Assessment of Environmental Flows in the Tyrol Region using MesoHABSIM

Master's Thesis

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Declaration of Authorship

I hereby certify that this master's thesis, under the title "Assessment of Environmental Flows in the Tyrol Region using MesoHABSIM" has been composed by me and is based on my own work, unless stated otherwise. All references have been quoted, and all sources of information have been specifically acknowledged.

Date: 31.08.2020 **Signature:** H. Sch

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Abstract

Ecohydraulic studies link ecological problems to hydraulic engineering and water management issues and have been becoming more and more attention, as the importance of the sustainability of river ecosystems has now been recognised. Such studies are based on the knowledge and understanding of the riverine ecosystem as a dynamic and diverse system which is influenced by the physical, chemical and biotic features of a river. These features are, however, majorly altered by anthropogenic activities which also affect the riverine habitat conditions and the organisms living in it. Habitat models mostly connect hydraulic variables to elements of habitat suitability and they are therefore valuable tools in ecohydraulic studies. Environmental flow assessment is an important part of ecohydraulics and is used to mitigate anthropogenic alterations. Four major groups of methods exist in this field of research: hydrological methods including look-up tables and desktop methods, hydraulic rating methods, habitat simulation methods and holistic methods. Here, the amount of detail considered, as well as the resolution and the accuracy of the ecological aspects included, increase from one method to another leading to the definition of basic flow values or a detailed ecology-based flow regime respectively. MesoHABSIM is a mesoscale habitat simulation model which has been used in several environmental flow assessments on a local as well as on a regional scale because it includes the biological as well as the hydromorphic aspects of the riverine habitat and additionally analyses the hydrological regime to define natural occurring habitat thresholds. Therefore, MesoHABSIM was used in this thesis and was applied in one reference site located in the River Leutasch or Leutascher Ache and in two sites within the bypass section of the Gemeinschaftskraftwerk Inn (Joint Venture Hydropower Plant Inn – GKI) in the Upper Inn River in order to develop environmental flow criteria for the Tyrol region (Austria). The habitat model was developed taking into account the habitat preferences of the expected fish community during the summer months, the habitat preferences of spawning and rearing brown trout during the winter months and the habitat preferences of spawning and rearing bullhead and European grayling during spring. Natural habitat conditions were observed in natural or renatured river stretches in both rivers, and uniform and monotone habitat conditions were observed for a channelized river stretch in the Upper Inn. The collected data on hydromorphic features was used to create habitat rating curves and was also used to develop a UCUT analysis (Uniform Continuous Under Threshold) for the River Leutasch. This led to the definition of habitat threshold values calculated for the Leutasch which were then applied in the Inn. Firstly, this thesis proves that the channelization of river stretches reduces and destabilises the habitat available for the native fish community, whereas river restoration measures have a great potential to improve habitat conditions. Secondly, the MesoHABSIM model provides environmental flow criteria which are in the same range as the minimum flow values previously developed for the GKI which shows the applicability of the MesoHABSIM model in this scientific field. Thirdly, the concept of FCMacHT used in the AMBER project which defines expected fish communities and associated habitat structures for regions in Europe is valid for the two alpine rivers. Therefore, the potential of this concept as part of the development of regional environment flow standards is also shown. However, additional research and data are necessary to prove and develop the idea of regional environmental flow standards for Europe further.

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1 Introduction

The Earth is not ours. It is a treasure we hold in trust for future generations.

