhead adult in Turbigo.

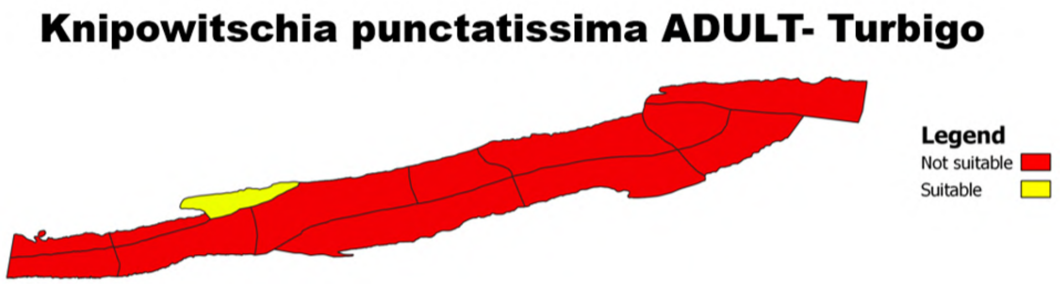

Figure 3.16: Habitat suitability for Italian spring goby adult in Turbigo.

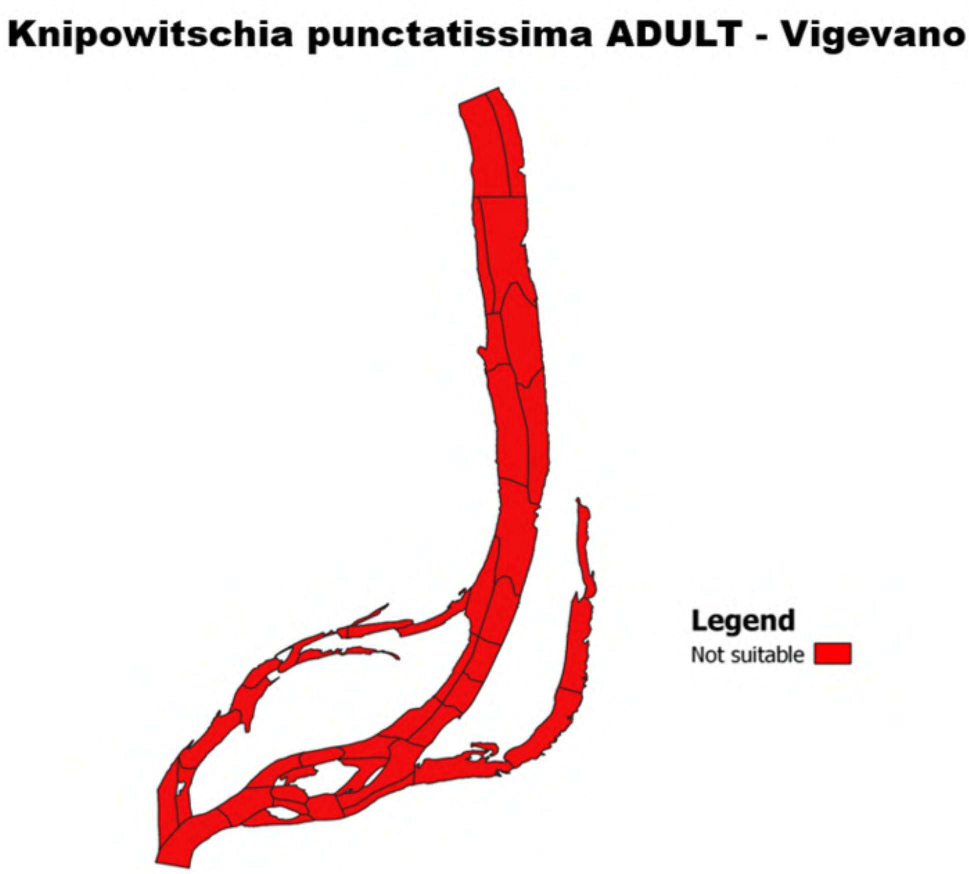

Figure 3.17: Habitat suitability for Italian spring goby adult in Vigevano.

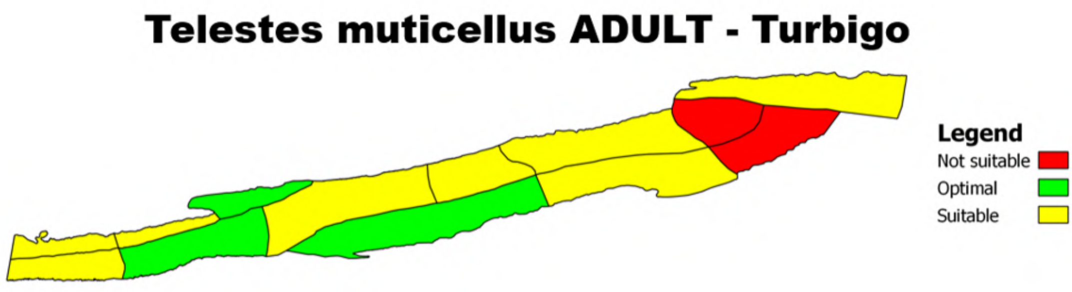

Figure 3.18: Habitat suitability for Italian vairone adult in Turbigo.

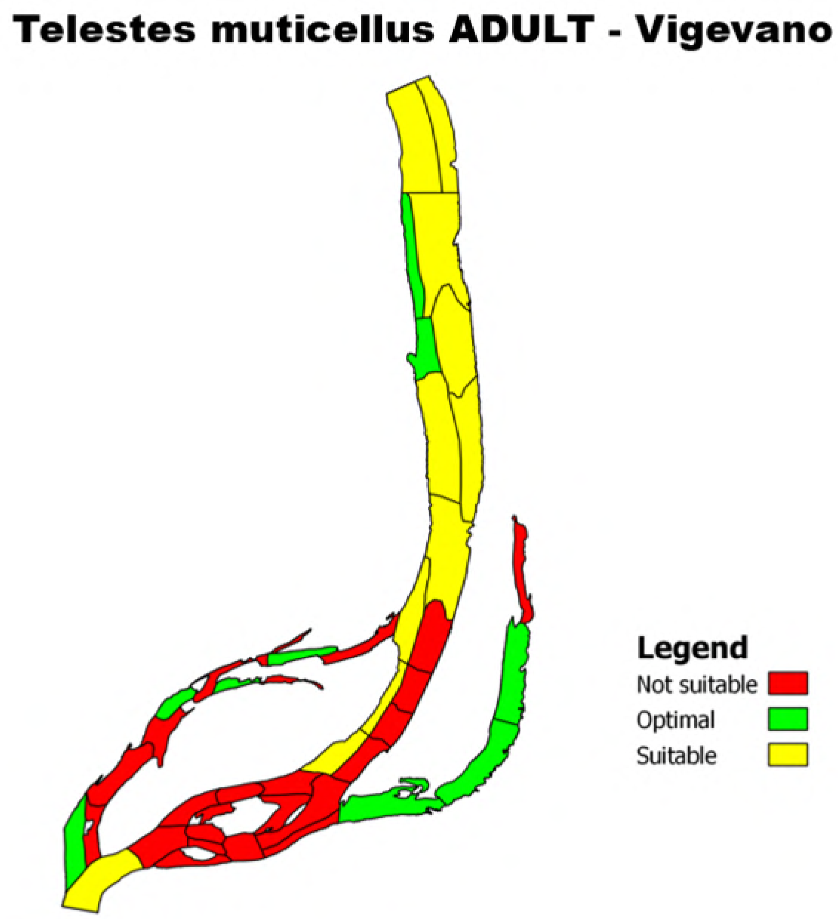

Figure 3.19: Habitat suitability for Italian vairone adult in Vigevano.

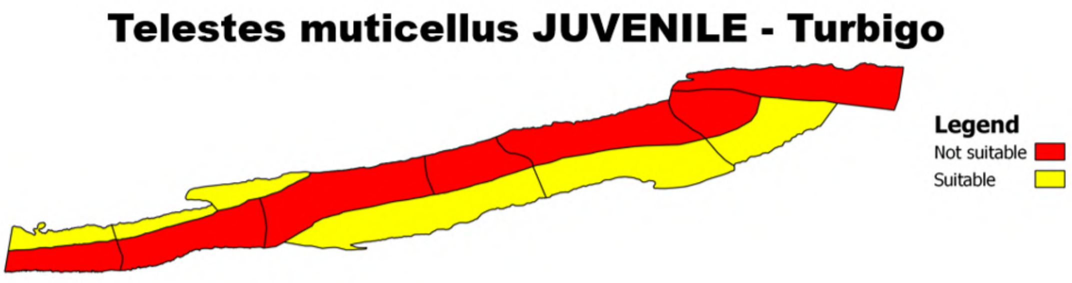

Figure 3.20: Habitat suitability for Italian vairone juvenile in Turbigo.

