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Hydropeaking in Alpine rivers: an ecosystem services approach

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Abstract

Rivers provide to society many important goods and benefits. Some of these ecosystem services depend on the river flow regime, which has been deeply modified by human structures and activities. These alterations have a direct influence on biodiversity, natural habitat and on the supply of river ecosystem services. The release of water from storage hydropower plants generates rapid flow and stage fluctuations (hydropeaking) in the receiving water bodies at a variety of sub-daily time-scales. In this thesis, we describe an approach to quantify such variations, which is easy to apply, requires stream flow data at a readily available resolution, and allows for the comparison of hydropeaking flow alteration amongst several gauged stations. Hydropeaking flow alteration is quantified by adopting a rigorous statistical approach and using two indicators related to flow magnitude and rate of change. We utilised a comprehensive stream-flow dataset of 105 gauging stations from Italy, Switzerland and Norway to develop and test our method. Next, we introduce a modelling approach to evaluate the spatial and temporal variations of a discharge-related ecosystem service, the rafting. The application of hydraulic and habitat models allowed to define spatially thresholds of suitability in each river reach and the application of an hydrological model allowed to assess temporally the suitability for the rafting navigability in different discharge conditions. We applied the method to the Noce River, an Alpine River in Northern Italy affected by hydropeaking. Our analysis showed that in this river, the water releases are fundamental to maintain high flow conditions required for rafting, which can be granted only by hydropower production especially in summer months. Together with present discharge conditions, our approach allows to analyse also the effects of an additional withdrawal which locally has a negative impact on river suitability. Finally, the application of the methodology was extended to include in the analysis the fish habitat and the small hydropower production, along with the rafting. The effects of hydropeaking on these ecosystem services were assessed in space and time. Hydropeaking has a strong influence on rafting navigability and less obvious consequences on the other services. Different management scenarios of the water releases from the hydropower plants were produce, with the aim to evaluate spatially the reciprocal effects of optimizing each ecosystem services. Only the scenario of rafting optimization will significantly increase rafting navigability, while the effects of other scenarios are less evident. Moreover, two additional increasing withdrawals have been simulated to evaluate their impacts on the services. The small hydropower withdrawals will have a negative impact on rafting and fish habitat, while the preservation of requirements for rafting will greatly affect the small hydropower production. This ecosystems-services based approach can be integrated in the decision-making process to evaluate river management alternatives.

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Chapter 1

Introduction

1.1 Ecosystem services

The human society, economic activities and well-being rely on the goods and benefits provided by natural systems. The natural cycles of nutrients and water, the provisioning of food and of other important materials are fundamental to support the survival of each living organism. The growth of human population and the effects of production activities are threatening the functionality of natural systems and the services that they deliver, which are called ecosystem services. Since the concept of ecosystem services has been developed and formulated (e.g., Costanza *et al.*, 1997; Daily, 1997), several studies have described these services (TEEB, 2010; MEA, 2005), which have been categorized in different classes as, provisioning services (e.g. water, genetic resources, hydro power), regulating services (e.g. water regulation, erosion regulation, natural hazard regulation), cultural services (e.g. cultural values, eco-tourism, cultural heritage) and supporting services (e.g. nutrient cycling, water cycling). The aims of these have been to develop a scientific basis for a sustainable use of ecosystems and to understand the pathway which transfers benefits and services from ecosystems to human societies and well-being (Haines-Young and Potschin, 2010). Biodiversity and the complex interactions among organisms are recognized as the foundation of ecosystems and related services (fig 1.1, MEA, 2005). Biodiversity plays a key role for maintaining ecosystem functions, it shows a positive correlation with ecosystem services (Rey Benayas *et al.*, 2009), and its decrease has a strong negative impact on the delivered ecosystem services (Balvanera *et al.*, 2006). The preservation of ecosystems guarantees also the conservation of processes and functions which deliver ecosystems services (Haines-Young and Potschin, 2010). The ecosystem services affects human well-being with benefits that could have economic, social and ecological values (TEEB, 2010) and, in turn, human activities have an influence on ecosystems and are

direct drivers of change and alterations. This cycle can be strongly influenced by policy makers and decision makers. In this perspective, the concept of ecosystem services and its worldwide and increasing diffusion have lead to a major comprehension of the fundamental role played by nature to sustain the society and how the building of a sustainable future requires the balancing between human activities and ecosystems (Costanza *et al.*, 2014).
In order to quantify the value of the natural capital "in terms comparable with economic services and manufactured capital" (Costanza *et al.*, 1997) and to incorporate these concepts into the decision making processes, the value of the services have been quantified by several authors (Costanza *et al.*, 2014; de Groot *et al.*, 2012; Kumar P., editor, 2010). Different techniques have been proposed also to assess the economic value of biodiversity (Farber *et al.*, 2002), but this value remains difficult to define (Salles, 2011). Moreover, the economic value of biodiversity is not anyhow sufficient to describe the ecological role of a process and its importance in the ecosystem (Sagoff, 2011).

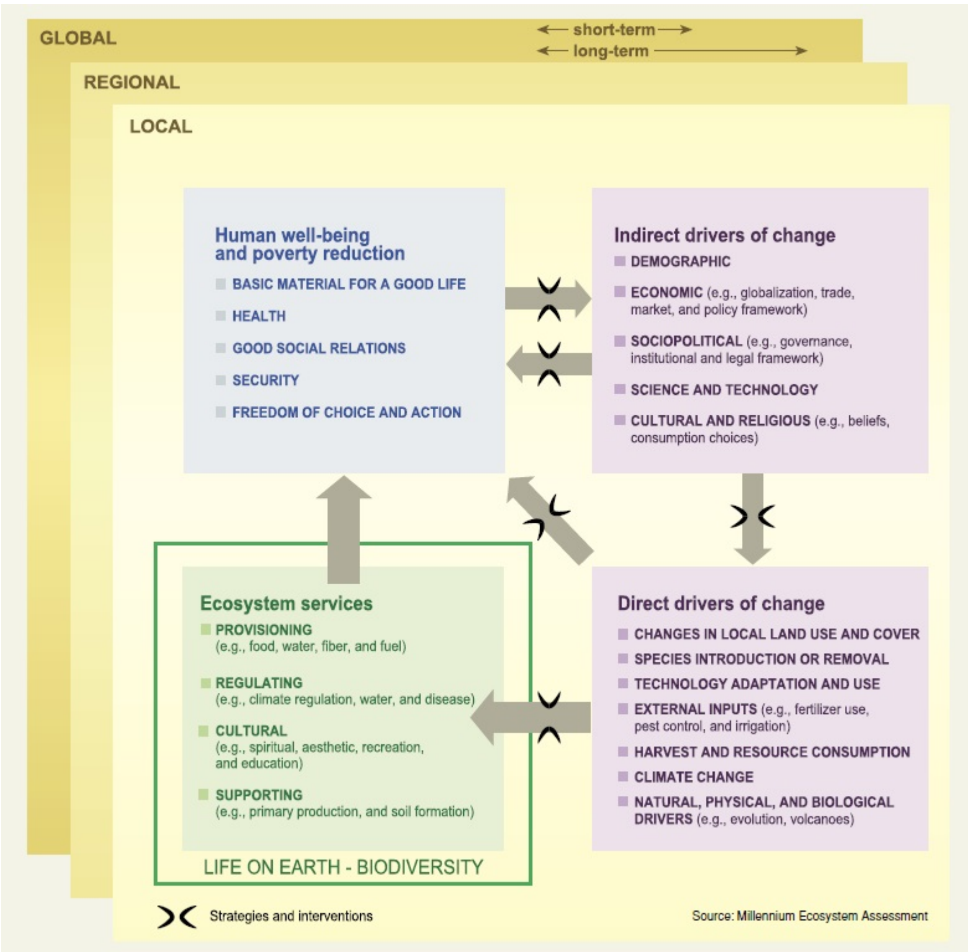


Figure 1.1: *Conceptual framework of interactions between ecosystem services, human well-being, biodiversity and drivers of change (Source: ©MEA, 2005).*

1.2 River ecosystem services

As other natural systems, freshwater bodies support a large variety of ecosystem services. Regulating and provisioning services such as floods control and water supply for multiple uses are among the most studied because they provide water and support fundamental enterprises such as agriculture and livestock (see TEEB, 2010). For example, Acharya and Barbier (2000) evaluated the economic price of groundwater recharge through agricultural practices in Northern Nigeria, Brouwer and van Ek (2004) evaluated the effects of alternative flood control policies under different perspectives in Netherlands, Laso Bayas *et al.* (2011) investigated the effects of the presence of cultivated trees on human infrastructure after a natural hazard as the 2004 Tsunami in Indonesia; several authors studied wetlands ecosystems and restoration projects (Moreno-Mateos and Comin, 2010; Schuyt and Brander, 2004) and fishery and its related values (Smith, 2007; Smith and Crowder, 2011).
Moreover, a consistent amount of other studies assessed the cultural and recreational services provided by freshwater systems: Johnston *et al.* (2002) studied the recreational fishing in estuarine environment; Hammitt *et al.* (2001) analysed the recreational experience of fishing, boating and bird watching in wetland areas; by applying the willingness to pay method; Carlsson *et al.* (2003) examined the walking facilities in wetlands as recreational service; Woodward and Wui (2001) investigated the preservation of wetlands from the perspective of the recreational hunting and fishing and of the observation of wildlife; Birol and Cox (2007) considered the bird watching and the habitat protection of bird species; Do and Bennett (2009) evaluated the willingness to pay for biodiversity protection in Mekong Delta; Jenkins *et al.* (2010) provided an economic value for waterfowl hunting in Mississippi wetland and Loomis *et al.* (2000) measured the total economic value of restoring ecosystem services in an the impaired Platte River basin.
Several works assigned an economic value to freshwater ecosystem services. Costanza *et al.* (1997) provided an exhaustive review of methods and values to assess ecosystem services, identifying water regulation and water supply as the most important services and suggesting for river and lakes a total value for ecosystem services of 8498 \$ per hay^{-1} worldwide. More recently, Russi *et al.* (2013) suggested a range for the total value between 1779 and 13487 \$ per hay^{-1}, estimated in 2007 in 12 different investigations. In detail, Russi *et al.* (2013) suggested values between 1169 \$ and 5776 \$ for provisioning services, between 305 \$ and 4978 \$ for regulating services and between 305 \$ and 2733 \$ for cultural (and recreational) services in freshwater habitats. According with this study, monetary values for the habitat services and for energy production have not been esti-

mated in literature (Russi *et al.*, 2013). On the national scale, Di Sabatino *et al.* (2013) studies proposed in Italy proper economic values for freshwater ecosystems and provided a total value of $11.93 \cdot 10^9$ \$ for freshwater biomes, with rivers alone accounting for $7.05 \cdot 10^9$ \$ for rivers (12400 \$ per hay^{-1}).
Some authors focused specifically on river ecosystem services. For instance, Thorp *et al.* (2010) provided a relationship between the hydrogeomorphology of a river and the ecosystem services they provide. Other authors focused mainly on a set of ecosystem services: Bangash *et al.* (2013) evaluated the effects of climate change on water provisioning and erosion control in a Mediterranean River Basin; Dugan *et al.* (2010) and Hoeinghaus *et al.* (2009) studied the threats posed by the dam construction to artisanal fishery which is an important ecosystem service in developing countries; Melstrom *et al.* (2015) evaluated the influence of fish biomass of five species on the selection of fish sites by anglers in Michigan. Rosso *et al.* (2014) proposed a multi-criteria analysis which identifies stakeholders potentially related to hydropower projects, with the aim of analysing the effects of different alternatives management considering several benefits provided by rivers, from environmental to sociological perspective. An exhaustive list of river ecosystem services has been produced by the REFORM project (Vermatt *et al.*, 2013).

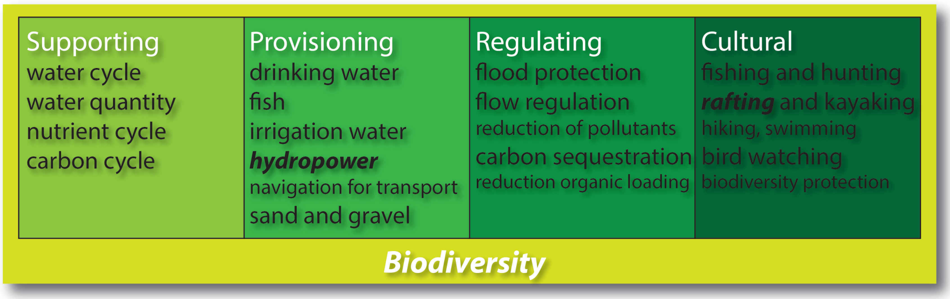


Figure 1.2: *Several ecosystem services delivered by rivers adapted from Vermatt* et al. *(2013). Services and biodiversity assessed in this work are highlighted.*

River recreational services are important economic benefits in some areas (Melstrom *et al.*, 2015; Russi *et al.*, 2013; Vincenzi *et al.*, 2008; Aas and Kaltenborn, 1995; Brown *et al.*, 1991), and they have been included in the local laws (Montana Water Protection Act, requirements for sport fishing and anglers Brown *et al.* (1991)), but only few works have quantified their economic relevance and their variations in specific, quantitative relation with the river flow regime and the influence of hydrogeomorphology is only partially known and understood (Pflüger *et al.*, 2010; Thorp *et al.*, 2010; Growns and James, 2005). Brown *et al.* (1991) reviewed several studies which analysed the recreational services under different point of view (e.g economic studies, studies focusing on minimum flows, on the direct or indirect effects of discharge on recreation) and concluded that expert judgement, direct experience of different flow levels, and the use of survey are necessary to understand the relation between recreation and flow regime. Moreover, they suggested the use of models as a fundamental tool to assess recreational suitability in present and future flow conditions. A framework to assess ecosystems services and goods provided by river floodplains with a connection to the hydrological regime has been described in Posthumus *et al.* (2010). Recently the work of Fanaian *et al.* (2015) applied the method suggested by Korsgaard *et al.* (2008) and links the economic value of a set of selected ecosystem services (hydropower, irrigated agriculture, fishery, wildlife tourism and flood regulation) with the annual flow regime of the impounded Zambesi River. They built several discharge scenarios in order to evaluate the effects of different regimes on the suitability of the ecosystem services and their related economic values, but did not studied the river hydraulic regime. Large and Gilvear (2014) proposed a GIS approach to evaluate the capability of a river to sustain eight ecosystem services on the basis of eighteen geomorphological features, but they did not focus on the hydrological regime and the related hydraulic variables.

1.3 River regulation and flow regime

Habitat changes in freshwater ecosystems are recognized as a driver for river biodiversity loss and habitat degradation is increasing over the last century (MEA, 2005). The flow regime and its variability are fundamental to sustain the biodiversity and the functionality of river ecosystems. This variability acts over a large spectrum of spatial and temporal scales ranging from hours to seasons, and it is important for maintaining hydraulic complexity, sediment transport, hyporheic exchanges, floodplain connections and habitat structure and complexity (Bunn and Arthington, 2002; Poff *et al.*, 1997). No other major component of the global biodiversity is declining as fast as freshwater ecosystems (Vörösmarty *et al.*, 2010) and its relation with flow regime has been thoroughly investigated and is now described in literature (e.g., Fette *et al.*, 2007; Looy *et al.*, 2007; Bratrich *et al.*, 2004). The review of Poff and Zimmerman (2010) provided an exhaustive categorization of flow alterations and related ecological response: the work pinpointed as many of the analysed studies evaluated the impacts of the alteration of the peak flow, of the average discharge, of the base flow and of the short-term variations.

According with Nilsson *et al.* (2005), most of the major river systems are heavily altered by impoundments and water diversion. The human development in many river watersheds has been lead by the perspective of maximizing certain water benefits. Services as agriculture, water provisioning for drinking and electricity generation often require the built and the operations of human structures as large dams. Among most important alterations induced on river systems by human presence, dams are known as a direct driver of freshwater ecosystems alteration and degradation (Aylward *et al.*, 2005; Nilsson and Berggren, 2000). Dams are built to control river flow, improve navigation, regulate flooding, and partly to produce hydroelectric power. A total of 48,000 large dams (over 15 meters high) exists worldwide and they contribute for the 19 % of the global electricity supply (WCD, 2000) and at least 3700 major dams are planned or under construction (Zarfl *et al.*, 2014). For example, in the European Alps seventy-nine percent of reaches are subjected to hydro-power operations (Truffer *et al.*, 2003). Hydropower is a pivotal energy asset for Europe and Alpine region and it will be an important resource to reach the EU 2020 objectives, already contributing for half of the renewable energy produced (Zervos *et al.*, 2011).

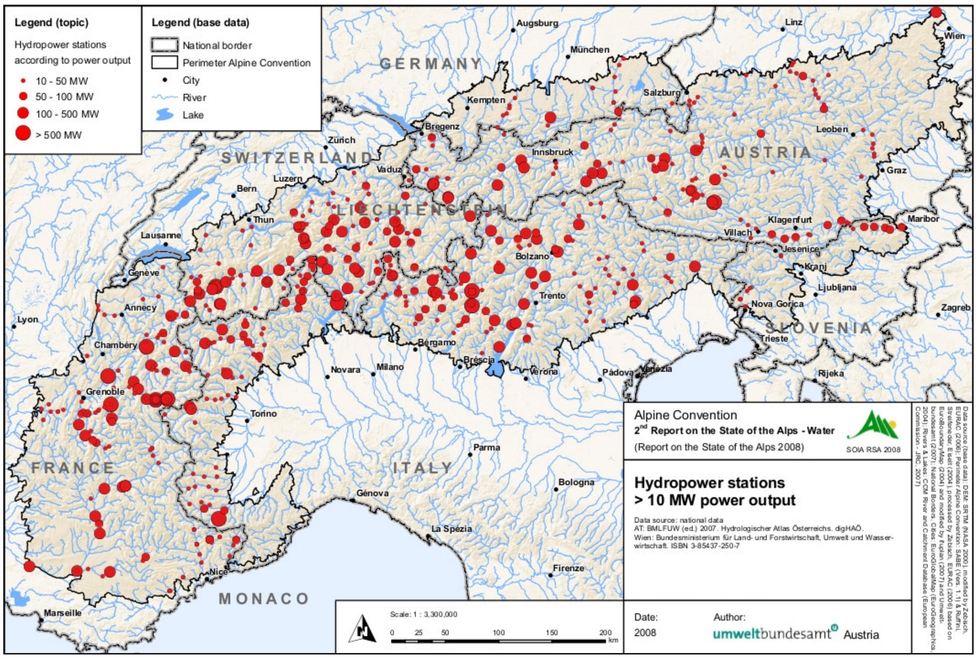


Figure 1.3: *Distribution of large hydropower plants in the Alps (Source: ©Alpine Convention (2009) author: Ingrid Roder).*

Although it is considered a green energy due to the absence of GHG emissions, the hydro-power production schemes have several and significant effects on discharge regimes (Bratrich *et al.*, 2004), and, consequently, on river biota (Fette *et al.*, 2007; Poff *et al.*, 1997; Poff and Zimmerman, 2010; Bratrich *et al.*, 2004). Hydropower production alters in particular the longitudinal connectivity (Bunn and Arthington, 2002) and the flow

regime, which is modified on seasonal, daily and sub-daily time scale by the production schemes (Zhang *et al.*, 2010). An important role is played by sub-daily variations that may induce heavy hydro-morphological alterations in a water course, while short-time scale (sub-daily) flow regime components can result from natural events such as strong snowmelt and rainfall events, in regulated rivers they often result from human activities as water releases from storage hydropower plants. The magnitude of natural events results in diel variations in flow of about 10% of the daily mean flow (Shuster *et al.*, 2008; Lundquist and Cayan, 2002), while anthropogenic water releases can cause much more severe variations (Zolezzi *et al.*, 2009). The occurrence of natural events is limited to few days (precipitations) and few months (snowmelt) during the year, while anthropogenic releases typically repeat each day of the year.
Figure 1.4 shows a typical example of such flow regime alterations, referring to the hydropower-regulated Noce River system in NE Italy. The first graph represents the yearly hydrograph of a glacial natural Alpine River, (fig. 1.4a), the Vermigliana Creek, tributary of the two stations to which panels b) and c) refer. It has a natural flow regime with higher discharges in spring-summer due to snow and ice melting. The first impacted gauged station is 23.8 km downstream a power plant with a full capacity of 6.5 m^3s^{-1}: the flow regime is not altered at the seasonal and monthly scale but sub-daily variations of the discharge are pervasive (fig. 1.4b). The third station is 2.2 km downstream a plant with a full capacity of 60 m^3s^{-1}. In this case, the natural flow regime is completely masked by flow regulation at each temporal scale (fig. 1.4c).

1.4 Hydropeaking

Among the discharge alterations induced by the hydropower production, a peculiar phenomenon is the sub-daily alteration of the flow regime, namely the hydropeaking, which refers to "rapid variations in power production by hydro-electric plants as a consequence of varying electricity generation and fluctuations in demand in the electricity market" (Sauterleute and Charmasson, 2014). Figure 1.5 illustrates the sub-daily variations of the flow regime. In natural glacial rivers, discharges follow a daily cycle (fig. 1.5a). Lake emissaries (figure 1.5b) or rain-fed rivers show discharge peaks only in presence of intense events. The timing and duration of the peaks induced by hydropeaking depends on electricity price set by market energy and are unpredictable on a purely deterministic basis (figure 1.5c).

These sudden variations of water level and discharges in rivers and lakes induced by releases from hydropower plants have a direct effect on daily and seasonal flow

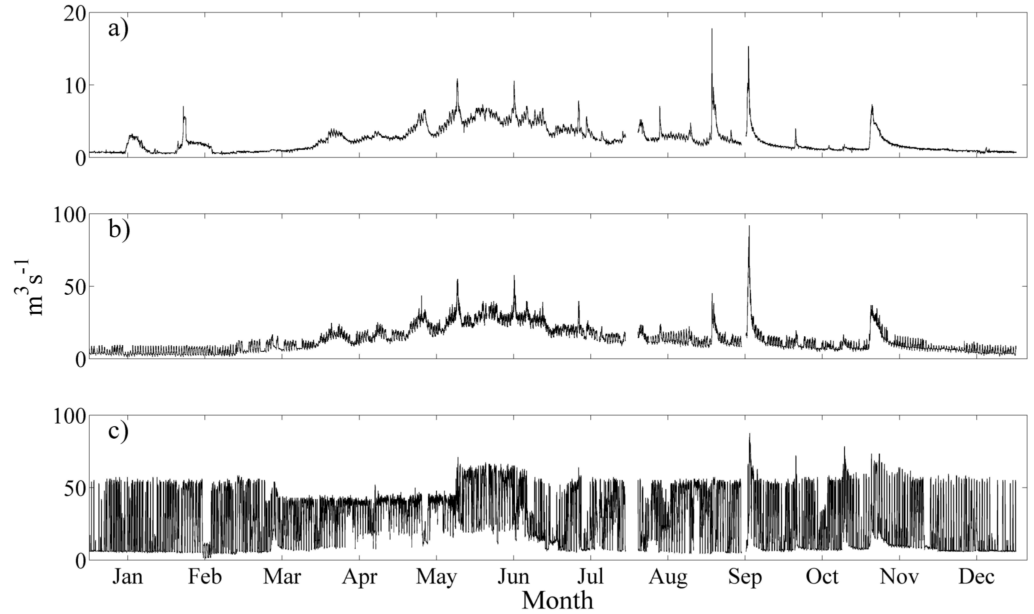


Figure 1.4: *The hydrograph of a glacial natural Alpine River (a) and of two gauged stations downstream hydropower plant releases (b and c).*

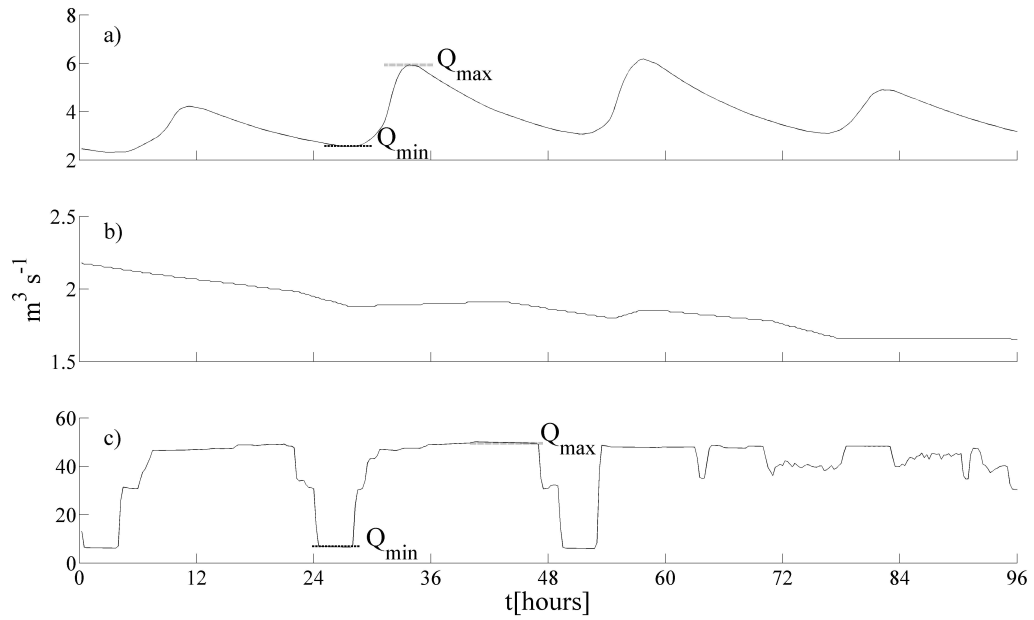


Figure 1.5: *Daily hydrograph of a) a natural river, b) a lake emissary and c) a river impacted by hydropeaking.*

regimes and with consequences on freshwater and river ecology. For instance, multiple daily waves cause a significant part of the benthic community to drift downstream and therefore the recolonisation is fundamental to sustain the benthic communities (Bruno *et al.*, 2010), which are otherwise not capable to self sustain. The repetition of hydropeaking events provokes an alteration of the structure and faunal composition of the benthic and riparian invertebrate community (Jones, 2013; Looy *et al.*, 2007) and hyporheic communities are also impoverished (Bruno *et al.*, 2009). Hydropeaking has a direct effect on the fish communities: stranding, increased mortality, habitat depletion are well-known effects (Tuhtan *et al.*, 2012; Scruton *et al.*, 2005; Halleraker *et al.*, 2003; Scruton *et al.*, 2003; Saltveit *et al.*, 2001; Moog, 1993), although morphology and river features have an important role in its mitigating effects, (Hauer *et al.*, 2013; Bunt *et al.*, 1999; Valentin *et al.*, 1996), highlighting the site-specific nature of hydropeaking impact. Moreover, dams and hydropeaking have an additional effect on river water temperature and consequently on the biota (Bruno *et al.*, 2013; Carolli *et al.*, 2012; Zolezzi *et al.*, 2011; Toffolon *et al.*, 2010; King *et al.*, 1998).

Consequences on the biological communities induced by hydrological alterations and hydropeaking can affect the success of the Water Framework Directive goals in affected reaches (European Parliament, 2000). Since biodiversity is a key driver to maintain ecosystem functions, processes and services, several methods have been proposed to evaluate the environmental flow requirements (Warfe *et al.*, 2014; Black *et al.*, 2005; Richter *et al.*, 1996), but they have been rarely implemented (Fanaian *et al.*, 2015). However, hydrological alterations are most commonly quantified using daily discharge data (Richter *et al.*, 1996), thus ignoring sub-daily variations, and few methods adopt flow data at the finer temporal resolution necessary for the quantification of hydropeaking-induced alterations (Meile *et al.*, 2011; Zimmerman and Letcher, 2010; Bevelhimer *et al.*, 2014; Sauterleute and Charmasson, 2014). For instance, Meile *et al.* (2011) proposed a set of three indicators and performed an analysis on different gauging stations along the Upper Rhone river. The authors used these indicators to define regulated and unregulated water courses. Zimmerman and Letcher (2010) developed a predictive method based on four "flashiness indices" that can be computed from hourly discharge data, and applied it to 30 gauging stations in the Connecticut River basin (USA) to compare the potential impacts of different types of dam operations. Recently, Sauterleute and Charmasson (2014) proposed an assessment tool based on eighteen hydropeaking parameters, grouped by magnitude, time and frequency. Their analysis provides detailed information that can be particularly useful for the assessment of hydrological impacts and potential mitigation measures in relation to hydropeaking. Bevelhimer *et al.* (2014) divided a set of streams in three different groups: without alterations, with peaking and run of the river hydropower plants and compared the respective flow regimes using different indicators that quantify magnitude, variation, frequency and rate of change of flow events at sub-daily (hourly) and daily scale. Because of its relevance, quantification of sub-daily alterations is becoming increasingly important in legislation at a regional, national and international level, as, for instance, in relation to the Water Framework Directive (European Parliament, 2000), in the Swiss Water Protection Act (FOEN, 2011), in the implementation of Italian national methodology for hydromorphological assessment of rivers (Rinaldi *et al.*, 2013) and in the Norwegian regulations on the renewal of hydropower licensing (Anonymous, 2012).

1.5 Aims and objectives

The general aim of this PhD work is to develop a methodology to quantify flow regime alterations related to hydropeaking and to quantify the mutual interactions among different river ecosystem services, with specific application to rivers regulated by hydropeaking. In order to tackle this challenge, the problem has been decomposed into three different broad research questions.

It is possible to develop an easy-to-use procedure to quantify at-a-station hydrological alterations caused by hydropeaking using commonly available flow-data, and allowing large scale (i.e. regional) comparison of such alteration among multiple river catchments?

Hydropeaking is widespread in the Alps and several methods have been proposed to assess it. However, they require data which are not readily available, such as historical data, or are complex and not easy and straightforward to be applied and to be interpreted because of the large set of parameters they involve. Thus, a new easy-to-use methodology based on few indicators, calculated from a temporally short, but spatially wide dataset will be developed to classify the "hydropeaking pressure" that we define as the physical alteration of flow regime due to hydropeaking. The classification of hydropeaking pressure resulting from the application of the proposed methodology is purely hydrological. The aim is to propose an easy to use and expeditious method that allows to analyse and compare a large number of river reaches.

It is possible to analyse, and with which method, the spatial and temporal quantitative impact of hydropeaking on the river suitability for a selected discharge-dependant recre-

ational service in an Alpine river?

Hydropeaking is most studied in relation with its effect on biodiversity and river biota. However, the effects of this phenomenon on cultural and recreational ecosystem services have not been quantified yet. The starting hypothesis for this analysis is that tools developed for biodiversity and habitat quality assessment can be useful to estimate also the capability of the river to support these recreational services.

Can a quantitative, general method be developed to quantify the mutual interactions among flow regime dependant river ecosystem services and river support to biodiversity in response to different flow regime management alternatives?

Quantitative assessment of river ecosystem services is scarce at present, and unexploited opportunities exist in particular in the case of flow-dependant ecosystem services. In these cases, indeed, available tools like hydrological and hydraulic models can be combined to predict the river physical response to different options of flow management. Moreover, the analogy with habitat suitability offers the opportunity to integrate key bio-physical information relevant to a variety of services and to biodiversity support.

Each question is elaborated into a series of sub-questions which are described and tackled in each chapter of this thesis, which is organized as follows. The chapter 2 describes a methodology to assess the hydropeaking pressure induced on river gauged stations. Most of the rivers are affected by hydropower production systems since the beginning of the last century, therefore a before-after impact comparison is not possible. We introduce a comparison between peaked and unpeaked gauged stations data series as a space-for-time proxy to overcome this limitation. In chapter 3 we describe in detail the area in which we have concentrated our studies. In chapter 4 we introduce an innovative application that integrates existing hydraulic, hydrological and habitat models in order to quantify the variations of river suitability for a discharge-related recreational ecosystem service, namely rafts navigability or rafting, in an Alpine river affected by hydropeaking. The concept of "rafting suitability" in analogy with "habitat suitability" is proposed and developed for the first time. The variations of rafting suitability is assessed at reach scale and at sub-daily temporal scale, according with discharge changes induced by hydropower production.

The chapter 5 describes a novel, general modelling approach to quantify the effects of various management scenarios and hydropeaking on a biodiversity proxy and on other river ecosystem services, with a specific focus on hydropeaking rivers. To allow comparison among different ecosystem services at different temporal and spatial aggregation scales such as the basin and annual scale, the "river suitability" for a given ecosystem service is introduced as a quantitative and comparable indicator. Several scenarios of large hydropower production and new withdrawals for small hydropower are analysed starting from reach and sub-daily scale. The modelling approach to ecosystem services we propose here can be easily integrated into the decision making process to evaluate the effect of different flow regime options and other ecosystem services. Conclusions and possible further development of the research are given in the last chapter (chapter 6).

Chapter 2

A simple procedure for the assessment of hydropeaking flow alterations

Based on the paper: Carolli M., Vanzo D., Siviglia A., Zolezzi G., Bruno M.C., Alfredsen K. A simple procedure for the assessment of hydropeaking flow alterations applied to several European streams. Aquatic Sciences, accepted for publication.

2.1 Introduction

In the chapter 1 we described several methods to assess the sub-daily flow regime alterations which in our opinion are difficult to broadly apply. In fact, the indicators proposed by Meile *et al.* (2011) and by Sauterleute and Charmasson (2014) can potentially be used to compare different levels of hydropeaking pressure among several streams but in both cases their application was limited to only one water course. Moreover, their methodology might not be broadly applicable, as the method proposed by Meile *et al.* (2011) requires long-term data of the same river watershed, which may not always be available. The large number of parameters adopted in the methodology of Sauterleute and Charmasson (2014) does not allow to make straightforward comparison among streams. The method proposed by Zimmerman and Letcher (2010) focuses on a single watershed and requires detailed data collection of the basin in order to assess the hydrological alterations induced by a different set of dam operations. The method proposed by Bevelhimer *et al.* (2014) aims to compare different streams but requires the calculation of a large set of indicators. In this chapter we will describe a new method we developed to assess the hydropeaking pressure at river gauged stations. We sought to develop a methodology to classify levels of "hydropeaking pressure", defined as the physical alteration of flow regime due to hydropeaking. Most of the large storage hydropower plants were built around the half of the past century in all three investigated countries, and discharge data at sub-daily resolution are available only for much more recent times. Therefore, we could not use a classical pre- and post-regulation comparison for each gauged station. Instead, our approach uses a space-for-time proxy to allow detecting hydrological alterations even if historical data are not available. The classification of hydropeaking pressure resulting from the application of the proposed methodology is purely hydrological and has no direct significance for the assessment of the effects on river ecology. The method has the following requirements:

i) it is easily implementable by using the smallest possible number of indicators, which are based on short time datasets that are commonly available at sub-daily sampling resolution;

ii) it allows comparison among different gauged stations in the same area;

iii) it distinguishes between types of hydropeaking pressure;

iv) it is statistically robust.