African Proverb

Anthropogenic activities are affecting and changing the natural ecosystems around the world more and more. The direct impacts on ecosystems such as land use change, pollution or regulation of rivers are as dangerous for the sustainability and functionality of these systems as indirect changes caused by global warming. Aquatic ecosystems are especially affected by anthropogenic activity as people have been systematically using and changing water bodies for centuries. Such changes in the natural aquatic ecosystem occur due to direct anthropogenic activities such as water abstraction, water pollution and river straightening but also due to indirect changes in atmospheric patterns which influence precipitation as well as the melting of ice and snow. River ecosystems have been altered regarding their appearance and extent, water quality, hydrological regime and the composition of species living in them. Furthermore, aquatic ecosystems are affected at their sources in mountainous areas, along their entire length, at their estuaries and mouths as well as in maritime regions. People use water bodies to supply drinking water or for municipal, agricultural or industrial purposes, for hydropower production and transportation and as a food source. Such anthropogenic activities can alter and destroy the productivity and sustainability of these ecosystems. It becomes clear that, on the one hand, we alter the ecosystems in order to benefit from them, but on the other hand, we are also dependent on aquatic ecosystems and their functions. As said by the African proverb cited here, it should therefore be our goal to protect natural ecosystems and use them in a sustainable way so that we and future generations continue to benefit from them.

Nowadays, ecosystem health is perceived as an important aspect which needs to be considered during the exploitation of natural resources. The necessity to find a balance between human needs and ecosystem protection is becoming more and more important. Over the last decades, laws for the protection of the environment and natural resources have been put into effect all over the world. Ecohydraulics has emerged as a new scientific field due to this recognition of the importance of ecosystem protection and management. It considers the ecological aspects in the field of hydraulic engineering and water resource management (Maddock et al. 2013). One major aspect in ecohydraulic studies is the assessment of environmental flows, which is the definition of the quantity and timing of the water which needs to remain in the river to sustain the ecosystem (Brisbane Declaration 2007; TNC 2018). The estimation and definition of environmental flows are being discussed widely around the world. Its importance was recognised several decades before which led to the development of scientific tools in this field of research. Available methods of estimating environmental flows differ largely in how detailed they consider the requirements of the ecosystems. The simplest forms are so-called look-up tables presenting single often constant flow values for stretches of rivers. Other methods concentrate on the analysis of the hydrological regime or simulate instream habitats as a basis for the assessment of environmental flows. In addition, holistic frameworks have been developed using interdisciplinary expert knowledge to define environmental flows. However, the implementation and application of these detailed and scientific strategies remain restricted to some river catchments. Despite the implementation of the Water Framework Directive as a European legislation for the protection of water bodies, no specific uniform legislation or standards for how to define environmental flows exist in the European Union.

This thesis presents one way of estimating and defining environmental flows in the alpine area of Tyrol, Austria. It uses the mesoscale instream habitat model MesoHABSIM which has been used in several environmental flow studies all over the world. In Austria and Germany, however, the application of MesoHABSIM, especially in the field of environmental flow, has not been common up to now. As part of this thesis, however, the MesoHABSIM approach is used in two rivers in Tyrol in order to develop an environmental flow management strategy for the region of Tyrol. This thesis is providing information and data for the FIThydro project (Fishfriendly Innovative Technologies for Hydropower), a research project funded by the European Union’s Horizon 2020. The project is coordinated by the Technical University of Munich and consists of several other research institutes and universities as well as consulting companies. It addresses mitigation measures and environmentally friendly solutions for hydropower plants to protect the fish population. In addition to the FIThydro project, this thesis includes results and data gained by the AMBER project (Adaptive Management of Barriers in European Rivers) which is also funded by the European Union’s Horizon 2020.

Results of the AMBER project show the ecological impact of different kinds of barriers on the river ecosystem (AMBER 2019). Dams and weirs were shown to have the strongest impact on the river system and the fish community (AMBER 2019). In addition, rheophilic, intolerant species, which represent large proportions of the fish community in the alpine region, were identified as the most sensitive towards changes in the river system and the hydrological regime (AMBER 2019). The alpine region can therefore be perceived as especially vulnerable regarding the alteration of river ecosystems due to two major factors. Firstly, the alpine area has great hydropower potential which results in the construction of dams and barriers. Secondly, the riverine species in the alpine area as well as the ecosystem in general are highly sensitive towards such activities. Thus, it is of major importance to define mitigation actions and management strategies in the alpine area to reduce the impacts of this on the ecological system. Hence, the alpine region has been selected as study area in this thesis.