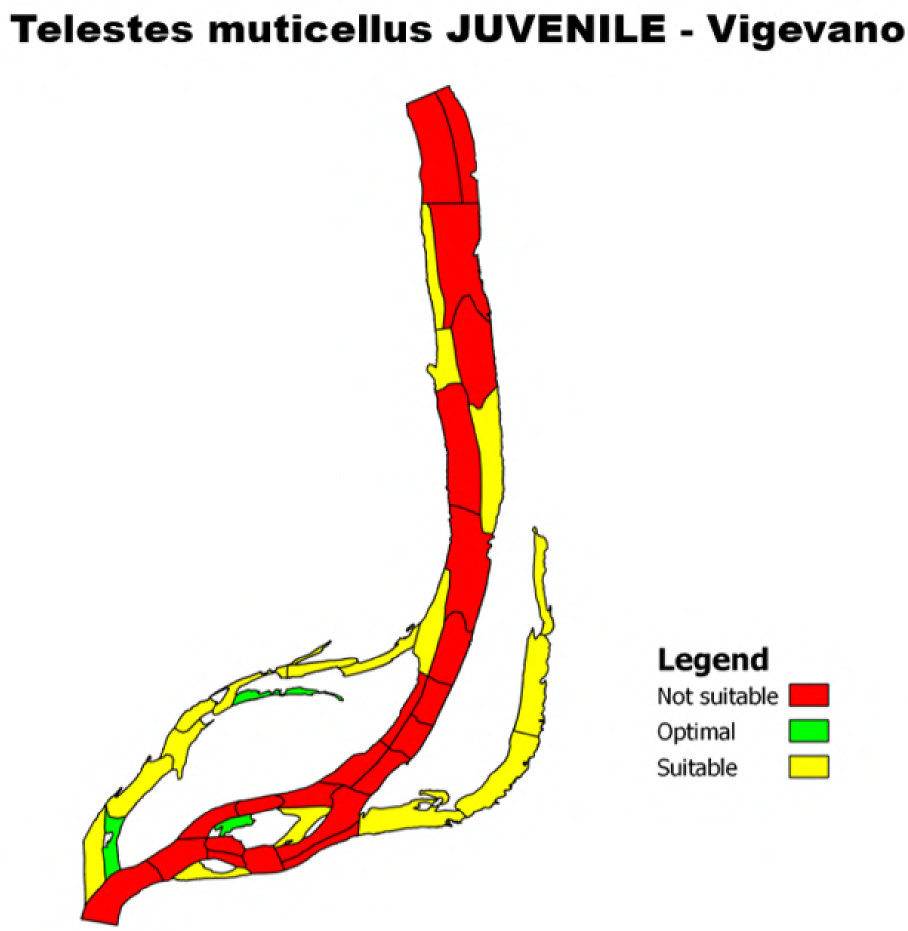

Figure 3.21: Habitat suitability for Italian vairone juvenile in Vigevano.

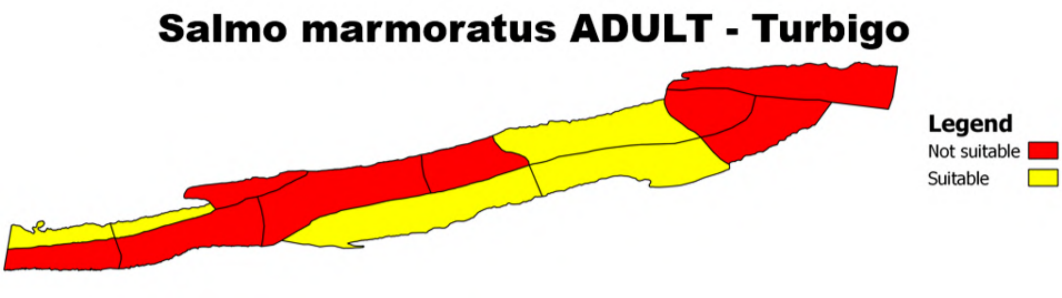

Figure 3.22: Habitat suitability for marble trout adult in Turbigo.

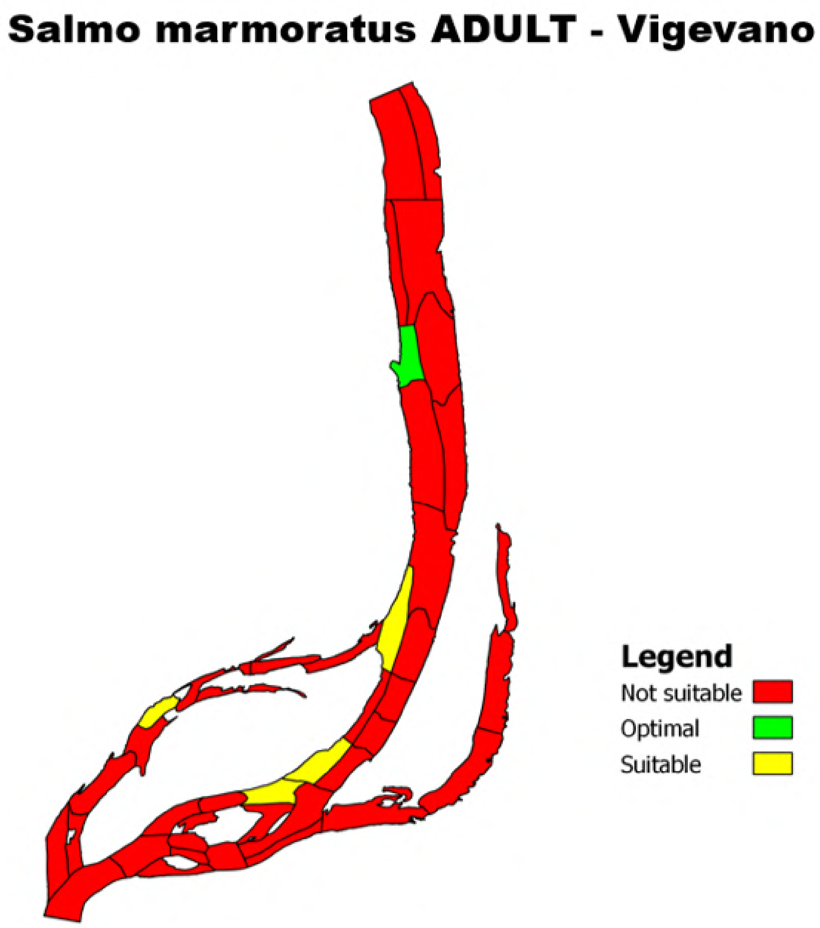

Figure 3.23: Habitat suitability for marble trout adult in Vigevano.

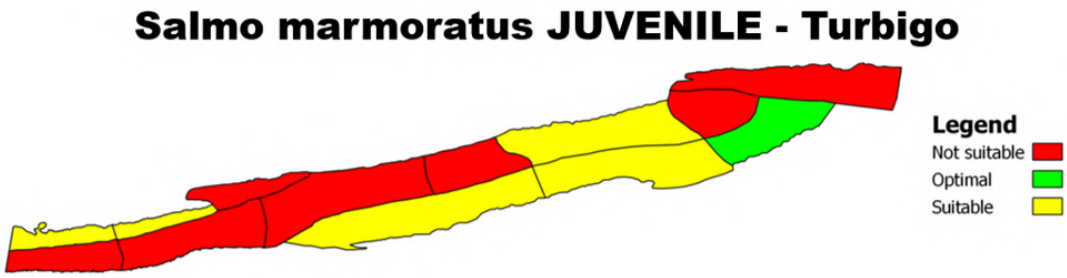

Figure 3.24: Habitat suitability for marble trout juvenile in Turbigo.

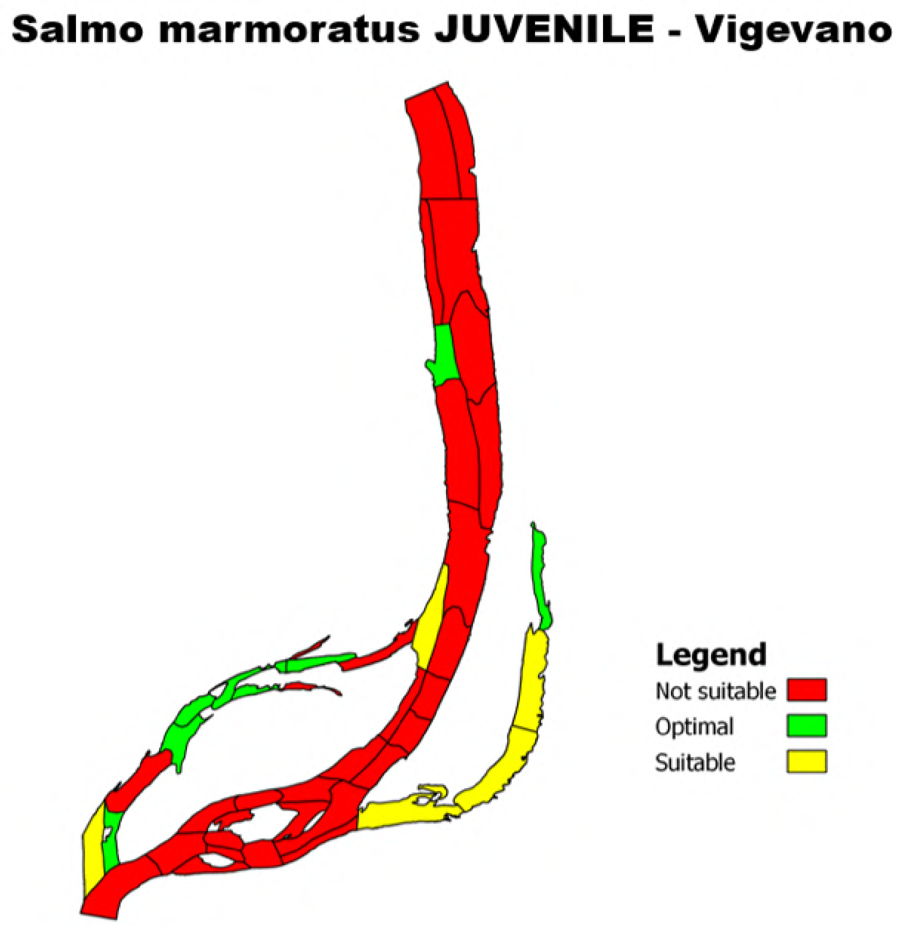

Figure 3.25: Habitat suitability for marble trout juvenile in Vigevano.