The chapter is organized as follows. In section 2.2 firstly we introduce datasets and study area, describing the existing flow alteration; secondly we define the method we used to quantify alterations: the indicators equation, the definition of thresholds and the conditional rules which classify the stations. In section 4.4, we describe the calculation of the indicators, of the thresholds for the different datasets analysed, and the classification of the gauging stations. In section 4.5 we discuss strengths and weaknesses of the indicators, the variability of thresholds, the changes in class of the gauging stations for different spatial and temporal scales, and we show the conclusion of our analysis.

2.2 Methods

2.2.1 Flow data selection

We used discharge data from 105 gauging stations located in Italy, Switzerland and Norway (Table 3.1), collected from public rivers monitoring agencies. Based on available GIS informations, and/or the analysis of the streamflow time series, we identified two different groups of gauges: the first group is characterized by the presence of an upstream water release from a storage hydropower plants (peaked stations) and the second one without any release (unpeaked stations). The first dataset was based on 28 gauges (16 peaked and 12 unpeaked) in the NE part of Italy (Trentino region, see Fig. 2.1 a). These stations are well-distributed on the entire regional area. We used a 1-year dataset (2012) at a resolution of 15 minutes. The second dataset included flow data from 36 gauging stations located in Switzerland, 18 of such stations are peaked and 18 unpeaked (see Fig. 2.1 b). The dataset is 6 years long (2007-2012) with a resolution of 15 minutes. Finally, the third dataset is from Norway (see Fig. 2.1 c), where we considered 14 peaked and 27 unpeaked gauges. The dataset is 6 years long (2007-2012) and the data resolution is 1 hour. Stream gauges were chosen in order to cover different river types: glacial, snow-fed, rain-fed, lake emissary, regulated rivers not affected by hydropeaking. The size of equivalent yearly datasets was calculated by multiplying the available number of years by the number of gauging stations, for a total of 490 data series, with 282 unpeaked and 208 peaked equivalent yearly datasets. The main characteristics of the datasets and of the climate of each country are presented in Table 3.1, and the list of the stations used for the analysis is given in Tables 2.2, 2.3, 2.4.

	Italy (IT)	Switzerland (CH)	Norway (NO)
Total stations	28	36	41
Peaked stations	16	18	14
Unpeaked stations	12	18	27
Data breakdown time [min]	15	15	60
Length of data record (available years)	1 year (2012)	6 years (2007-2012)	6 years (2007-2012)
Size of the equivalent yearly dataset (peaked and unpeaked stations)	28	216	246
Size of the equivalent yearly dataset (peaked stations)	16	108	84
Size of the equivalent yearly dataset (unpeaked stations)	12	108	162
Latitude Limits	$45°$-$46°30'$	$45°$-$48°$	$57°$-$71°$
Longitude limits	$10°$-$11°50'$	$5°$-$11°$	$5°$-$31°$
Climate (Kottek *et al.*, 2006)	Polar tundra, snow fully humid cool summer, snow fully humid warm summer	Polar tundra, continentally fully humid cool summer, continentally fully humid warm summer	Polar tundra, snow fully humid cool summer, continentally fully humid cool summer

Table 2.1: *Summary of features of the three datasets.*

2.2.2 Indicators

As a starting point we considered two of the three indicators proposed by Meile *et al.* (2011) and we conveniently modified them in order to provide a single indicator for an easy classification of the data series. Namely, the first indicator, $HP1$, is a non-dimensional measure of the magnitude of hydropeaking and is defined as follows:

$$HP1_i = \frac{Q_{max,i} - Q_{min,i}}{Q_{mean,i}},\ i \in [1, 365]; \qquad (2.1)$$

$$HP1 = median(HP1_i)\ . \qquad (2.2)$$

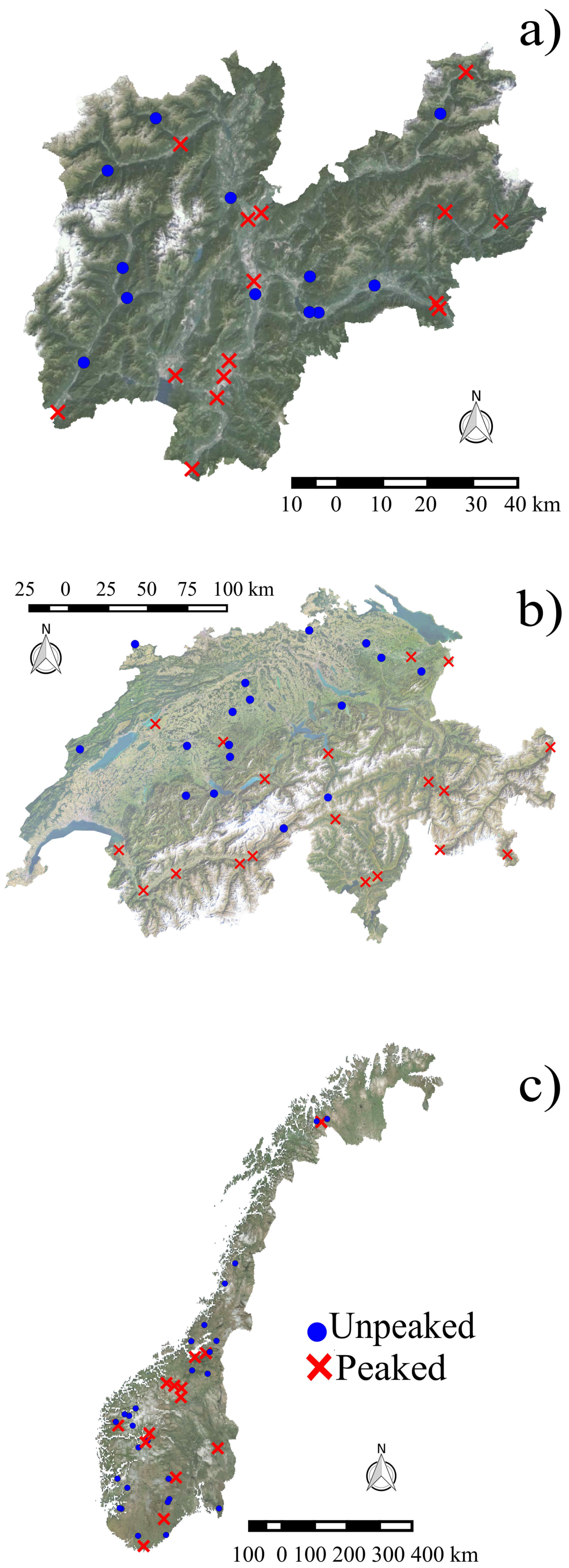


Figure 2.1: *Geographic distribution of the (a) Italian gauging stations, (b) Swiss gauging stations, and (c) Norwegian gauging stations. Circles represent the unpeaked stations, and crosses the peaked stations.*

where subscript $_i$ denotes the day of the year. $HP1$ is defined as the annual median of daily values of $HP1_i$, calculated as the difference between the maximum and the minimum discharge value ($Q_{max,i}$ and $Q_{min,i}$, respectively) over the i^{-th} day, normalized by the discharge daily mean value ($Q_{mean,i}$).

The second indicator, $HP2$, measures the temporal rate of discharge changes and is defined as follows:

$$\begin{aligned} (HP2_k)_i &= \left(\frac{\Delta Q_k}{\Delta t_k}\right)_i = \left(\frac{Q_k - Q_{k-1}}{t_k - t_{k-1}}\right)_i, \ i \in [1, 365] && (2.3) \\ HP2_i &= P_{90}|\left(HP2_k\right)_i|; && (2.4) \\ HP2 &= median(HP2_i). && (2.5) \end{aligned}$$

where Q_k refers to each available discharge datum (e.g. $[1 \leq k \leq 24]$ for data sampled every 60 minutes). It represents the annual median of daily values of $HP2_i$, which is the 90^{th} percentile (P_{90}) of the discretized time derivative of the instantaneous stream-flow series. $HP2$ is a dimensional parameter and it is expressed in $m^3 s^{-1} h^{-1}$. The ninetieth percentile P_{90} was arbitrarily chosen as a measure of the daily rate of change because it is a conservative estimation of the cut-off value for extreme high flow events and allows excluding possible error measurements. We used the absolute value of P_{90}, this taking into account ramping rates of the hydrographs in both directions, i.e. increasing and falling limb. Finally, we used annual median values to characterize each gauged station with a distinctive yearly value for both indicators. The median value is used, for instance, as the measure of central tendency for the non-parametric approach for the hydrological alteration parameters of IHA7 (Richter *et al.*, 1996).

2.2.3 Hydropeaking thresholds and pressure classes

For the quantification of the hydropeaking pressure we identified a threshold for each indicator: TR_{HP1} and TR_{HP2}.

The thresholds are calculated from the 282 unpeaked datasets using a non-parametric method (Tukey, 1977), in order to avoid a priori assumptions on normality in data distribution. The values of the two thresholds correspond to the values of the two estimators which separate the outliers from the rest of the unpeaked distribution.

The chosen outlier estimators which correspond to the thresholds' values are:

$$\begin{aligned} TR_{HP1} &= P_{75}\left(HP1_i^{unp}\right) + 1.5(P_{75} - P_{25})\left(HP1_i^{unp}\right); && (2.6) \\ TR_{HP2} &= P_{75}\left(HP2_i^{unp}\right) + 1.5(P_{75} - P_{25})\left(HP2_i^{unp}\right), && (2.7) \end{aligned}$$

where $HP1_i^{unp}$ and $HP2_i^{unp}$ are the daily values of the two indicators for unpeaked stream gauges and P_{75} and P_{25} are the 75^{th} and the 25^{th} percentile of the distribution, respectively.

Once the thresholds (2.6) and (2.7) are identified, the following conditional rules are applied to each station to identify three different classes of hydropeaking pressure:

1. **Class 1**: *Absent or low pressure.* $HP1 < TR_{HP1}$ and $HP2 < TR_{HP2}$. The gauged station is statistically similar to an unpeaked gauged station.

2. **Class 2a**: *Medium pressure.* $HP1 > TR_{HP1}$ and $HP2 < TR_{HP2}$. $HP1$ indicator is above threshold and the gauged station is an outlier in hydropeaking magnitude compared to unpeaked group.

3. **Class 2b**: *Medium pressure.* $HP2 > TR_{HP2}$ and $HP1 < TR_{HP1}$. $HP2$ indicator is above threshold and the gauged station is an outlier in temporal rate of discharge variations compared to unpeaked group.

4. **Class 3**: *High pressure.* $HP1 > TR_{HP1}$ and $HP2 > TR_{HP2}$. Both indicators are above thresholds.

Watershed	Gauging station	Group	HP1	HP2	Class
Vanoi	Caoria	Peaked	1.12	1.14	2a
Avisio	Cavalese	Peaked	1.13	2.39	3
Cismon	Fiera di Primiero	Peaked	0.82	0.81	2a
Noce	Malè	Peaked	0.59	2.15	2b
Noce	Marco	Peaked	0.43	3.60	2b
Noce	Mezzolombardo	Peaked	1.62	17.25	3
Noce	Pellizzano	Peaked	0.81	3.02	3
Brenta	Ponte Filippini	Peaked	0.39	1.16	1
Adige	Ponte San Lorenzo	Peaked	0.39	17.21	2b
Chiese	Ponte Tedeschi	Peaked	2.16	7.44	3
Leno	Rovereto	Peaked	1.26	1.29	3
Adige	San Michele all' Adige	Peaked	0.36	8.25	2b
Sarca	Torbole	Peaked	0.18	0.34	1
Fersina	Trento	Peaked	1.60	0.70	2a
Adige	Villalagarina	Peaked	0.38	13.55	2b
Adige	Vo Destro	Peaked	0.47	13.19	2b
Brenta	Borgo Valsugana	Unpeaked	0.16	0.22	1
Brenta	Caldonazzo	Unpeaked	0.80	0.34	2a
Avisio	Campitello	Unpeaked	0.29	0.26	1
Fersina	Canezza	Unpeaked	0.43	0.16	1
Chiese	Cimego	Unpeaked	0.10	0.18	1
Brenta	Levico	Unpeaked	0.12	0.12	1
Sarca	Preore	Unpeaked	0.29	0.59	1
Rabbies	Rabbies	Unpeaked	0.25	0.17	1
Avisio	Soraga	Unpeaked	0.21	0.34	1
Sarca	Spiazzo	Unpeaked	0.28	0.36	1
Sporeggio	Sporeggio	Unpeaked	0.21	0.36	1
Noce	Vermigliana	Unpeaked	0.24	0.16	1

Table 2.2: *Italian gauged stations grouped by the values of the hydropeaking indicators $HP1$ and $HP2$, and relative hydropeaking pressure class (calculated from a one year data record).*

Watershed	Gauging station	Group	HP1 Min	HP1 Max	HP2 Min	HP2 Max	Class
Ticino	Bellinzona	Peaked	0.60	1.28	10.39	15.00	2b-3
Rhone	Branson	Peaked	0.39	0.64	10.17	16.60	2b
Aare	Brienzwiler	Peaked	0.68	0.97	8.44	10.57	2b-3
Saltina	Brig	Peaked	0.39	0.54	0.12	0.15	1
Rhein	Diepoldsau, Rietbrucke	Peaked	0.46	0.58	20.01	24.95	2b
Hintherrhein	Fursteanu	Peaked	0.91	1.66	14.22	18.30	3
Aare	Hagneck	Peaked	0.49	0.72	21.94	34.09	2b
Poschiavino	Le Prese	Peaked	0.41	0.75	0.66	1.00	1-2a
Inn	Martina	Peaked	1.63	1.89	20.12	25.87	3
Ticino	Polleggio, Campagna	Peaked	0.93	2.55	5.49	12.99	3
Rhone	Porte du Scèx	Peaked	0.34	0.55	12.39	16.53	2b
Ticino	Riazzino	Peaked	0.60	1.28	11.63	16.79	2b-3
Reuss	Seedorf	Peaked	0.51	0.63	6.16	9.19	2b
Rhone	Sion	Peaked	0.38	0.61	6.39	8.84	2b
Mera	Soglio	Peaked	0.18	0.32	0.17	0.34	1
Sitter	St. Gallen, Bruggen	Peaked	1.26	1.70	2.80	5.11	3
Albula	Tiefencastel	Peaked	0.67	1.23	3.74	4.87	2b-3
Vispa	Visp	Peaked	0.75	1.23	4.12	5.66	3
Reuss	Andermatt	Unpeaked	0.18	0.27	0.16	0.26	1
Sitter	Appenzell	Unpeaked	0.34	0.47	0.14	0.18	1
Aare	Bern-Schonau	Unpeaked	0.06	0.08	0.81	1.47	1-2b
Allaine	Boncourt, Frontiere	Unpeaked	0.16	0.33	0.03	0.07	1
Emme	Eggiwil, Heidbuel	Unpeaked	0.38	0.46	0.06	0.13	1
Alp	Einsiedeln	Unpeaked	0.31	0.45	0.05	0.12	1
Emme	Emmenmatt	Unpeaked	0.26	0.30	0.24	0.41	1
Kander	Hondrich	Unpeaked	0.15	0.22	0.35	0.56	1
Langeten	Huttwill, Haberenbad	Unpeaked	0.16	0.20	0.04	0.07	1
Thur	Jonschwil, Muhlau	Unpeaked	0.28	0.42	0.65	1.12	1-2b
Ilfis	Langnau	Unpeaked	0.22	0.28	0.15	0.21	1
Luthern	Nebikon	Unpeaked	0.20	0.25	0.03	0.05	1
Simme	Oberwil	Unpeaked	0.14	0.22	0.15	0.26	1
Rhone	Reckingen	Unpeaked	0.13	0.20	0.09	0.22	1
Glatt	Rheinsfelden	Unpeaked	0.08	0.09	0.06	0.10	1
Areuse	St. Sulpice	Unpeaked	0.12	0.24	0.02	0.10	1
Murg	Wangi	Unpeaked	0.22	0.56	0.07	0.23	1
Wigger	Zofingen	Unpeaked	0.14	0.18	0.10	0.14	1

Table 2.3: *Swiss gauged stations grouped by the values of the hydropeaking indicators $HP1$ and $HP2$, corresponding maximum and minimum value of hydropeaking indicators $HP1$ and $HP2$ and hydropeaking pressure class changes (calculated based on six year data record).*

Watershed	Gauging station	Group	HP1 Min	HP1 Max	HP2 Min	HP2 Max	Class
Numedalslagen	Bruhaug	Peaked	0.27	1.54	1.36	5.80	1-2b
Driva	Driva power plant	Peaked	0.20	0.71	6.08	16.54	2b
Driva	Driva v/Elverhøy bru	Peaked	0.14	0.22	0.97	2.56	1-2b
Tokke	Elvarheim	Peaked	0.07	0.08	2.06	3.18	1
Fortun	Fortun	Peaked	0.17	0.19	1.50	2.45	1-2b
Osaelva	Fosshaug	Peaked	0.23	0.27	1.19	2.94	1-2b
Stjordalselva	Hegra bru	Peaked	0.34	0.80	0.98	2.40	1-2b
Otra	Heisel	Peaked	0.11	0.13	1.21	1.71	2b
Gáivuoneatnu	Holm bru	Peaked	0.19	0.23	1.34	2.25	1-3
Marna	Kjølemo	Peaked	0.26	0.37	1.31	2.02	2b
Gaula	Rathe	Peaked	0.10	0.34	0.69	1.85	2b-3
Sokna	Sokna power plant	Peaked	0.15	0.17	1.25	2.07	1-3
Laerdalselvi	Stuvane	Peaked	0.15	0.34	0.75	1.75	2b
Laerdalselvi	Stuvane power plant	Peaked	0.06	0.26	0.27	0.76	2b
Storana	Ardalsvatn	Unpeaked	0.10	0.14	0.38	0.56	1
Ordola	Ausbygdai	Unpeaked	0.16	0.25	0.12	0.33	1
Supphelleelvi	Boyumselv	Unpeaked	0.19	0.29	0.02	0.22	1
Stenselva	Brekke	Unpeaked	0.17	0.20	0.22	0.48	1
Jolstra	Brulandsfoss	Unpeaked	0.09	0.11	0.31	0.50	1
Driva	Driva v/Risefoss	Unpeaked	0.14	0.19	0.10	0.26	1
Gaula	Eggafoss	Unpeaked	0.17	0.20	0.13	0.28	1
Fusta	Fustvatn	Unpeaked	0.07	0.12	0.18	0.34	1
Storelva	Gloppenelv	Unpeaked	0.14	0.29	0.07	0.51	1
Helgaa	Grunnfoss	Unpeaked	0.19	0.21	0.32	0.58	1
Boelva	Hagadrag	Unpeaked	0.07	0.10	0.41	0.51	1
Forra	Høggås bru	Unpeaked	0.16	0.19	0.19	0.37	1
Kvitla	Hovefoss	Unpeaked	0.19	0.33	0.13	0.88	1
Sokna	Hugdal Bru	Unpeaked	0.23	0.28	0.21	0.43	1
Storana	Kalltveit i Årdal	Unpeaked	0.23	0.28	0.09	0.14	1
Kileai	Kilen	Unpeaked	0.14	0.18	0.02	0.03	1
Nordelva	Krinsvatn	Unpeaked	0.13	0.20	0.04	0.12	1
Flamselvi	Lavisbrua	Unpeaked	0.08	0.14	0.07	0.14	1
Storana	Leirberget i Årdal	Unpeaked	0.11	0.18	0.09	0.29	1
Lilleelv	Lilleelv	Unpeaked	0.08	0.13	0.01	0.01	1
Manndalselva	Manndalen Bru	Unpeaked	0.13	0.18	0.04	0.09	1
Mevatnet	Mevatnet	Unpeaked	0.09	0.10	0.02	0.05	1
Oysterelva	Øyungen	Unpeaked	0.09	0.16	0.02	0.10	1
Guddalselva	Seimfoss	Unpeaked	0.10	0.16	0.03	0.08	1
Stryn	Strynsvatn	Unpeaked	0.05	0.07	0.11	0.20	1
Reisaelva	Svartfossberget	Unpeaked	0.07	0.10	0.12	0.27	1
Lygna	Tingvatn	Unpeaked	0.10	0.14	0.06	0.16	1

Table 2.4: *Norwegian gauged stations grouped by the values of the hydropeaking indicators $HP1$ and $HP2$, corresponding maximum and minimum value of hydropeaking indicators $HP1$ and $HP2$ and hydropeaking pressure class changes (calculated based on six year data record).*

2.2.4 Statistical and sensitivity analysis

Preliminary χ^2 goodness-of-fit tests were run on each equivalent yearly data series (each gauged station for each year, for a total of 490 data series) to check for a possible normality of data; the tests were not significant for only 48 of 490 data series, thus allowing to reject the null hypothesis of normal distribution of discharge data and supports the choice of non-parametric estimators used in this analysis.

The non-parametric thresholds defined by equations (2.6) and (2.7) can vary based on several factors, such as the climate of the investigated regions (i.e. southern or northern Alpine region or the Scandinavian Alps, in our case), the length of the considered $HP1_i^{unp}$ and $HP2_i^{unp}$ records (i.e single or multiple years), the breakdown time of the original dataset (data analysed at 15 or 60 minutes), and the number of stations used to compute them. If the hydropeaking thresholds change (eq. (2.6) and (2.7)), the same peaked gauged station may fall within different pressure classes, therefore we performed a set of analysis to assess the robustness of the method, and the sensitivity of the hydropeaking thresholds to the choice of reference unpeaked stream gauges. To achieve this goal thresholds calculation from the unpeaked group data was performed by building four different sub-datasets according to the following criteria, which correspond to the most relevant sources of variability in calculating the thresholds:

1. **Choice of country/geographical area**: thresholds were calculated by dividing the dataset in different countries (Italy, Switzerland and Norway). Multi-year datasets were available for every gauged station of Switzerland and Norway, and each year of record was considered as a different dataset;

2. **Choice of year**: thresholds were calculated for each year for all unpeaked stream gauges, when multiple years were available, for a total of 12 different threshold values for each indicator;

3. **Choice of number of stations required for the calculation**: thresholds calculation was repeated on an increasing number of stations extracted from the entire unpeaked dataset with a random sampling technique to avoid bias (random sampling without replacement). The random extraction was performed 1000 times from 2 to 275 stream gauges ($n-1$), thresholds were calculated for each extraction and a mean value of each threshold was eventually calculated over all the extracted thresholds;

4. **Choice of streamflow data time resolution**: thresholds were calculated from data with a resolution of 15 minutes and 60 minutes. Data acquired every 15 minutes

were available only for the Italian and Swiss datasets. When data were collected at 15 minute intervals, we selected a subset of data corresponding to the hourly measurements (one out of four consecutive measurements).

The robustness of the method was assessed by applying a pairwise Mann-Whitney U, to test if each of the resulting sub-datasets was extracted by the same original population of data. If the test is not significant, each sub-dataset is extracted from the same population of unpeaked gauged stations. Mann-Whitney is the non-parametric ranking alternative of the Student t test. The following step consisted in calculating the thresholds using all the sub-datasets for each of the four criteria (i.e. 6 sub-datasets for the "Year" criterion), and applying the pairwise Mann-Whitney U test to assess whether the resulting thresholds correspond to the same class distribution for all dataset. Classes were iteratively calculated using all possible combinations of hydropeaking thresholds for each sub-datasets (e.g Italian, or Swiss, or Norwegian unpeaked stations) and a Mann-Whitney test comparing each pair of classes within each subset was applied. For instance, six thresholds (three for each indicator) were calculated for different countries. Classes for each station were recalculated three times using the six different thresholds (three class values for each station). If the test is not significant, the classification of the stations does not significantly differ between each possible pair of thresholds within each sub-datasets.

2.2.5 Validation of the procedure

We have validated our method through the following procedure. First we have randomly chosen an additional control dataset within a comprehensive list of Swiss hydrometric stations for which thirty year long streamflow data series at sub-daily time resolution is available. The random extraction selected six Swiss gauged stations with 30 year-long streamflow records for a total of 180 data series, which we did not label *a priori* as peaked or unpeaked. We then run the analysis using the thresholds calculated on the entire dataset to compute the classification. This "blind" classification exercise resulted in attributing to each of the 180 yearly datasets one of the four different classes of hydropeaking alteration. Only afterwards we have *a posteriori* verified whether each of the chosen six control stations are found downstream of intermittent hydropower releases from storage hydropower plants, labelling them as "peaked" or "unpeaked". The final step of the validation has been to assess whether (i) yearly datasets, predicted by our method to have either moderate (classes 2a, 2b) or high hydropeaking pressure/alteration, belong to *a posteriori* identified "peaked" gauged stations; and whether (ii) yearly datasets belonging to *a posteriori* identified unpeaked stations group in class 1 (absent or low alteration). The outcome of such validation procedure for the proposed method has been considered satisfactory on the basis of the correspondence between the method predictions and the *a posteriori* assessment of the peaked and unpeaked stations.

Furthermore, we analysed yearly data series of five Swiss and one Norwegian gauged stations which were reconstructed to the pre-anthropogenic conditions by Jordan (2007) through the application of an hydrological model which can reproduce the river flow regime without the hydropower schemes (for more details about the Swiss stations, see Jordan 2007). The five Swiss stations are: Rhone River at Branson, Saltina River at Brig, Rhone River at Sion and Port-du-Scèx and Vispa River at Visp. The Norwegian station is the Sokna power plant gauged station on the Sokna River.

2.3 Results

This analysis is conducted considering a total of 490 discharge data series, corresponding to one year of data for each of the 105 examined gauging stations (see Table 2.1) and for the entire length of the database (6 years or 1 year).

2.3.1 Peaked versus unpeaked stations: cumulative distributions of hydropeaking indicators

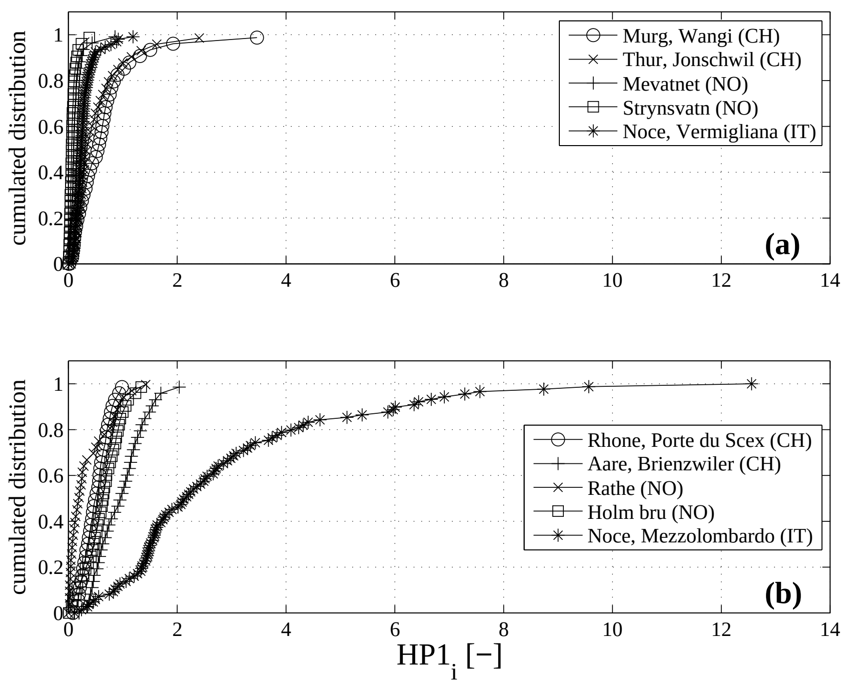


Figure 2.2: *Cumulative distribution of $HP1_i$ for some representative a) unpeaked and b) peaked gauged stations.*

The cumulative distributions of the two indicators $HP1_i$ and $HP2_i$ are shown in

Figures 2.2 and 2.3, respectively, for a selected subset of representative unpeaked and peaked stations: we selected the datasets with the highest and lowest median values of the two indicators, plus three datasets of random choice. The peaked stations show a higher degree of variability and larger median values and interquartile range for both indicators., The median value of $HP1$ for the entire dataset of unpeaked stations (282 data series) is 0.17 and the daily values $HP1_i$ are generally well-distributed around the median with interquartile distance equal to 0.26. Rare events (e.g. extreme summer storms, intense snow and ice-melting) are included in the higher 99^{th} percentile (P_{99}) which equals to 2.33 with a maximum value of 15.00. The median value of $HP1_i$ for the peaked group is 0.46 and the interquartile distance 0.69, suggesting a greater inter- and intra- stations variability for this group. Extreme values for the peaked group are higher with a P_{99} of 3.52 and a maximum value of 24.

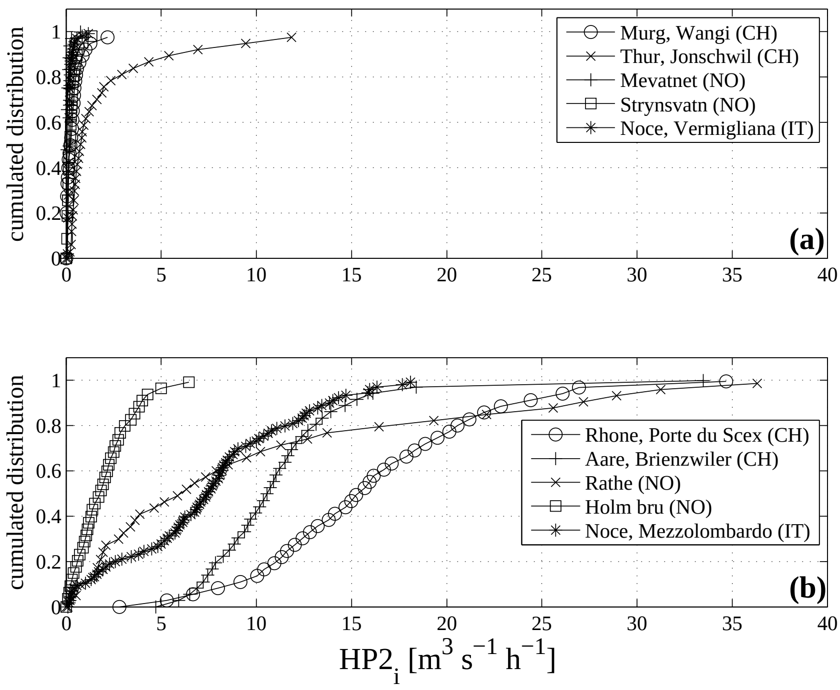


Figure 2.3: *Cumulative distribution of $HP2_i$ for some representative a) unpeaked and b) peaked gauged stations.*

For the second indicator $HP2$ the differences between the two groups is more evident. In fact, the entire dataset of unpeaked stations has a median value of 0.17 $m^3s^{-1}h^{-1}$ and an interquartile range of 0.48 $m^3s^{-1}h^{-1}$ while the peaked group has a median value of 3.48 $m^3s^{-1}h^{-1}$ and an interquartile range of 9.74 $m^3s^{-1}h^{-1}$. Differences in extreme $HP2_i$ values between the two groups are qualitatively analogous to those detected in the case of $HP1_i$, with P_{99} of 8.69 and 39.53 $m^3s^{-1}h^{-1}$ and maximum values of 166 $m^3s^{-1}h^{-1}$ and 366 $m^3s^{-1}h^{-1}$ for the unpeaked and peaked group, respectively.

2.3.2 Class of hydropeaking alteration for the examined stations

Figure 2.4 shows the distribution of the stations in the dataset in the $HP1$ and $HP2$ indicators space. Each panel refers to stations in a different country (a: Italy, b: Switzerland, c: Norway) and it is divided into four classes of hydropeaking alteration (or pressure, Section 2.2.3) by the corresponding thresholds computed with reference to the unpeaked group of stations for that country. For each of the three different countries all the stations in the unpeaked group, except one, are below the hydropeaking thresholds TR_{HP1} and TR_{HP2} (class 1). Only one of the peaked stations falls in class 2a, i.e., river reaches characterized by high magnitude of hydropeaking (high $HP1$) and small values of the flow rate of change (small $HP2$) are very rare in the analysed dataset. For the peaked group of the Italian dataset (Fig. 2.4a and Table 2.2), 43% of the gauged stations belong to class 3, 45% to class 2b, and 6.2% to class 1. Twenty-six percent of the Swiss peaked stations (Fig. 2.4b and Table 2.3) falls in the high pressure class (class 3) while 49% falls in the moderate pressure class 2b, and 25% in the low pressure class. Finally, the peaked Norwegian rivers (Fig. 2.4c and Table 2.4) are characterized by 11% of the dataset belonging to class 3, 69% to class 2b, and 20% to class 1.

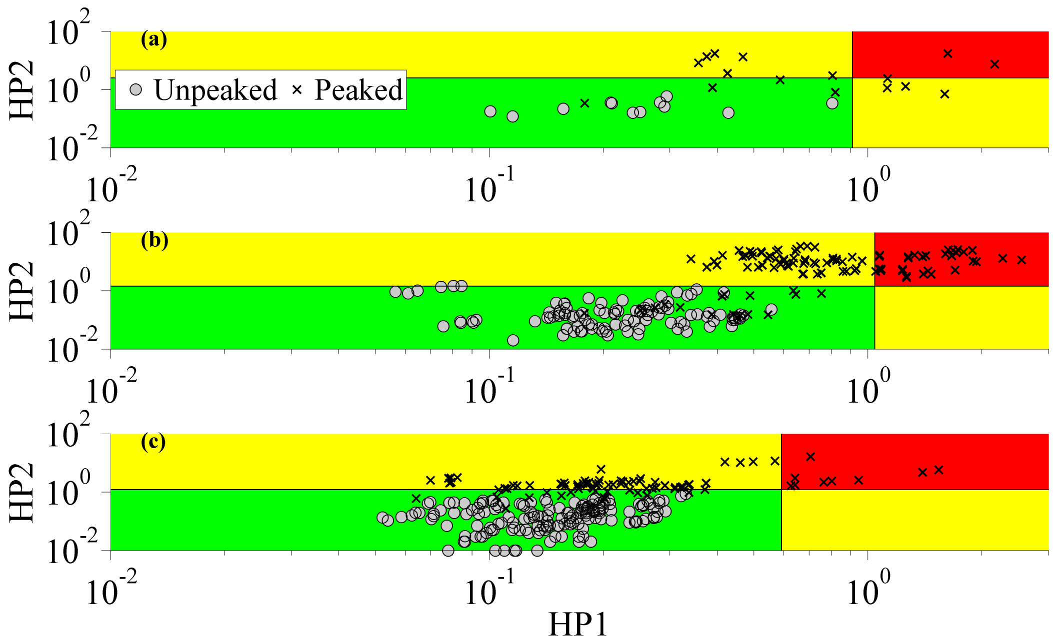


Figure 2.4: *Dataset distribution in classes of different pressures for Italian (panel a), Swiss (panel b) and Norwegian (panel c) data. Thresholds are calculated for each country. Different groups are denoted with cross (unpeaked) and circles (peaked). The space in the $HP1$ and $HP2$ plane is divided in 4 different regions identified by the two thresholds TR_{HP1} and TR_{HP2} which were computed for the three geographical regions considered. The four regions identify the three different classes of hydropeaking pressure: class 1 (absent or low pressure, green colour, left bottom); classes 2a and 2b (moderate pressure, yellow colour, right bottom and left top respectively) and class 3 (high pressure, red colour, right top).*

The global distribution of the entire dataset is summarized in Figure 2.5. Thresholds are calculated over the entire unpeaked dataset (282 data series). Ninety-eight percent of unpeaked stations belong to pressure class 1, 1% to class 2a and 1% to class 2b. Eighteen percent of peaked stations belong to class 1, 0.5% to class 2a, 56.5% to class 2b and 25% to class 3.