Furthermore, this thesis is based on the idea of developing environmental flow assessment methods on a regional scale. Such standards would facilitate the implementation of similar environmental flow rules in one region and when calibrated in every region in the European Union could be used as a basis for environmental flow estimations. The AMBER project divided all European rivers into 15 different Fish Community Macro Habitat Types (FCMacHT, AMBER 2019) based on which similar environmental flow standards could be developed and applied. This thesis, therefore, generates data for one of these European regions, the alpine region or in this case especially the Tyrol region, in order to apply and prove this idea of regional environmental flow standards. In addition, one river stretch used in this study is part of a test case of the FIThydro project, which is why the results of this study can directly be used as part of the research project and can be compared to previously developed environmental flow rules.

The first part of this thesis, Chapter 2, consists of a literature review firstly regarding ecohydraulic principles and ecological aspects which need to be considered in river management. Secondly, habitat modelling methods are presented and explained. Thirdly, environmental flows are defined and different methods in this field of research are described and analysed. As the mesoscale habitat model MesoHABSIM is applied in this thesis, the model development, its applications and its methodology are presented in detail and compared to other habitat models in Chapter 3. Chapter 4 presents the objective of this thesis regarding study cases and gives some background information about the data and methods used. Then, the application of MesoHABSIM in the two studies cases, Leutasch (Leutascher Ache) and Upper Inn, is described in detail. Chapter 5 presents the study area considering the catchments as well as hydrological and ecological aspects of the two rivers. Chapters 6 describes the construction of the MesoHABSIM model focusing on data collection and the biological model. The obtained results of the MesoHABSIM model are then shown in Chapter 7 and are interpreted in Chapter 8. Finally, the results of this thesis are discussed in Chapter 9. Chapter 10 describes the conclusions which can be drawn from this thesis and Chapter 11 then summarises the content of this thesis.

2 Literature Review

2.1 Ecohydraulics

2.1.1 Term and Definition

All over the world, population growth, urbanization, industrialisation and intensive agriculture have led to an increase in water needs. In turn, the growing awareness of the importance of functioning ecosystems has led to the development of protective management strategies for water systems. Due to this, it has become necessary to balance the needs of the population with the needs of ecosystems which results in the necessity for integrative and interdisciplinary sciences such as ecohydraulics (Wood, Hannah, and Sadler 2008; Maddock et al. 2013).

Jorde and Schneider (2015c) define ecohydraulics as the science of the assessment of the link between hydraulic conditions, environmental processes, hydro-morphological processes and structures and the reaction of river-connected biological communities. The goal of ecohydraulics is to make sure that research questions dealing with sustaining “both natural ecosystems and the demands placed upon them by the contemporary society” are more widely discussed (Maddock et al. 2013). It is not a newly developed science, on the contrary, it uses existing sciences such as hydraulics, hydrology and biology as well as their methods for different integrative applications (Jorde and Schneider 2015c). Ecohydraulic studies focus on channel-forming processes and channel dynamics, instream flows and their connection to habitat availability and stream ecology (Petts 2008) as well as the assessment of human impact on the river ecosystems in general (Maddock et al. 2013). Additional terms such as ecohydrology and hydroecology are used to describe interdisciplinary science linking hydrology, geomorphology and ecology (Petts 2008; Fohrer 2016). Some authors define ecohydraulic as a subdiscipline of ecohydrology (Wood, Hannah, and Sadler 2008). However, definitions of these terms remain ambiguous, which impedes the exact demarcation of these terms (Wood, Hannah, and Sadler 2008). Nevertheless, the development of several similar terms shows the importance and necessity of such interdisciplinary approaches. Ecohydraulic approaches are used to assess aquatic systems and the impact of human activity especially in the area of habitat modelling (Jorde and Schneider 2015c). The following sections give some basic information about river ecosystems, how they are influenced by humans and how these impacts can be assessed using ecohydraulic studies such as habitat modelling.