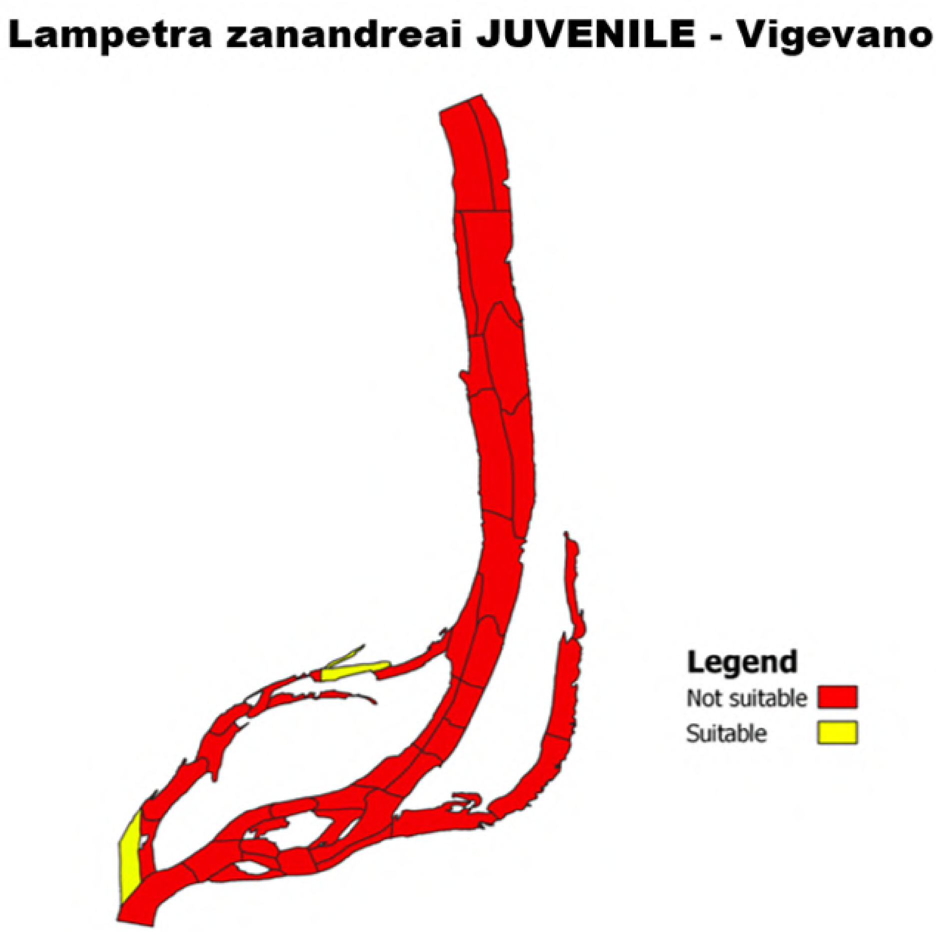

Figure 3.26: Habitat suitability for Po brook lamprey juvenile in Vigevano.

Chapter 4

Discussion and Conclusions

4.1 Surveys

4.1.1 Hydromorphological surveys

The data obtained from the gauging station in Vigevano, which has information on the flow passing through that area since 2004, makes it possible to analyze the flows that were measured in the field. It is necessary to make this analysis to have an idea of whether these flows, which were used to perform the simulations of habitat suitability, are actually representative of low flow conditions. The red horizontal line in Figure 4.1 marks the flow measured on the day of the surveys (23.33 m^3/s). As can be seen, that day presented one of the lowest flows in the last three years. Assuming that the conditions of the river were not disturbed that day, we can say that the flows measured in the studied sections are representative of low flow conditions. Besides, the FDC in Figure 4.2 shows that the measured flow on the 4th of August of last year (red line) is exceeded approximately 100% of the time considering the series between 2004 and 2022. From the PDF in Figure 4.3 it was obtained that the probability of having a flow lower or equal to the measured one is 0.94%.

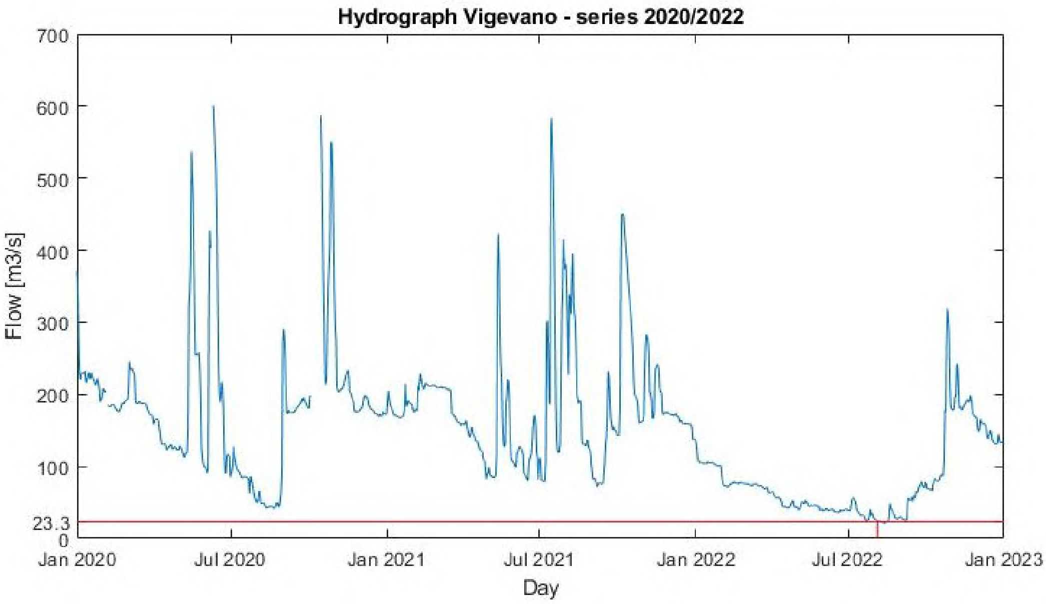

Figure 4.1: Discharge measured on the Vigevano reach (4th August 2022) in the hydrograph.

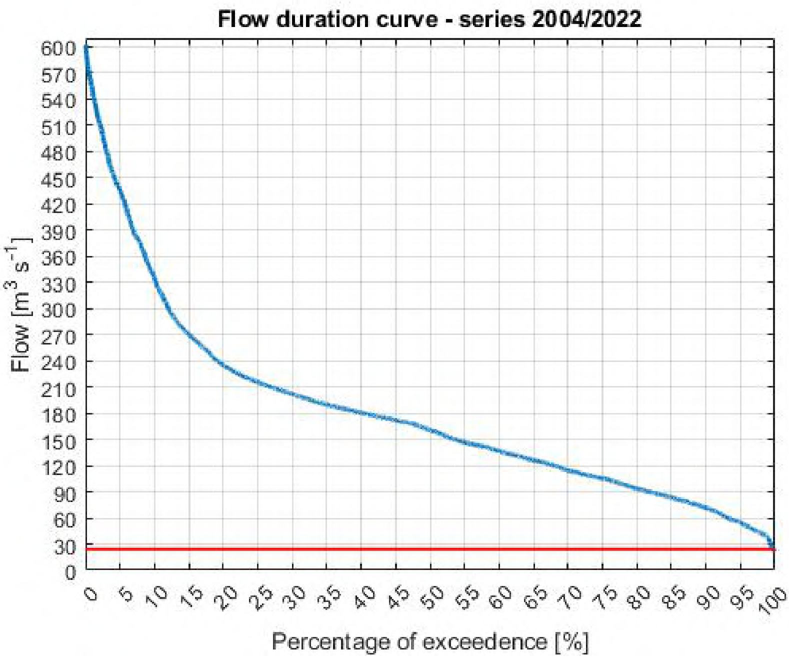

Figure 4.2: Percentage of exceedance of the discharge measured on the Vigevano reach (4th August 2022).