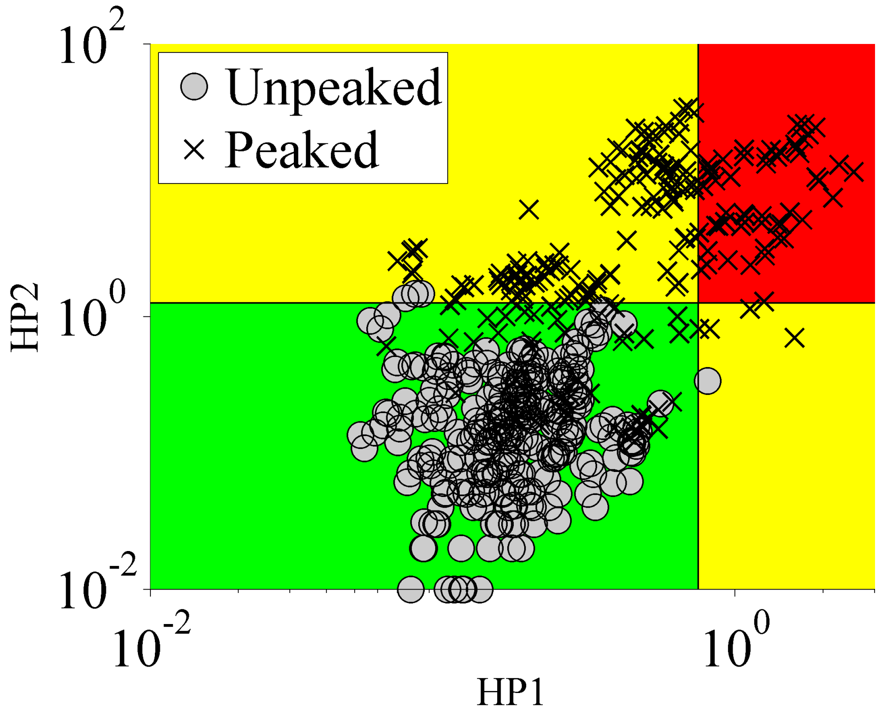


Figure 2.5: *Global distribution of all datasets in classes of different pressures. Thresholds calculated over the entire unpeaked dataset. Different groups are denoted with cross (unpeaked) and circles (peaked).The four regions identify the three different classes of hydropeaking pressure: class 1 (absent or low pressure, green colour, left bottom); classes 2a and 2b (moderate pressure, yellow colour, right bottom and left top respectively) and class 3 (high pressure, red colour, right top).*

2.3.3 Hydropeaking thresholds variability

We analysed how the hydropeaking thresholds TR_{HP1} and TR_{HP2} change depending on the sources of variability previously described in Section 2.2.4. The results for the first three sources of variability (choice of country, year and number of reaches) are summarized in Table 2.5. TR_{HP1} ranges between 0.96 and 1.14 and TR_{HP2} from 1.18 to 1.66 for the Swiss stations among all the years while TR_{HP1} ranges between 0.56 and 0.66 and TR_{HP2} from 1.10 to 1.59 for the Norwegian stations. For $HP1_i$ (Fig. 2.6 a)), Swiss data series show an higher variability and the highest values of P_{75} (box upper bound) and threshold (whiskers), while lowest values are recorded for Norway data series. Mann-Whitney tests underline significant differences in $HP2_i$ distribution ($p < 0.01$), although Swiss and Norway data series are slightly different ($p = 0.046$, Fig. 2.6 b))and Trentino data series resulted highly different ($p < 0.001$). Mann-Whitney tests pinpointed significant differences among the distributions of $HP1_i$ in the unpeaked group for the three countries ($p < 0.001$). In particular, the $HP1_i$ values for the Swiss stations were highly variable. The Mann-Whitney tests highlighted significant differences in $HP1_i$ and $HP2_i$ distributions ($p < 0.05$) between each pair of geographical areas. The distribution of $HP1_i$ and $HP2_i$ is different among areas (Fig. 2.6).

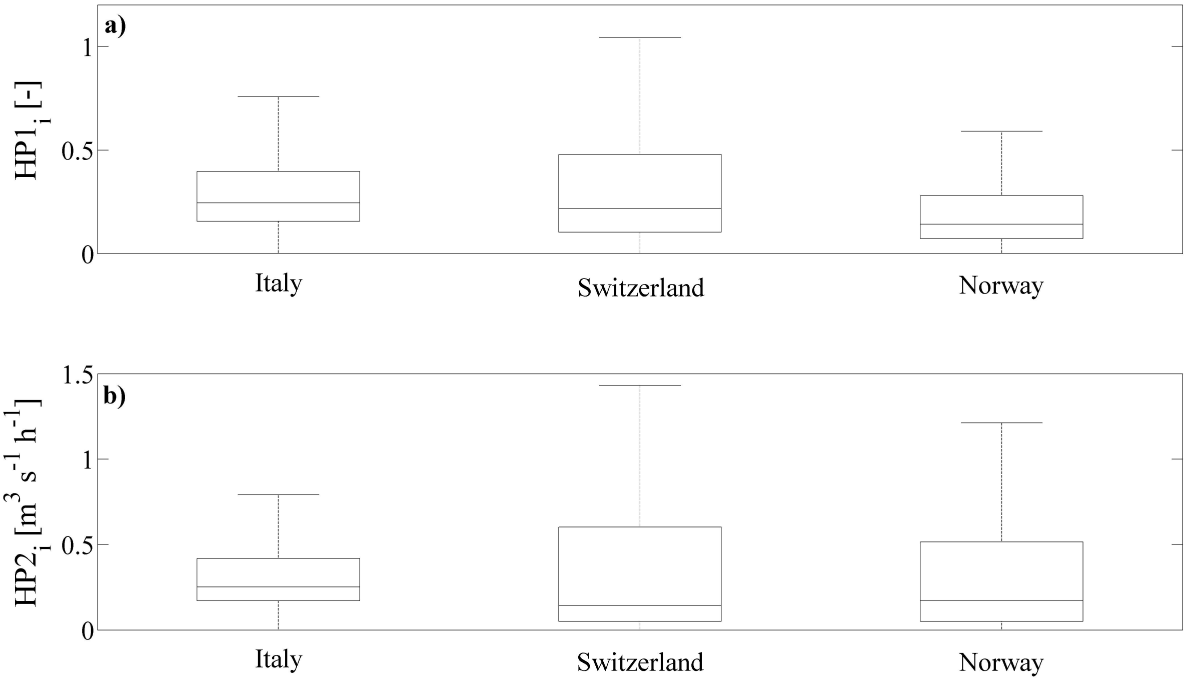


Figure 2.6: *Distribution of $HP1_i$ and $HP2_i$ in unpeaked reaches divided by area. The box represents the interquartile range, the whiskers the range of the outliers.*

The hydropeaking thresholds calculated using unpeaked flow data series belong to the same year (Fig. 2.7) were significantly different for each pairwise comparison (Mann-Whitney, $p < 0.001$), with the exception of pairwise comparison of indicators for years 2008 vs 2012 ($p = 0.40$ for $HP1$ and $p = 0.42$ for $HP2$).

The assessment of the number of data series required to correctly define $HP1$ and $HP2$ thresholds showed that a minimum of 51 data series is required. In fact, using more than 50 unpeaked data series resulted in distributions of $HP1$ and $HP2$ not significantly different from the total distribution (Mann-Whitney tests, $p > 0.14$ for all pairwise comparisons), i.e., not further depending on the number of chosen yearly data series. The boxplots in Figure 2.8 show the variability of the thresholds calculated on an increasing number of data series (x axis), randomly extracted.

Finally we tested if the hydropeaking thresholds change for different distributions based on breakdown time, i.e. $15'$ vs $60'$. The resulting distributions were highly different with $p < 0.001$ for both indicators. It is worth mentioning that the calculated confidence

	Year	TR_{HP1}	TR_{HP2}
Italy	2012	0.76	0.79
Switzerland	2007	1.10	1.61
	2008	1.00	1.33
	2009	1.09	1.42
	2010	0.97	1.36
	2011	1.14	1.18
	2012	1.01	1.66
	Mean	1.04	1.43
Norway	2007	0.61	1.36
	2008	0.56	1.10
	2009	0.59	1.16
	2010	0.56	1.59
	2011	0.66	1.59
	2012	0.57	1.27
	Mean	0.59	1.21
	N° of data series		
N° of data series for the computation	2	0.71	1.15
	5	0.73	1.17
	10	0.75	1.23
	50	0.75	1.22
	100	0.75	1.23
	150	0.75	1.23
	200	0.75	1.23
Global thresholds	282	0.75	1.26

Table 2.5: *Hydropeaking threshold variability as function of: country, different years and number of gauged stations used for the computation.*

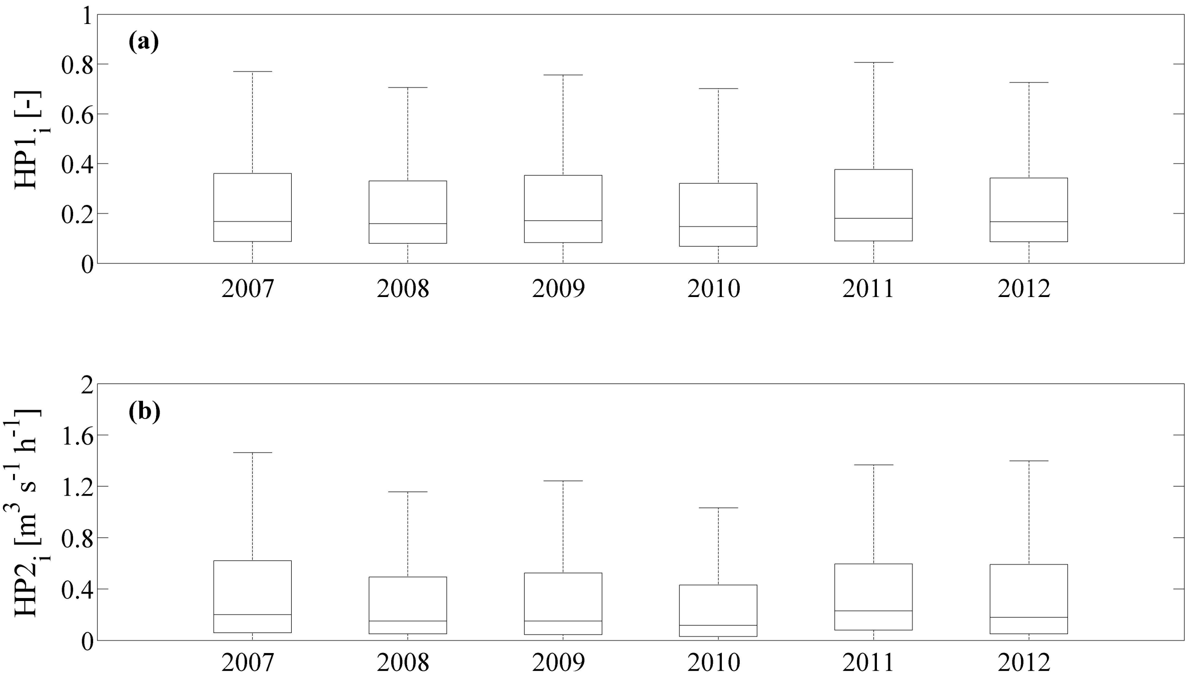


Figure 2.7: *Distribution of $HP1_i$ and $HP2_i$ in unpeaked reaches divided by year. The box represents the interquartile range, the whiskers the range of the outliers.*

intervals were very narrow (0.7482 ± 0.001 for $HP1$ and 1.2315 ± 0.002 $m^3s^{-1}h^{-1}$ for $HP2$, global thresholds), and therefore not included in the analysis of threshold variability.

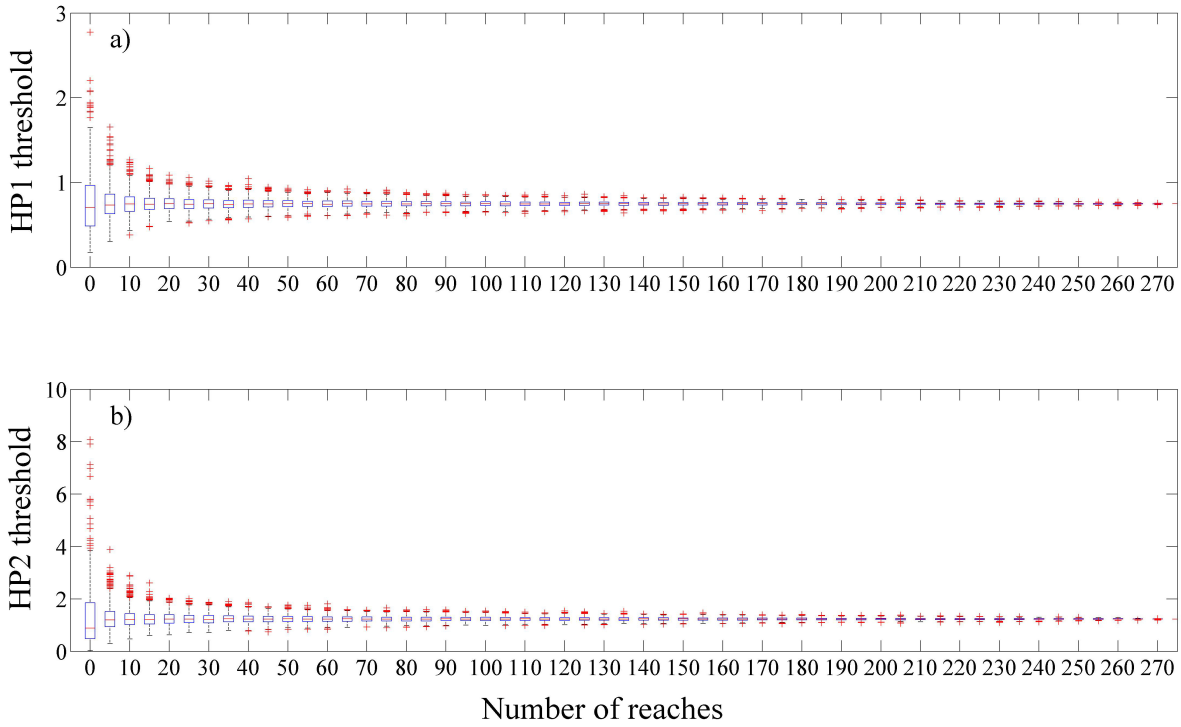


Figure 2.8: *Threshold for $HP1$ (a) and $HP2$ (b) calculated on an increasing number of reaches, selected at random. The red line indicates the median, the boxplot the interquartile range and the red cross the extreme values, respectively.*

2.3.4 Class changes of stations with thresholds variability

As the distributions used to calculate the thresholds significantly differed within each of the main criteria used to define the reference group of unpeaked stations (i.e. choice of country, year, number of stations and data resolution), we analysed if such thresholds variability would result in changes in the classification of hydropeaking alteration of the gauged stations, i.e. we investigated if a gauged station would change its hydropeaking pressure class due to thresholds changes. The class changes of the peaked group due to thresholds variations among the three countries were not significant ($p > 0.16$). For thresholds calculated referring to different years, changes were also not significant (lowest $p = 0.18$), although the comparisons were conducted between a one-year dataset of one station with thresholds calculated within the overall unpeaked data of that same year ($p < 0.001$). When the comparison of classes was performed with a progressively increasing number of stations, changes were significant only if thresholds were defined using less then 10 stream gauges ($p < 0.001$). Classes calculated using different data breakdown times were not significantly different with a minimum p value of 0.24. The classification of the unpeaked stations never changed significantly for any of the four criteria, with a lowest p value of 0.36.

Table 2.6 summarizes the frequency of class changes associated with threshold variability due to different choice of country, years (Switzerland and Norway datasets), number of stations used for the calculation (from 2 stations up to 275) and breakdown time ($15'$ vs $60'$, Switzerland and Italy datasets) to define the reference group of unpeaked stations. The frequency of class changes measures how many times a given data series of a station belongs to the same class. It is quantified through a value in the interval (0:1), with 0 meaning that no changes between classes occur, 1 meaning that changes in classes occur for each comparison within dataset. For instance, the frequency of 0.1 recorded in peaked Italian stations (first row and first column, Table 2.6) means that each stream gauge falls in the same class 90 % of the times, when classes were calculated using the three different country-specific thresholds values.

	Peaked			Unpeaked		
	IT	CH	NO	IT	CH	NO
Geographical areas	0.10 (0)	0.09 (0)	0.06 (0)	0.02	0.03	0
Years	-	0.09 (0)	0.15 (0.035)	-	0	0
Breakdown time	0 (0)	0.04 (0)	-	0	0.03	-
N° of data series	0.01 (0)	0 (0)	0 (0)	0	0.01	0

Table 2.6: *Frequency of class changes for different hydropeaking threshold, calculated for all the possible sub-datasets. In brackets the frequency of changes between class 1 and class 3.*

We verified which class changes occurred more frequently in the peaked stations (see Tables 2.2, 2.3, 2.4, last column). The percentage of changes was always very low in peaked stations and very often equal to zero in unpeaked stations. For all the possible sources of variability (Table 2.6) the frequency of changes between class 1 and class 3, which is obviously the most critical for the robustness of the proposed methodology, was always zero except for one case (Norway, thresholds calculated referring to different years), still with a very low frequency (3.5%). Two Norwegian gauged stations were responsible for this change (see Table 2.4): Sokna River station in Melhus at the Sokna power plant (once for the six year data record), and Holm Bru station (Kafjord River, twice).
Considering the entire dataset, the most frequent changes occurred from class 2b to 3 (10.2 %) much less changes occurred between class 1 and 2b (4.2 %), while no changes were detected between 1 and 2a, 2a and 2b, and between 2a and 3.

2.3.5 Validation of the procedure

The random selection of the control dataset extracted station 2019, Aare-Brienzwiler; 2070, Emme-Emmenmatt; 2473, Rhein-Diepoldsau; 2152, Reuss-Luzern; 2372, Linth-

Mollis and 2425, Kleine Emme-Littau. The control and the original dataset overlapped for eighteen yearly data series, i.e. six yearly data series for each of 2019, 2070 and 2473 stations. We computed the indicators ($HP1, HP2$) for the 180 yearly data series of the chosen six control stations and assigned classes of hydropeaking alteration using the global thresholds (see Table 2.5, last row). Results are reported in Figure 2.9. Three stations (2019, 2473, 2372) were predicted to lay always above at least one of the two thresholds for each of their thirty year long data series, therefore falling either in class 2b or in class 3 (Fig. 2.9). The thirty yearly data series for each station always fell within the same class, except for station 2372 that shifted between classes 2b and 3 over time (after 1998), possibly due to changes in hydropower production patterns that altered both the rate and the magnitude of hydropeaking (denoted with a lozenge in Figure 2.9). According to the procedure described in Section 2.5, were labelled as unpeaked. After the analysis, we have further verified whether or not the six control stations are actually found downstream of intermittent releases from storage hydropower plant: stations (2019, 2473, 2372) are actually located downstream storage hydropower plant releases, and have been therefore *a posteriori* labelled as peaked, while (2070, 2152, 2425) are not, and have been therefore *a posteriori* labelled as unpeaked. Finally, comparing the outcomes of the classification predicted by our method with the *a posteriori* labelling procedure has yielded a 100 % correspondence, namely: yearly datasets having either moderate (class 2b) or high (class 3) hydropeaking alteration, belong to *a posteriori* identified "peaked" gauged stations (i.e. 2019, 2473, 2372); and yearly datasets belonging to *a posteriori* identified unpeaked stations (i.e. 2070, 2152, 2425) group in class 1 (absent or low hydropeaking alteration).

The analysis of the simulated data series confirmed that the method can detect the hydropeaking pressure. Table 2.7 summarizes the results of the validation. The table shows as four stations resulted in class 2b (Branson, Rhone; Porte du Scèx, Rhone; Sion, Rhone) and in class 3 (Visp, Vispa), while the data series simulated by Jordan (2007) for the same stations resulted in class 1. The station of Brig is in class 1 both for real and simulated data. The Norwegian gauged station changed from class 1 to 3 using real data (class changes discussed below), while resulted in class 1 for the simulated data series.

Watershed	Gauged station	Group	HP1	HP2	Class (Real data)	Class (Simulated data)
Rhone	Porte du Scèx	Peaked	0.08	1.22	2b	1
Rhone	Branson	Peaked	0.07	1	2b	1
Rhone	Sion	Peaked	0.07	1.08	2b	1
Saltina	Brig	Peaked	0.06	0.28	1	1
Vispa	Visp	Peaked	0.09	0.18	3	1
Sokna	Sokna P.P.	Peaked	0.17	0.16	1-3	1

Table 2.7: *Values of the two indicators calculated on the simulated data and comparison between classes of real and simulated data series, respectively.*

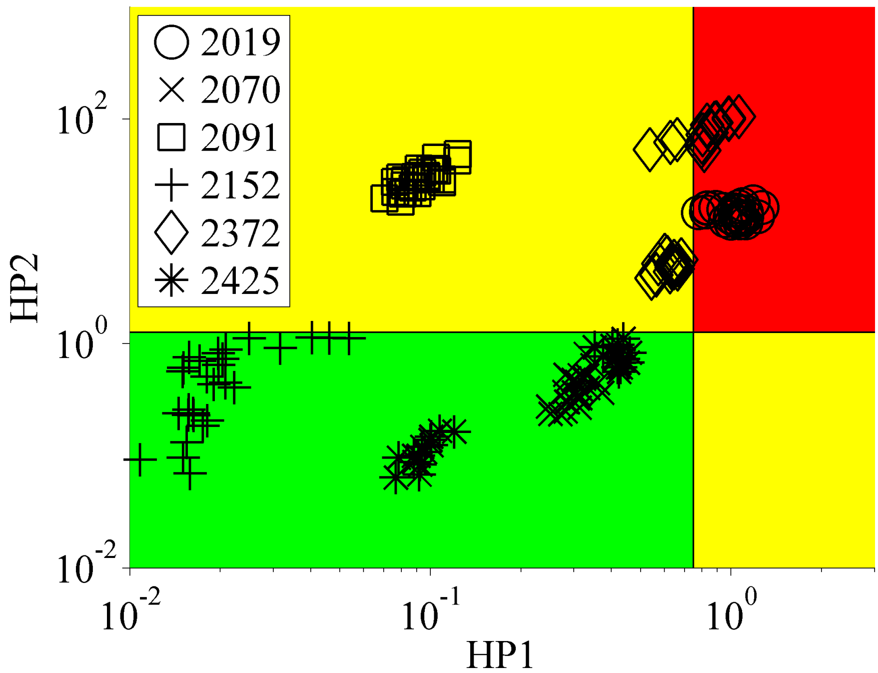


Figure 2.9: *Distribution of six stations used as control group. The displayed thresholds are the global thresholds. Different groups are denoted with cross (unpeaked) and circles (peaked). The four regions identify the three different classes of hydropeaking pressure: class 1 (absent or low pressure, green colour, left bottom); classes 2a and 2b (moderate pressure, yellow colour, right bottom and left top respectively) and class 3 (high pressure, red colour, right top).*

2.4 Discussion

Several other studies have applied indicators in different countries to analyse and quantify sub-daily flow fluctuations in regulated rivers (Meile *et al.*, 2011; Zimmerman and Letcher, 2010; Sauterleute and Charmasson, 2014; Bevelhimer *et al.*, 2014). In our approach, the main hydrological differences between peaked and unpeaked rivers can be captured analysing the discharge signal focusing on two indicators: the magnitude of hydropeaking and the rate of change in discharge ($HP1$ and $HP2$). The use of these two indicators allows classifying river stations based on their degree of alteration and assessing the sub-daily flow variations induced by water releases from storage hydropower plants. The statistical analysis of class changes proposed by our method (see Table 2.6) shows that classes remain the same even if the geographical location, year and temporal resolution of the discharge dataset used to calculate the thresholds changes. However, some stations moved between classes when different years were analysed. Two changes of class are particularly relevant: changes between medium and high hydropeaking pressure classes, and changes between low and any of the other hydropeaking pressure classes. Changes from medium to high pressure classes can be considered less relevant than changes between low pressure and any of the others for water managers, who should prioritize actions on heavily impacted river reaches. Only few stations (four in the Swiss dataset and one in the Norwegian dataset) slightly changed among peaked classes over time (from class 2b to 3 class). Some peaked stations were distributed near the thresholds and showed class changes between low and moderate pressure classes (1 to 2b). In this respect, the thresholds calculated on the entire dataset (Figs. 2.5 and 2.9) can be considered as *universal*, i.e. they clearly identify, for all the entire dataset, the stations with high hydropeaking pressure.

The robustness of the approach is confirmed by the example of the two Norway gauged stations (the Sokna power plant station on the Sokna River and the Holm bru station on the Kafjord River) which are the only gauged stations which showed extreme variability (e.g between low and high pressure classes) throughout the entire dataset. These stations were not regulated for part of the analysed period, which may explain the observed changes in class. The Sokna River station recorded periods of low peaking frequency, e.g. for a period in 2010 when the plant was shut down for maintenance, and in spring of 2012 when it ran continuously for weeks due to high inflow and large snowmelt. The Kafjord River experienced close-to-natural flood episodes especially in spring for the entire six year period, which may have been over imposed on the daily hydropeaking-induced flow regime alterations.

The thresholds derived by the application of our method are general and representative of a large set of unpeaked gauged stations. In fact, when validating the procedure, the unpeaked stations in the control dataset always grouped in class 1 of pressure classification (Fig. 2.9). Moreover, the data series of peaked stations but reconstructed before anthropogenic impacts resulted always in class 1 of pressure. Our analysis also showed that extreme class changes (from 1 to 3) are rare among peaked stations for different years, suggesting that the proposed methodology can characterize each station by using only one standard year. However, it is advisable to choose the longest available dataset in order to reduce the error rate; if a yearly dataset is chosen, it should be representative of the range of typical discharge variations, and it should be selected by technicians and practitioners with a good knowledge of the river systems.

A second outcome of our method regards the data breakdown interval at which the discharge data are measured. Previous research assessed the data breakdown time required to capture sub-daily flow variations (Zimmerman and Letcher, 2010; Bevelhimer *et al.*, 2014); these authors used both hourly and daily data and concluded that hourly data are necessary. Our results are in agreement with Bevelhimer *et al.* (2014) but as a further step we showed that a resolution lower than $60'$ is not necessary. In fact, the use of different breakdown time did not influence the indicators because class variations were not

detected. Therefore, the classification is not statistically different using data at 15′ or 60′ breakdown time.
The methodology we proposed requires sub-daily data from unpeaked rivers to derive the thresholds to be used for the classification. From our analysis emerges that 10 data series of one year (e.g. 10 gauged stations for 1 year from unpeaked sites) are sufficient to produce robust thresholds. However, when 10 data series of one year are not available, the global thresholds (i.e extracted from the entire dataset) defined in Table 2.5 may be used for the classification. In fact, the exploration of all the possible sources of variability in the dataset (e.g. geographical areas, years, etc..) showed that unpeaked and peaked stations never significantly change classes when thresholds change (Table 2.6). The caveat is to use data from similar climatic regions, in our case data from mountain streams and rivers. Finally, our results show that the distributions from which the hydropeaking thresholds are computed differed significantly within each source of variability (country, years, etc.), and a minimum dataset size of 50 gauged stations is required to define the thresholds. In fact, this subset was statistically representative of the entire dataset of the unpeaked stations.

2.5 Conclusions

In this chapter, we described as our method is able to characterize the hydropeaking pressure for each station on the basis of:

i) the use of the smallest possible number of indicators, one for the intensity and one for the velocity of discharge variations. The data analysed are short term data usually collected by the local and national agencies, with a minimum data resolution of 60 minutes;

ii) the *a priori* separation of the stations from three mountain areas in peaked and unpeaked group and the comparison between the two groups;

iii) the definition of thresholds for the quantification of the hydropeaking pressure;

iv) the large size of the analysed dataset, which included 496 data series and lead to statistically robust conclusions.

The methodology can effectively be used as a first screening to prioritize sites for the implementation of flow regime restoration. Such sites would, however, need further investigation of the biotic effects of the same hydropeaking pressure which can vary from reach to reach, depending on a variety of local and non-local factors, such as channel morphology, bed sediment composition, water quality, presence of other hydro-morphological stressors (Valentin *et al.*, 1996; Bunt *et al.*, 1999; Hauer *et al.*, 2013).

Chapter 3

Study area

3.1 Introduction

Since the present PhD research focuses mainly on a single catchment, in this chapter we will introduce the study area in order to provide a detailed description of the river current conditions. We describe the main geographical features of the river, followed by the characterization of the river quality which was assessed by applying indicators of environmental, morphological and hydrological quality. The indicators were developed in a EU Water Framework Directive perspective (European Parliament, 2000) and they are in use at national level.
The river quality was assessed using the following standard methods: the E.B.I. (Ghetti, 1997) and the MacrOper (Buffagni *et al.*, 2008) indexes for the ecological quality, the LIM index (Decr. Leg. 152/99, 1999) for the chemical quality and the IQM index (Rinaldi *et al.*, 2013) for the morphological quality. All indexes produce five categories of quality: class 1 (excellent), class 2 (good), class 3 (moderate), class 4 (poor), class 5 (bad) quality. The data for the quality of the river have been provided by the Provincial Agency for Environmental Protection (APPA), which regularly performs the long-term monitoring. These data were integrated with *ad-hoc* sampling campaign conducted for the assessment of river ecosystem services. In particular, during the 2012-2013 period we collected and sorted samples to assess the environmental quality (MacrOper index) and we performed on field observations to evaluate the morphological quality. The indices of ecological and hydro-morphological quality were applied to identify areas of particular environmental value. The analysis of hydro-morphological quality is complemented by the analysis of the hydropeaking pressure obtained from the application of the method developed in the chapter 2. The analysis of the quality elements provided in this chapter set the broad framework for the analysis of flow-regime dependant ecosystem services developed in the

following chapters.

3.2 Geographical features

The study site selected for our analysis is the Noce River. It is a right tributary of the second longest Italian river, the Adige River in Trentino, NE Italy. The river sources from two main tributaries, Noce Nero Creek and Noce Bianco Creek. The Noce Nero originates from the Corno dei Tre Signori peak at 3360 m a.s.l. and flows into the artificial lake of Pian Palù. The Noce Bianco creek is a glacial stream and originates from the Vedretta de la Mare at 2710 m a.s.l.. After two km it receives the water from the Larcher Creek, which is a snow-fed stream, and flow towards the bottom of the valley. At 1200 m a.s.l. the two creeks meet and form the Noce River. This river flow through the Val di Sole and Val di Non and meets the Adige River near Zambana town at 200 m a.s.l..
Along its course, the Noce River receives several tributaries. The most important are the Vermigliana River, the Meledrio River, the Rabbies River in the upper basin. Into the lake of Santa Giustina into it receives also the water of the Novella Creek. The basin has an area of 1360 km^2, with 1306 km^2 included within the province of Trento. The main course is approximately 105 km long. The upper part of the catchment hosts several large glaciers (e.g Forni glacier, De la Mare glacier, Presanella glacier) for a 8% of glaciation of the basin.

The studied reach is between the confluence with Vermigliana River and Santa Giustina reservoir (in green in fig. 3.1). Lateral major and minor tributaries are responsible for spatial discharge variability, therefore the catchment can be conveniently partitioned in several sub-basins. We divided the main course in four reaches with nearly homogeneous discharge conditions (Fig. 3.1):

1. Reach 1. Downstream the confluence with the Vermigliana River to the confluence with the Lores Creek (Small tributary);
2. Reach 2. Downstream the previous reach to the confluence with the Meledrio Creek;
3. Reach 3. Between the confluence with the Meledrio Creek and the confluence with the Rabbies River;
4. Reach 4. Downstream the confluence with the Rabbies River to the Santa Giustina lake.

The main characteristics of the four reaches, from upstream to downstream, are reported in Table 3.1.

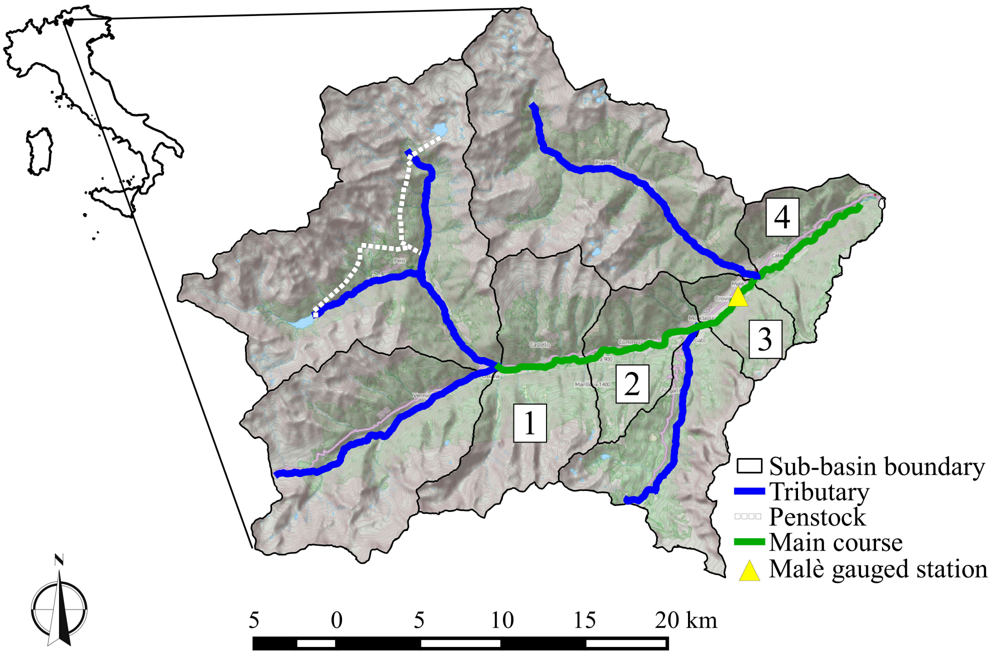


Figure 3.1: *Map of the Upper Noce River catchment where the study reach is located. The dotted white line indicates the penstock which sets the origin of hydropeaking at the junction with the Noce Bianco River, a major tributary of the Noce River. The blue lines denote tributaries, the green line the study site, the numbers indicates the four reaches in which the site is divided On the upper left, the location of the basin in Italy.*

Reach	Length (km)	Avg slope (%)	Avg width (m)
1	3.8	0.015	27.7
2	8.5	0.02	33.6
3	4.5	0.016	39.9
4	7.5	0.015	38.6

Table 3.1: *Summary of reach physical features.*

A characteristic of the Noce River, such as for other Alpine rivers, is the alteration of the flow regime due to various uses of the water resources, which is of particular relevance for the present study. In terms of withdrawal volumes, hydroelectric use is predominant if compared with irrigation and drinking water. The figure 3.2 shows the withdrawal licences in the area, where the number of water abstraction for drinking purposes is the dominant, though not in terms of abstracted volumes of water.