2.1.2 River Ecosystems

River ecosystems are highly diverse as they include highly complex and dynamic processes (Wood, Hannah, and Sadler 2008; Patt, Jürging, and Kraus 2011). These processes involve several interdisciplinary sciences (Rutschmann 2013). Therefore, ecological processes within the ecosystem itself as well as influential factors need to be understood in order to assess the impact of human activities on aquatic ecosystems.

Furthermore, lotic ecosystems are open systems, meaning several fluxes of matter and energy exist within the ecosystem itself as well as from outside sources (Patt, Jürging, and Kraus 2011).

These different environmental factors lead to the creation of diverse habitats and biotic communities (Patt, Jürging, and Kraus 2011). Additionally, most of the attributes of these systems change spatially and temporally creating dynamic systems (Maddock et al. 2013; Jorde and Schneider 2015a). Lotic ecosystems are structured using physical, chemical and biotic processes and features as well as their interactions (Maddock et al. 2013). These can also can be used to characterize an ecosystem as presented in the following sections (Patt, Jürging, and Kraus 2011).

2.1.2.1 Physical Features

The physical characteristics of a river's ecosystem are heavily influenced by the flow regime in the river. On a local scale, the flow regime can be described by the velocity and depth of the water. It creates diverse structures resulting in diverse habitat conditions due to a high spatial and temporal variability (Patt, Jürging, and Kraus 2011). Furthermore, the water provides transport possibilities for abiotic and biotic components as well as organisms (Jorde and Schneider 2015a).

The flow regime controls the morphological processes in a river such as erosion, transport and deposition of sediment or organic material. Natural dynamic flow processes lead to a high variability of morphological structures not only in the riverbed itself but also on its banks and floodplains (Patt, Jürging, and Kraus 2011). The morphological structures in the river depend on the size and composition of the substrate as well as its layer thickness (Patt, Jürging, and Kraus 2011; Jorde and Schneider 2015a). The diversity of substrates and morphological structures creates different habitat conditions resulting in a complex biological community. For example, the existence of cover structures such as undercut banks and boulders is an essential parameter for habitat suitability (Jorde and Schneider 2015a).

Poff et al. (1997) additionally recognized the importance of the natural flow regime in a river over a longer time period. The authors define the flow regime as the characteristic pattern of flow quantity, timing and variability (Poff et al. 1997). The characteristic flow regime of a river is influenced by the river size and the climate, geology, topography and vegetation in its catchment (Poff et al. 1997). Poff et al. (1997) identified five critical components of a natural flow regime: the magnitude of discharge, the frequency of occurrence, the duration of a specific flow condition, the timing or predictability of flow changes and the rate of flow changes. These components influence physical habitat features such as sediment size and heterogeneity or channel and floodplain morphology (Poff et al. 1997) and determine, how often and how long floodplains are inundated. Bunn and Arthington (2002) also defined flow as a major determinant of a physical habitat.

Water temperature and insolation are also important physical characteristics of a riverine ecosystem (Jorde and Schneider 2015a). Both factors are additionally linked to chemical features as insolation can change the water temperature which then influences chemical processes such as the oxygen level. They are also connected to biotic components as temperature and isolation control life processes such as respiration and primary production.

2.1.2.2 Chemical Features

Patt, Jürging, and Kraus (2011) describe the chemical features in a river ecosystem. First of all, oxygen concentrations in rivers are essential for all organisms. As already mentioned, the solubility of the oxygen in the water depends on the water temperature, with higher solubility in cooler waters. High oxygen levels can occur due to cooler temperatures, shading effects and turbulences especially in headwaters. The oxygen level can be reduced by biochemical degradation processes. Other inorganic substances, especially phosphor and nitrate concentrations, depend on the geological conditions of the watershed. Phosphor and nitrate are important nutrients and their concentrations control primary production and thus influence the biotic features. (Patt, Jürging, and Kraus 2011)