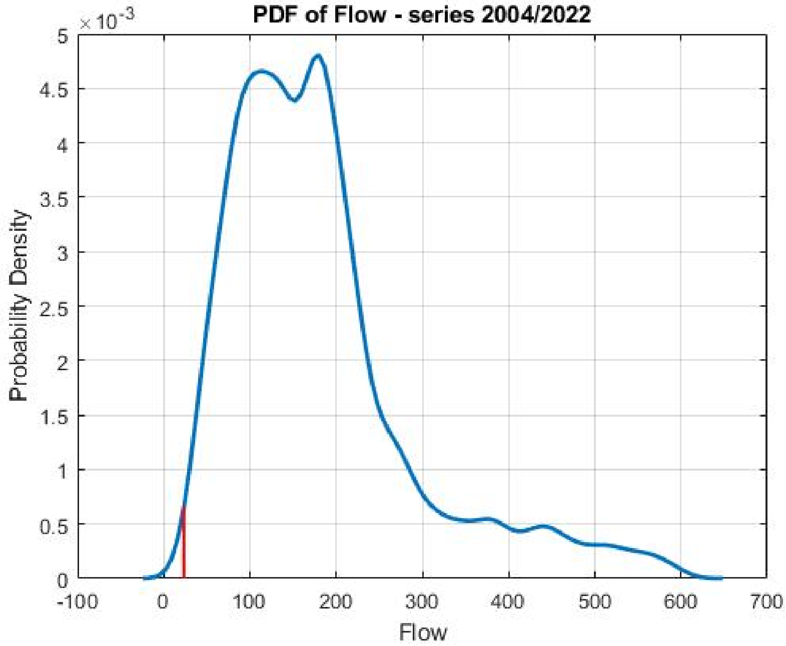

Figure 4.3: Probability density of the discharge measured on the Vigevano reach (4th August 2022).

4.1.2 Biological surveys

From the results of the fish sampling shown in Tables 3.1 and 3.2, it can be seen that in both river reaches there was a historical presence of Italian spring goby and marble trout, but none of them have been seen in those areas in recent years. The same happened for Po brook lamprey in the Vigevano reach. The Italian golden loach was never present in the studied stretches, which is why the habitat suitability of the reaches for this species was not considered important for this study. The Italian vairone is the only studied species whose abundance has not significantly changed in Turbigo and Vigevano. This may be related to the fact that a large percentage of the studied reaches is suitable for vairone even in low flow conditions.

The case of the bullhead is particularly interesting, since even though it has been found in Turbigo in the last years, in just one year its abundance has decreased from very abundant in May 2022 to absent in April 2023. A factor that could influence this sudden decrease could be the presence of new predators since the three biological surveys show that the decrease in bullhead is correlated with an increase in catfish (*Silurus glanis*), which is an allochthonous species and a predator.

It is important to consider the influence of exotic predator species on the changes in the biodiversity of the river, since, unlike the species studied in this investigation, they are not very sensitive to temperature rises due to climate change. According to Salmaso et al. (2016), who performed a study in the Ticino River, the most abundant allochthonous species, such as bitterling or European catfish, have higher upper limits of resistance than the autochthonous species (37°C and 32°C, respectively). Furthermore, almost all of the exotic species recorded in that study have a thermal tolerance equal to or above 30°C. This, combined with the fact that alien species have a wider range of temperature preferences, could lead to a competitive disadvantage for indigenous species, which suggests that allochthonous species could modify the instream community structure [5].

4.2 Hydrodynamic models

In order to validate the simulations, a scatter plot comparing the real and simulated water depth was elaborated using the MatLab software for each section, which are shown in Figures 4.4 and 4.5. As can be seen, the value of R2 is 0.95 for both reaches, which means that the simulations can be used for biological modeling. In the scatter plots, we can notice the presence of some outliers, showing mainly the presence of points where the simulated water depth was lower than the real one in the case of Vigevano. This can be due to the fact that there was a lot of algae in that studied reach, which can lead to an underestimation of the water depth when it was simulated using a DEM.

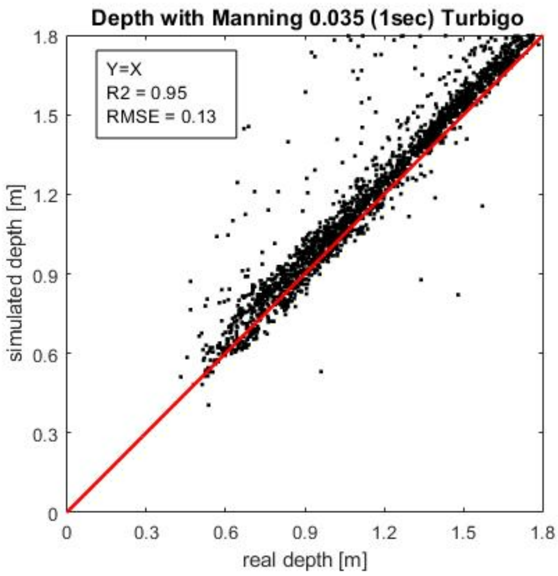

Figure 4.4: Frequency distributions for the Turbigo reach.

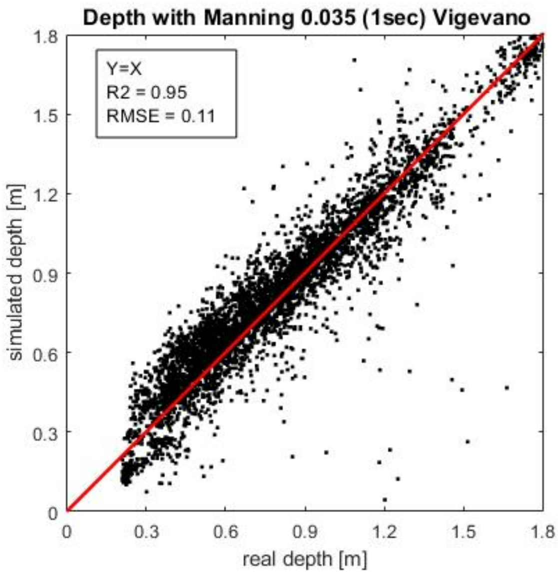

Figure 4.5: Frequency distributions for the Vigevano reach.

4.3 Habitat suitability maps

To better understand which hydromorphological factors had more influence on the non-suitability of the habitat, frequency distribution histograms of water depth, current velocity, and substrate composition were developed using just the non-suitable HMUs (the ones in red in the habitat suitability maps). This analysis will be useful in the case that habitat restoration measures have to be implemented.

4.3.1 Cottus gobio

Figure 3.15 shows that a bit less than half of the area of the studied section in Turbigo is not suitable for adult bullhead, which means that, in general, the reach of the river is suitable for bullhead. For the non-suitable HMUs, the frequency distribution histograms shown below were built. As explained in Section 2.3, bullhead prefers to live in water with low water depth and high velocity, like riffles, with the presence of mesolithal or macrolithal substrate. From the histograms is possible to conclude that the main habitat limitation for bullhead in Turbigo are the areas that are too deep, and with very low velocities.

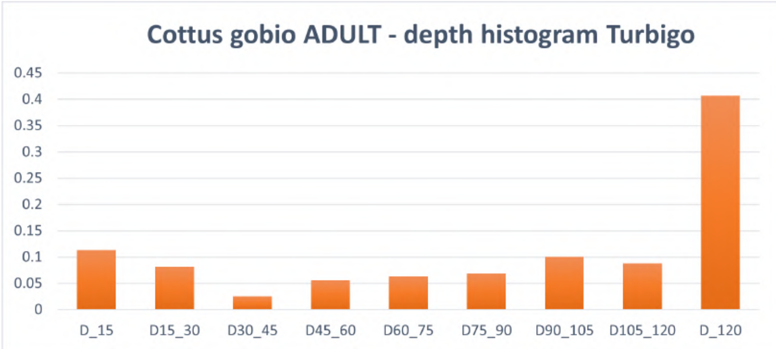

Figure 4.6: Frequency distribution of water depth for the non-suitable HMUs of Turbigo for bullhead adult.

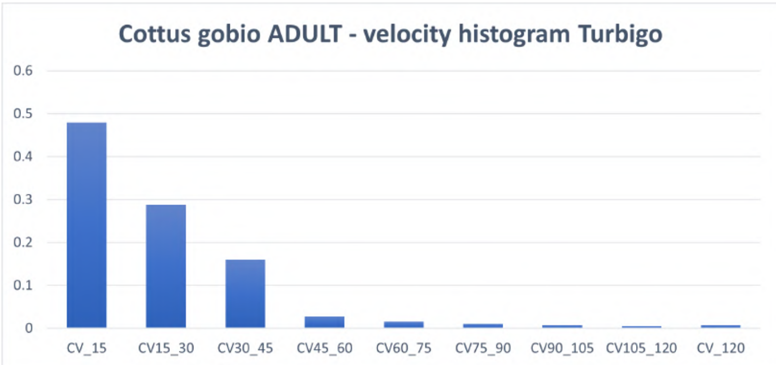

Figure 4.7: Frequency distribution of velocity for the non-suitable HMUs of Turbigo for bullhead adult.