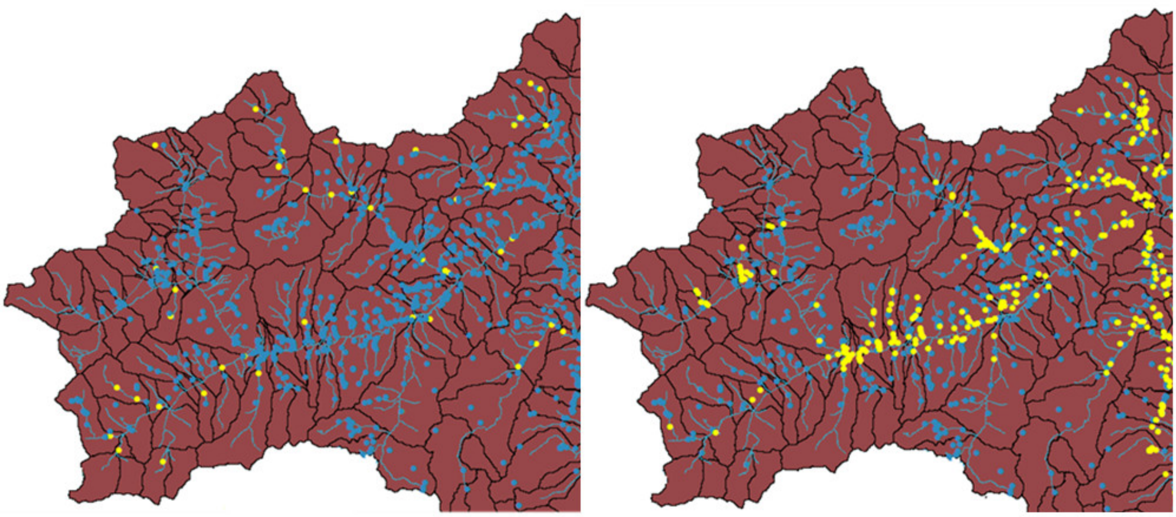


Figure 3.2: *Number of withdrawals for different water uses in the basin. In the left panel, the yellow spots denote withdrawals for small hydropower production purposes; in the right panel the yellow dots indicate the agricultural withdrawals.*

3.3 Ecological quality

The monitoring of the ecological quality of Noce River in Val di Sole has been done within the network of systematic monitoring of the main waterways of the Province of Trento, which is active since 1990, and since 1995 is performed by the Provincial Agency for Environmental Protection (APPA). Since 1999, the river Noce has become one of the six rivers in Trentino included in the long-term monitoring network (along with Adige, Avisio, Brenta, Sarca and Chiese). The biological quality has been classified since 1990 on the basis of the value of EBI (extended biotic index). The EBI is calculated by the analysis of the macroinvertebrate communities that colonize the river ecosystems. These communities are composed by species with various levels of sensitivity to environmental changes and with different ecological roles (Ghetti, 1997). Since macro invertebrates have relatively long life cycles, the index provides integrated information over time about the effects caused by different sources of disturbance (physical, chemical and biological).

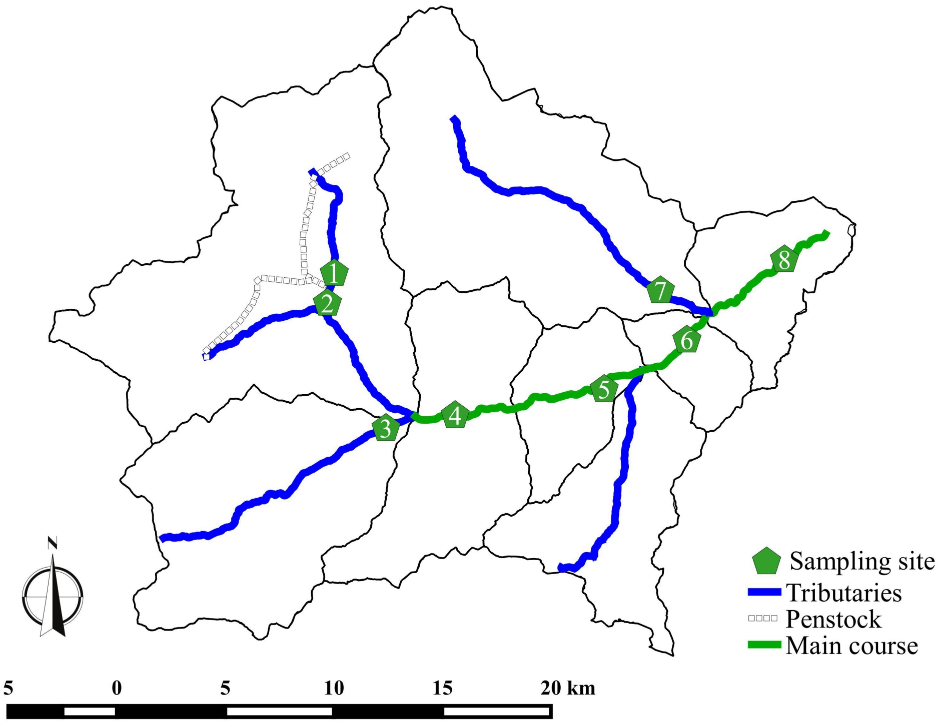


Figure 3.3: *Stations for EBI and MacrOper sampling.*

The introduction of the EU Water Framework Directive (European Parliament, 2000) has required the application of a new method to meet its requirements. The chosen method is at national level in Italy the MacrOper (Buffagni *et al.*, 2008), which classifies the water bodies on the basis of their ecological status, assessed by the sampling and the analysis of the macroinvertebrate communities, as well as the EBI index. The monitoring of water courses according to the MacrOper criteria started in 2009.
In the year 2009 and 2011 the chemical and biological monitoring was conducted over 80 water bodies in the river network. For the upper course of the Noce River, monitoring of the quality of the ecological component were carried out from 1990 in several river stations distributed along the main course (fig. 3.3); two stations on the tributaries were selected as reference sites (stations 3 and 6, fig. 3.3). Long term EBI data have showed a good class of quality for all the stations. Only station 8 showed a third quality class in the past, with a progressive amelioration in the last years (class 2) due to the connection of urban sewers to the sewage network.

In the last years, the MacrOper index pointed out that only station 6 is in excellent ecological status (fig. 3.4). This station is characterized by an almost completely wooded area along the water course, with typical series of willows, black poplar, alder and white species "hardwood" (lime, ash etc.). At the base of the right bank, a series of clear water springs support a community of submerged plants. This mosaic of habitat diversity and

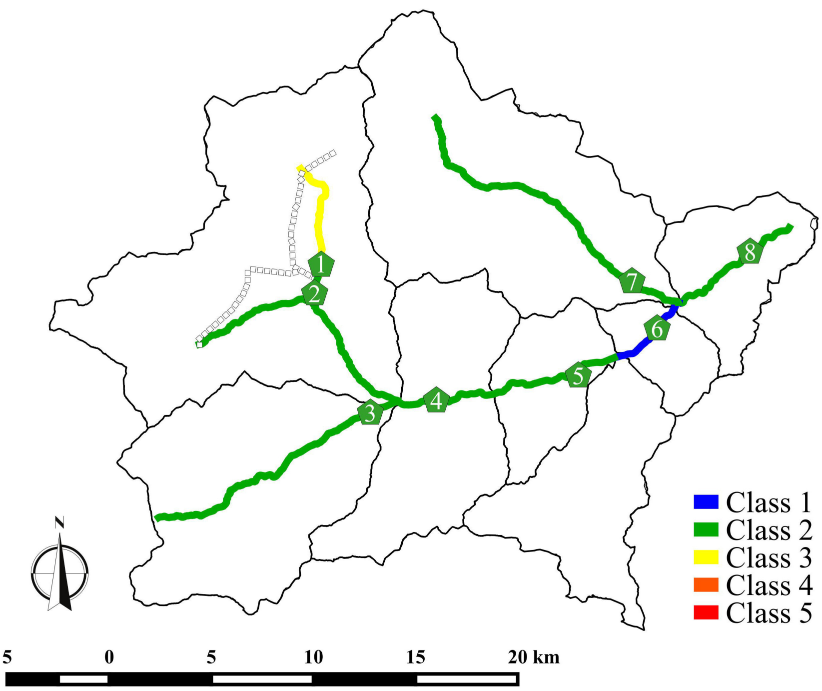


Figure 3.4: *Classes of MacrOper index for the year 2012 in the different sampling stations and the subtended. The blue color denote an excellent quality class, green a good quality class, yellow a moderate quality class, orange a poor quality class and red a bad quality class.*

plant productivity obviously supports a diverse and abundant benthic community. In the remaining stations, the quality is good, with the exception of the stations upstream of the main hydropower plant (number 1 in fig. 3.4), subjected to a regime of minimum flow release from the upstream dam, from which sediments are periodically released especially in summer: these two factors have a negative effect on the benthic fauna.

The work by Bruno *et al.* (2009) underlined a loss of biodiversity of hyporheic species downstream the hydropower plant, in comparison with non impacted upstream station which showed a well-established hyporheic community.

The fish species living in the river are mainly the marble trout and the brown trout, (*Salmo trutta marmoratus*, *Salmo trutta* respectively), with the latter introduced by the artificial management of the fish population. Other species are the bullhead (*Cottus gobio*) and the arctic char (*Salvelinus alpinus*). Specimens of rainbow trout (*Oncorhynchus mykiss*) were introduced for sport fishing reasons but the species did not start a stable community.

Sixty-eight bird species were identified in the area, five of which are typical of aquatic environments: teal, cormorant, sandpiper, shoveler and dipper. Other species frequent the forests of the riparian zones, both for nesting and hunting: owl, kestrel, buzzard, sparrowhawk, whinchat, siskin, swallow, shrike, white wagtail, redstart, kingfishers, wren, gray heron, marsh tit, blue tit, crested tit, woodpecker, nuthatch, black woodpecker, green woodpecker, hoopoe. The presence along the river of the golden eagle must refer to sightings of individuals which nests in high altitude. Many of these species were detected in the area of station 6, that represents an important zone for birds (Personal communication. Data source: Banca dati MUSE Sezione Zoologia dei Vertebrati; Paolo Pedrini; Natura 2000). It has to be mentioned that the area of station 6 is a Site of Community Importance (SCI) and is the only protected site along the river course in the entire basin.

3.4 Chemical quality

The data of water chemical quality were provided by the Agency for Environmental Protection of the Autonomous Province of Trento (APPA TN), and they refer to different sampling campaigns carried out from 1999 to 2010. The LIM index is calculated from these data (Decreto Legislativo 152/1999, 1999) and is based on a series of physical-chemical and microbiological parameters that describe the chemical state of the water. The index is obtained by the sum of scores resulting of seven parameters, called macro-descriptors. The macro-descriptors are representative of the general conditions of the river: the percentage of dissolved oxygen, the degree of pollution from organic sources (measured by the concentration of Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD_5)) and the trophic state (NH_4, NO_3 and total phosphorus). Regarding microbiological pollution the only indicator used for the calculation of the LIM is the abundance of *Escherichia coli*. A numerical score is assigned to each parameter: the value is higher when the pollution level is low. The sum of these values results in different classes of chemical quality. The analysis of the single parameters allows to hypothesize which are the possible pollution sources.

In general, the chemical quality of the river was good or excellent (fig. 3.5). Lower values of the dissolved oxygen, COD and BOD_5 due to the presence of organic matter were observed in station number 2 and 8. The quality have improved starting from 2003 in the first station but not in the second. The presence of low concentrations of organic matter characterized the tributaries upstream of human impacts. It was observed that the concentration of ammonium decreased from 1999 to 2010 in all stations except in station 8, while nitrates tend to increase in station 4 and 5. Even the concentration of phosphorus decreased with time, with the highest values in station 8. The last parameter is the concentration of *Escherichia coli*, which provides an estimate of pollution of faecal origin in the water course, and whose concentration in surface water is in relation to the quantity of sewage discharged and the self-purifying capacity of the water body. A water

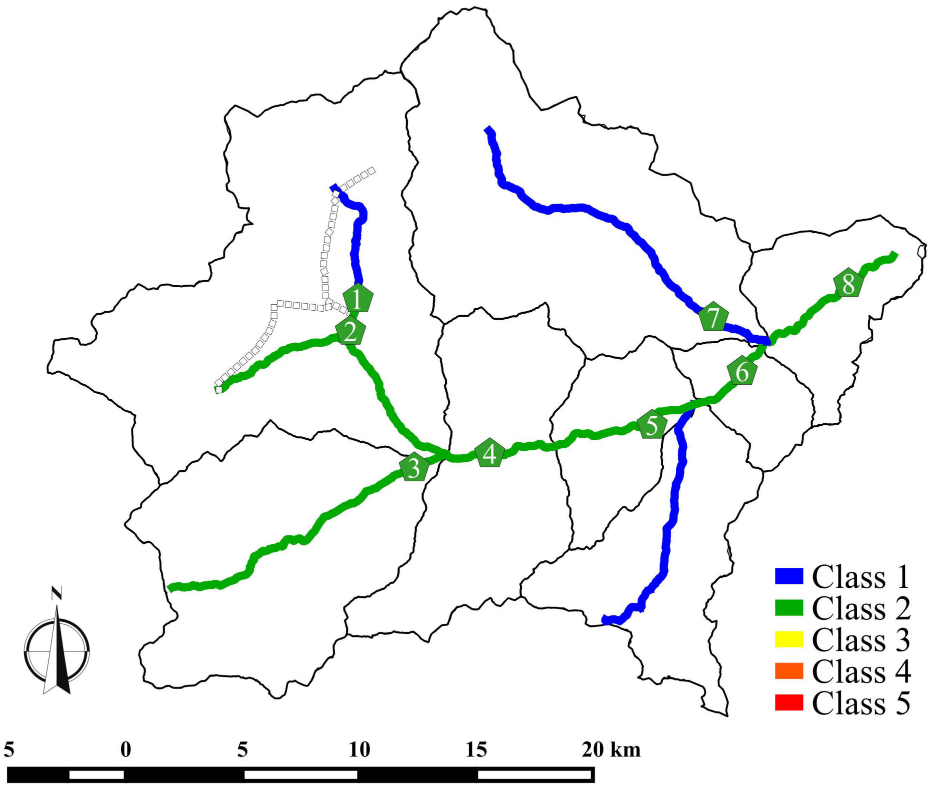


Figure 3.5: *Classes of LIM index referring to the last campaign (year 2010). The blue color denote an excellent quality class, green a good quality class, yellow a moderate quality class, orange a poor quality class and red a bad quality class.*

body class 1 or 2 class should not contain more than 1000 units ever 1000 mgl^{-1}. From 2007 the recorded values were always below this threshold.
It has to be mentioned as the slightly higher pollution values in station 8 were probably due to the absence of connection of the urban sewers with the local wastewater treatment plant, at least for some villages in the lower part of the valley. The urban pipe network has been improved in the last years, with direct effects on the environmental and chemical quality.

3.5 Morphological quality

The evaluation of the morphological quality of the main course of the Noce River was carried out by our group and by the Agency for Environmental Protection in 2012 using the MQI method (Morphological Quality Index, Rinaldi *et al.*, 2013). This method divides the river in segments and evaluate the morphological quality of a river on the basis of the observations of the geomorphological processes, of the presence of human structures and in terms of long-term morphological variations. The index is calculated by answering to different questions and summing the scores of each question.
The Noce River in Val di Sole is a hilly-mountainous basin. The main course has been divided into 12 segments, taking into account several factors: hydrological discontinuities (tributaries), the size of the plain, channel width, artificiality, bed morphology, significant changes in the longitudinal profile (slope). Aerial photos, topographic and geological maps were analysed using GIS to identify these factors. The first parameter measured for a subdivision of the preliminary stretch is the degree of confinement, which is the percentage of stretch in contact with the slopes.
The Noce River has a flood plain of limited width and the degree of confinement is described by a relative index, which is the ratio between the width of the flood plain and the channel width and it is a measure of how much a river is confined in comparison with its floodplain. The Noce River is naturally delimited by the valley slopes in most of its course. The application of this index divides the river in six segments. A further subdivision is given by the crossing with the main tributaries, which divides in three additional segments for a total of nine segments. The morphological classification of the riverbed is another parameter. For confined segments, the method distinguishes between single channel and multiple channel. The Noce River is currently a single channel river for most of its course, except for a few short parts which show central bars. For semi-confined traits an index of sinuosity is defined as the ratio between the length of the water course and of the valley. Only one trait can be considered as meandering on the basis

of this index. Another division is defined by the recognition of the forms of the bottom, which are steps, riffle-pool sequences and the flat bed. In the study area we detected the riffle-pool sequences and the flat bed. Human structures are also considered for a further division of the traits.

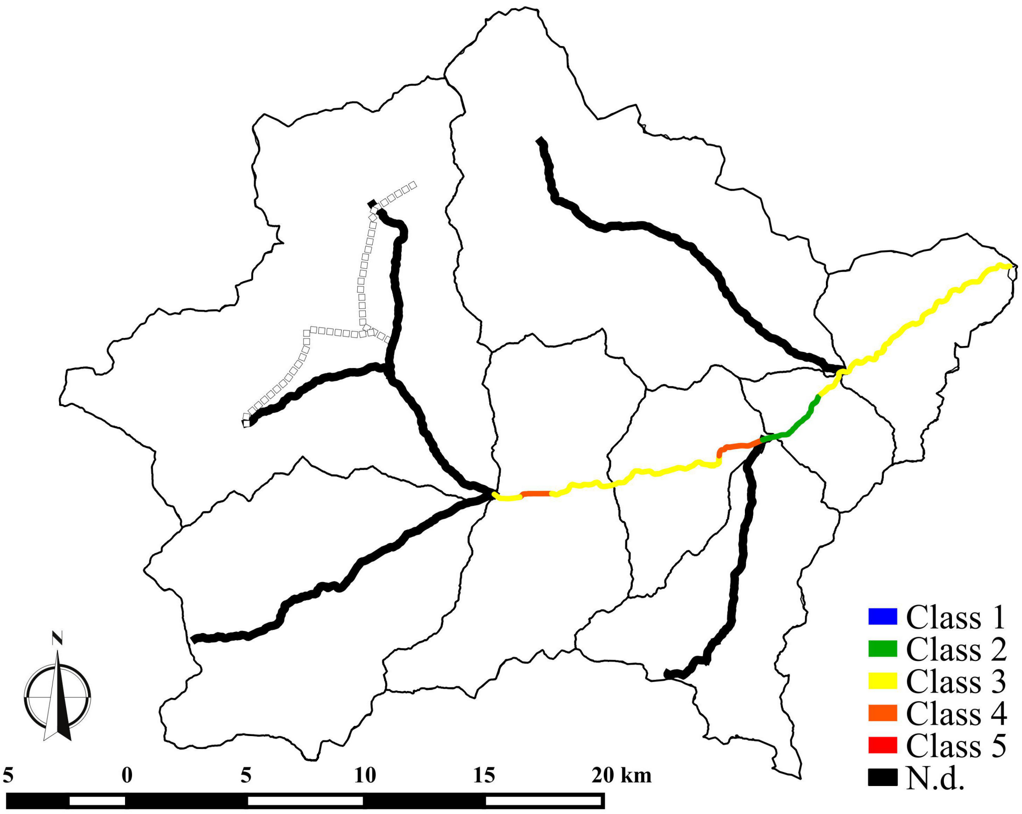


Figure 3.6: *Morphological quality (MQI) of the main course of the Noce River. The blue color denote an excellent quality class, green a good quality class, yellow a moderate quality class, orange a poor quality class and red a bad quality class. The black color indicates reaches which were not assessed.*

Using these parameters, the four segments described at the beginning of this chapter were divided in a total of 12 traits. In general, the upper course of the Noce River is confined by the valley's slopes, and only in some places the river has the space to move laterally and change its course.

The result of the index calculation for the entire basin is a class 3 (moderate), with the classes of the different traits that vary from class 2 to class 4 (good and poor, respectively). The geomorphological features of the river are altered by the complex of the human interventions made over the years. A low morphological quality index resulted due to the presence of human structures, which alters the transport of sediment and woody material, due to the anthropogenic modifications of the cross sections, the disruption of sediment continuity and due to the removal of woody material. The alteration of the continuity in the transport of sediment and woody material is mainly due to the presence of large dams, bridge piers, sills, bridles and crossbars that were built in almost the entire course of the river. In some traits the bed was artificially reshaped. The artificial management of the riverine area to maintain human activities such as agriculture, fisheries, is necessary but it decreases the naturalness of the river and prevent the development of the riparian communities. The presence of embankments and levees also prevents processes such as erosion and lead to a lower quality of the river. Other structures influence the morphological status of the Noce River. The dams located near the headwaters heavily alter both liquid and solid discharge and greatly affect the final index. The levees and embankments, which are necessary for the prevention of flood risk, are another factor that influences the morphological quality along with the management of sediment and woody material.

3.6 Hydrological regime

The flow regime of this river is typical of Alpine glacial and snow-fed rivers: high discharges in spring and early summer due to snow- and ice-melting and in fall due to rain-fall, and low discharges in late summer and winter (fig. 3.7).

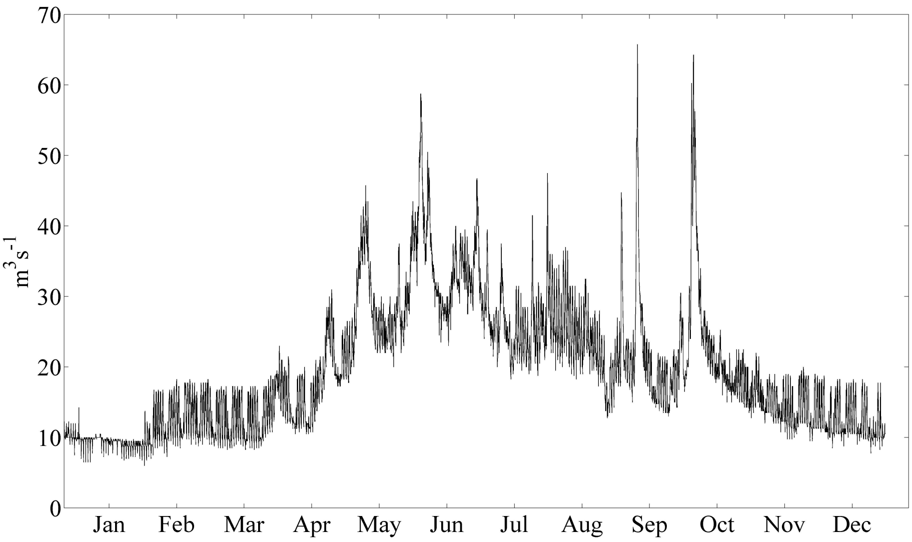


Figure 3.7: *The Noce River flow regime measured at Malè gauged station. The regime is typical of an Alpine River with maximum discharge in summer and autumn and low flow in winter. In addition, this river is affected by hydropeaking (smaller daily peaks).*

However, the Noce River and its catchment have been subjected to human alterations such as the reduction of the river area, channelization and the construction of dams to hydropower production. Its waters are intercepted by dams to form three main reservoirs: Pian Palù and Careser reservoirs in Pejo valley near the headwaters, and Santa Giustina reservoir in Val di Non, which is the largest in the basin and one of the biggest in the Alps. In this study, we will focus only on the two dams upstream the Santa Giustina reservoir (fig. 3.8).

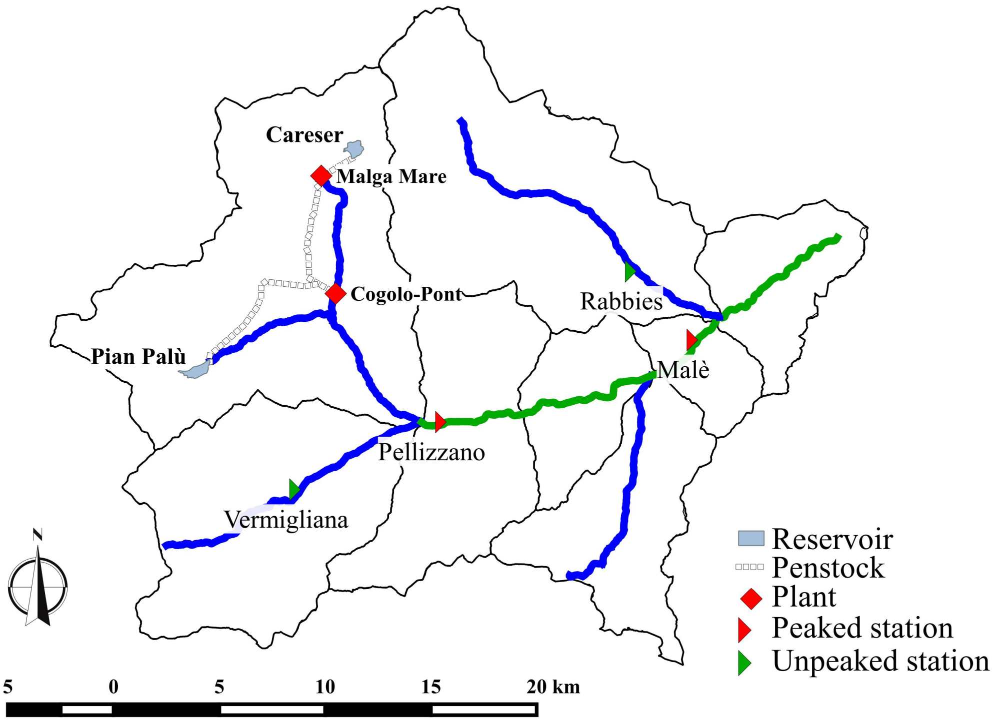


Figure 3.8: *Reservoirs, hydropower plants and gauged stations in the upper part of the Noce River basin.*

The first system of hydropower plants, namely Malga Mare (1964 m a.s.l.), uses the water of the Careser reservoir, with a maximum withdrawal of 3.0 m^3s^{-1}. From this plant depart penstock which receives also the water from the Pian Palù reservoir, and feed the main plant of Cogolo-Pont (1208 m a.s.l.), with a maximum range discharge of 7.6 m^3s^{-1} and 6.4 m^3s^{-1} from Malga Mare and Pian Palù respectively, with an hydraulic head of 622 m and 750 m. Other water uses are spread in the basin. A particular relevance has the mini and small hydropower production which have an installed capacity of 3 Mw. The national and regional laws requires the release of a minimum vital flow (MVF) for each river basin. The MVF has been calculated according to the local plan for the water uses (P.G.U.A.P., 2014), which calculates the MVF in $ls^{-1}km^{-2}$ for each basin by considering different variables: area of the catchment, mean altitude of the catchment, hydrological regime, mean annual precipitation and the main river source. The MVF values for each section is obtained by multiplying the coefficient of the basin for the area subtended to the river section. Table 3.2 summarizes the values of Minimum vital flow in the studied reaches and for the sub-reaches subjected to the new withdrawals.

The flow regulation associated with hydropower production involves the releases of

Reach	December-April (m^3s^{-1})	May-November (m^3s^{-1})
1	0.97	1.48
2	1.23	1.86
3	1.55	2.35
4	2.25	3.49

Table 3.2: *Minimum vital flow (MVF) divided by each sub-reach and by season.*

discharge at intervals of irregular and unpredictable duration and timing, as they depend on the production choices which are in turn linked to the performance of the energy market. Thus, it determines the phenomenon of hydropeaking, which is the object of particular attention in the entire Alpine area. Figure 3.8 shows the position of the gauging stations in the basin, with two peaked stations along the main course. The application of the indicators described in the previous chapter shows that one of the peaked stations (Pellizzano, the upstream station) is in the highest class of hydropeaking pressure and the pressure decreases according to the distance from the release (Fig. 3.9). Thus, during the day the river experience basically two different flow regime: daily minimum flow defined by a stage of no hydropower production and daily maximum flow defined by the maximum release from plants. A third stage can be observed during transition between the formerly described phases or when the plants are not working at maximum capacity.

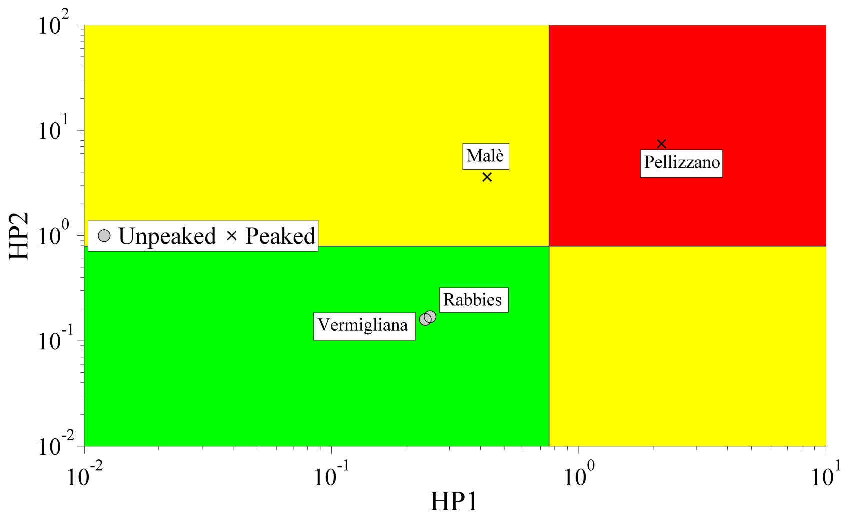


Figure 3.9: *Results of the application of the two indicators on the Upper Noce River gauged stations for the year 2011.*

3.7 Conclusions

The Noce River is in good or excellent environmental conditions, both by a chemical and ecological perspective. The morphological quality is lowered by the complex of human interventions and activities in this populated catchment and in particular the hydropower production scheme has a relevant effect. On the other hand, the application of the indicators introduced in chapter 2 shows as the hydrological regime of the river is heavily modified by hydropower production and hydropeaking. Consequently, beside other socio-economical characteristic which will be described in the following chapters, the Noce River represents an optimal case study to assess the effects of hydropeaking on Alpine river ecosystem services.

Chapter 4

Modelling recreational flows: assessment of rafting suitability

4.1 Introduction

The general aim of this chapter is to describe the concepts and the application of a modelling approach able to quantify spatial and temporal variations of recreational services in rivers subjected to hydropeaking (second research question, chapter 1). We specifically focus on the rafting navigability as target recreational service and apply the methodology to an impounded Alpine river. Among the different types of services provided by rivers, rafting and canoeing are considered a subset of recreational and cultural services (Russi *et al.*, 2013). Boating and navigability for recreational activities are cited in literature (Brown *et al.*, 1991; Hammitt *et al.*, 2001; Thorp *et al.*, 2010), but only few works addressed quantitatively the variation of suitability for navigation at discharge variations, and usually by applying only the expert-judgement method (Shelby *et al.*, 1998). Therefore, the specific objectives of this chapter are:

i) to develop an integrated, model-based methodology to assess the flow requirements and the space-time variability of river suitability for rafting in hydropeaking rivers using daily flow data;

ii) to apply this method to a river system that is worldwide well-known for rafting activities and is also subject to hydropeaking;

iii) to predict how future flow management can affect the provision of recreational flow for rafting activities.

4.2 Study Area

The methodology introduced in the present chapter is applied to the Noce Alpine River which we described in chapter 3. In addition, the Figure 4.1 shows also the location of the uptake and the water release of a new withdrawal, denoted by the red triangle and green triangle in the map. Several data are available for this catchment from public agencies: river cross sections, at an average distance of 100 meters were provided by the Servizio Bacini Montani (Autonomous Province of Trento, via G.B. Trener 3, Trento, Italy); stream-flow data series were provided by Rete di monitoraggio in tempo reale dellUfficio Dighe - Servizio Prevenzione rischi of the Autonomous Province of Trento.

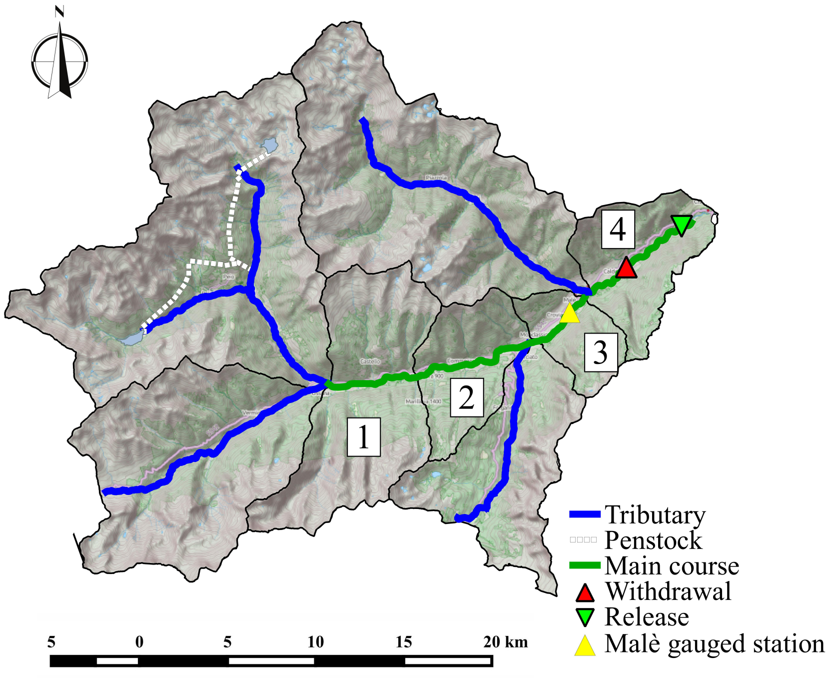


Figure 4.1: *Map of the Upper Noce River catchment where the study reach is located. The blue lines denote tributaries, the dotted line indicates the penstock, the green line points out the studied reach, the numbers indicates the sub basin in which the area is divided, the red and green triangles denote uptake and release respectively and the yellow triangle indicates the river main gauging station.*

4.3 Methods

4.3.1 Rationale of the methodology

The rationale of the method is that when hydrological and hydraulic data are available or can be modelled and when a relation between these data and the suitability by an ES can be defined through preference functions or preference curves, principles of habitat modelling can be applied to simulate any type of flow-dependent ecosystem services. Habitat modelling is a technique developed and applied to assess and predict the suitability of an habitat by a given specie on the basis of its relation with physical, geographical or ecological variables (e.g., Vezza *et al.*, 2014; Bain and Jia, 2012). The use of models allows to evaluate spatially and temporally the flow conditions and to predict suitability under present and future discharge management scenarios. In this section, we describe the integrated methodology we applied to assess flow requirements and river suitability in space and time and quantify the variations of "recreational flow" in different flow conditions. In subsection 4.3.3 we introduce the preference curve we constructed to use as input in the habitat model, in order to evaluate the potential for the selected ES and define thresholds for suitability. In subsection 4.3.2 we describe our approach to model flow regime patterns with daily hydrological model, to model hydraulic parameters and implement them in a habitat model. The methodology can be summarized as follow:

- Step 1.1: definition of the relation between rafting and physical variables through the calculation of preference function or preference curve;
- Step 1.2: simulation of the hydraulic parameters, in a representative discharge range for the river reach of interested;
- Step 2: computation of rafting suitability thresholds through habitat modelling. The water surface calculated by the hydraulic model is used as input data in the habitat model, together with the preference curves. The aim of the habitat model is to define thresholds of suitability which allow to evaluate habitat quality in space at different discharges;
- Step 3.1: flow regime simulation of scenarios and of duration curves in different flow regimes through a hydrological model;
- Step 3.2: application of the thresholds to flow regime patterns. Thresholds are applied to duration curves to evaluate the rafting spatial and temporal suitability in different flow regimes.