2.1.2.3 Biotic Features

Biological communities in rivers are connected by a food chain or prey-predator relationships. Primary production, changing inorganic substances into organic, makes up the first step in the food chain followed by herbivorous and finally carnivorous species. Decomposers then transform organic materials back into inorganic substances and this ends the food chain. The availability of food as well as possible competition for food sources are therefore important biotic factors which influence the composition of a biological community in a river. The biotic features in a river depend on the connectivity from the source of the river to its mouth as well as to its tributaries and flood plains as this permits migration and exchange processes. Finally, organic structures such as submerged and emerged vegetation, roots and woody debris are also important biotic features which influence the habitat structure in a river. (Patt, Jürging, and Kraus 2011)

2.1.2.4 River as Habitat

Regarding rivers as habitats, the different features of the river ecosystem mentioned above are also the most important parameters influencing habitat suitability. It is essential to realise that species adapt to specific ranges of these physical, chemical and biotic characteristics. On the other hand, this means that the biota within the ecosystem also depends on such conditions (Jorde and Schneider 2015a).

Poff et al. (1997), who focussed on the flow regime, realised that due to the predictability of the natural flow regime, the biota in the river ecosystem evolved in a way which caused all naturally created habitats to be exploited. In addition, aquatic species developed life history strategies in response to the flow regime (Bunn and Arthington 2002). This means the critical life events of some aquatic species are linked to certain flow events within the natural flow regime, such as spawning, emerging from resting stage or migration (Bunn and Arthington 2002). On a smaller scale, deep water can be used as winter habitat or can provide protection against predators, while shallow waters with higher temperatures can provide a habitat for juvenile fish (Jorde and Schneider 2015a).

The topography, geology and climate in specific regions influence the habitat conditions directly. Due to this, habitat conditions gradually change from the river source to its mouth. This fact was detected several decades ago and led to the distinction of specific ecological regions, in which the similar topographic and climatic circumstances lead to specific compositions of species (Jungwirth 2003; Patt, Jürging, and Kraus 2011). River stretches can therefore be classified into specific ecological or fish regions, in which similar fish species which adapted to the particular conditions can be expected. For example, rheophilic and specialised species such as salmonids can be found in the alpine region or in high gradient streams near the river source, whereas eurytopic, limnophilic or indifferent as well as generalised species are commonly located in low gradient streams near the river mouth (Jungwirth 2003).

These examples show that all previously mentioned features of an ecosystem as well as their combinations and spatial and temporal variabilities are essential for a diverse and sustainable biotic community. Hence, changes in the natural flow regimes or other characteristics of river ecosystems change the natural composition of species. Therefore, river ecosystems should be addressed in a holistic manner taking into account all of their features and combinations as well as their temporal and spatial variability (Patt, Jürging, and Kraus 2011).

2.1.3 Anthropogenic Impacts on Rivers

Historically, rivers have always been important for the human populations when it comes to providing drinking water and food as well as giving people the possibility to irrigate their land and transport things. Rivers have been used since several centuries, especially in Europe and North America (Jorde and Schneider 2015c). Since the first half of the 19th century, however, people have started to systematically use and modify rivers worldwide and after World War II particularly the construction of large hydropower dams has led to extreme changes in river ecosystems (Jungwirth 2003). Hand in hand with the increasing need for water all over the world, the changes in rivers have also increased globally (Vezza 2010). The main reasons for the changes in river ecosystems are flood protection, supplying water, irrigation and hydropower production (Poff et al. 1997; Rosenberg, McCully, and Pringle 2000) .

Several decades ago, people started to address pollution problems in rivers, for example, by establishing wastewater treatment plans (Jorde and Schneider 2015c). More recently, hydro-morphological problems have become focus of water management strategies (Jorde and Schneider 2015c), especially since the European Water Framework Directive (WFD, Directive 2000/60/EC, European Commission 2000) includes hydro-morphological aspects for the assessment of the ecological status (Maddock et al. 2013). The WFD came into action in December 2000 and its goal is to achieve at least “Good Ecological Status” in most water bodies in Europe (Directive 2000/60/EC, European Commission 2000). However, many aspects of natural rivers are still negatively influenced by human activities which is shown in the following sections.