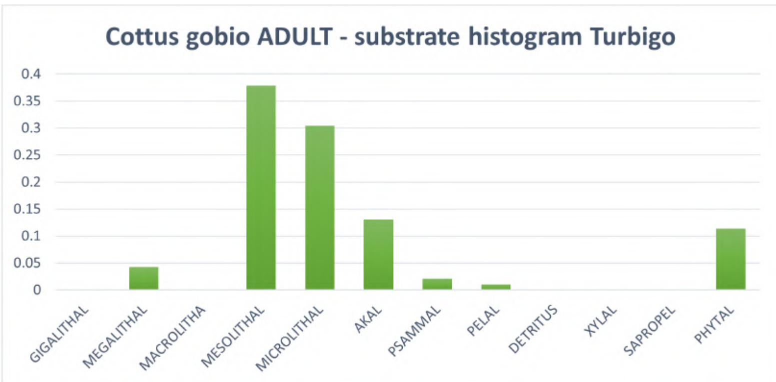

Figure 4.8: Frequency distribution of substrate for the non-suitable HMUs of Turbigo for bullhead adult.

4.3.2 Knipowitschia punctatissima

For the Italian spring goby, it could be seen from the simulations that there is no habitat in the Vigevano section, and only one suitable HMU in the Turbigo reach, so there is an important habitat limitation for this species in the studied areas. To better comprehend which hydromorphological characteristics are limiting the habitat of this fish, the histograms underneath can be studied, along with the biological model shown in Section 2.6. It can clearly be seen in the histograms that the main problem is the substrate composition of the riverbed, since in both river reaches there is mainly microlithal and mesolithal, without enough presence of pelal.

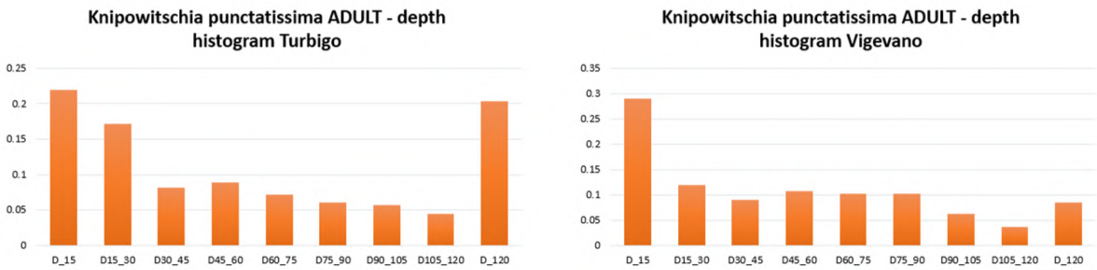

Figure 4.9: Frequency distribution of water depth for the non-suitable HMUs of Turbigo and Vigevano for Italian spring goby adult.

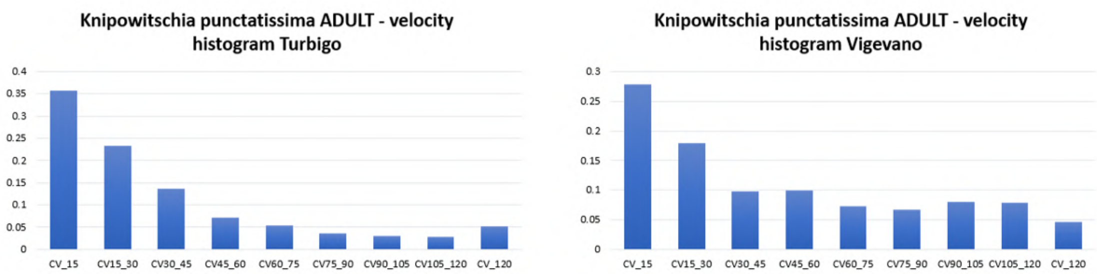

Figure 4.10: Frequency distribution of velocity for the non-suitable HMUs of Turbigo and Vigevano for Italian spring goby adult.

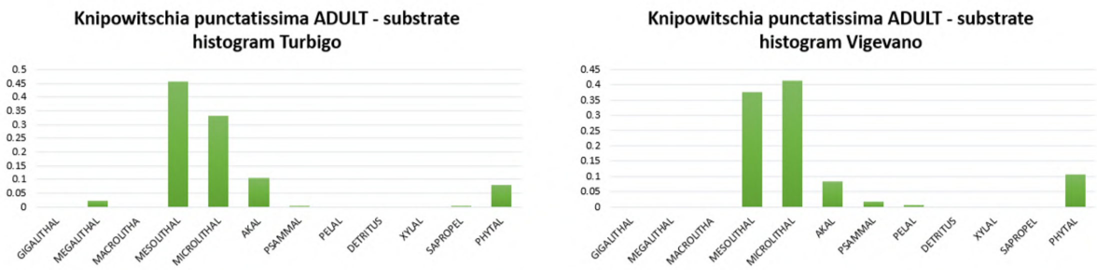

Figure 4.11: Frequency distribution of substrate for the non-suitable HMUs of Turbigo and Vigevano for Italian spring goby adult.

4.3.3 Telestes muticellus

The Italian vairone is the only one of the studied species that does not seem to have changed its abundance significantly in the last few years in the studied reaches. This is probably related to the fact that the habitat of the studied sections is in general suitable for this fish, especially in the case of adults. For adult vairone almost all of the HMUs were suitable, many of them even optimal. In the case of juveniles, there is less suitable area in the studied sections, which is why frequency distribution histograms were built and analyzed using the biological model for juvenile vairone. From the histograms shown below, it can be seen that both the water depth and velocity are too high for juvenile vairone in the non-suitable HMUs in both of the studied sections.

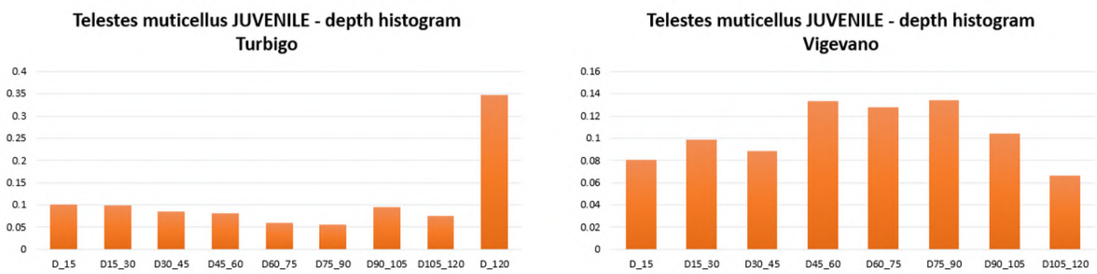

Figure 4.12: Frequency distribution of water depth for the non-suitable HMUs of Turbigo and Vigevano for juvenile Italian vairone.

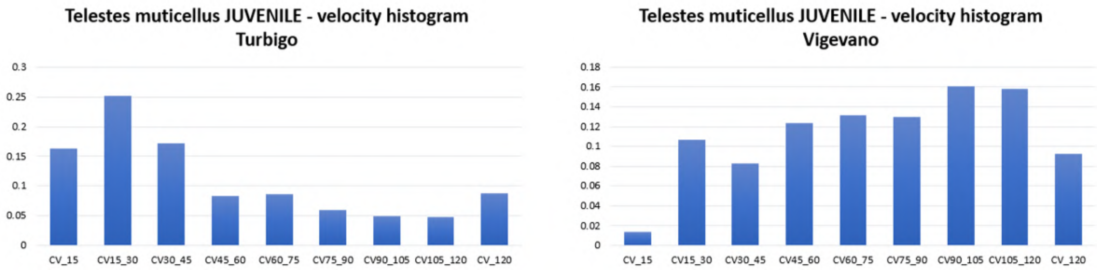

Figure 4.13: Frequency distribution of velocity for the non-suitable HMUs of Turbigo and Vigevano for juvenile Italian vairone.

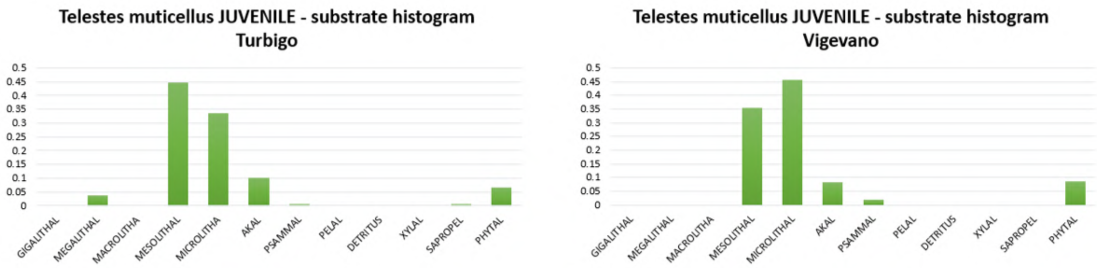

Figure 4.14: Frequency distribution of substrate for the non-suitable HMUs of Turbigo and Vigevano for juvenile Italian vairone.