The work flow of the methodology is shown in Figure 4.2. We evaluate the accuracy of the approach to model real conditions by comparing simulated discharge values with real data.

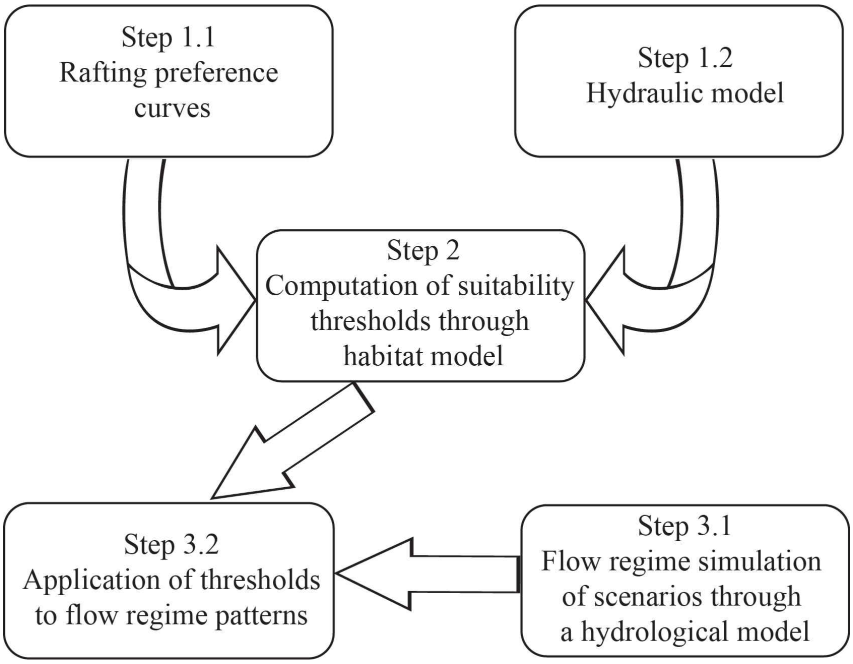


Figure 4.2: *Schematic work flow of the proposed methodology.*

4.3.2 Hydraulic, habitat and hydrological models

Three main models have been applied in this method: Hec-Ras (hydraulic model), CASiMiR (habitat model) and GEOTRANSF (hydrological model). We used Hec-Ras version 4.1 to model the hydraulic parameters. Hec-Ras is a widely used hydraulic model that can perform one-dimensional steady or unsteady flow computations, under different types of boundary conditions (USACE, 2002a; USACE, 2002b). We used spatially distributed water depth and velocity values calculated by the hydraulic model and geometry river data to perform habitat analysis at different discharge values.
The Computer Aided Simulation Model for In-stream Flow Requirements (CASiMiR hereafter) habitat model is widely used (e.g Mouton *et al.* (2007); Tuhtan *et al.* (2012); García *et al.* (2011)) to simulate physical habitat preferences for biotic organisms like fish or macroinvertebrates at different flow stages . CASiMiR can account for preferences for water depth, water velocity and substrate, and computes suitability values on the basis of preference curves. The combination of the three parameters has been often taken as a representative description of the habitat suitability for fish (Armstrong *et al.*, 2003). CASiMiR model allows to evaluate other ecological parameters when data are available (e.g shading, cover). The combination of preference curves and hydraulic parameters

yields an habitat suitability index (HSI hereafter), which is a measure of the capability of a habitat to meet species requirements. The software combines the HSI for each preference curve in a single habitat suitability for each cell of the computational domain used for hydraulic simulations, allowing to choose different aggregation methods (i.e., arithmetic mean, geometric mean and product). Other relevant parameters for the habitat modelling which can be calculated by CASiMiR are Weighted Usable Area (WUA hereafter) and Hydraulic Habitat Suitability (HHS hereafter). The WUA is calculated by multiplying each cell for its suitability value and sum the cell with equal SI (Equation 4.1),

$$WUA = \sum_{i=1}^{n} A_i SI_i, \tag{4.1}$$

where SI_i is the habitat suitability index for the i_{th} computational cell and A_i is the area of the i_{th} cell.

HHS is the WUA divide by the total wetted area (Equation 4.2),

$$HHS = \frac{1}{A_{tot}} \sum_{i=1}^{n} A_i SI_i, \tag{4.2}$$

where A_{tot} is the total wetted area.

GEOTRANSF (GEOmorphological Tool for Reconstructing Anthropogenic effects on Surface Fluxes) is an accurate, geomorphologically-based, hydrological model designed to perform continuous simulations with daily time-step in human impacted catchments. Besides a detailed hydrological models chain describing the run-off production process, the model takes into account anthropogenic effects such as the presence of reservoirs and spatially and temporally varying water uses (Majone *et al.*, 2005; Majone *et al.*, 2006). The model partitions the watershed in different sub-basins according to natural and artificial flow variations and it is capable to reconstruct stream flows time series at daily temporal resolution at any location within a catchment and allows to easily perform scenario-based analysis, such as those related to climate and land use changes, different water policy options, increased storage capacity of the system, changes in irrigation techniques or increased number of water withdrawals. The application of GEOTRANSF for the purposes of this study, concerns the reconstruction of the long term discharge distribution along a river trench characterized by the presence of several withdrawals, and impacted by different types of human regulations. We simulated different flow patterns using the hydrological model and produced discharge duration curves at river cross-sections of interest, which are representative of the present conditions and of future management plans.

4.3.3 Choice of recreational service and preference curve

The recreational service selected for this case is rafting, since it is an activity spread in the Alpine area. The preference curve for rafting was built on the basis of expert judgements, which indicated water level recorded at a reference hydrometric station as the preference hydraulic indicator. In the study, twenty-three rafting guides and local experts, belonging to five different rafting centres, were personally interviewed to provide indications of the water level ranges that guarantee suitable, optimal or bad conditions for navigation. They were asked to indicate a minimum and a maximum threshold of suitability: below the minimum, navigability is not possible because occurring of too low depth in at least one river section; above the maximum navigability is considered dangerous for recreational uses. Furthermore, the experts suggested lower and upper thresholds for optimal navigability conditions. The suitability values assigned to each of the above threshold range between 0 and 1, with 0 indicating unsuitable conditions and 1 corresponding to optimal values conditions.

4.3.4 Computation of recreational flow requirements

We combined hydraulic and habitat models to perform the computation of spatially distributed flow requirements and of rafting suitability. In the case study, a unique Manning's roughness coefficient for the whole reach was calibrated by measuring water surface level at known discharges yielding an n value of 0.04 $m^{-1/3}s$. A discharge range between 0.5 m^3s^{-1} and 100 m^3s^{-1}, which is approximately the biennial flood, was simulated under steady flow conditions. We constructed *ad-hoc* a stage curve discharge to convert water level values into discharge values.
Recreational flow requirements have been computed in the form of spatially distributed discharge thresholds for rafting suitability and optimality. In the study case, the spatial scale of aggregation has been the individual reach, resulting in four different thresholds for suitability and optimality. The computation has been performed according to the following procedure. First, the discharge values corresponding to the water level thresholds indicated by the rafting experts are computed through the hydraulic model. These discharge values coincide with the discharge thresholds (i.e. recreational flow requirements) for the reach where the reference hydrometer is located. This "reference reach" coincides with reach number 3 in the Noce River case. Second, the frequency distribution of flow depth values for the same reach is analysed, and the mean local value for each threshold discharge is recorded. Third, the threshold discharge values for every other reach is computed as the one yielding - in at least one cross section for that reach - the minimum water depth value associated with the corresponding lower

threshold and the maximum water depth value associated with the corresponding upper threshold in the reference reach. Furthermore, longitudinal continuity is checked for every examined reach to be suitable for rafting. The obtained discharge values along every entire reach are chosen as the recreational flow requirements. The thresholds were applied to calculate percentage of suitability in time from the duration curves obtained with the hydrological model. A similar approach was used to calculate suitability on real data. Since the rafting season begin in May and end in September, our analysis focused only on this period.

4.3.5 Spatially and temporally distributed rafting suitability and hydropeaking scenarios

Hydropeaking has a typical sub-daily cycle, while most hydrological models for human impacted basins, simulates daily stream flow data. Therefore a set of idealized hydrological scenarios have been designed to approximate the actual hydropeaking conditions. Before the liberalization of the energy market, the management policy led to a high flow regime during day and a low flow regime during night, but patterns of production and, consequently, pattern of discharge have radically changed in the last years. To assess the status of the rafting suitability during these different flow regimes two separate patterns are simulated with the GEOTRANSF model, one that reconstructs the high flows occurring when maximum hydropower production is ongoing from the reservoirs (*MaxHp*) and one that reconstructs the low flows when hydropower production is stopped (*NoHp*). In both simulations, registered daily outflows are used to consider water volumes released from the dams. Furthermore, other two flow patterns are simulated: one related to a completely natural situation (*Nat*), i.e. no dams are present and no withdrawals are active within the catchment, and one describing the actual average daily flow (*Act*), with water release from the dams taken as the average registered daily outflow, i.e. the sum of the minimum environmental flow plus hydropower production volumes. Therefore we end up with five set of run-off distributions along the river reaches.

To summarize the five idealized simulated flow patterns are:

1. *Natural (Nat)*: a theoretical flow pattern without any human effects;
2. *Maximum hydropeaking (MaxHp)*: flow pattern which simulates maximum discharge from the hydropower plant extended to 24 hours;
3. *No hydropeaking (NoHp)*: flow pattern which simulates no hydropower water use from the reservoir, i.e. only minimum environmental flow is released from the dams

into the river;

4. *Actual (Act)*: flow pattern which simulates daily mean discharge values;

5. *Future management (Fut)*: flow pattern which simulates an hypothetical new withdrawal of 4 m^3s^{-1} in the downstream river reach 4.

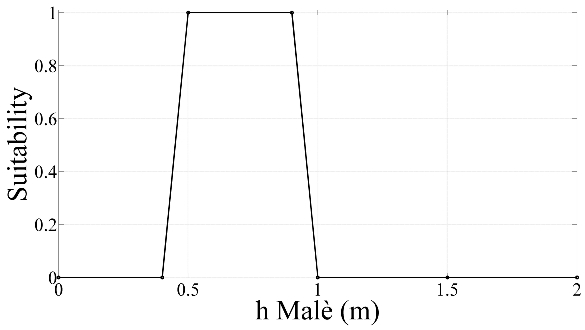
For the 3rd reach, real data are available and we used them to evaluate the predictability of navigability. We compared monthly duration curve constructed using real data collected at hourly time-scale in the station of Malè between 1998 and 2010, with the duration curves produced by the hydrological model at daily scale. We tested for normal distribution of the data and, since the normality requirements are not met, we tested for significant differences among distributions using Mann-Whitney U non-parametric test.

4.4 Results

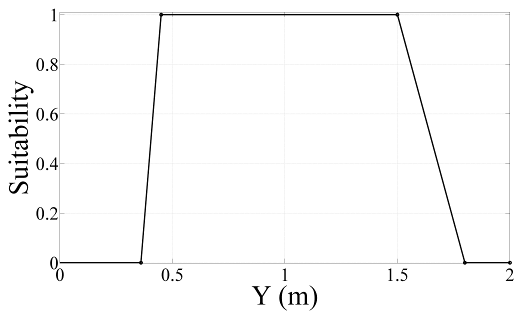
In this section, we describe the results of the application of the methodology to the case study described in section 4.2. Using the preference curve showed in subsection 4.4.1, the habitat modelling was used to define for each reach (spatial dimension) discharge thresholds which guarantees river suitability for navigability (Subsection 4.3.4). For each basin and sub-basin, the hydrological model produced several flow patterns which resembles river's discharge conditions induced by hydropeaking (Subsection 4.3.5). We applied the thresholds to the flow patterns, in order to evaluate navigability in different months and in different hydropeaking conditions (temporal dimension, Subsection 4.3.5.

4.4.1 Recreational flow requirements

As a result of the interviews, the preference curve for rafting navigability has been constructed (Fig. 4.3). The experts completely agreed on the thresholds, although one of the contacted rafting centres did not participated to the interviews. However, 4 out of 5 rafting centres and related guide answered to the questions for a total of 19 out of 23 experts and they use the thresholds as a rule during rafting activities to guarantee a safe and satisfying experience. On the basis of expert opinion, the limiting factor for rafting is the water level. The navigation is impossible along several parts of the river when water level is below 0.4 m assessed visually by rafters. The upper threshold is equal to 1 m, and optimal values are between 0.5 and 0.9 m. It is worth to mention that the conditions of unsuitability do not occur in the gauged river section but the river is unsuitable in several parts of its course when the preferences are not met. These rules are an objective and expeditious method to check the discharge conditions of the river, which can greatly change during the day.



a) Rafting requirements at Malè station



b) Rafting requirements for the entire river

Figure 4.3: *a) Preference curve for rafting suitability resulting form the interviews with local experts. The controlling hydraulic metric is the water level measured at a reference hydrometric station (Malè for the presented case study). b) Rafting requirements simulated with the hydraulic model as the minimum depth for the lower threshold and maximum depth for the upper threshold in the reference reach corresponding to the water level at the Malè section.*

The Table 4.1 shows the discharge limits for each reach and for the reach subjected to the future withdrawal, calculated using the preference curve showed in Figure 4.3 b).

Reach	Lower discharge threshold (m^3s^{-1})	Upper discharge threshold (m^3s^{-1})	Optimal discharge range (m^3s^{-1})
1	13.5	45.0	23.5-45.0
2	16.5	50.0	25.0-35.0
3	15.5	50.0	25.0-50.0
4	17.25	65.0	23.5-55.0
W	12.5	65.0	19.5-65.0

Table 4.1: *Reach-specific recreational flow thresholds of suitability and optimality, expressed in* m^3s^{-1}.

As a first screening, we applied expert opinion to real data in order to assess the real navigability from 1990 to 2012. We used water level data collected in a single gauging station and the effective navigation was estimated by applying the preference curve to these data. Hence, the analysis of real data can be considered as a proxy of the real river navigability in the last 10 years. We analysed daily data from 8 a.m to 6 p.m. from May to September for the entire period (1990-2012). During early spring, late fall and winter months rafting activities are absent, therefore the ES is not used in fall, winter and early spring. Figure 4.4 shows the real suitability of the river in last 22 years, aiming to characterize the real condition of the river in the past decades. The navigation was suitable for more than 50% of time in the period 1990-2000 in all months. Starting from 2001, the conditions ameliorated in spring and early summer but they worsened in August and September. Moreover, in the last 5 year, the condition of unsuitability increased in August and accounted for almost the 50% of the time in September.

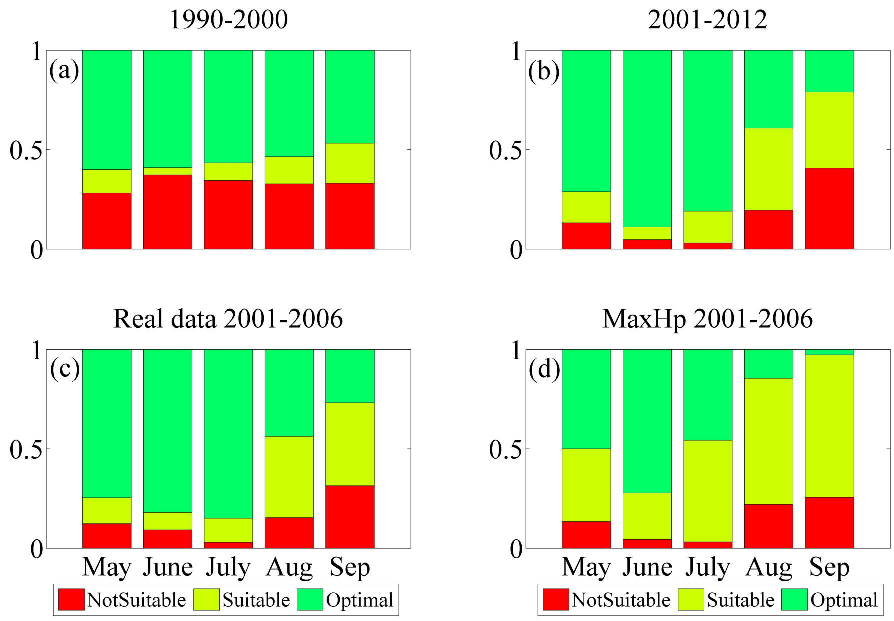


Figure 4.4: *Real suitability expressed in percentage between 0 and 1 in last 20 year divide in two periods: 1990-2000 a) and 2001-2012 b); and comparison of real data (c) with simulated flow pattern d) in model calibration period (2001-2006). Green bar color denotes optimality, pale green denotes suitability and red denotes unsuitability. Each pattern is divided in months.*

The Figures 4.5, 4.6 and 4.7 show the results of the application of the CASiMir model in a selected sub-reach: the rafting suitability changes according to discharge variations.

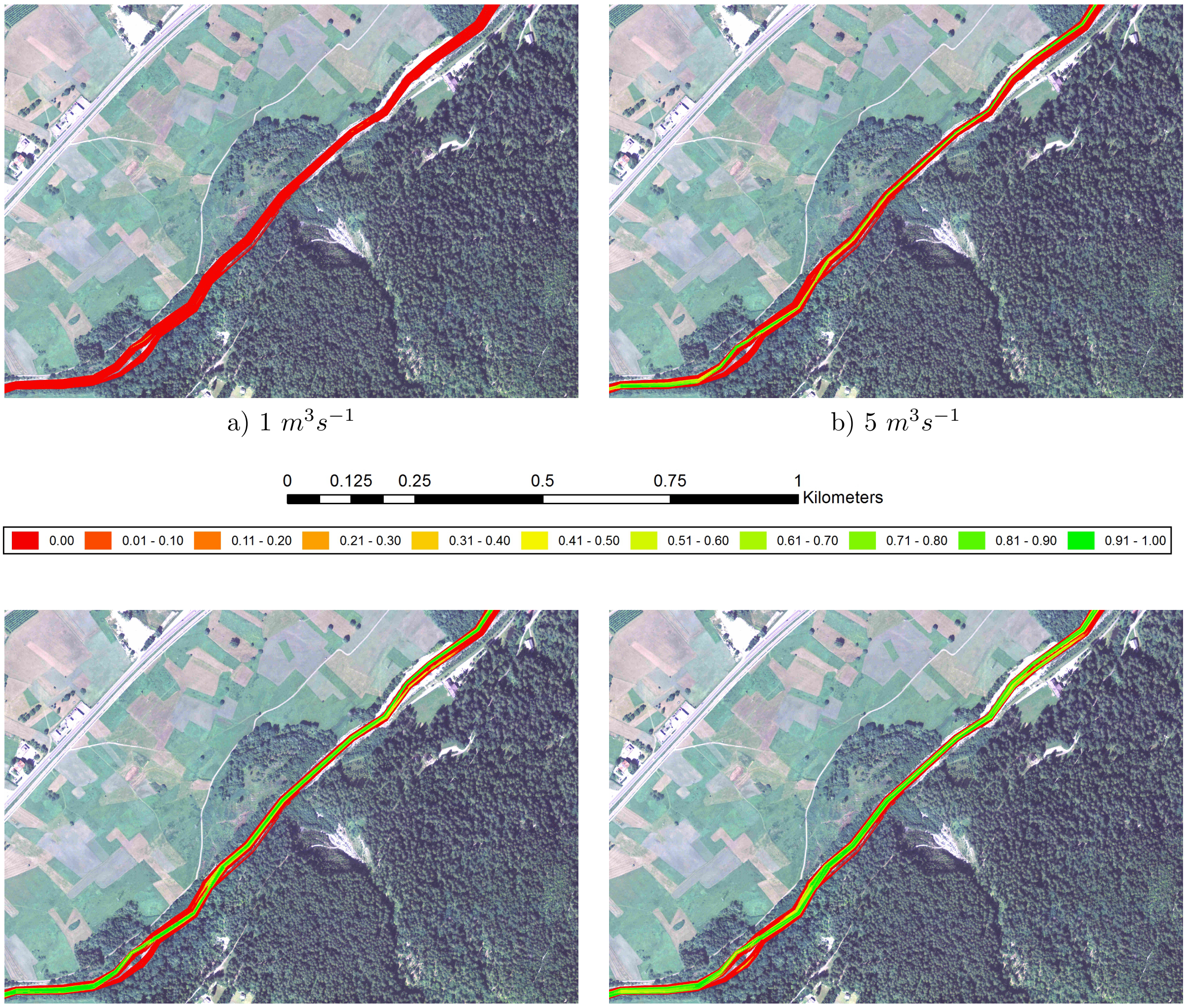
We tested for significant differences between monthly real data and modelled duration curves with 20 pairwise Mann-Whitney U comparisons (each month of each pattern compared with same month of real data, results in Table 4.2). Comparisons were significant for *NoHp*, *Act* and *Nat* flow patterns. The duration curves resulted not significantly different when *MaxHp* flow pattern and real data distributions were compared.

	May	June	July	August	September
Act	0.001**	0.001**	0.004*	0.006*	0.001**
NoHp	0.001**	0.001**	0.001**	0.001**	0.22
Nat	0.001**	0.001**	0.001**	0.001**	0.29
MaxHp	0.24	0.96	0.24	0.14	0.001**

Table 4.2: *Results of Mann Whitney U test. * significant, ** highly significant.*

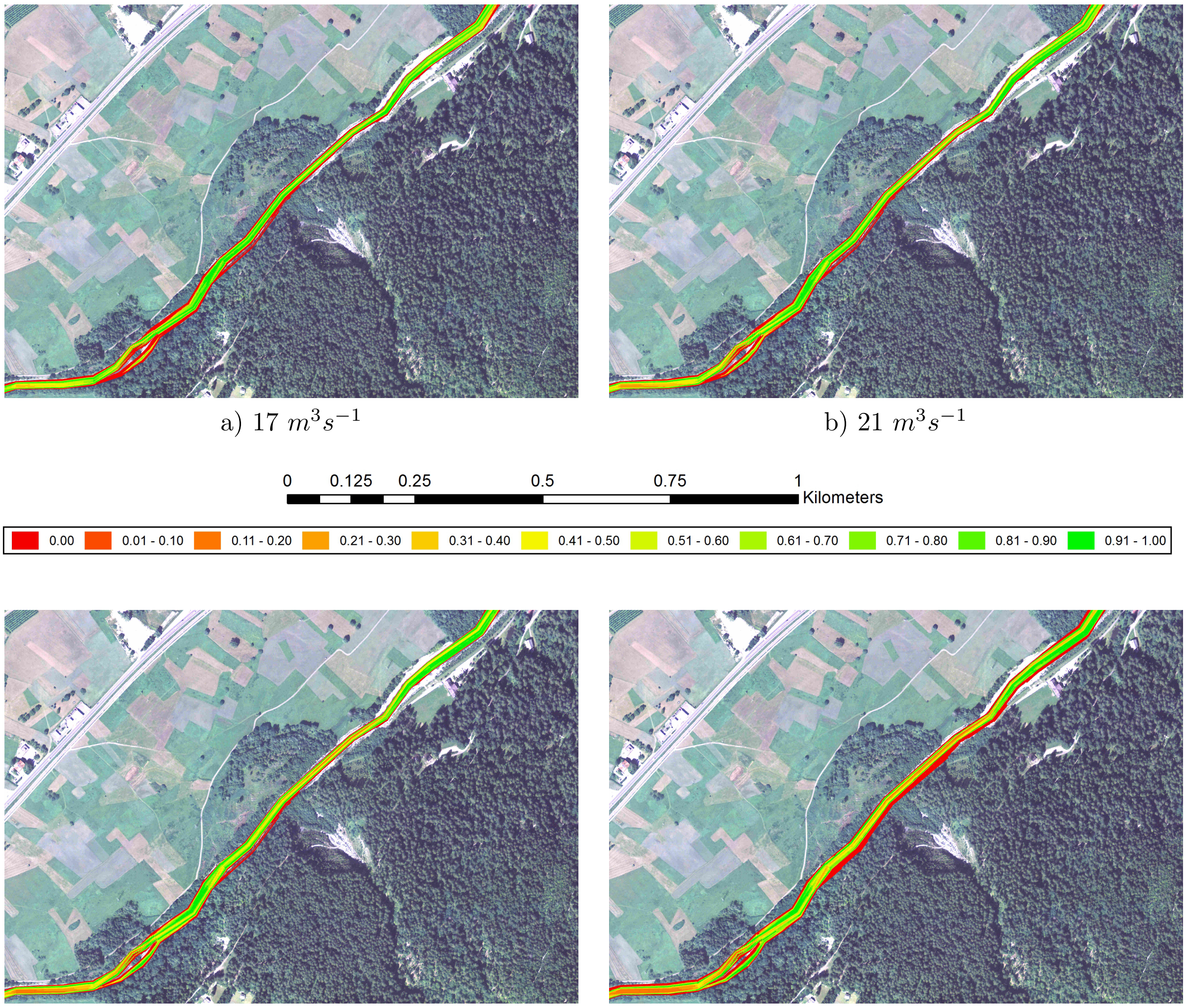
4.4.2 Space-time distributed rafting suitability

Since the aim of the method is to evaluate the variation of suitability for rafting under different flow conditions, we decided to show the results divided by flow patterns. For each pattern, we described the suitability in each reach. Moreover, we described the results divide by month due to seasonal discharge variations. Figure 4.8 shows a visual representation of the method. Thresholds defined with CASiMiR (vertical lines, Fig. 4.8)



a) 1 m^3s^{-1} b) 5 m^3s^{-1} c) 9 m^3s^{-1} d) 13 m^3s^{-1}

Figure 4.5: *Example of the variations of the rafting suitability (1 to 13 m^3s^{-1} flow range) in a selected sub-reach. The color gradient ranges from red to yellow to green, pointing out a suitability of 0, 0.5 and 1 respectively.*



a) 17 $m^3 s^{-1}$ b) 21 $m^3 s^{-1}$

c) 25 $m^3 s^{-1}$ d) 29 $m^3 s^{-1}$

Figure 4.6: *Example of the variations of the rafting suitability (17 to 29 $m^3 s^{-1}$ flow range) in a selected sub-reach. The color gradient ranges from red to yellow to green, pointing out a suitability of 0, 0.5 and 1 respectively.*

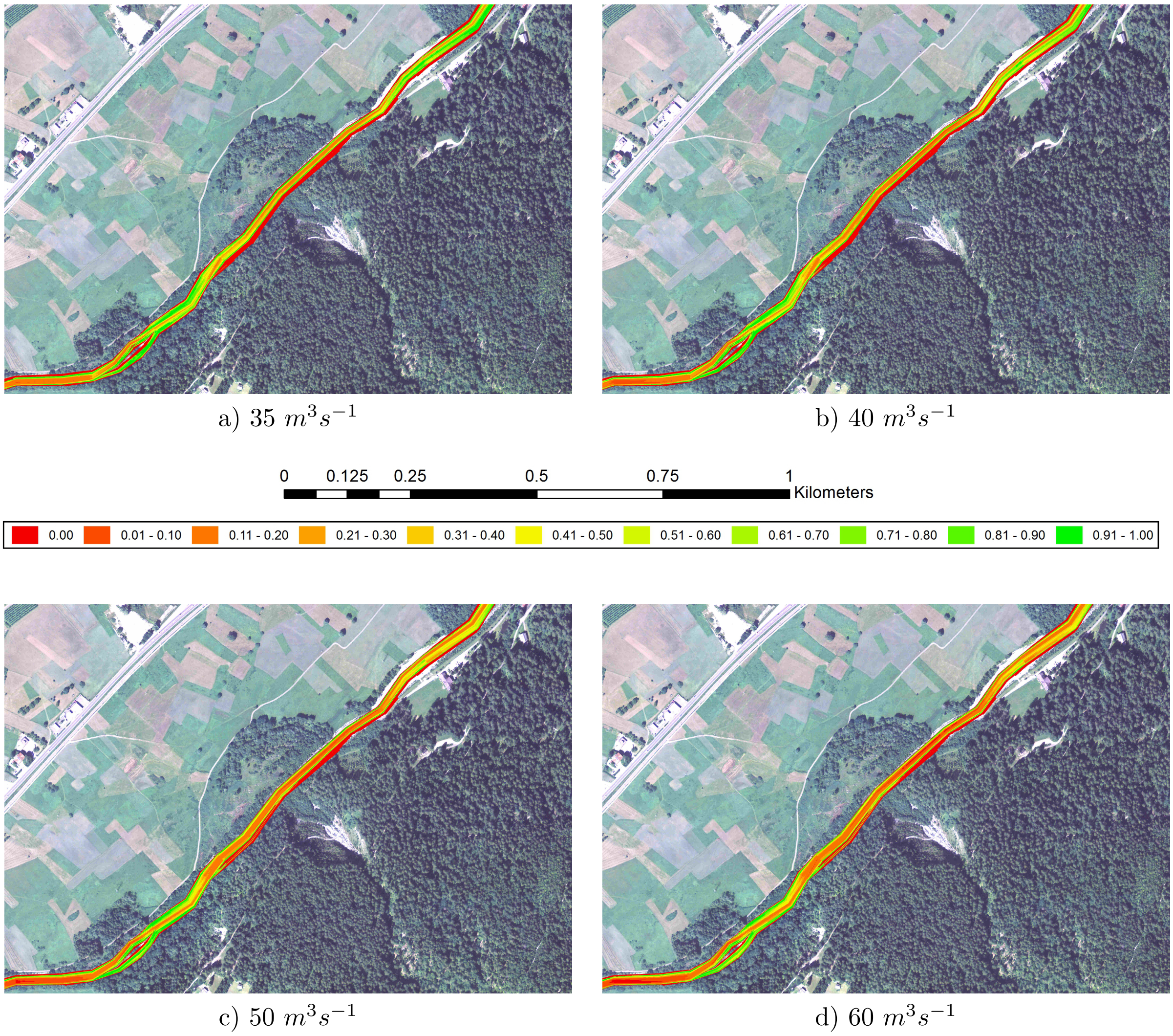


Figure 4.7: *Example of the variations of the rafting suitability (35 to 60 m^3s^{-1} flow range) in a selected sub-reach. The color gradient ranges from red to yellow to green, pointing out a suitability of 0, 0.5 and 1 respectively.*

were applied to duration curves (curves in Fig. 4.8), in order to calculate the percentage of time in which the reaches remain in the same class of Suitability (Persistence in Suitability Class, PSC hereafter). We calculated optimal, suitable and unsuitable PSC for each flow pattern and each month (Fig. 4.9 and Tables 4.4 and 4.5).

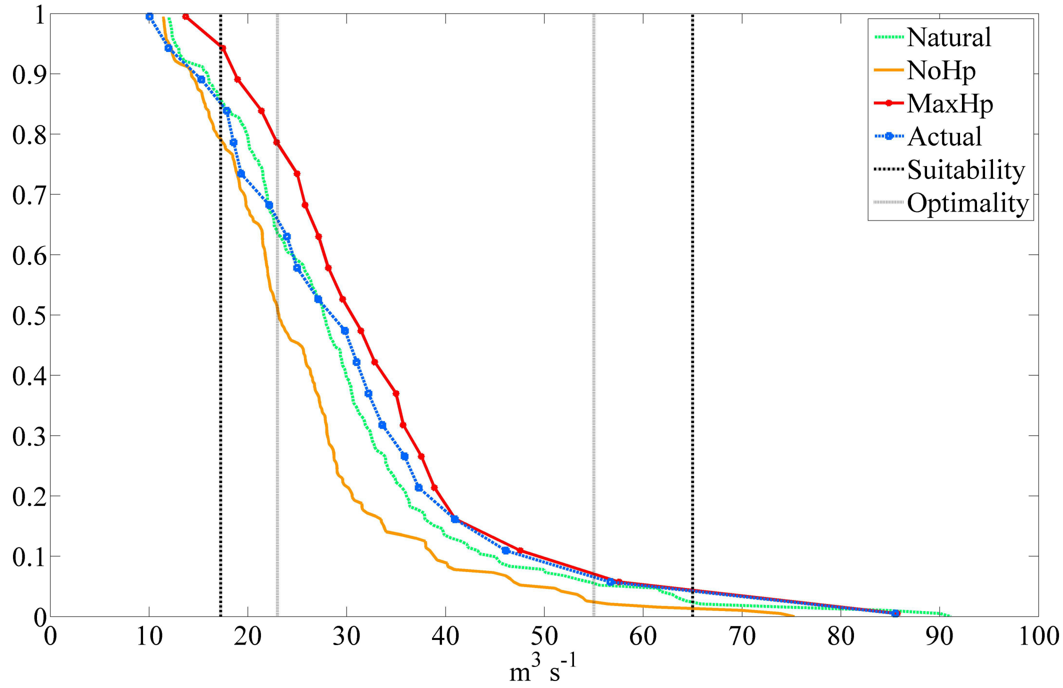


Figure 4.8: *Example of the duration curves and thresholds relative to the fourth reach. Four flow patterns are represented here: dotted green line is the Nat pattern, orange line is the NoHp pattern, red line is the MaxHp pattern and blue dotted line is the Act pattern. Dotted black an grey lines are the thresholds of suitability and optimality, respectively.*

Figures 4.10 and 4.11 visually represents the variations of suitability for the entire river, divided in reaches, and in time, for *NoHp* and *MaxHp* patterns. In general, in all the flow patterns we can highlight that suitability decreased from May to September, according with the decrease of discharges which is typical of rivers with snow and ice-melting flow regimes. The river is less suitable in reaches 1 and 2, upstream the confluence of two of the three main tributaries. The theoretical *Nat* flow pattern does not ensure good river conditions for navigability. According with the results, the river is largely unsuitable in this pattern, especially in reach 1 and 2. Only in June and July the river conditions are good for navigation in all the reaches, with a minimum PSC of 76% in reach 2 (suitable plus optimal percentage). In August and September the river is not suitable, with a minimum value of 44% of the time in reach 3 in August and a maximum value of unsuitability of 96% in September for reach 2. The maximum optimal value is 69% in reach 4 in June. Since the *Nat* pattern is simulated and does not resemble real conditions, this pattern were not further investigated.