2.1.3.1 Physical Alterations

Physical alterations in a river ecosystem are mostly connected to hydrological changes which can be defined as anthropogenic disruption in the magnitude and timing of water flow (Rosenberg, McCully, and Pringle 2000). Such alterations mainly occur because of the construction of dams or barriers but also due to channel straightening, the exploration of groundwater aquifers, inter-catchment water transfers or land use changes (Poff et al. 1997; Rosenberg, McCully, and Pringle 2000).

Dams or even small barriers disrupt the lateral connectivity and additionally change the natural flow regime downstream as they are used for water storage and water abstractions. Dams lead to flow stabilisation including the dampening of flood peaks which changes of the duration and frequency of floods (Bunn and Arthington 2002; Jungwirth 2003). Similarly, the exploitation of groundwater and the withdrawal of water for municipal water supply or irrigation as well as inter-catchment water transfers reduce the discharge in rivers and alter the flow regime which affects the physical habitats in riverine ecosystems (Rosenberg, McCully, and Pringle 2000; Jorde and Schneider 2015a). Furthermore, channel straightening alters the flow regime leading to an increase in flow velocity which changes the physical conditions in riverine ecosystems and further reduces the structural diversity (Patt, Jürging, and Kraus 2011; Jorde and Schneider 2015a). In addition, channelling and flood protection measures destroy the connection between a river and its floodplains (Jorde and Schneider 2015a).

Impoundments lead to a decrease in velocity and an increase in water depth upstream from the barriers which creates a significantly different thermal regime to those that normally occur in running water (Bunn and Arthington 2002; Jungwirth 2003). The reduced flow velocity additionally affects the transport capacity which leads to sedimentation processes and the capture of sediment behind dams resulting in a reduction of the geomorphological processes downstream (Jungwirth 2003; Patt, Jürging, and Kraus 2011; Jorde and Schneider 2015c). Furthermore, the removal of riparian vegetation often connected with impoundments and channel straightening additionally increase the degree of insolation resulting in a higher primary production (Patt, Jürging, and Kraus 2011).

In addition to direct changes in the river, changes in land use in the catchment can affect the physical characteristics of the riverine ecosystem (Poff and Zimmerman 2010). Intensified timber harvesting, livestock grazing or agriculture as well as urbanisation influence hydrological processes in the catchment which lead to increased overland flows and the increased risk of flooding which also changes the physical conditions of a river (Poff et al. 1997).

2.1.3.2 Chemical and Biotic Alterations

Patt, Jürging, and Kraus (2011) describe the effects of chemical and biotic alterations on the river ecosystem. Changes in the oxygen concentration occur due to changes in the flow regime, insolation and primary production. The nutrient concentration in wastewater and the increasing use of fertilizers in agricultural areas also increase primary production resulting in possible eutrophication. Artificial toxic substances can pollute river ecosystems and destroy native fish species. Finally, alterations of river channels and the construction of dams destroys biological connectivity and therefore the exchange and migration possibilities of species. Anthropogenic processes, which only directly influences some specific species, can indirectly lead to negative impacts on the whole biological community in the river and the ecosystem in general, as a food chain connects different organisms within the river. (Patt, Jürging, and Kraus 2011)

2.1.3.3 Alteration due to Hydropower

In Europe, the amount of rivers which are used for hydropower production is extremely high, especially in alpine areas (Jungwirth 2003). The construction of hydropower plants highly affects the physical conditions of riverine ecosystems as well as the floodplains. In particular, the construction of dams together with the diversion or abstraction of water affects the ecosystem as already explained in Section 2.1.3.1. However, there are also some more specific impacts of hydropower plants. Firstly, the hydro-electric use of rivers causes changes the flow regime due to the artificial abstraction, storage and release of water. Especially the sudden artificial changes in the flow, so-called hydropeaking, create unnatural and unpredictable conditions which native species are not used to (Poff et al. 1997; Patt, Jürging, and Kraus 2011). Secondly, the turbines themselves can lead to the injury and death of fish. The impacts of dams and hydropower production together show that hydropower plants change the habitat condition in rivers significantly. Mitigation measures in rivers affected by hydropower plants, such as the definitions of environmental flows (Section 2.3), are therefore especially important (Poff et al. 1997; Rosenberg, McCully, and Pringle 2000; Bunn and Arthington 2002; Jungwirth 2003; Patt, Jürging, and Kraus 2011).