4.3.4 Salmo marmoratus

Turbigo

In the case of marble trout, the Turbigo reach was mostly non-suitable for adults. In the case of juveniles, a bit less than half of the section was suitable, presenting an HMU that was considered optimal. The following histograms present the frequency distribution of water depth, velocity, and substrate composition for the non-suitable HMUs, for both adults and juveniles:

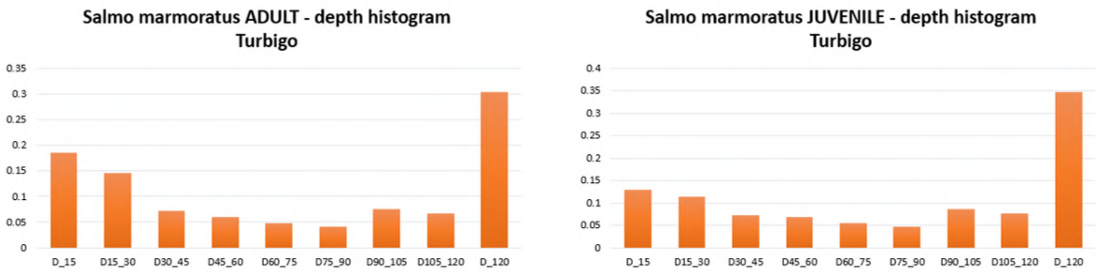

Figure 4.15: Frequency distribution of water depth for the non-suitable HMUs of Turbigo for marble trout adult and juvenile.

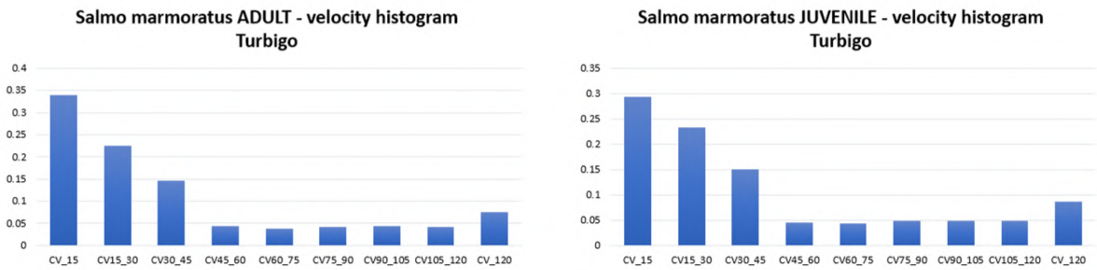

Figure 4.16: Frequency distribution of velocity for the non-suitable HMUs of Turbigo for marble trout adult and juvenile.

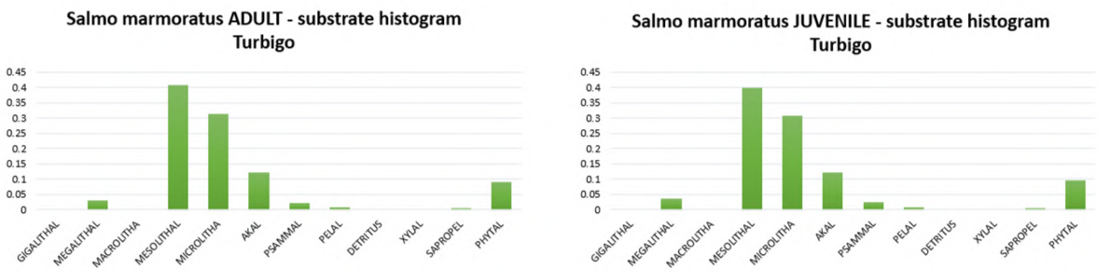

Figure 4.17: Frequency distribution of substrate for the non-suitable HMUs of Turbigo for marble trout adult and juvenile.

Looking at the histograms and considering the habitat preferences of adult marble trout, it can be noticed that in the non-suitable HMUs, the water depth and the velocity were too low. Besides, adult marble trout prefer a riverbed with presence of macrolithal or megalithal substrate. In the case of juveniles, the main limitation was found to be that in the non-suitable HMUs, the water depth was too high.

Vigevano

In Vigevano there was almost no suitable habitat for adult marble trout, while in the case of juveniles, there is habitat in the lateral channels, as can be seen in the habitat suitability maps. Frequency distribution histograms for the non-suitable HMUs were built to understand the situation:

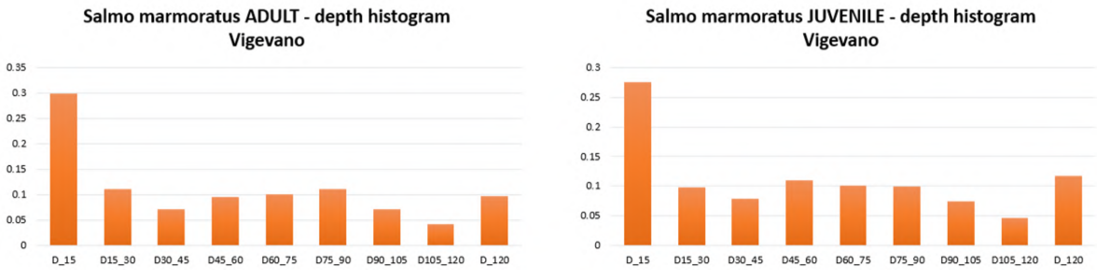

Figure 4.18: Frequency distribution of water depth for the non-suitable HMUs of Vigevano for marble trout adult and juvenile.

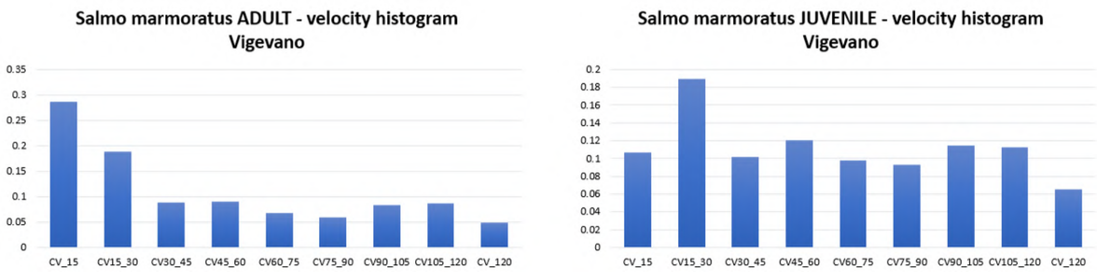

Figure 4.19: Frequency distribution of velocity for the non-suitable HMUs of Vigevano for marble trout adult and juvenile.

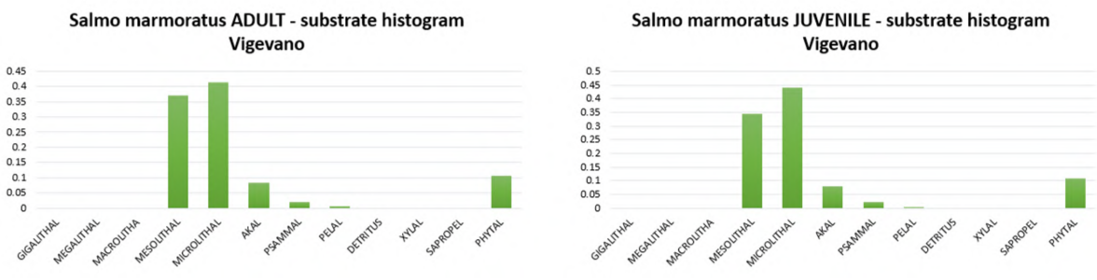

Figure 4.20: Frequency distribution of substrate for the non-suitable HMUs of Vigevano for marble trout adult and juvenile.

With the histograms and the biological models for marble trout adult and juvenile, is possible to see some problems. For example, the water depth and velocity under the measured discharge are too low for adult marble trouts, and also the substrate composition is not adequate since there is no megalithal or macrolithal. In the case of juveniles, the same problem was seen for the water depth, but for them, the current velocity in the non-suitable HMUs was too high. Also for juveniles the substrate composition was not the most appropriate since they prefer macrolithal and mesolithal and in the main channel of Vigevano reach the substrate was mainly microlithal.

4.3.5 Lampetra zanandreai

Since there is no historical presence of *Lampetra zanandreai* in the Turbigo reach, the analysis for this species is done only for the Vigevano section. Figure 3.26 shows that only 3 of 44 HMUs of Vigevano are suitable for Po brook lamprey, which means that the hydromorphological characteristics in that area are a limitation for the presence of this species. To understand the problem is useful to analyze the frequency distribution histograms shown below. From the histograms and the biological models is possible to deduce that the main limitation of the Vigevano reach for Po brook lamprey is the substrate composition, since they need sandy soil, and in that section, the substrate is composed mainly of microlithal and mesolithal.