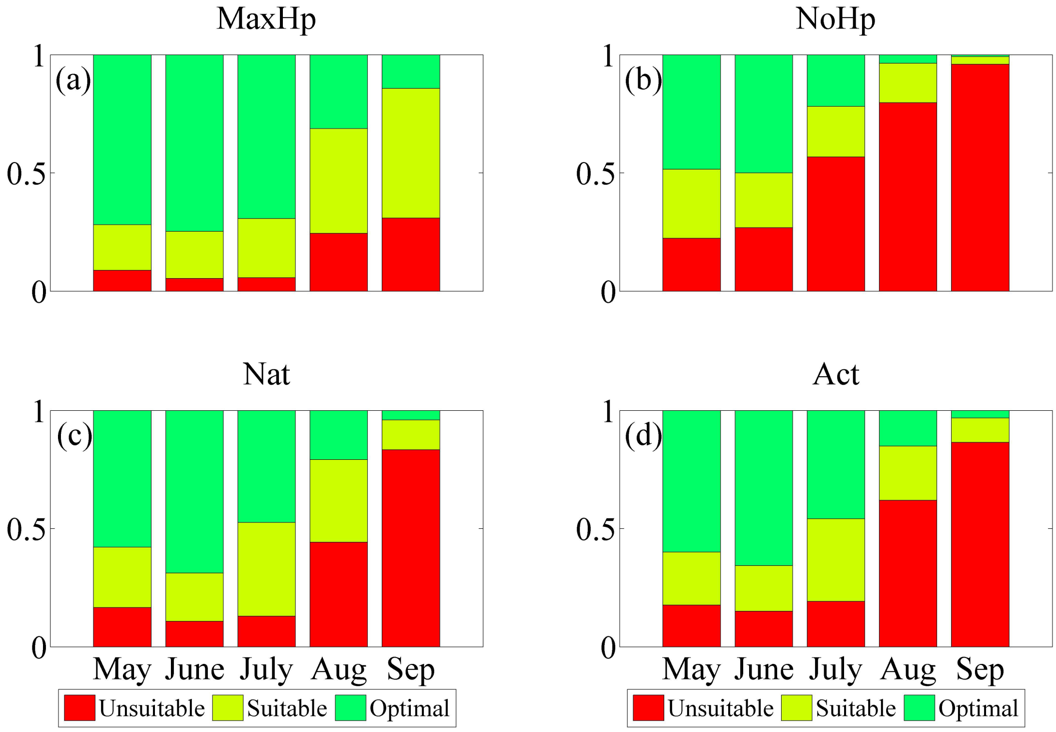


Figure 4.9: *Suitability for navigability (expressed in percentage) for fourth reach divided by flow pattern (a MaxHp, b NoHp, c Nat, d Act). Green bar color denotes optimality, pale green denotes suitability and red denotes unsuitability. Each pattern is divided in months.*

		May	June	July	August	September
Reach1	Unsuitable	0.52	0.16	0.25	0.61	0.95
	Suitable	0.35	0.44	0.55	0.36	0.04
	Optimal	0.13	0.41	0.20	0.03	0.01
Reach2	Unsuitable	0.35	0.13	0.29	0.73	0.96
	Suitable	0.46	0.54	0.55	0.24	0.04
	Optimal	0.18	0.32	0.16	0.03	0.00
Reach3	Unsuitable	0.19	0.11	0.11	0.48	0.88
	Suitable	0.41	0.27	0.62	0.46	0.10
	Optimal	0.40	0.62	0.27	0.06	0.02
Reach4	Unsuitable	0.17	0.11	0.13	0.44	0.83
	Suitable	0.26	0.20	0.40	0.35	0.13
	Optimal	0.58	0.69	0.47	0.21	0.04

Table 4.3: *Percentages of suitability, unsuitability and optimality in Nat flow pattern divide by reach and by month.*

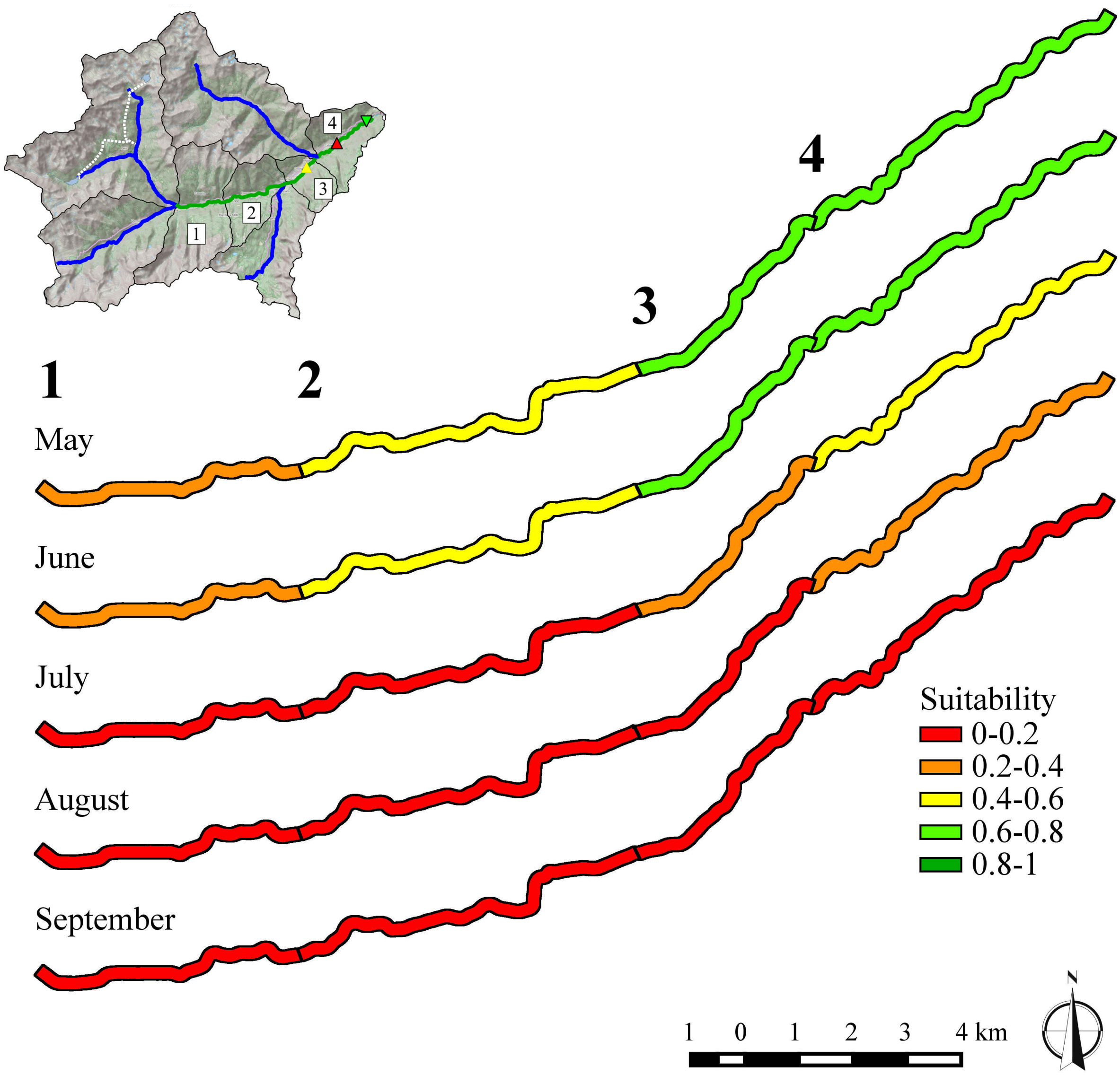


Figure 4.10: *Spatially (4 reaches) and temporally (5 months) distributed rafting suitability under the NoHp flow regime scenario. expressed through the value of PSC (Persistence in suitability class). The colors range from red (unsuitability) to green (optimality).*

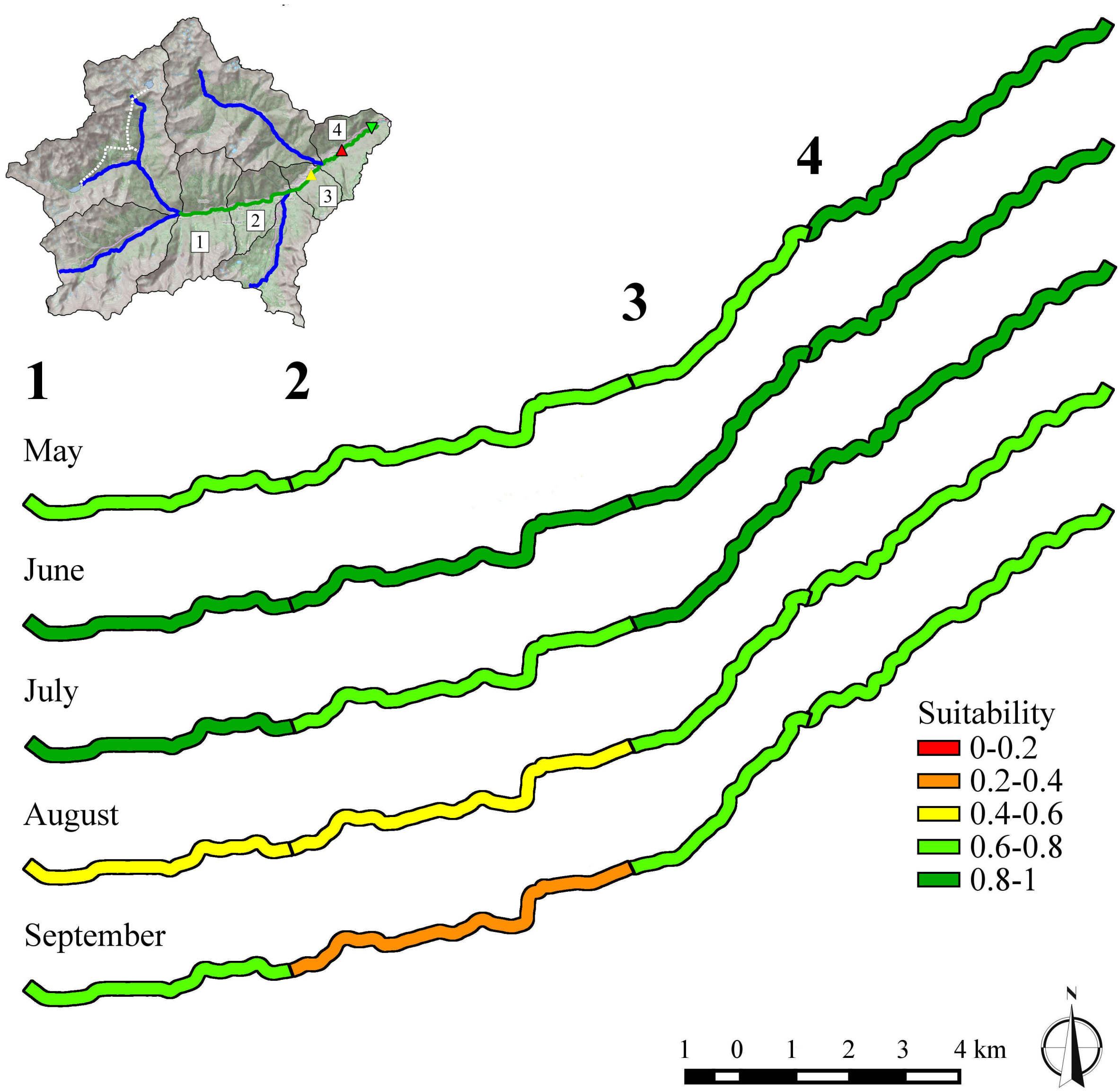


Figure 4.11: *Spatially (4 reaches) and temporally (5 months) distributed rafting suitability under the MaxHp flow regime scenario. expressed through the value of PSC (Persistence in suitability class). The colors range from red (unsuitability) to green (optimality).*

In *NoHp* pattern the river is unsuitable in August and September in all the reaches, with a minimum value of 80% of unsuitability in reach 4 in August and a maximum value of 98% in reach 1 in September (Table 4.4). However, in September unsuitable PSC is between the 96% of reach 4 and the 98% of reach 1. Only in May and June in reach 3 and 4 rafting conditions are suitable for less than the 50% of the time, with a minimum unsuitable PSC of 22% in reach 3 and 4 in May. In general, optimal conditions are rare in *NoHp*, with a maximum value of optimal conditions of 50% in June in reach 4.

		May	June	July	August	September
Reach1	Unsuitable	0.77	0.60	0.87	0.98	0.98
	Suitable	0.20	0.34	0.12	0.02	0.02
	Optimal	0.03	0.06	0.01	0.01	0.00
Reach2	Unsuitable	0.58	0.56	0.82	0.97	0.98
	Suitable	0.35	0.33	0.16	0.02	0.01
	Optimal	0.07	0.11	0.03	0.01	0.01
Reach3	Unsuitable	0.22	0.29	0.66	0.87	0.97
	Suitable	0.54	0.40	0.24	0.11	0.02
	Optimal	0.23	0.31	0.09	0.02	0.01
Reach4	Unsuitable	0.22	0.27	0.57	0.80	0.96
	Suitable	0.29	0.23	0.21	0.17	0.03
	Optimal	0.48	0.50	0.22	0.04	0.01

Table 4.4: *Percentages of suitability, unsuitability and optimality in NoHp flow pattern divide by reach and by month.*

MaxHp pattern shows the best conditions among all flow patterns (Table 4.5). Navigability is above the suitable thresholds for most of the time in May, June and July for all the reaches, with a maximum percentage of suitability of 95%. In August in reach 1 and 2 the suitability conditions decreases (i.e. the reaches are suitable for the 42% of the time), while reach 3 and 4 shows good conditions for the 70% of the time in August as well. September is a critical month in this flow pattern: unsuitable PSC increase in all reaches, with a minimum value of 28% in reach 3 and maximum of 79% in reach 2.

In *Act* pattern rafting is suitable during May and June for all the reaches, but the percentage of unsuitability is higher in reach 1 and 2, especially in May when the PSC was unsuitable for 52% and 42%, respectively. As in the other flow patterns, the worst months for navigability are August and September, when the PSC is unsuitable for a minimum of 62% in reach 3 and 4 and a maximum of 98% in reach 2 of the time.

4.4.3 Effects of water withdrawals on rafting suitability

The applied model and the methodology we propose here can be used as a decision tool to estimate the effects of future withdrawals on selected ES, in any part of the watershed. For instance, we simulated an hypothetical additional withdrawal of 4 m^3s^{-1} and evaluated how the rafting conditions will change under different flow patterns. The

		May	June	July	August	September
Reach1	Unsuitable	0.31	0.13	0.15	0.46	0.39
	Suitable	0.50	0.39	0.65	0.52	0.60
	Optimal	0.19	0.48	0.20	0.02	0.01
Reach2	Unsuitable	0.26	0.16	0.21	0.59	0.73
	Suitable	0.45	0.47	0.59	0.38	0.26
	Optimal	0.30	0.38	0.20	0.04	0.01
Reach3	Unsuitable	0.10	0.05	0.05	0.23	0.28
	Suitable	0.37	0.24	0.58	0.65	0.70
	Optimal	0.53	0.71	0.37	0.12	0.02
Reach4	Unsuitable	0.09	0.05	0.06	0.24	0.31
	Suitable	0.19	0.20	0.25	0.44	0.55
	Optimal	0.72	0.75	0.69	0.31	0.14

Table 4.5: *Percentages of suitability, unsuitability and optimality in MaxHp flow pattern divide by reach and by month.*

		May	June	July	August	September
Reach1	Unsuitable	0.52	0.22	0.36	0.73	0.94
	Suitable	0.39	0.42	0.52	0.26	0.06
	Optimal	0.09	0.35	0.13	0.02	0.01
Reach2	Unsuitable	0.42	0.24	0.39	0.81	0.98
	Suitable	0.43	0.45	0.44	0.16	0.02
	Optimal	0.15	0.32	0.17	0.03	0.01
Reach3	Unsuitable	0.18	0.15	0.17	0.62	0.90
	Suitable	0.35	0.28	0.58	0.34	0.08
	Optimal	0.47	0.58	0.26	0.04	0.02
Reach4	Unsuitable	0.18	0.15	0.19	0.62	0.87
	Suitable	0.22	0.19	0.35	0.23	0.10
	Optimal	0.60	0.66	0.46	0.15	0.03

Table 4.6: *Percentages of suitability, unsuitability and optimality in Act flow pattern divide by reach and by month.*

selected reach is a 1.4 *km* sub-reach within the fourth reach, which is the most important reach for rafting activities. We applied a conditional rule to maintain discharge values above a minimum of 2.25 m^3s^{-1} which is the Minimum Vital Flow in Reach 4 (Servizio Gestione Risorse Idriche ed Energetiche, Settore Acque, 2014).
Firstly, we identify the sub reach affected by the new withdrawal and we defined a new sub basin. We calculated with GEOTRANSF new duration curves which take into account the new withdrawal and with the CASiMiR model we defined thresholds within the sub reach. The limits of suitability are summarized in Table 4.1, last row, and used to calculate percentages of suitability for the reach interested by the new withdrawal, in order to compare the variations among present and future discharge management policies. The Table 4.7 summarizes the variation of the rafting conditions, which are shown in Figure 4.12. In general, the new withdrawal causes a decrease of suitability in all the flow patterns in all months. In detail, the unsuitable PSC in *NoHp* pattern increases especially in July, when the percentage increased of 17%. On the other hand, a withdrawal of 4 m^3s^{-1} is sufficient to cause a decrease of suitability even in *MaxHp* pattern, especially in August and September, when conditions of unsuitability increased of 38% and 40%, respectively (Fig. 4.12 panel (c) and (d)). The new withdrawal induces a huge variation also in the *Act* pattern, especially in July and August, with an increase of unsuitability of 23% and 21%, respectively.

		May	June	July	August	September
Natural	Unsuitable	0.10	0.08	0.28	0.30	0.13
	Suitable	-0.01	-0.01	-0.14	-0.20	-0.10
	Optimal	-0.10	-0.07	-0.14	-0.10	-0.02
No Hp	Unsuitable	0.14	0.12	0.17	0.14	0.02
	Suitable	-0.01	-0.05	-0.11	-0.13	-0.02
	Optimal	-0.14	-0.08	-0.06	-0.01	0.00
Max Hp	Unsuitable	0.08	0.08	0.15	0.38	0.40
	Suitable	0.04	-0.02	0.11	-0.23	-0.29
	Optimal	-0.12	-0.06	-0.26	-0.15	-0.12
Actual	Unsuitable	0.14	0.10	0.23	0.21	0.10
	Suitable	-0.03	-0.04	-0.08	-0.14	-0.08
	Optimal	-0.11	-0.06	-0.16	-0.08	-0.02

Table 4.7: *Differences in suitability with the new withdrawal in each flow pattern in each month.*

4.5 Discussion

The habitat modelling approach is applied in literature to study different fish species and communities in several river types (e.g., Vezza *et al.*, 2015a; Bain and Jia, 2012; Valavanis *et al.*, 2004) and it has been proposed as a tool for river management (Mouton *et al.*, 2007), as well as the environmental flow assessment methods (Richter *et al.*, 1996; Poff

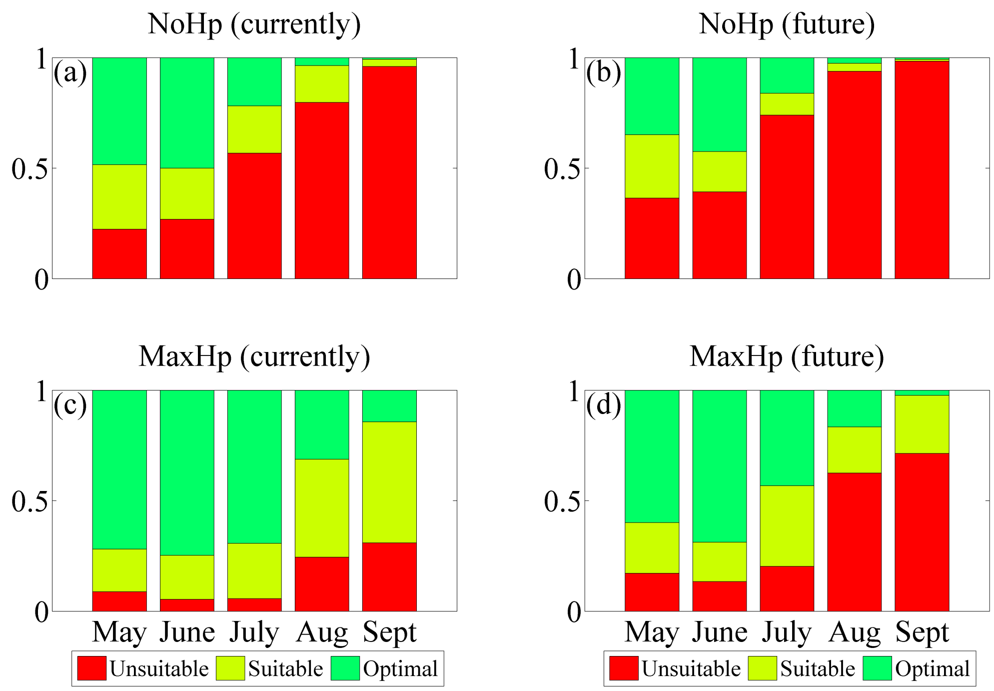


Figure 4.12: *Suitability for navigability (expressed in percentage) for fourth reach divided by flow pattern (a NoHp at current state, b NoHp in future management, c MaxHp at current state, d MaxHp in future management). Green bar color denotes optimality, pale green denotes suitability and red denotes unsuitability. Each pattern is divided in months.*

et al., 2010). Generally, recreational flow requirements are studied in relation with their effects on stream habitat (Baldigo *et al.*, 2010; Doyle and Fuller, 2011), but they have been rarely quantified (Shelby *et al.*, 1998). The modelling approach has been suggested by Brown *et al.* (1991) as a method to assess recreational flows, but to our knowledge its application has never been described in literature. Russi *et al.* (2013) underlines a lack of informations about freshwater ecosystem services, with few works studying navigability for recreational purposes (Brown *et al.*, 1991; Hammitt *et al.*, 2001; Thorp *et al.*, 2010). The general aim of our work is to describe the application of the concepts of the habitat modelling in order to quantify the variations of a recreational service according to flow variations. The use of hydrological and hydraulic models allow to assess present navigability conditions, and to simulate their variations in future management scenarios.

We choose to use a one-dimensional hydraulic model because we analysed a long reach and the river geometry needed for the application of a two-dimensional model was not available. The Noce River is mostly a single channel river and a one-dimensional model can be satisfactory for the purposes of our analysis. However, the use of a two-dimensional model could provide locally more detailed spatial informations and extend the application of this method to other ecosystem services and to river restoration projects. In this application, only water level was necessary to assess the suitability of the river, as water depth was identified by experts as the limiting factor for rafting. For other ecosystem services, additional variables such as water velocity, substrate or bio-physical variables might be taken into account. Since the approach we propose in this work is spatially and temporally distributed, it allows to evaluate locally also the effects on navigability of new additional withdrawals. As an example, we simulated a new withdrawal of 4 m^3s^{-1} which decreased the river suitability in each flow pattern in each month, with a clear negative effect also in high discharge in August and September, which are the most important months for tourism. It has to be mentioned that the described effects are not universal and can vary among different reaches: if any other reach with different morphology and hydraulic features would be analysed, the results could be significantly different. However, the method can be applied to several rivers. The large and small hydropower production are widespread in the Alpine area and three of the world best ten rivers for white water rafting (National Geographic Travel, 2014) are impounded by dams and the construction of hydropower schemes is planned on other three, therefore a method able to simulate future management scenarios could find a broad application.

The Noce River is a typical case study of the Alps for both hydropeaking and rafting activities, which are diffused in the region (Truffer *et al.*, 2003; Maddock *et al.*, 2008). The use of the hydrological model allowed to evaluate discharge and ecosystem service variations in time. GEOTRANSF, as many hydrological models which account for anthropic water uses, is able to produce output data at a daily scale. Therefore, to resemble sub-daily conditions of the river, we computed different flow patterns. The different conditions experience by this river are in particular no production (*NoHp*) and high production (*MaxHp*) stages. The statistical comparison among modelled flow patterns and real data underlined that the *MaxHp* pattern is the best approximation of the real condition. Hence, maximum daily discharges are apparently the conditions occurring more frequently in the analysed period.

The analysis of the different patterns demonstrated that only the presence of hydropower releases guarantees the navigability of the river in all the rafting season (May to September). The navigability resulted suitable in all the flow patterns in May and June, with the exception of *NoHp* pattern, which presents low suitability conditions even in July. The conditions of suitability occur rarely in all the flow patterns for August and September, except for *MaxHp* which guarantees suitable conditions for most of the time. We can conclude that the large hydropower production is fundamental to ensure the navigability of the Noce River for the entire rafting season. Similar situations has been described by Baldigo *et al.* (2010) and Doyle and Fuller (2011) in which the authors presented the effects on the biota of artificial releases planned to sustain recreational activities. Dif-

ferently, in our case study the water is not released occasionally with the specific aim of sustaining recreational activities but one or more times per day as a consequence of hydropower production, with secondary positive effects on rafting. On the other hand, hydropeaking has several known negative ecological impacts on river communities (e.g., Tuhtan *et al.*, 2012; Bruno *et al.*, 2010; Scruton *et al.*, 2005). The dual and conflicting nature of hydropeaking suggests the needs to simulate and to find trade-off alternatives among ecosystem services in regulated rivers.
This modelling approach is able to analyse the conditions for navigability in space and time and it can be extended to each ecosystem service which depends on and can be related to the flow regime through preference functions. Due to its flexibility and its capability to analyse future management alternatives, the method can be applied in decision making processes and integrated in decision support systems.

4.6 Conclusions

The model-based approach introduced here is **i)** able to evaluate spatially and temporally rafting conditions at current state and it can be used also to investigate future changes in local river uses and water management policy. An important conclusion is that **ii)** in this river only the release from the hydropower plant guarantees suitable conditions for rafting, also in comparison with a simulated natural flow pattern. Especially in August, which is the most important month for tourism, the release from hydropower plant has to be ensured, to maintain the supply of this recreational ecosystem service. Moreover, the river is heavily exploited by new and additional demands for water withdrawal **iii)** but their licence has to take into account that new withdrawals could locally decrease the suitability of the river, even in high discharge. The method is flexible and allows to extent the analysis in space and to other ES, in order to evaluate the effect of future withdrawals and water management policies on rafting or other flow-related ecosystem services, as it will be showed in the next chapter.

Chapter 5

An approach to quantify mutual interactions among ecosystem services in hydropeaking rivers

5.1 Introduction

The general aim of this chapter is to extend the modelling approach presented in chapter 4 to quantify the mutual interactions among flow-regime dependant ecosystem services. Its significance relates to management choices at the catchment level, which result in modifications of the flow regime, and, in turn, on the spatial and temporal availability of a set of selected provisional and cultural ecosystem services. The method is developed and applied with reference to the Noce River case study, which flow regime is crucially affected by hydropeaking. The method integrates hydrological, hydraulic and habitat models that can be applied at multiple spatial scales and different aggregation levels. The method is formulated in a generalized way so that it can adapted to other case studies and also to include other ecosystem services.
Furthermore, in this chapter, with reference to the Noce River case study, through the application of the proposed method, specifically we aim to assess:

i) the capability of the river to sustain different ecosystem services at present flow management practices;

ii) the effects on ecosystem services of several management scenarios by simulating different policies of releases by the upstream large hydropower plant;

iii) mutual interactions among selected cultural and provisioning ecosystem services in response to different future scenarios of water withdrawals for run-of-the-river small hydropower plants.

The chapter is organized as follows. In section 5.2 we briefly recall the characteristics of the study area, and we describe the selected ecosystem services. In section 5.3 we show the methods applied to calculate the flow requirements for each ecosystem service, the procedure we selected to evaluate the suitability of the river reach for each ecosystem service and the different flow regime scenarios for which the mutual ecosystem services interactions are examined. In section 5.4 we describe the results of our analysis with reference to the Noce River case study; in section 5.5 we discuss the findings of the analysis and in section 5.6 we provide conclusions.

5.2 Study area and ecosystem services

The river selected for this study is the upper course of the Noce River previously described in chapter 3. Several scenarios of flow regime have been considered, in relation to present management plants that are actually relevant to the study area. Namely, we simulated two additional withdrawals for Run-of-the-river (RoR) power plants showed in Figure 5.1. Some technical characteristics of the analysed withdrawals are reported in Table 5.1.

RoR power plants	Length (m)	Slope	Head (m)	Average reach width (m)	Reach length (m)
W1	2585	0.011	28.4	27.6	2711
W2	2282	0.02	46.3	26.9	2472

Table 5.1: *Physical characteristics of the reach affected by the simulated Run-of-the-river hydropower plants.*

The flow regime changes in relation with different variables and, in this study, spatially varies because of the presence of lateral tributaries (3 large tributaries, 4 reaches), presence of new withdrawals and on their magnitude (2 additional withdrawals and various possible discharge uptakes for each one). Temporally, flow regime has intra-year variations (seasonally, monthly scales) as well as sub-daily variations induced by hydropower production (3 most frequent conditions: no hydropeaking, maximum hydropeaking and average hydropeaking). The suitability of the river for the selected ecosystem services depends on the river morphology and also on the different flow regime scenarios, and consequently on the variables formerly described.
The ecosystem services selected for this study are reported in Table 5.2. We evaluated how they change according with the variations in flow regime. Support to biodiversity,

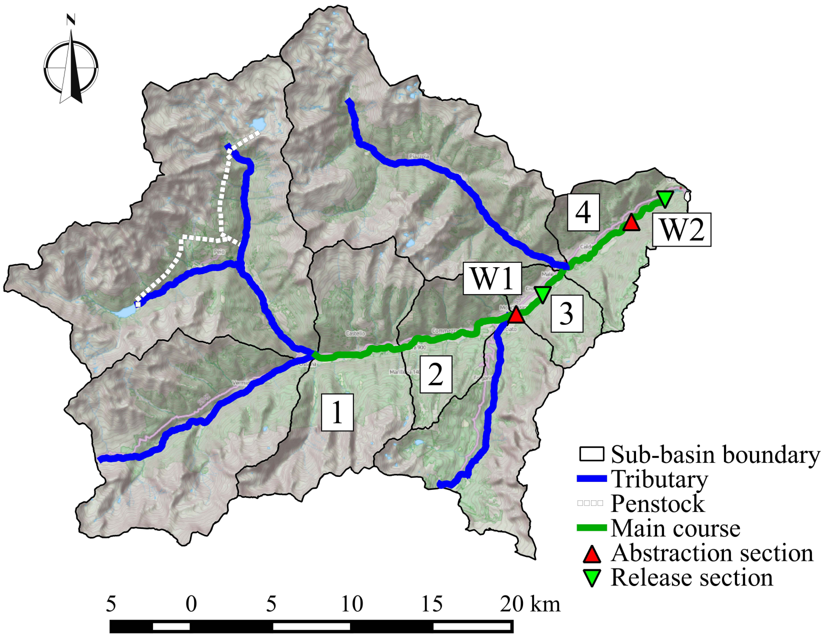


Figure 5.1: *Map of the Noce River basin. The river system is composed by tributaries and reaches in the main course. The map shows the location of two potential new water withdrawals (W1 and W2) that are among the examined controls on flow regime scenarios that may determine different interaction among the selected services. Red triangles denote the abstraction sections and the green triangles denote the release sections of the two withdrawals W1 and W2.*

though not strictly representing an ecosystem service, has been evaluated because its conservation and protection are fundamental to support ecosystem services (MEA, 2005) and because of environmental non-deterioration requirements posed by EU and national regulation (European Parliament, 2000).

	Service	Proxy
Biodiversity	Fishing	Adult marble trout habitat suitability
Recreational service	Rafting	Rafting suitability
Provisioning service	Hydroelectricity production	Small and mini hydropower plants

Table 5.2: *Summary of the selected ecosystem services and biodiversity.*

We choose the marble trout (*Salmo trutta marmoratus*) as a proxy for the biodiversity: in general, the preservation of high-level predators is considered pivotal for biodiversity conservation (Sergio *et al.*, 2006). The marble trout is an endemic native species of Southern Alps and it is an endangered species, which often produce hybrids with brown trout (Meraner *et al.*, 2007). Spawning takes place in November-December and eggs hatch in general in April (Vincenzi *et al.*, 2007). A good habitat quality from the hydraulic point of view can be an indicator of the capability of the river to sustain a population of marble trout. Actually, the trout population is managed by a local agency and young and adult specimen are artificially hatchery-reared and released in the stream.

Recreational fishing, both marine and freshwater, has become a popular recreational activity increasing the demand for games fish and suitable fishing areas (Holmlund and Hammer, 1999). Hatchery-reared fish at the moment are needful to maintain a population of marble trout which can be captured by anglers. The evaluation of habitat is fundamental in present and future management practices because fish richness and density can be greatly affected by the habitat quality (Eklöv *et al.*, 1999). In some Southern Alps rivers, fly fishing is one of the main attraction for tourist and it is one of the most profitable economic activity in the Soca River (Vincenzi *et al.*, 2008). According with Dudgeon *et al.* (2006), "the income from the sports fishing activities became an incentive to preserve the spawning habitat of marble trout (*Salmo trutta marmoratus*) in the Soca River, Slovenia, with an economic benefit of US dollars $2.9 \cdot 10^6$ per year", which is an important income for the tourism of the area accounting for the 44% of all tourist revenues.

Rafting and canoeing activities have become popular in the Noce River area in the last years since the 1993 Slalom Canoeing World Championship and they have become an important income for the local population during the summer season. In fact, this river is considered one of the best river in Europe and in the world for rafting activities (National Geographic Travel, 2014; Lonely planet, 2014).

Alpine river systems are exploited by large hydropower production and several small and mini plants are already operating in the catchment. Small hydropower plants are usually defined as those plants with an installed capacity lower than 10 MW, while plants with capacity lower than 1 MW or lower than 0.1 MW are considered mini and micro hydropower plants, respectively. In Italy, the energy from the small hydropower account for the 16% of the gross installed capacity, and plants with power $<$ 1 MW account only for 3% (European Small Hydropower Association Consortium, 2011). Installed power of small and mini hydropower plants will increase in next years by 23% and the produced energy will increase by 16%, according with the plan of the ministry for the economic development (Ministero dello sviluppo economico, 2010), which is the national strategy plan to meet the objectives of the Directive 2009/28/EC (European Parliament, 2009). In addition, the requests of new withdrawals have increased in the last years, especially from local agencies and governments and the relevance of small and mini hydropower plants have been increasing.