2.1.3.4 Effects on Habitat of Native Biota

As shown in the previous sections, anthropogenic alterations in rivers or in their catchments are numerous and diverse. They affect river ecosystems, riverine habitats and the riverine community in several ways. Based on the principle that the biota in a river ecosystem develop in response to the naturally occurring characteristic features (Poff et al. 1997; Bunn and Arthington 2002), changes in river ecosystems have a direct impact on the living organisms within them.

Particularly the physical alterations due to hydrological alterations have a direct impact on the riverine biota, but also chemical and biotic as well as thermal changes influence the habitat quality for native biota. For example, changes in the oxygen or nutrient concentration can lead to the extinction of species which are especially sensitive to such changes. Additionally, thermal changes in the river affect the growth and reproduction processes of fish (Bunn and Arthington 2002). Changes in the hydrological regime due to changes in land use often go hand in hand with the channelization of rivers which increases the amount of overland flow as well as the size and frequency of flood waves leading to the degradation of physical habitats in river channels (Poff et al. 1997). For example, the small scale diversities of physical habitats such as shallow margins or cover structure are reduced or destroyed by such processes. Dams and barriers are considered to be the primary destroyer of aquatic habitats and a major cause of hydrological alterations (Rosenberg, McCully, and Pringle 2000). As previously explained, the storage and withdrawal of water creates artificial flow regimes downstream from the dam which differ significantly from the natural flow regimes. Most often the flow is stabilised and loses the characteristic pattern of the catchment which the native biota is used to (Poff et al. 1997; Bunn and Arthington 2002). The loss of specific flow events, which are of importance for the life events of some species, can lead to the extinction of some species (Rosenberg, McCully, and Pringle 2000). The reduced magnitude of floods additionally reduces the duration and extent of the inundation of riparian areas which results in a loss of habitat for riparian species as well as in the loss of nursery, spawning and foraging areas of riverine species (Poff et al. 1997; Rosenberg, McCully, and Pringle 2000). Furthermore, floods initiate morphological processes, such as the removal of fine sediments from the substrate layers which increases the accessibility of the substrate layers for invertebrates (Jungwirth 2003). In addition, the interstitial is essential for the spawning processes of some species such as salmonids (Jungwirth 2003). Therefore, a reduction in frequency and magnitude of floods affects and reduces reproduction processes connected to the substrate. Hydropeaking creates physical conditions which the native fauna is not used to. It can lead to a high mortality rate of riverine species due to physical stress, washing out or stranding after rapid dewatering (Poff et al. 1997). Furthermore, barriers prevent important migration processes which affect species reproduction and result in the extinction of some species (Bunn and Arthington 2002).

Petts (2008) summarizes the effects of human river alterations by focussing on the flow regime and the riverine habitats, which he calls the “lessons learned from the control-by-construction agenda of the 20th century”:

- Loss of flood flows to reset instream, riparian and floodplain habitats
- Reduction in low flows causing habitat limitations and change
- Loss of hydrological clues of life cycle behaviour (migration, spawning)
- Unnatural seasonal flow variation
- Unnatural rates of flow rise and recession (hydropeaking)

In general, the anthropogenic alteration of river ecosystems is associated with reduced biodiversity and changes in the biota composition of highly specialised species to more generalist (Poff et al. 1997; Bunn and Arthington 2002; Poff and Zimmerman 2010). These negative effects of anthropogenic alterations in river ecosystems should be considered during the planning of water management actions and mitigation measures.