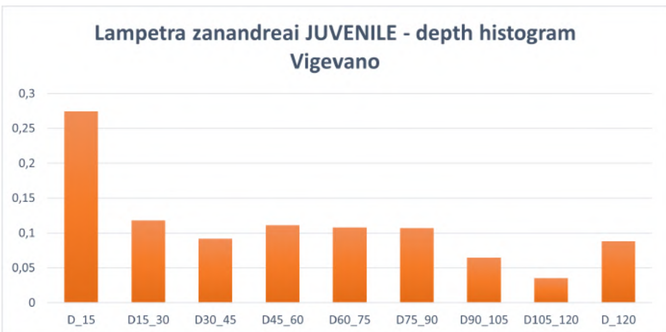

Figure 4.21: Frequency distribution of water depth for the non-suitable HMUs of Vigevano for Po lamprey.

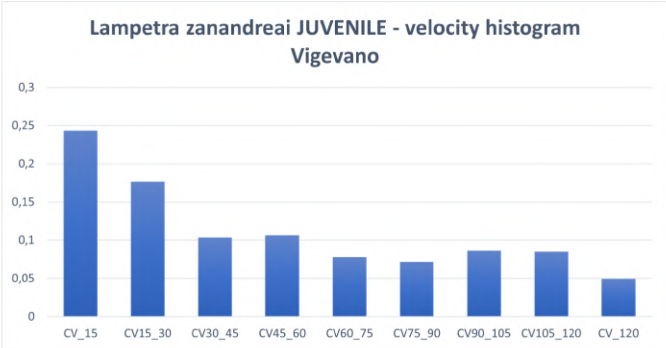

Figure 4.22: Frequency distribution of velocity for the non-suitable HMUs of Vigevano for Po brook lamprey.

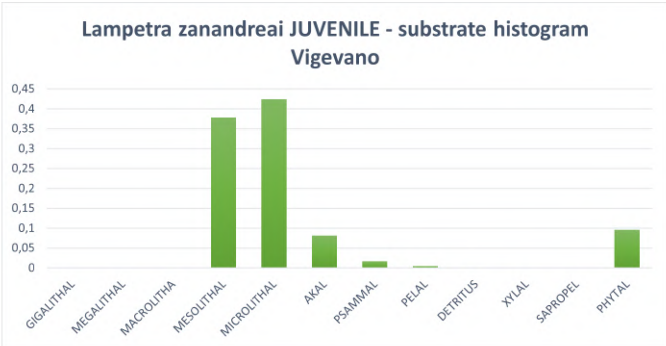

Figure 4.23: Frequency distribution of substrate for the non-suitable HMUs of Vigevano for Po brook lamprey.

4.4 Conclusions

This research aimed to assess habitat availability in two reaches of the Ticino River under low flow conditions to contribute to the T°Cino project, whose objective is to define mitigation strategies for the problems arising due to climate change. To accomplish this, several field surveys were performed during low flows, considering topographic and hydromorphological information, water temperature, and fish sampling. With the obtained data, it was possible to apply the MesoHABSIM methodology by performing 2D hydrodynamic simulations in HEC-RAS. These simulations were used alongside the orthophotos to delineate and describe hydromorphological units in ArcGIS Pro. These HMUs were used as input in the SimStream-Web service to obtain habitat suitability maps for five species that are of particular interest because of their thermal sensitivity and their historical presence in the studied sections of the river. After obtaining the habitat suitability maps they were analyzed along with the results of the fish sampling, to understand the relations between the abundance of the species and the simulated habitat availability as a function of the hydromorphological characteristics of the river (water depth, current velocity, presence of cover, and substrate composition).

From the results of the fish sampling that have been carried out since last year and previous knowledge about the historical presence of the studied species in the two river reaches it could be seen that in both stretches there was a historical presence of Italian spring goby and marble trout, but none of them have been seen in those areas recently. The same happened for Po brook lamprey in the Vigevano reach. The Italian vairone was the only studied species whose abundance has not significantly changed in either of the sections. Concerning bullhead, a drastic decrease in its abundance was observed in Turbigo during the last year.

The habitat suitability maps were obtained for the measured flow in the field in August 2022, which was proved to be representative of a low flow period. The maps showed that the hydromorphological conditions of both studied sections are suitable for vairone, especially for adults, which makes sense with what has been found during the fish sampling. In the case of Po brook lamprey and Italian spring goby, the habitat of the studied areas is not suitable under the measured discharge, which was found to be because the substrate of the riverbed is not adequate for this species. This probably means that the reason why there has been no recent presence of this species in the studied sections is mainly due to the morphological conditions of the river. For the marble trout, there was a more suitable area for adults than for juveniles, and more in Turbigo than in Vigevano. In both Vigevano and Turbigo, the habitat is mostly non-suitable for marble trout due to limitations in terms of water depth, velocity, and substrate composition, which explains the fact that there is no recent presence of this species. Nevertheless, the amount of suitable area for marble trout in Turbigo was not very different from the one for bullhead, and bullhead were recently found in that part of the river. This could mean that there is another factor influencing the presence of marble trout in that section, like water temperature or the presence of alien species. Regarding the bullhead, more than half of the Turbigo section was found to be suitable, which makes particularly interesting its drastic decrease in the last year. In the non-suitable areas, it was found that the water depth and velocity were not appropriate. Also, looking at the results of the fish sampling performed by the T°Cino project, a correlation was found between the decrease in the abundance of bullhead and an increase in the abundance of catfish (*Silurus glanis*), which is an exotic predator.

After performing field surveys and applying the MesoHABSIM method, it can be concluded that the habitat of two species, i.e. bullhead, and marble trout, is limited during low flow periods. In the case of Po brook lamprey and Italian spring goby, the problem of lack of habitat was found to be more related to the morphological conditions of the river than to the discharge conditions. It can also be concluded that there are other factors besides the low flows and the morphology that are influencing the decrease in the abundance of species, like the water temperature and the presence of new predators. This information can be used in combination with further research to find the best mitigation strategies to be applied in the different parts of the river.

There is still a lot to do to have more complete knowledge of which are the main factors affecting the biodiversity of the Ticino River. In August a water surface temperature survey via drone will be performed to understand how water temperature is influencing the presence of the studied species. However, it would also be helpful to perform more research about the thermal tolerance of the target species, since there is not much information available in the literature for those specific species, and it is necessary to understand the influence of the temperature changes on their presence in the river. Finally, it would also be useful to repeat the mesohabitat suitability assessment for different discharge conditions and for the rest of the river reaches studied by the T°Cino project, so that habitat rating curves can be obtained, and a more adequate e-flow can be proposed in the river.

Bibliography

[1] IPCC. «WG III contribution to the Sixth Assessment Report.» In: *Technical Summary* (2021) (cit. on p. 1).

[2] UN. «What Is Climate Change?.» In: (2022), https://www.un.org/en/ (cit. on p. 1).

[3] H. Pham, S. Torresan, A. Critto, and A. Marcomini. «Alteration of freshwater ecosystem services under global change – A review focusing on the Po River basin (Italy) and the Red River basin (Vietnam).» In: *Science of the Total Environment* (2018), pp. 1347–1365 (cit. on p. 1).

[4] J. Dorts, G. Grenouillet, J. Douxfils, S. Mandiki, S. Milla, F. Silvestre, and P. Kestemont. «Evidence that elevated water temperature affects the reproductive physiology of the European bullhead Cottus gobio.» In: (2012) (cit. on pp. 1, 15).

[5] F. Salmaso, S. Quadroni, G. Gentili, and G. Crosa. «Thermal regime of a highly regulated Italian river (Ticino River) and implications for aquatic communities.» In: (2016) (cit. on pp. 1, 11, 14, 15, 60).

[6] M. Spada and S. Arduino. «Piano di Riqualificazione del Corridoio Ecologico del Fiume Ticino 2021-2031.» In: *Istituto Oikos* (2021) (cit. on pp. 1, 7, 11).

[7] European Commission. «CIS guidance document nº31 - Ecological flows in the implementation of the Water Framework Directive.» In: (2015) (cit. on p. 2).

[8] P. Vezza, A. Zanin, and P. Parasiewicz. «Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale.» In: *ISPRA - Manuali e Linee Guida 154/2017.* (2017) (cit. on pp. 2, 4, 5).

[9] K. Suska and P. Parasiewicz. «Application of the Mesohabitat Simulation System (MesoHABSIM) for Assessing Impact of River Maintenance and Restoration Measures.» In: *Water, 12(12), 3356.* (2007) (cit. on pp. 2, 5).

[10] P. Parasiewicz. «The MesoHABSIM model revisited.» In: *River Research and Applications 23.8* (2007), pp. 893–903 (cit. on p. 4).

[11] P. Vezza, D. Ghia, and G. Fea. «Quantitative Habitat Models for the Conservation of the Endangered European Crayfish Austropotamobius pallipes Complex (Astacoidea: Astacidae).» In: *A Global Overview of the Conservation of Freshwater Decapod Crustaceans.* (2016) (cit. on p. 4).

[12] M. Rinaldi, B. Belletti, L. Nardi, L. Mao, and M. Bussettini. «Sistema di rilevamento e classificazione delle Unità Morfologiche dei corsi d'acqua (SUM) – Versione aggiornata 2016.» In: *Istituto Superiore per la Ricerca e la Protezione Ambientale (ISPRA).* (2016), Manuali e Linee Guida 132/2016 (cit. on pp. 4, 33).