5.3 General description of the methodology

The proposed methodology can be summarized as follows:

- Step 1.1: Selection of flow regime-dependant ecosystem services and definition of the related preference functions. Main ecosystem services are identified according with different type of analysis, such as stakeholder analysis, and the preference functions are determined using various techniques (i.e., expert judgement, field sampling, literature review). Preference functions can be defined as a mathematical relations or other types of algorithms that express the linkage between flow properties (i.e., water depth, velocity, inundation dynamics, etc.) and quantitative indicators of the river suitability for the considered ecosystem services;

- Step 1.2: application of the hydraulic model. The use of this model allows to simulate the spatial distribution of the local values of the hydraulic parameters on which preference relations (Step 1.1) are based;

- Step 2: computation of suitability thresholds through habitat model, which allows to calculate the spatial distribution of the river suitability and to define minimum and maximum suitability thresholds for each ecosystem service at different spatial scales;

- Step 3.1: flow regime simulation of scenarios through a hydrological model. The model shall be able to deal with human effects in the catchments (reservoirs, abstractions, etc.) and to simulate the streamflow time series at the relevant time scale (i.e., daily in most cases; sub-daily in hydropeaking rivers). The outcome of the hydrological model application is the streamflow time series at selected sections along the examined river reach, which are selected on the basis of the relevant spatial scales for the ecosystem services evaluation;

- Step 3.2: application of the suitability thresholds to flow regime patterns. The thresholds are applied to the results of the hydrological model in order to compute duration/persistence of suitable/unsuitable/optimal conditions over a given period/time scale of interest and to calculate how such durations change under different flow regime scenarios corresponding to different priority choices for each ecosystem service.

- Step 4: spatial and temporal aggregation at the relevant scale. The river suitability for each ecosystem service can vary in time and space: suitability computed at local scales can be aggregated at larger, more relevant scales for management through different weights that can be assigned to take into account the different importance of a time period or river reach/subreach on each ecosystem service;

- Step 5: comparison of ecosystems services response to management alternatives of flow regime and river systems. By simulating spatial and temporal variations, different management alternatives of the flow regime and of the river system can be proposed, and the comparative response of mutual interactions among the analysed ecosystem services can be quantified.

The Figure 5.2 shows the work flow of the methodology.

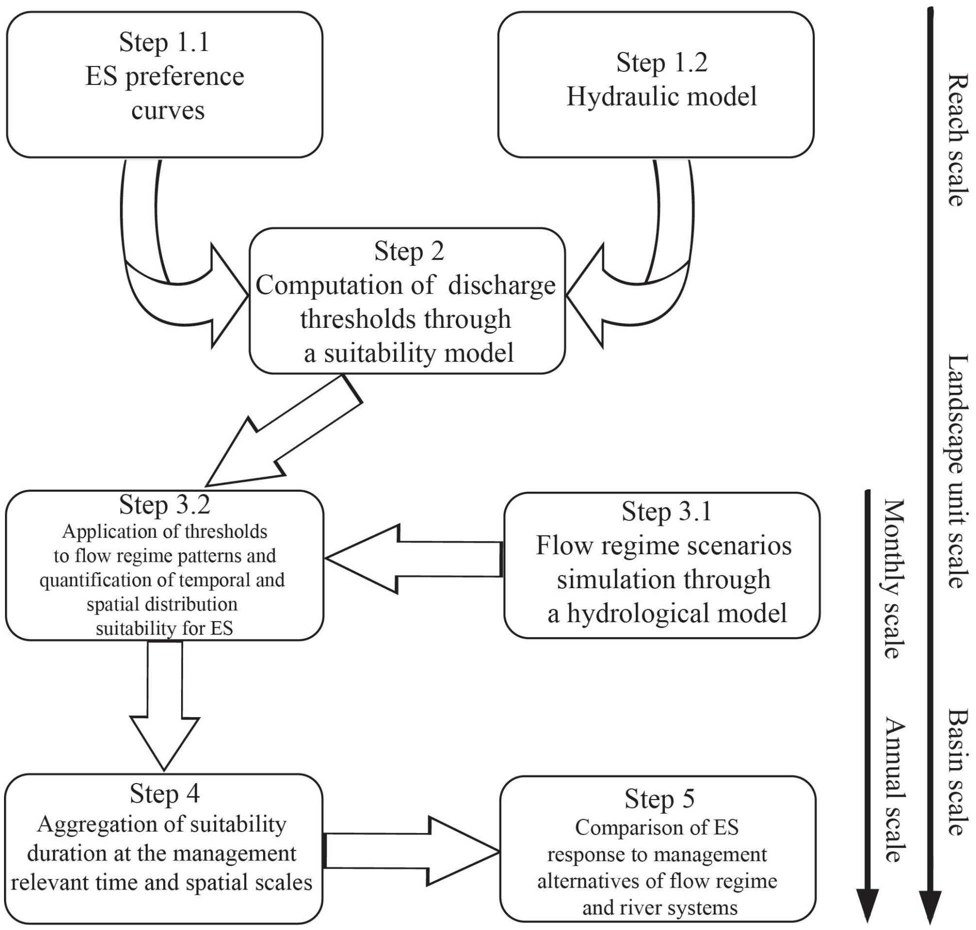


Figure 5.2: *Work flow of the methodology. On the right, the spatial and temporal scales to which the method can applied.*

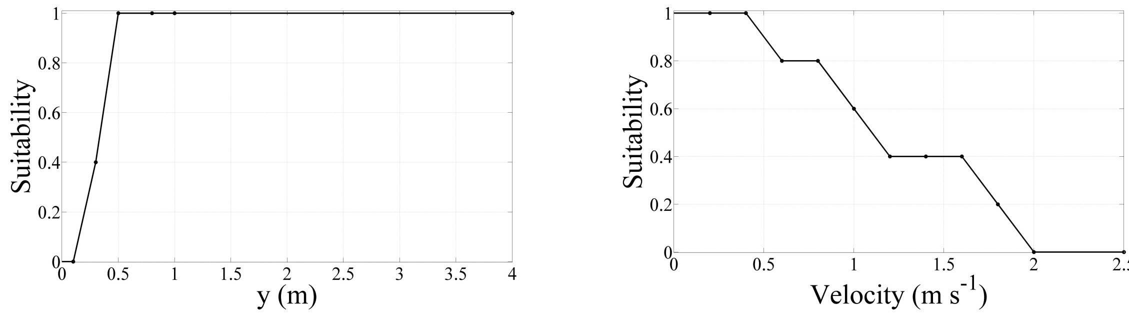
5.3.1 Application of the methodology to the Noce River case study

We identified the ecosystem services which are discharge-related and were considered most important for the local communities on the basis of an existing socio-economic survey (Panizza and Acerbi, 2012) and of a series of meetings with stakeholders (Step 1.1). The link between flow regime and the services listed in Table 5.2 was provided by preference curves in the case of rafting and fishing, and by the relation between with drawn discharge and produced power in the case of hydroelectricity production.
Next (Step 1.2), a relevant discharge range (0.5 to 100 m^3s^{-1}) for the Noce River case study has been simulated by the hydraulic model. The one-dimensional Hec-Ras hydraulic model was considered suitable to describe the river hydraulics for this application, because 1) the studied reach is mainly a single thread river with poor morphological variability (USACE, 2002a; USACE, 2002b) and 2) because the relevant spatial scale for ecosystem services assessment is two-three orders of magnitude larger compared to the channel width. The one-dimensional hydraulic model performed the computation of water depths and velocities at steady flow and we performed a mixed discharge calculation.
Hydraulic parameters were used as input in the habitat model, which evaluated spatially the potential suitability of each river section at different flow stages by integrating hydraulic variables and preference curves. In the case of rafting and fishing, we applied the one-dimensional CASiMiR habitat model (Schneider *et al.*, 2010), which requires preference functions to estimate suitability (univariate preference curves or fuzzy rules) and it is used usually for fish habitat assessment (e.g., Mouton *et al.*, 2007). The suitability model has allowed to compute thresholds values in terms of water discharge for each ecosystem service (Step 2).
Subsequently (Step 3.1), the GEOTRANSF hydrological model (Majone *et al.*, 2005) has been used to compute monthly flow duration curves for the four examined reaches and for the sub-reaches subject to the future withdrawal W1 and W2 (Fig. 5.1). This model is designed to analyse impacted catchment at daily scale, taking into account structures as reservoirs and artificial spatial and temporal variations of water uses. The temporal variations of the sub-daily flow regimes were simulated by computing three different flow patterns: the first pattern, denoted with *NoHp*, resembling the absence of hydropower releases; *MaxHp* simulating the maximum releases from hydropower plants; and *MeanHp* simulating mean daily flow values (see also chapter 4). By applying the thresholds to the monthly duration curves for every reach, intervals of suitability have been spatially and temporally defined. Due to large variations in sub-daily flow conditions, the suitability for flow-related ecosystem services can abruptly and greatly change during the day. GEOTRANSF simulates data at daily scale, therefore a technique based on assigning

different weights to each flow pattern was developed to approximate the actual sub-daily conditions of the river through one single daily value, on the basis of the analysis of the peak duration and intensity.
According with suitability, the importance of each ecosystem service varies in space and time as well. Therefore we assigned different weights to each month and calculate a single value for each ecosystem service in order to allow the comparison among the different ecosystem services (Step 4). Finally, by changing the ratio among the flow patterns and simulating additional withdrawals, we produced several management alternatives and evaluate the response of the selected ecosystem service and their mutual interactions (Step 5).

Biodiversity: fish habitat suitability

Suitability curves for fish were constructed starting from univariate preference curves for nearby rivers found in literature (Hydrodata and Studio, 2002), validated by in-situ sampling campaigns (Fig. 5.3). In this study, we consider suitability of the river only by assessing the hydraulic variables, namely water depth and velocities. Other abiotic and biotic variables as substrate, cover or shading are known to be relevant drivers on fish habitat (e.g., Vezza *et al.*, 2015b), but they were not accounted for in this analysis because of the long and intense field work required for the evaluation of these variables in a long river reach such as the one described here. Moreover, our purpose was not to characterize in detail fish habitat, but to calculate a reasonable proxy to be compared with other indications of flow-related ecosystem services. Two different campaigns (December and July) of fish collection using the electrofishing techniques were conducted on a large tributary, the Rabbies River, which was chosen because the fish population in this stream is nearly pristine and because the main course of the river is difficult or impossible to sample for most part of the year due to hydropower operations. The fish were sampled in two different zones of the tributary and classified according with Delling *et al.* (2000). During this campaigns, specimens were collected, measured, weighted and released in the river. Twenty-nine juveniles and 41 adults were collected in December and 77 juveniles and 20 adults in July. Juveniles were divided from adult specimens on the basis of the body length: below 25 centimetres specimens were considered juveniles. Depth and water velocity values were collected in different points of the areas and related with fish capture. The curves from literature were slightly adjusted on the basis of the collected data.



a) Marble trout water depth requirements b) Marble trout water velocity requirements

Figure 5.3: *a) Water depth a) and velocity b) preference curves for marble adult trout suitability resulting from literature and sampling campaigns.*

Recreational: rafting

The Noce River is considered one of the best river in Europe and in the world for rafting activities (National Geographic Travel, 2014; Lonely planet, 2014). For this ES, the preference curve was constructed by interviewing rafting guides, local experts and rafting centres owners, which provided minimum and maximum level of water depth required for a safe navigation. These values have been assessed at gauged station in Reach 3. The preferences for a given water depth were expressed in percentage and distributed between 0 and 1, with 0 indicating that the river is not suitable and 1 corresponding to the optimal suitability.

Run-of-the-river hydropower plants

The new withdrawals were included in the hydrological model by simulating hypothetical licences for a maximum discharge of Q_c, with a release in the river equal to at least the minimum vital flow Q_{MVF} showed in Table 3.2. Table 5.3 summarizes the values of minimum vital flow for the sub-reaches subjected to the new withdrawals and it is calculated using the method briefly presented in chapter 3.

	December-April (m^3s^{-1})	May-November (m^3s^{-1})
W1	1.55	2.35
W2	2.25	3.49

Table 5.3: *Minimum vital flow for the reaches subjected to the new withdrawals, divided by season.*

The flow withdrawal algorithm does not allow any withdrawal if the flow $Q(t)$ is minor of or equal to Q_{MVF}. If the flow is greater than minimum vital flow, the model simulates a withdrawal equal to the discharge exceeding the minimum vital flow up to the maximum licensed withdrawal. For example, if the minimum vital flow is set at 2.25 m^3s^{-1} and the withdrawal is 4 m^3s^{-1}, the flow which can be withdrawn is actually equal to 0 if the flow rate passing through is less than 2.25 m^3s^{-1}, will be equal to the difference between the flow rate and the minimum vital flow if the flow rate is less than 6.25 m^3s^{-1} and it will be of 4 m^3s^{-1} if the flow rate in the channel is greater than 6.25 m^3s^{-1}. This procedure, in general, has allowed to obtain for each withdrawal two time series: $Q_r(t)$ is the discharge released in the river and shall be used to assess rafting and habitat suitability in the withdrawn reach, and $Q_w(t)$ is the withdrawn discharge, which is used to assess the reach suitability for RoR hydropower production. The algorithm used to calculate $Q_r(t)$ and $Q_w(t)$ reads as follows:

$$Q_r(t) = Q(t) - Q_c,\ if\ Q(t) > (Q_{MVF} + Q_c); \tag{5.1}$$

$$Q_r(t) = min[Q(t), Q_{MVF}],\ if\ Q(t) < (Q_{MVF} + Q_c); \tag{5.2}$$

$$Q_w(t) = Q(t) - Q_r(t). \tag{5.3}$$

The power of the hydropower plants is defined by the equations:

$$P(t) = \eta\gamma\Delta H Q_p(t); \tag{5.4}$$

$$P_m = \eta\frac{1}{\Delta t}\int_{\Delta t}\gamma\Delta H Q_p(t)\mathrm{d}t\,, \tag{5.5}$$

where P is the power at time t, η is the efficiency of the turbine, γ is the water specific weight, ΔH is the hydraulic head and $Q_w(t)$ is the withdrawn discharge at time t. P_m is average the power that can be produced in a period Δt.

5.3.2 Suitability thresholds' definition

In this section, we describe the method we applied to fix and calculate thresholds of suitability for the ecosystem services. Local velocity and water depth values were calculated by the hydraulic model and used as input for the habitat modelling. To define thresholds, we followed different rules for each ecosystem service. A detailed description of the rules we used to set the flow requirements is introduced below.

Fish habitat suitability

Suitability thresholds for marble trout are defined on the basis of the weighted usable area (WUA), which is computed by the habitat model. The WUA weights each cell of the domain by its suitability values, calculated with the product of preference curves and hydraulic parameters. The effective habitat area is the sum of the weighted areas, as shown in equation 4.1. The maximum WUA for each reach can be seen as the maximum ecological potential or reference condition for the reach and each value of WUA at each discharge is related with the maximum value of WUA according with equation 5.6 (modified from Vezza *et al.* 2015a).

$$Suit(Q_i) = 1 - \frac{|WUA_{Max} - WUA(Q_i)|}{WUA_{Max}}, \qquad Suit(Q_i) \in [0,1]. \tag{5.6}$$

In equation 5.6 $Suit(Q_i)$ is the suitability value of the trait at a given discharge Q_i, $WUA(Q_i)$ is the weighted usable area at discharge Q_i and WUA_{Max} is the maximum weighted usable area or reference condition for the reach. By applying Equation 5.6, we obtained different values of $Suit(Q_i)$ for the marble trout habitat ranging from 0 to 1. We considered as thresholds of minimum habitat quality the flow values which provide a $Suit(Q_i)$ above 0.4. This value has been defined by a sensitivity analysis as follows. Discharge thresholds have been identified for each value of $Suit(Q_i)$ ranging from 0.1 to 0.7 and the suitability distributions at different flow values for each pattern and each reach have been calculated using these thresholds. The distributions of the suitability values computed with different discharge ranges were compared with a control distribution of suitability for an hypothetical species which does not have any flow requirement (i.e., the habitat is suitable at any discharge value). For the comparison we applied a one tailed paired t test to the distributions of each reach and each pattern and supposed that the mean of the distribution of the theoretical species is larger than the mean of the distributions of the marble trout ($\mu < \mu_0$). The minimum value of $Suit(Q_i)$ for which the distributions of suitability of trout resulted significantly different from the suitability distribution of the hypothetical species in any given reach has been chosen as value which identifies the minimum significant value of $Suit(Q_i)$ (0.4 in this case, Table 5.4). The aim is to find a procedure which objectively identifies the lowest discharge range for which the suitability distribution is significantly different from the suitability distribution calculated for the entire set of discharges. It is worth to mention that this values of habitat quality are not absolute values but are related with the maximum ecological potential of the reach.

	Lower threshold (m^3s^{-1})	Upper threshold (m^3s^{-1})	$WUA_{Max}(m^2)$	Wetted Area (m^2)
Reach1	3.0	27.0	19908.7	120055.7
Reach2	3.0	70.0	25696.	193049.0
Reach3	3.0	50.0	20353.3	157147.0
Reach4	3.0	40.0	26660.8	209785.0
W1	3.0	35.0	7174.2	52352.4
W2	2.0	30.0	8342.9	73768.7

Table 5.4: *Discharge thresholds for marble trout habitat suitability.*

Rafting suitability

The thresholds were defined in a conservative way: a river reach was considered suitable for rafting if any of its cross-sections resulted suitable. Thresholds for rafting were defined by interviews in Reach 3 at the river main gauged station. According with expert judgement, the conditions of unsuitability do not occur in this section but when the preferences are not met in this area, the river is not navigable in several parts of its course. The minimum discharge values that guarantees the longitudinal continuity in each section along the entire reach were chosen as thresholds. The navigation is impossible along several parts of the river when water level is below 0.36 meters and above 1.8 meters. A detailed description of the construction of the rafting preference curve is given in chapter 4, sections 4.3.3 and 4.3.4. The discharge values corresponding to the water depth are shown in Table 5.5.

	Lower threshold (m^3s^{-1})	Upper thresholds (m^3s^{-1})
Reach1	13.5	45.0
Reach2	16.5	50.0
Reach3	15.5	50.0
Reach4	17.25	65.0
W1	15.5	50.0
W2	17.2	65.0

Table 5.5: *Thresholds of potential suitability for rafting.*

Hydroelectricity production through Run-of-the-river power plants

Preferences for hydroelectricity production has been computed as follows First, a reference value for the maximum meaningful withdrawal on the reach has been established by computing the yearly mean flow for each river reach and selecting the minimum value as limiting factor. The minimum value is 8.35 m^3s^{-1} (Reach 1), which becomes 7.09 m^3s^{-1} when minimum vital flow is guaranteed, hence the maximum meaningful withdrawal has been chosen as 7 m^3s^{-1}. Table 5.1 summarizes several features of the sub-reaches selected for the simulation of the new withdrawals. The thresholds for small hydropower plants are easily defined: all the water quantity above the minimum vital flow can be theoretically withdrawn. Hence, the minimum vital flow of each reach is considered as the lower threshold and the maximum threshold is defined by minimum vital flow plus the value of the withdrawal. Table 5.7 shows the installed capacity of the two plants in different uptake alternatives, expressed in MW and with a simulated 80% efficiency of the turbines. Note that, according to the definition of small and mini hydropower plants described above, the same plant can become small or mini according with the withdrawn discharge.

Withdrawal	1 m^3s^{-1}	2 m^3s^{-1}	3 m^3s^{-1}	4 m^3s^{-1}	5 m^3s^{-1}	6 m^3s^{-1}	7 m^3s^{-1}
W1	1	1.99	2.94	3.88	4.75	5.58	6.34
W2	1	2	2.97	3.92	4.84	5.72	6.53

Table 5.6: *Mean yearly flow which can be withdrawn, given a maximum uptake capacity in the different subreaches.*

Withdrawal	1 m^3s^{-1}	2 m^3s^{-1}	3 m^3s^{-1}	4 m^3s^{-1}	5 m^3s^{-1}	6 m^3s^{-1}	7 m^3s^{-1}
W1	0.14	0.29	0.42	0.56	0.68	0.8	0.91
W2	0.36	0.73	1.08	1.42	1.76	2.08	2.37

Table 5.7: *Capacity of small hydropower plan expressed in Mw, with a 80% efficiency of the turbines.*

5.3.3 Application of thresholds to flow regime patterns

The thresholds showed in Tables 5.4, 5.6 and 5.5 were applied to the duration curves for each month and for each flow pattern, to calculate the suitability for each ecosystem service. Several Mann-Whitney U tests were run to detect significant differences among the suitability for each ecosystem service in different flow patterns. Whenever differences were detected, we choose to apply the one-tailed test in order to identify the direction of the differences: a significant increase or decrease of values between flow patterns pointed out the requirements of an ecosystem service for smaller or larger discharges.

5.3.4 Aggregation criteria

Aggregation of different flow patterns

The method has been developed as a tool which can be applied in decision-making process, therefore we need to reduce the number of variables, in order to simplify the comparison among the ecosystem services and the overall applicability. In order to meet this goal, the different flow patterns, which resembles different sub-daily condition, have been aggregated to a unique scenario. This suitability value has been calculated assigning a different weight to each flow pattern, on the basis of the monthly sub-daily duration of each pattern. Firstly, we needed to quantify the daily duration of each flow pattern. We calculated the duration of each state expressed in percentage, using the method described in Zolezzi *et al.* (2011) and analysing the real water depth collected in 2006 by a gauging station immediately downstream the large hydropower plant. The application of this method allowed to identify the number, the starting and ending time, the duration and the intensity of the hydropeaking events: the sum of the differences between ending and starting time gives the hours per month in which power plant is active, and the maximum intensity gives a measure of the hours of maximum production. Two flow patterns, namely *MaxHp* and *NoHp*, resemble the conditions of a river subjected to hydropeaking, which can be during the day in one of the two case, zero production or maximum production. An intermediate stage has been considered as a third condition, which we imposed as the mean daily flow, simulated in a third pattern called *MeanHp*. In this case, the intermediate stage was defined as a phase when the hydropower plants are working, but not at their full capacity. The following equations describes the procedure:

$$
\begin{aligned}
\Delta_{Hp} &= \sum (T_e - T_s)\,; && (5.7)\\
\Delta_{NoHp} &= H_{Month} - \Delta_{Hp}\,; && (5.8)\\
\Delta_{MaxHp} &= H_{Hp}^{MaxIntensity}\,; && (5.9)\\
\Delta_{MeanHp} &= H_{Month} - (\Delta_{NoHp} + \Delta_{MaxHp})\,, && (5.10)\\
& && (5.11)
\end{aligned}
$$

where Δ_{Hp} in Eq 5.7 is the number of hours of hydropeaking production, T_e and T_s are ending and starting time of the events, respectively, Δ_{NoHp} and H_{Month} in Eq. 5.8 are the number of no production and the total number of hours per month respectively, Δ_{MaxHp} is the total hours of production at maximum capacity ($H_{Hp}^{MaxIntensity}$), Δ_{MeanHp} in Eq. 5.10 is the hours of production but not at full capacity. With these equations we calculated monthly the coefficient of duration of each flow pattern, expressed in percentage. The sum of these coefficients is equal to 1. The results of this computation are given in Table 5.8: for example, in August the *NoHp* accounts for the 68% of the time, the *MeanHp* for the 22% and the *MaxHp* for 10% of the time. The monthly values of suitability for each service were calculated by the application of the following equation:

$$S_{i,j} = a_i S_i^{NoHp} + b_i S_i^{MaxHp} + c_i S_i^{MeanHp}\,, \qquad (5.12)$$

where S_j is the suitability for the j^{-th} service for the i^{-th}-month ($i \in [1, 12]$); a, b

and c are the monthly coefficient of the suitability calculated by equations 5.11 in the different flow patterns *NoHp*, *MaxHp* and the *MeanHp*, respectively. Yearly, the Noce River is in *NoHp* for the 43% of the time, in *MaxHp* for the 35% of the time and in the *MeanHp* for the 22% of the time. The final result is a flow pattern which resembles the real conditions of the river.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
NoHp	0.47	0.41	0.53	0.39	0.43	0.34	0.2	0.68	0.32	0.3	0.39	0.64
Act	0.16	0.17	0.12	0.26	0.23	0.23	0.35	0.22	0.43	0.4	0.11	0.06
MaxHp	0.37	0.42	0.35	0.35	0.34	0.43	0.45	0.1	0.25	0.3	0.5	0.3

Table 5.8: *Coefficient of duration of each pattern for each month, expressed in percentage.*

Aggregation from monthly to yearly time scale

Weights were assigned on a monthly basis. Thus, we were able to take into account not only the hydropeaking induced sub-daily variations of the flow regime, but also to evaluate the consequences of the monthly variations. Following the approach proposed by Korsgaard *et al.* (2008) and applied by Fanaian *et al.* (2015), it is possible to summarize data in a single value by assigning different weights to each month for each ecosystem service, as shown in the equation 5.13.

$$ES_j = \sum_{i=1}^{n} w_i S_{i,j} , \tag{5.13}$$

where ES_j is the suitability for the j^{-th} service; w_i is weight of the suitability for each month ($i \in [1, 12]$) and is subject to the rule $\sum_{i=1}^{12} w_i = 1$; S is the suitability for each month i.

The weights for each ecosystem service were assigned on different basis. For adult marble trout we set the same weight to each month, because the habitat for the specie should be in good conditions for the entire year to support the life cycle. Only weights of November and December are slightly higher, because they correspond to this specie spawning season (Vincenzi *et al.*, 2007)(First column, Table 5.9).

For rafting, we choose the presence of tourists during different months using the mean of the presence in the 2009-2013 period (Table 5.10). The rafting season begins in May and ends in September, thus we assigned a weight of 0 to the October-April period. The weights for the month from May to September were calculated by normalizing each month's presence by the total presence of the period and are expressed in percentage. The second column of Table 5.9 shows the weights assigned to each month for rafting.

The weights for small hydropower suitability were calculated using the mean monthly price of the electricity for the 2008-2013 period (expressed in €MWh^{-1}, Table 5.10). Each monthly value was standardized by the total price and expressed in percentage (Third column, Table 5.9).
The use of these weights allows to built different management scenarios by maximizing alternatively the weight assigned to each ecosystem service.

	Adult trout	Rafting	Small hydro plant
January	0.08	0	0.1
February	0.08	0	0.08
March	0.08	0	0.07
April	0.08	0	0.07
May	0.08	0.02	0.07
June	0.08	0.08	0.07
July	0.08	0.34	0.07
August	0.08	0.45	0.07
September	0.08	0.11	0.09
October	0.08	0	0.1
November	0.1	0	0.09
December	0.1	0	0.12

Table 5.9: *Monthly weights assigned to each ecosystem service. The sum of the monthly weight is equal to 1.*

	Number of tourists	Price (€MWh^{-1})
January	11893	59.7
February	12137	49.7
March	10885	44
April	2531	47.1
May	538	43.7
June	2007	44.8
July	8608	42.2
August	11227	39.5
September	2582	55.5
October	409	57.9
November	212	52.2
December	7124	69.7

Table 5.10: *Data used to define weights for rafting and electricity. The number of tourists is the mean of monthly presence in 2009-2013 and the price of electricity is the monthly mean price of 2008-2013.*

5.3.5 Flow management scenarios

The application of the method allows to assess the current state of the ecosystem services provided by the river. Moreover, we evaluated the variations of the ecosystem services according with different management of large hydropower releases. For this task, we used the current state as reference and we simulated four scenarios. Large hydropower management scenarios were built in order to maximize the provision of each ecosystem

service by simulating a different policy of releases from the large hydropower plants, e.g. by changing the coefficient of duration of each flow pattern, calculated with equations 5.11.
Firstly, we identified the critical months for each ecosystem service and secondly we balanced the flow patterns in order to augment the suitability for the ecosystem services. Regarding the small hydropower production, we considered only the suitability for the maximum withdrawal (7 $m^3 s^{-1}$). The first three scenarios maximize in turn the different ecosystem services (adult trout, rafting and small hydropower production) and one additional scenario (Monthly balanced) was produced as control conditions scenario. The following list summarizes the scenarios and how they are built:

1. Present state. Present large hydropower production conditions;
2. Marble trout. A clear monthly preference was not evident for this ecosystem service, therefore we balanced the production among the difference months: only the flow regime in winter was slightly increased to mitigate the effects of the low flows and it was decrease in high flow conditions in spring and summer;
3. Rafting. For this ecosystem service, the most important months are during summer, which corresponds to the periods of low suitability, due to the predominance of the *NoHp* pattern. Therefore, we simulated an increasing in production (and flow regime) from May to September. In order to balance the duration of each flow pattern within the year (e.g, to balance the released water volume), we reduced the *MaxHp* pattern in spring, fall and winter;
4. Small hydropower plants. We increased the flow by increasing the production patterns in winter, when the price of electricity is higher (Table 5.10).
5. Control scenario: we assigned the same duration of the flow pattern to each month without any preference for the ecosystem service.

Significant differences among each scenario were assessed using a Kruskal-Wallis ANOVA (Group variable: scenario).

We added in the domain also two new withdrawal for mini and small hydropower plants (Fig. 5.1), with the aim to assess locally the impacts of the new withdrawals on each ecosystem service and to evaluate their sustainability. We evaluated also different alternatives for the two hydropower plants, with the aim of studying the effects of the quantity of water withdrawn for small hydropower production on each ecosystem service. Last, we produced four management scenarios which in turn guarantees suitable flow regime conditions for the different ecosystem services, in order to evaluate several management scenarios of the small hydropower plants. The scenarios are:

1. present conditions. At the present conditions, only the minimum vital flow defined by local and national laws has to be guaranteed;

2. Marble trout: the additional withdrawal has to guarantee suitable conditions for marble trout on the basis of thresholds described in Table 5.4;

3. Rafting: conditions for navigability are always ensured (Table 5.5);

4. Marble trout and rafting: both services are maintained by the new withdrawal.

According with these scenarios, the new withdrawals are regulated to optimize rafting and biodiversity. Since the small and mini hydropower production will increase in the next years, the assessment of their effects on the river system and its services will be important for the decision-making process and the management of water resources.

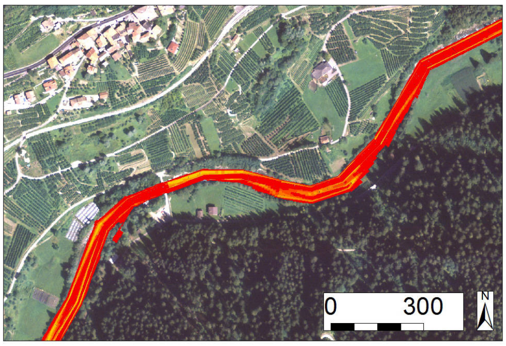
5.4 Results

The results of the habitat modelling allow to evaluate the effects of morphology and flow variations on each ecosystem service, through the use of typical habitat maps (Fig. 5.4). On the basis of the habitat modelling results and of these maps, limiting area and values were identified and related with the flow regime to set the thresholds. The spatial suitability results were aggregated in values for each ecosystem service and for each reach.

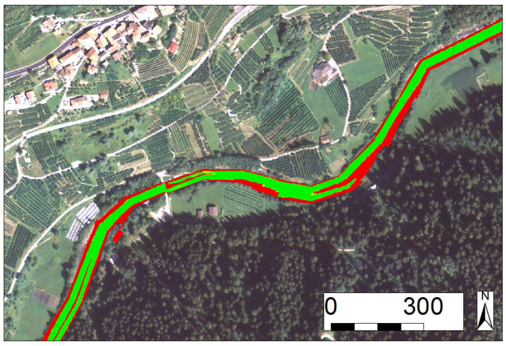
The application of the thresholds to the duration curves allowed to calculate range of suitability for each ecosystem service in space and time. The Table 5.11 is an example of the obtained results. For each ecosystem service and each reach, we calculated a suitability value for each of the variables described above (12 months, 3 flow patterns). The spatial variability of the services was grouped by reaches described in chapter 3 and in Figure 5.1.

5.4.1 Current state

The results of the statistical comparison among ecosystem services in each flow pattern are summarized in Table 5.12: rafting showed a significant increase of suitability in patterns with higher flows (i.e., medians are significantly higher in *MaxHp* and *MeanHp* patterns) and also small hydropower production showed a preference for higher flows (i.e.,



a) Trout, 40 $m^3 s^{-1}$



b) Rafting, 40 $m^3 s^{-1}$

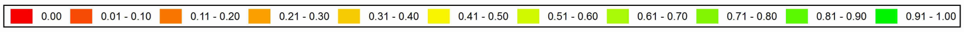


Figure 5.4: *Example of spatial suitability of a trait for biodiversity and rafting. The distances are expressed in meters.*

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
MaxHp	0.16	0.1	0.16	0.28	0.91	0.95	0.94	0.76	0.69	0.52	0.59	0.28
NoHp	0.01	0	0.01	0.05	0.78	0.73	0.43	0.2	0.04	0.12	0.17	0.1
Act	0.29	0.13	0.23	0.48	0.93	0.97	0.99	0.91	0.8	0.66	0.56	0.27

Table 5.11: *Example of the results of the method. Suitability of an ecosystem service (rafting) for the reach 4, in the three flow patterns and for each month. For example, for rafting and for the MaxHp flow pattern, in August reach 4 is suitable for the 76% of the time.*

higher suitability values for *MaxHp* pattern in comparison with *NoHp* pattern). For the marble trout no significant differences were detected. The suitability scores divided in three flow pattern were summarized in a unique daily value according with the equations 5.12, to take into account the temporal variability of flow regime and, consequently, of suitability.