[13] P. Vezza, P. Parasiewicz, M. Spairani, and C. Comoglio. «Habitat modelling in high gradient streams: the meso-scale approach and application.» In: *Ecological Applications 24(4)* (2014), pp. 844–861 (cit. on p. 4).

[14] P. Vezza, P. Parasiewicz, M. Rosso, and C. Comoglio. «Defining minimum environmental flows at regional scale: Application of mesoscale habitat models and catchments classification.» In: *River research and applications, 28* (2012), pp. 675–792 (cit. on p. 5).

[15] P. Parasiewicz, J.G. Rogers, P. Vezza, J. Gortázar, T.P. Seager, M.A. Pegg, W. Wisniewolski, and C. Comoglio. «Applications of the MesoHABSIM Simulation Model.» In: *John Wiley & Sons, Ltd EBooks.* (2013) (cit. on p. 5).

[16] B. Pinna. «A novel approach to model the macroinvertebrate distribution in braided rivers». In: *Master thesis. Politecnico di Torino* (2020) (cit. on pp. 5, 23–26, 30, 31).

[17] A. Winkler, D. Antonioli, A. Masseroni, R. Chiarcos, M. Laus, and P. Tremolada. «Following the fate of microplastic in four abiotic and biotic matrices along the Ticino River (North Italy).» In: *Science of the Total Environment* (2022), https://doi.org/10.1016/j.scitotenv.2022.153638 (cit. on p. 6).

[18] F. Salmaso, G. Crosa, P. Espa, and S. Quadroni. «Climate Change and Water Exploitation as Co-Impact Sources on River Benthic Macroinvertebrates.» In: (2021), https://doi.org/10.3390/w13192778 (cit. on pp. 6, 11).

[19] A. Nessi, A. Balestrieri, A. K. Winkler, A. Casoni, and P. Tremolada. «Kingfisher (Alcedo atthis) diet and prey selection as assessed by the analysis of pellets collected under resting sites (River Ticino, north Italy).» In: *Aquatic Ecology,* (2021), pp. 135–147 (cit. on p. 6).

[20] G. Buttner, J. Feranec, G. Jaffrain, J. Mari, G. Mauche, and T. Soukup. «The CORINE land cover 2000 project». In: *EARSeL eProceedings, 3(3),* (2004), pp. 331–346 (cit. on p. 6).

[21] CIRF. «T°Cino - Migliorare la conservazione e riqualificazione del fiume Ticino conoscendo e mitigando il riscaldamento delle acque.» In: *Relazione di avanzamento attività – 31 gennaio 2023* (2023) (cit. on pp. 8, 22–24, 26–29).

[22] Consorzio del Ticino. «Schema derivazioni». In: (2023), www.ticinoconsorzio.it (cit. on p. 12).

[23] JV. Ward. «Thermal characteristics of running waters.» In: *Hydrobiologia* (1985), 125:31–46 (cit. on pp. 14, 15).

[24] JD. Olden and RJ. Naiman. «Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity.» In: *Freshwater Biol.,* (2010), 55:86–107 (cit. on p. 14).

[25] G. Knaepkens, L. Bruyndoncx, L. Bervoets, and M. Eens. «The presence of artificial stones predicts the occurrence of the European bullhead (Cottus gobio) in a regulated lowland river in Flanders (Belgium).» In: *Ecology of Freshwater Fish 11,* (2002) (cit. on p. 15).

[26] IUCN. «Cottus gobio.» In: (2013) (cit. on p. 15).

[27] M. Gosselin, G. Petts, and I. Maddock. «Mesohabitat use by bullhead (Cottus gobio),» in: (2010) (cit. on p. 15).

[28] G. Delmastro, G. Giudice, and E. Lodi. «Il Cobite mascherato Sabanejewia larvata (De Fil.) nelle acque del fiume Ticino.» In: (1987) (cit. on p. 16).

[29] P. Bianco. «Mediterranean endemic freshwater fishes of Italy.» In: *Biol. Conserv., 72 (2).* (1995), pp. 159–170 (cit. on pp. 16, 18).

[30] IUCN. «Knipowitschia punctatissima.» In: (2013) (cit. on p. 16).

[31] A. Carosi, R. Padula, L. Ghetti, and M. Lorenzoni. «Endemic Freshwater Fish Range Shifts Related to Global Climate Changes: A Long-Term Study Provides Some Observational Evidence for the Mediterranean Area.» In: (2019), https://doi.org/10.3390/w11112349 (cit. on p. 17).

[32] F. Marchetto, S. Zaccara, F. Muenzel, and W. Salzburger. «Phylogeography of the Italian vairone (Telestes muticellus, Bonaparte 1837) inferred by microsatellite markers: evolutionary history of a freshwater fish species with a restricted and fragmented distribution.» In: *BMC Evol Biol 10, 111.* (2010) (cit. on p. 17).

[33] M. D'Amen, P. Bombi, L. Traversetti, and M. Scalici. «Relazione fra la presenza di Telestes Muticellus (Bonaparte, 1837) e Rutilus Rubilio (Bonaparte, 1837) e alcune caratteristiche ambientali.» In: *Italian Journal of Freshwater Ichthyology,* (2017) (cit. on p. 17).

[34] Y. Souchon and L. Tissot. «Synthesis of Thermal Tolerances of the Common Freshwater Fish Species in Large Western Europe Rivers.» In: *Knowledge and Management of Aquatic Ecosystems 405(405).* (2012) (cit. on p. 17).

[35] E. Bohl, M. Herrmann, B. Ott, B. Seitz, and J. Heise. «Untersuchungen zur Fortpflanzungsbiologie, Entwicklung und zu den Lebensräumen von Schneider (Alburnoides bipunctatus BLOCH 1782) und Strömer (Leuciscus souffia agassizi VALENCIENNES 1844) – Abschlussbericht über die Untersuchungen 2002–2004,» in: *Bayerisches Landesamt für Wasserwirtschaft, Abteilung Gewässerökologische Forschung, Referat Fischökologie,* (2004) (cit. on p. 17).

[36] V. Ginot, Y. Souchon, and P. Roger. «Impact de l'élévation artificielle de température induite par le fonctionnement du Centre Nucléaire de Production Electrique du Bugey (fleuve Rhône) sur les communautés de poissons.» In: *Hydroecol. Appl., 8.* (1996) (cit. on p. 17).

[37] Autorità di Bacino del Fiume Adige. «Curve di Preferenza del Temolo e della Trota Marmorata. Realizzazione di un esercizio sperimentale di alcune derivazioni d'aqua sul fiume adige finalizzato alla valutazione del minimo deflusso.» In: (2002) (cit. on p. 18).

[38] N. Pankhurst and H. King. «Temperature and Salmonid Reproduction: Implications for Aquaculture.» In: *J. Fish Biol., 76,* (2010), pp. 69–85 (cit. on p. 18).

[39] B. Barton. «General biology of salmonids. In Principles of Salmonid Aquaculture (Pennell, W. & Barton, B. A., eds)». In: *Amsterdam: Elsevier.* (1996), pp. 237–246 (cit. on p. 18).

[40] P. Bianco. «Lethenteron zanandreai (Vladikov,1955).» In: *The Freshwater Fishes of Europe.* (1986), pp. 237–246 (cit. on p. 18).

[41] I. C. Potter. «The Petromyzoniformes with Particular Reference to Paired Species.» In: *Canadian Journal of Fisheries and Aquatic Sciences, 37(11).* (1980), pp. 1595–1615 (cit. on p. 19).

[42] G. Negro, S. Fenoglio, E. Quaranta, C. Comoglio, I. Garzia, and P. Vezza. «Habitat Preferences of Italian Freshwater Fish: A Systematic Review of Data Availability for Applications of the MesoHABSIM Model.» In: (2021) (cit. on pp. 19, 20).

[43] C. Rondinini, A. Battistoni, and C. Teofili. «Lista rossa IUCN dei vertebrati italiani 2022.» In: (2022), Comitato Italiano IUCN e Ministero dell'Ambiente e della Sicurezza Energetica, Roma (cit. on p. 21).

[44] T. Corbin. «Learning ArcGIS Pro.» In: (2015) (cit. on p. 30).

[45] G. W. Brunner. «HEC-RAS River Analysis System, 2D Modeling User's Manual (CPD-68A).» In: *U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC).* (2016) (cit. on p. 31).

[46] D. R. Muñoz, D. Yin, R. Bakhtyar, H. Moftakhari, Z. Xue, K. T. Mandli, and C. Ferreira. «Inter-Model Comparison of Delft3D-FM and 2D HEC-RAS for Total Water Level Prediction in Coastal to Inland Transition Zones.» In: *Journal of the American Water Resources Association* (2021), pp. 34–49 (cit. on p. 33).

[47] West Virginia Department of Environmental Protection. «Pebble Count.» In: (2023) (cit. on p. 34).

[48] SimStream. «User Manual.» In: *Version 1.0.0.* (2021) (cit. on p. 35).

[49] V. T. Chow. «Open-channel Hydraulics.» In: *MacGraw-Hill Book Co., NY* (1959) (cit. on p. 45).

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