	MaxHp vs *NoHp*	*MaxHp* vs *MeanHp*	*NoHp* vs *MeanHp*
Rafting	0.001***	0.99	0.003**
Marble Trout	0.75	0.18	0.91
Small Hydropower	0.04*	0.89	0.21

Table 5.12: *Values of p for the comparison among suitability for different ecosystem service in each flow pattern. *, **, *** mean significant, very significant and highly significant differences, respectively.*

At the current state, the river resulted suitable for marble trout and small hydropower production, in all its reaches as showed in Figure 5.5. The suitability for rating was much lower in all the reaches compared with other ecosystem services, with the highest value in the fourth reach. In fact, the river was suitable for rafting activities only for the 33% of the time in Reach 2 and for the 52% of time in reach 4. The bad conditions for rafting were mainly due to the low flow in August (Table 5.8) which is in addition the most

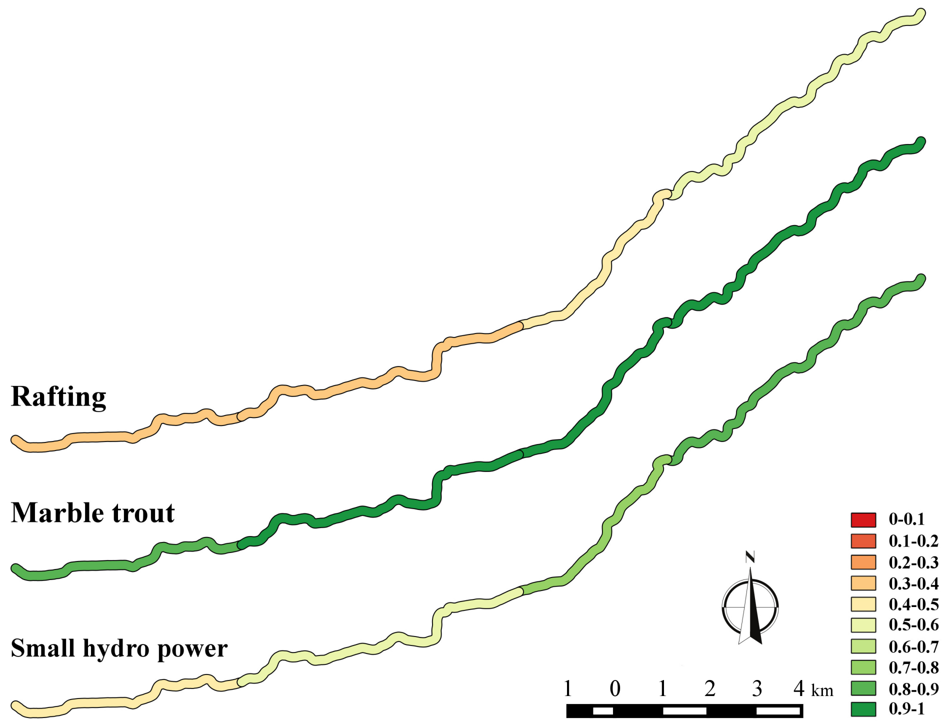


Figure 5.5: *Current state of the ecosystem service on yearly basis. Colors denotes ranges from red (low suitability) to yellow (moderate suitability) to green (good suitability).*

important month for touristic activities because it is the period with the most visitors during summer (Table 5.10). For the marble trout, the daily and seasonal variations of flow regime did not have a clear effect on the habitat of the fish, which was almost close to the maximum ecological potential in all reaches (lowest value 83% in reach 1). However, it is worth to mention that we never took into account the variations of the wetted area and we will discuss this point below. The river resulted capable to sustain small hydropower production in all the studied reaches in each month with uptake equal or smaller than 3 m^3s^{-1}. Above this threshold, the river was not able to support the withdrawals for the entire year. The maximum production of 7 m^3s^{-1} showed in Figure 5.5) was not always sustainable, with low suitability values in the first two reaches (48 and 56% respectively). The higher suitability in the third and fourth reaches supported and reinforced our choice to simulate new withdrawals within these areas (70 and 85%).

5.4.2 Large hydropower management scenarios

Figure 5.6 shows the results of the scenario analysis divided by reach. The amelioration of the habitat quality for trout in the scenario which optimizes the trout requirements was limited to a maximum of 3% in the reach 1. On the contrary, rafting suitability decreased of 8% in the same reach, while the effects on small hydropower were negligible. The scenario which maximized rafting increased the suitability of each reach, for a maximum increase of 30% of suitable time in the reaches 3 and 4 in comparison with the current state. The negative effects on the other ecosystem services were less intense, with a maximum decrease of 1% of suitability for trout and of 7% for small hydropower production, respectively. In the fourth scenario of optimization of small hydropower production, the suitability for hydropower slightly increased, with a maximum of 7% in reach 2. The effects on habitat trout were negligible, while the rafting suitability decreased of a maximum of 6%. The effects on trout habitat and small hydropower of the last scenario were negligible, with variations of ± 1% for both these services, while an increase in rafting suitability was detected in the last two reaches, with a maximum of 3%. The application of the Kruskal-Wallis ANOVA pointed out as the only scenario which showed significant differences from the current and the control scenarios was the Rafting maximized scenario, with a $p = 0.045$. In the other cases, the analysis does not detect significant differences ($p > 0.05$).

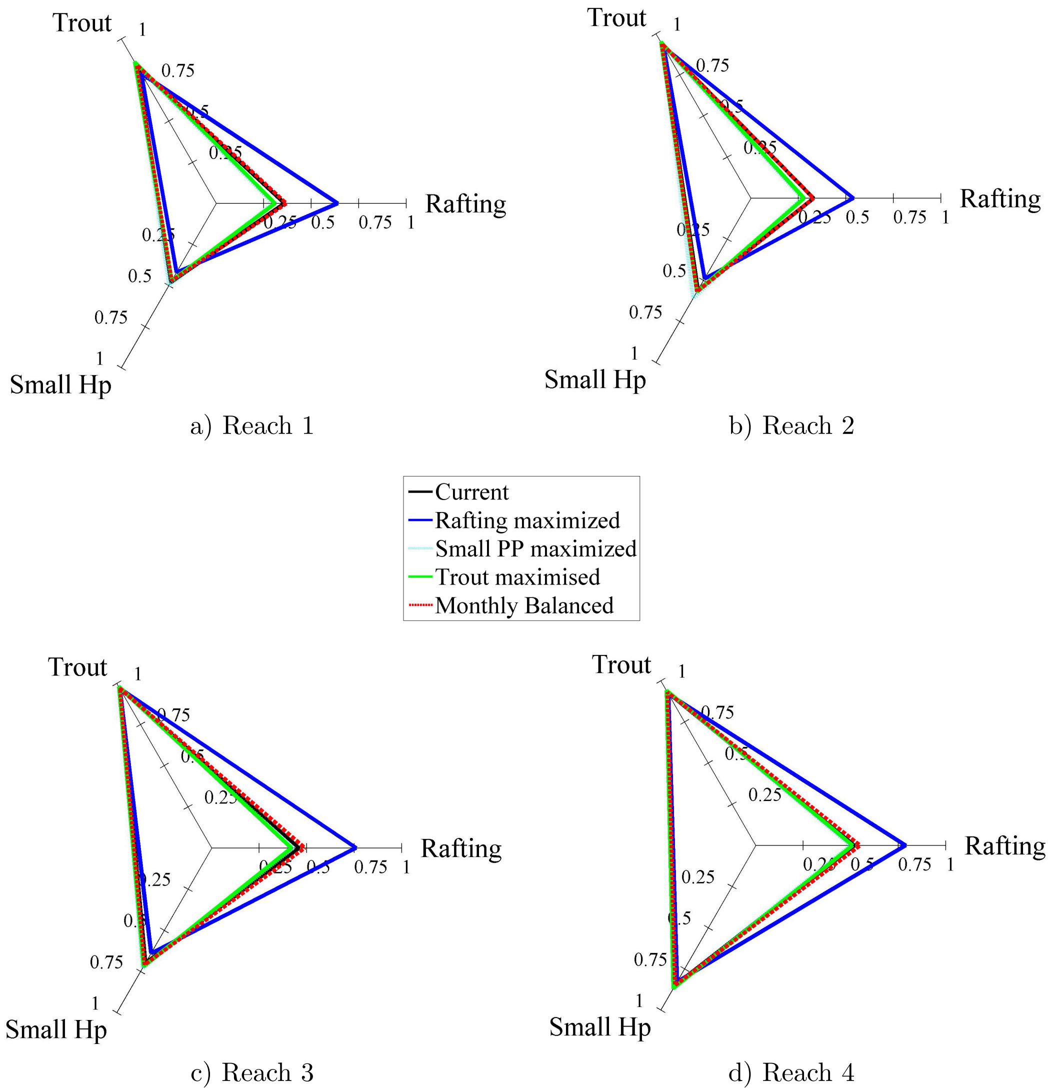


Figure 5.6: *Variations of the two ecosystem services and biodiversity in the four reaches in five different large hydropower management scenarios. Each axis represents an ecosystem service: trout habitat, rafting and small hydropower production. The values varying from 0 (no suitability) to 1 (optimal suitability). The lines denote the different scenarios: red for the current management scenario, blue for the rafting optimized scenario, light blue for small hydropower maximized scenario, green for the trout optimized scenario and red for the control scenario balanced among months.*

5.4.3 Small hydropower alternatives

Besides the effects of large hydropower production, we assessed the impact of additional withdrawals licensed for small hydropower production purposes. We simulated two new Run of the River (RoR) small hydropower plants within reach 3 and reach 4, which were identified as the most suitable (Fig. 5.5). RoR plants produce continuously electricity and does not induce hydropeaking. We simulated several alternatives ranging from 1 to 7 m^3s^{-1}. The results are summarized in Figure 5.7, 5.8.
Figure 5.7 shows the effects of the new small plants on rafting. In this case, a withdrawal of 1 m^3s^{-1} is sufficient to decrease the suitability in the W2 reach. An increasing uptake greatly reduces the navigability, from a current 42% of suitable time to a 18% with 7 m^3s^{-1} and from 60% to a 25%, in W1 and W2 respectively. In general, additional withdrawals would decrease the suitability for rafting in both areas.
On the contrary, the effects on trout habitat are controversial: the habitat would greatly decrease in W1, from 95% to 54% with increasing uptakes, while in W2 we noticed a a slight amelioration of the conditions (from 88% to 93%). The opposite effect of the additional withdrawals in the two areas for trout habitat is due to the different morphology of the river: in W2, the river is more channelized and narrower (the mean width is the same as W1 but with higher flows), thus a decrease of flow velocity and water depth which would have a negative impact on habitat trout in W1, will have a positive effect in W2 instead.
The small hydropower production will obviously increase with increasing uptakes. However, only alternatives with of 1 and 2 m^3s^{-1} would be always sustainable in W1 and in W2 a 3 m^3s^{-1} was sustainable as well. The sustainability of the maximum withdrawal of 7 m^3s^{-1} was 75% in W1 and 89% in W2.

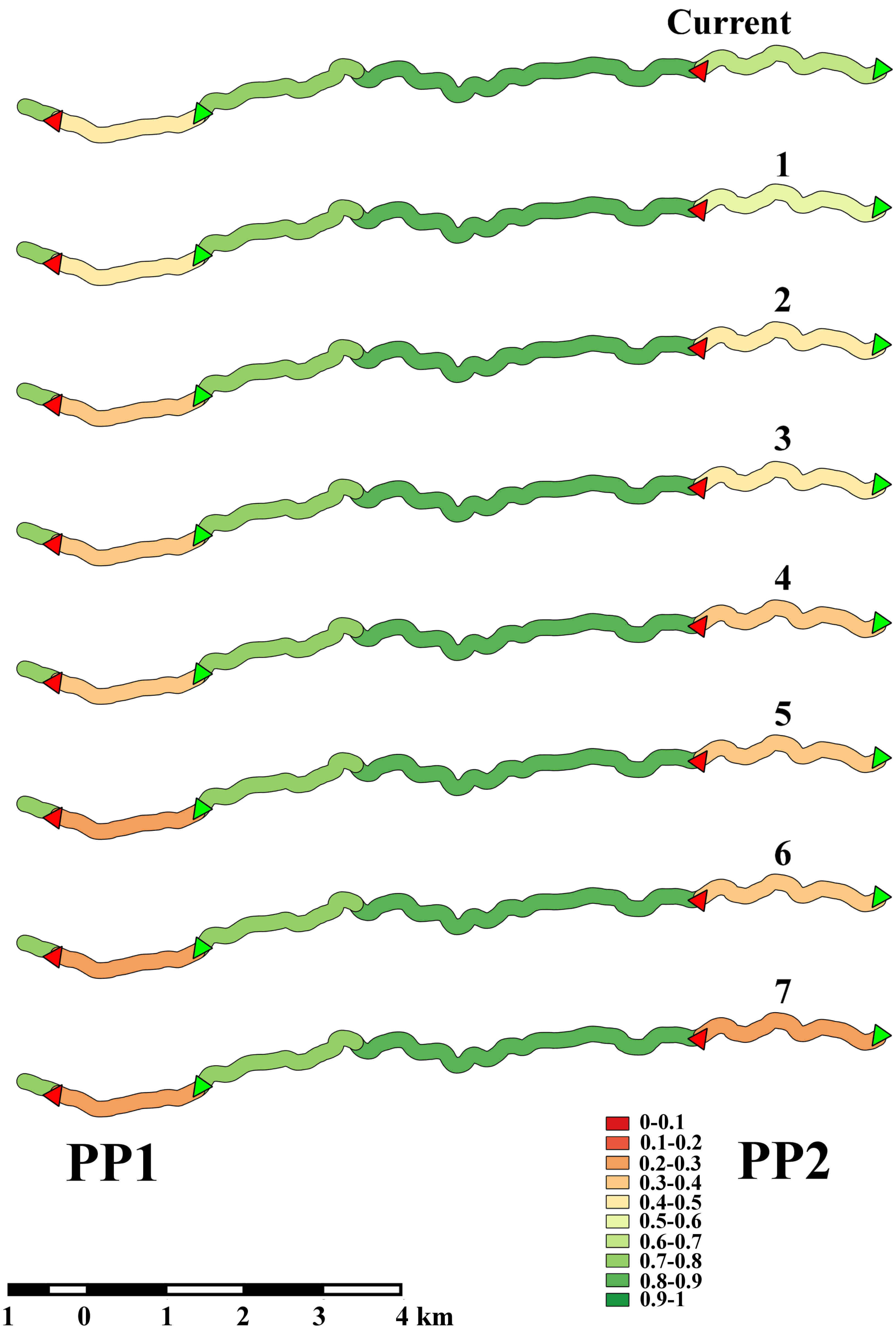


Figure 5.7: *Effects of additional withdrawal on rafting suitability. The suitability was divided in 10 classes of equal distance ranging from 0 to 1. Red triangles denote the uptakes and green triangles denote the releases.*

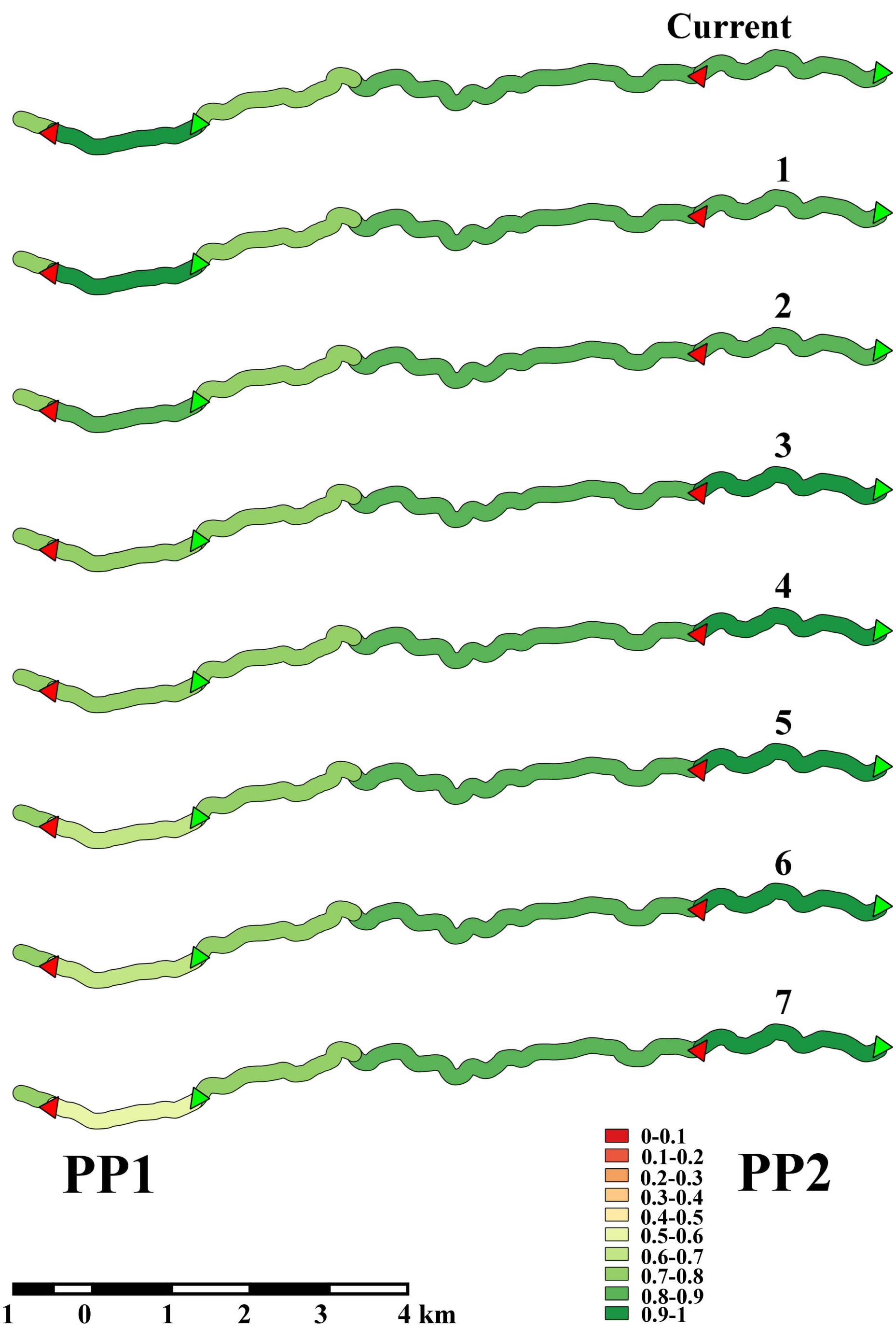


Figure 5.8: *Effects of additional withdrawal on trout habitat. The suitability was divided in 10 classes of equal distance ranging from 0 to 1. Red triangles denote the uptakes and green triangles denote the releases.*

Figure 5.9 shows the effects of the different management scenarios, which maintain in turn the flow needs for the different ES. The preservation of the requirements for the adult trout had a clear effect in W1: the suitability for small hydropower plants decreased progressively from 94% to 54% from 1 to 7 m^3s^{-1}. The maximum loss in comparison with the current management state was in correspondence with the withdrawal of 5 m^3s^{-1}, with a loss of 20% of the suitability. The effects were less conspicuous in W2, with a loss of 8 and 10% compared to the current state, only for larger withdrawals (6 and 7 m^3s^{-1}).
The effects of the preservation of flow regime requirements for navigability were more severe: in W1 the loss increased from 18% to 33% and similar values resulted also in W2 (15% to 33% of loss). The preservation of the requirements for both biodiversity proxy and navigability decreased the suitability a minimum of 24% and 15% and a maximum of 38% and 36%, in W1 and W2 respectively.

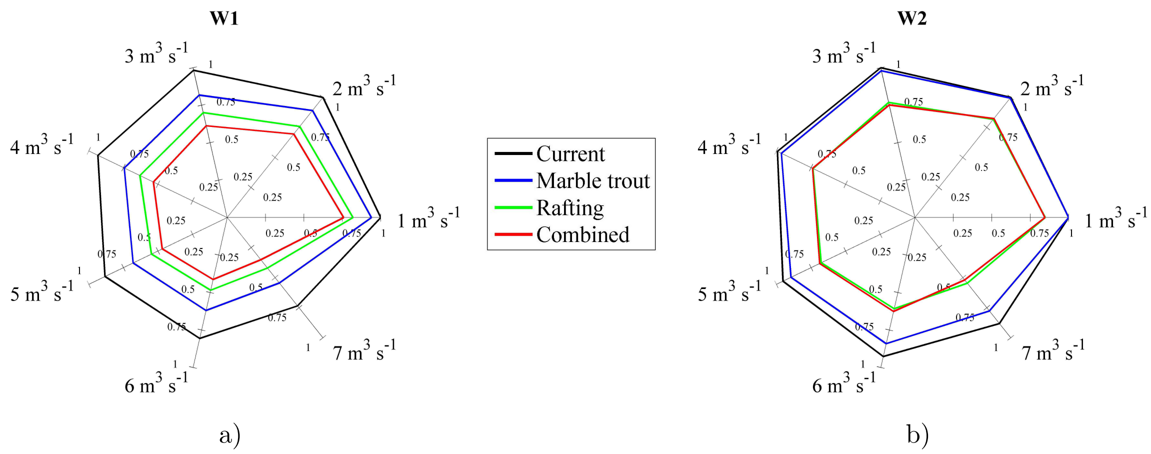


Figure 5.9: *Effects of the optimization of the different management alternatives on the hydropower production, varying between 0 and 1. The lines denote the different alternatives: the black line is the current management of the flow, the blue line is the alternative which maximizes the trout habitat, green line maximizes the rafting suitability and red line maximizes both trout and rafting.*

5.5 Discussion

The methodology introduced in chapter 4 aims to quantify the effects of flow variations not only on rafting but in general on ecosystem services and on a biodiversity in an Alpine River affected by hydropower production. Our case study did not included other services such as water provisioning or agriculture and considered only the services which are most relevant for local communities, from economic and environmental perspective.
At the current state, the river is capable to sustain the different ecosystem services. However, the low flow conditions during summer months are critical for rafting, which is in fact the service with the lowest values of suitability, especially in the first two reaches.

The small hydropower production along the main course is sustainable only in third and fourth reaches, as well.The habitat trout used as proxy for the biodiversity deserves an analysis. In fact, a detailed evaluation of the habitat for the trout might requires the application of a two dimensional model (Person *et al.*, 2014). Whereas for rafting the water depth is the only limiting factor and for hydropower plants the water available for withdrawal is the only relevant variable, the habitat quality of the trout can vary locally and depends largely on the river morphology. Moreover, we are aware that some important variables such as substrate, cover or shading were not evaluated (Bain and Jia, 2012): our results about quality of trout habitat are considering only the hydraulic parameters. We did not apply a two dimensional model nor complex biological models (e.g., Vezza *et al.*, 2014; Bain and Jia, 2012; Ahmadi-Nedushan *et al.*, 2008) because the general aim was not to evaluate in detail the fish habitat, but to quantify the effects of hydrological variations by comparing the impacts on different ecosystem services. For this purpose, we introduced as index to evaluate the variations of fish habitat a metric which does not take into account the variations of the wetted area such as for example the HHS (see Eq. 4.2, chapter 4.3.2). The HHS is expressed as the ratio between the WUA and the wetted area, it is a dimensionless parameter and it is calculated by the habitat model. In our case study, HHS showed always values below 0.22, meaning that only the 20% of the wetted area is usable. Thus, this river does not appear to be particularly suitable for the life-cycle of marble trout. We decided to use the ratio between WUA at different flows and the WUA_{Max} considered as reference condition in order to identify which flows provide better conditions to sustain biodiversity within the same river reach: in our study, the parameter in equation 5.6 is more sensitive to the variations of discharge than HHS. However, it is worth to mention as this method is flexible and if the application of a two-dimensional model or the integration with an economic model will be required, they will be easily introduced into the procedure.
One of the highlights of this approach is that it works at a low spatial scale, if compared to other procedures to evaluate flow variations (Fanaian *et al.*, 2015; Large and Gilvear, 2014). The spatial and temporal scale are subsequently reduced to allow comparative assessment of differing reaches, to favour comparison between ecosystem services and be useful as support tools for decision makers at a basin scale. The results can be easily downscaled to analyse in space and time some interesting cases at a smaller scale. In our study the suitability is calculated at the reach scale, which is in the order of magnitude of meters, and at a daily temporal scale, and only latter aggregated in a summarizing suitability value at annual, sub-basin or basin scale. The partial values are easily retrieved and can be used in case of detailed analysis, i.e. evaluate the local impact of additional

withdrawals or river restoration projects.

5.5.1 Effects of large hydropower

The main factor which influences the river flow is the releases from the large hydropower plant, which are sometimes in conflict with the requirements of some of the ecosystem services. We demonstrated as different policies of releases from the large hydropower could have a direct effect, especially on rafting. In fact, this services will greatly benefit from an increase in summer flows, simulated by the rafting maximized scenario, with a negligible effect on the other ecosystem services (Fig. 5.6). According to the ANOVA analysis, the scenario which optimizes rafting is the only significantly different from the current state and from the control scenario. This result is not surprising: the river flow regime is already managed in a way to optimize the income from this activity, both for large or small hydropower plants. The differences for trout habitat are negligible, since the ecological potential of the river is already expressed at almost full capability. However, the weighted summation limits the time horizon to only one year and underestimates the impacts on trout habitat because stresses and damages in the case of services such as fisheries and biodiversity can be carried for several years (Fanaian *et al.*, 2015). It is worth to mention that the major impact induced by the hydropeaking on fish communities is mainly due to the sudden variation of the discharge and not to the intensity of the variations (Irvine *et al.*, 2014), and combined with the absence of some ecological variables in the trout habitat model could lead to an underestimation of the effects of flow regime and hydropower on biodiversity. Our analysis underlines as to optimize the navigability of the river for recreational activities, a different management of the large hydropower plant is necessary, with a minor effect on biodiversity and on the other ecosystem services.

5.5.2 Small hydropower alternatives

Unlike the large hydropower production, both the new withdrawals would have effects on both ecosystem services and on biodiversity. The increase of the withdrawals will decrease the rafting suitability and it will affect positively or negatively the trout habitat depending on the local characteristic of the sub reach. Moreover, withdrawals above 2 m^3s^{-1} and 3 m^3s^{-1} are generally not suitable for the entire year in W1 and W2 respectively. Since the aim of this method is to assist policy and decision makers, we make a comparison of the monetary values and losses of rafting and small hydropower production in case of maximization of one of these two services. The comparison with the biodiversity is not straightforward because its monetary value is not easily established (Salles, 2011). It is worth to mention as the two small hydropower plants are very different, as pinpointed in Tables 5.1 and 5.7. The economic value was assigned to the hydropower production on the basis of the price of the electricity in the 2008-2013 period. The economic value of rafting activities was calculated by multiplying the suitability values, the maximum number of daily trips (3), the mean price per person for each trip (50 €) and a mean of 30 person per day for the entire season. Table 5.13 shows the results of this analysis for increasing withdrawals. The first two columns show the earnings for a small hydropower plant with different withdrawals and with an efficiency of the turbines of 80%, the columns 3 and 4 show the income from the hydropower plants, taking also into account the rafting losses, columns 5 and 6 show the loss of small hydropower when rafting is maximized and finally the last two columns show the loss of rafting when small hydropower is maximized.

	Gross total income (k€)		Total income including rafting losses (k€)		W, rafting maximized (k€)		Rafting, W maximized (k€)	
	W1	W2	W1	W2	W1	W2	W1	W2
1	64	159	6	159	-11	-24	-58	0
2	127	322	48	300	-31	-59	-79	-22
3	184	478	76	427	-53	-111	-108	-50
4	231	626	102	546	-75	-162	-130	-79
5	266	742	114	634	-101	-215	-151	-108
6	285	853	112	723	-114	-293	-173	-130
7	296	924	102	773	-127	-352	-194	-151

Table 5.13: *Total yearly income from a small hydropower plant with an efficiency of 80% is shown in the first two columns. The columns 3 and 4 show the annual incomes from small hydropower production considering the losses for rafting activities. Total yearly losses for small hydropower plants when rafting is maximized (columns 5 and 6) and for rafting when hydropower is maximized (columns 7 and 8). Each value is expressed in k€.*

From the economic perspective, the construction of the W1 withdrawal is less profitable: a withdrawal of 2 m^3s^{-1} in the W2 would produce more incomes than an uptake of 7 m^3s^{-1} in W1. When we take into account the rafting losses, the W1 seems to be even less feasible as incomes are significantly lower. The preservation of rafting requirements would be very expensive for both plants, decreasing the incomes by a minimum of 15% and a maximum of 40% for both plants. On the other hands, incomes for rafting would be decreased by a minimum of 16% and a maximum of 55% in W1 and a minimum of 0% and a maximum of 42% in W2. It is worth to notice as withdrawals of 1 and 2 m^3s^{-1} in W2 affects rafting incomes for 0 and 5%. The rafting economic losses are just an estimation, since the exact number of person attending this activity during the summer is not available. Moreover, it does not take into account less popular activities as kayak or hydro-speed. However, an economic value was provided to underline as the licence of new withdrawals can be profitable but it has also a clear economic effect on incomes from other flow-related activities. The effects on trout habitat can be either negative (W1) or a negligible (W2) and was not quantified by a monetary perspective.

5.6 Conclusions

Our analysis underlined as the flow regime of the river is fundamental not only to sustain the biodiversity and the natural processes but to provide as well other ecosystem services. The effects of the variations of the flow regime can be very different. At the current state, **i)** the different flow regimes imposed by the large hydropower production have a negligible effect on biodiversity and biological communities, but on the contrary they are necessary to support recreational ecosystem services and to sustain small hydropower production in low flow periods. Several management scenarios were tested **ii)** in the perspective of maximizing services different than hydropower production, with a direct and significant effect only on rafting in a annual time-span. This method can be used as a supporting tool for decision-makers to simulate the consequences of management alternatives. Furthermore, **iii)** our method allows to quantify the effect of future withdrawals licensing by quantifying the variations of river suitability for ecosystem services in relation with spatial and temporal flow alterations. In general, the addition of new withdrawals will decrease the suitability for rafting activities and will have a negative or small effect on biodiversity proxy. The hydropower plants generate relevant incomes for local stakeholders but an ecosystem services approach is able to take into account also the economic losses for other services (such as recreational) and the effects on biodiversity. Thus, our method can be applied in a broader perspective by policy and decision makers to weigh how spatial and temporal variation of flow regime affects not only the hydropower production but the entire set of river ecosystem services.

Chapter 6

Conclusions

The main objective of the thesis is to study the alterations of the flow regime induced by hydropeaking and to quantify the relations between the flow regime and several ecosystem services in rivers affected by hydropeaking. Each chapter aimed to answer to one of the main research questions introduced in chapter 1. The answers to these questions are reported below.
Finally, in the last section of this chapter we will propose further research developments.

6.1 Synthesis and main conclusions

It is possible to develop an easy-to-use procedure to quantify at-a-station hydrological alterations caused by hydropeaking using commonly available flow-data, and allowing large scale (i.e. regional) comparison of such alteration among multiple river catchments?

A method has been proposed as an easy-to-use tool to analyse to which extent river reaches are affected by hydropeaking; it allows to classify river gauged stations in four different classes of "hydropeaking pressure", that are defined on the basis of an unpeaked group of reference stations. Class changes among extreme classes (i.e. high pressure, absent or no pressure) due to the variations of tool's settings are rare, thus confirming its robustness. These rare class changes can be explained by the different power plant management schemes used in different years. The application of the proposed methodology is purely hydrological and has no direct significance for the assessment of the effects on the river ecology; the proposed methodology is nonetheless particularly interesting for management. Moreover, the robustness of this methodology, and the relative ease of application, can potentially lead to its use in regulatory and monitoring activities as in the classification of the stream ecological and hydromorphological conditions required by the EU Water Framework Directive (European Parliament, 2000). The proposed method has already been integrated into a quantitative evaluation procedure to classify the stream hydromorphological quality at a national level in Italy by the Institute for Environmental Protection and Research (Istituto Superiore Per la Protezione e la Ricerca Ambientale - ISPRA) in the broader context of a national methodology to assess hydrological and morphological status of the rivers (Carolli *et al.*, 2014). The ease of use assures that the method could be used by competent authorities (i.e., public agencies, river basin managers); if calibrated according to the different conditions of one country, it could cover the full range of physical conditions, morphological types, degree of artificial alterations existing there.

It is possible to analyse, and with which method, the spatial and temporal quantitative impact of hydropeaking on the river suitability for a selected discharge-dependant recreational service in an Alpine river?

Purely economical valuations of recreational services are frequent, but studies of the effects of hydrological regime and human water management on these services are rarely conducted. Our approach aims to introduce a quantification of the variations of the suitability of a recreational service according to hydropeaking and other flow regime alterations. The modelling approach we described in the chapter 4 aims to quantify the temporal and spatial suitability of a river for a recreational activity such as rafting, in a flow regime associated with the hydropeaking. The key idea is to adopt an analogous approach to the widely used habitat suitability modelling by developing specific rafting preference curves based on expert judgements. The proposed method is able to evaluate the variations of rafting suitability in a long modelling domain, both in space (reach scale) and time (from seasonal to daily variations of the flow regime). In the case study of the Noce River, the hydropeaking is necessary to guarantee rafting activities during summer months, which would provide largely unsuitable conditions even in a hypothetical natural flow regime. This method can be applied to other case studies, because several rivers in which the rafting activities are important have been or will be affected by dams and hydropower production. The approach is flexible and allows to simulate present and future management scenarios and the consequences on rafting suitability. In the case of Noce River, we simulated also a small additional withdrawal, which is sufficient to significantly lower the navigability in the subtended area.

Can a quantitative, general method be developed to quantify the mutual interactions among flow regime dependant river ecosystem services and river support to biodiversity in response to different flow regime management alternatives?

The methodology introduced in the chapter 4 is able to jointly quantify the variations of rafting suitability, of a biodiversity proxy (adult marble trout habitat suitability) and of the suitability for run-of-the-river hydropower plants under different flow regimes. Values of suitability calculated at reach and daily scale can be upscaled at the management relevant space and time scales. At the present state, a significant effect of the variation of the flow regime on suitability was detected for rafting and for run-of-the-river hydropower plants, while the effects of the flow regime variations on trout habitat are not significant. The analysis of scenarios for the large hydropower production pinpointed as different management of the releases can improve rafting navigability, while the different scenarios would have a small effect on the trout habitat and on run-of-the-river hydropower. Moreover, we demonstrated as the addition of new withdrawals will decrease the suitability for trout habitat and the rafting suitability and incomes, while viceversa the preservation of the requirements for rafting and fish habitat will greatly affect the production of run-of-the-river plants and related incomes. The method can be applied at several spatial and temporal scales, from reach to basin scale and from sub-daily to annual scale, and it can be integrated in the decision making process to evaluate mutual interactions among different ecosystem services in response to different flow management alternatives, according to different priority choices for one or more ecosystem services.

6.2 Further research developments

This thesis aimed at quantifying the mutual interactions among selected river ecosystem services in relation with the flow regime especially in rivers subject by the hydropeaking, which is a common alteration of the flow regime in mountain areas. Several other topics can be implemented and some of them will be briefly introduced below.

1. Assessment of the dynamic stage of the hydropeaking. In our modelling approach, we did not take into account the velocity of the variations induced by hydropeaking on river discharge which were assessed by the second hydropeaking indicator. This velocity is known to induce, for example, stranding events of fish and macroinvertebrates drift. Thus this parameter should be considered and its impact quantified especially in an evaluation of the effects on biodiversity;

2. Introduction of climate change scenarios. Another source of variability of the flow regime is the climate change (CC). Climate change scenarios are modelled by several

hydrological models and can be simulated in order to introduce the evaluation of the effects of climate change on future policies;

3. Introduction of other ecosystem services. We evaluate a biodiversity proxy, the hydropower production and a recreational service, but the rivers provide a set of other fundamental ecosystem services. The application of this methodological approach to different case studies which provides other services can lead to a better understanding and a better management of river and its ecosystem services.

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