Poff and Zimmerman (2010) reviewed existing literature and ongoing research creating a quantitative relationship between the alteration of the natural flow regime and its ecological response, which should be used as a basis for river management. They could not establish a quantitative relationship. Qualitatively, however, they showed that for fish in particular, alterations of the parameters of the ecosystem are always connected to a decline in abundance, diversity and demographic rate (Poff and Zimmerman 2010). This shows that the definition and quantification of the relationship between river alteration or management actions and their ecological responses are still challenging scientists (Lamouroux et al. 2017). Lamouroux et al. (2017) summarized the difficulties which occurs during the establishment of general, quantitative models of ecological alterations as:

- The diversity and natural variability of flow regimes and their alteration
- The varying hydraulic effects of flow alteration, depending upon the morphology of stream reaches
- The complexity of biological responses influenced by many biotic and abiotic factors
- The limitations of ecological monitoring
- The inconsistent design and report of environmental water monitoring studies

The awareness and knowledge of the negative impacts of human activity is the first step towards river management improving the situation in rivers and protecting the ecosystems within (Maddock et al. 2013). Many research projects already exist focussing on river restoration and rehabilitation (Maddock et al. 2013). Nevertheless, as shown by Poff and Zimmerman (2010) and

Lamouroux et al. (2017) these negative impacts are not easily identified, quantified or addressed. This fact has led to the development of ecohydraulic methods which should provide a basic understanding of and possibility to simulate riverine ecosystem. Such methods include the modelling and assessment of aquatic ecosystems called habitat modelling.

2.2 Habitat Modelling

Habitat modelling strategies have existed in North America since the 1970s and have commonly been used in Europe since the 1990s (Tharme 2003; Jorde and Schneider 2015c). Most habitat models assume the existence of a relationship between the level of flow and the physical habitat (Linnansaari et al. 2013). Habitat models are used to predict the response of aquatic biota to habitat modification and to quantify available habitat under specific circumstances (Adaptive Management of Barriers in European Rivers (AMBER) 2018). They assess the influence of environmental factors on the distribution of available habitat for species and communities (Noack, Schneider, and Wieprecht 2013). Simulations of different discharge scenarios and their corresponding physical habitat are then used to define thresholds of an optimal as well as a critically low amount of physical habitat (Acreman and Dunbar 2004; Linnansaari et al. 2013). Such methods can be applied in the fields of water resource management and river regulation or restoration (Petts 2008; Noack, Schneider, and Wieprecht 2013). Some applications of habitat modelling in water management are named here:

- Developing reference conditions and reference habitat templates (e.g. Parasiewicz 2007b)
- Creating a basis for decision making in river restoration planning (e.g. Parasiewicz 2008)
- Estimating environmental flow values (e.g. Parasiewicz 2008; Vezza 2010; Vezza et al. 2012; Dunbar, Alfredsen, and Harby 2012; Parasiewicz et al. 2018)
- Developing river management strategies in the framework of the European Water Framework Directive (WFD) (e.g. Schneider et al. 2013)
- Assessing the modification of habitat due to morphological changes by combining a habitat model and a morphological model (e.g. Bui, Abdelaziz, and Rutschmann 2013)

2.2.1 Habitat Scales

River habitats are grouped into the following kinds of habitat: microhabitats (cm to several m), mesohabitats (10 m to 100 m) and macrohabitats (100 m to several km) (Jungwirth 2003; Jorde and Schneider 2015a). Microhabitats are characterized by local flow velocities, water depth, substrate and cover structures (Jungwirth 2003; Jorde and Schneider 2015a). Mesohabitats, on the other hand, are described using the averaged values of flow velocity as well as additional parameters for the morphology of the river (Jorde and Schneider 2015a). Finally, temperature, channel structure, morphology and discharge are important parameter which characterize macrohabitats (Jorde and Schneider 2015a). Meso- and macrohabitats can be described as habitats used by a biological community or population while microhabitats are habitats of an individual species at a specific time in its life (Jungwirth 2003).

The modelling of an instream habitat is based on these groups as well and it depends on the research objective which habitat is used (Jorde and Schneider 2015e). However, mostly microhabitat models are used which link the results of commonly used hydraulic models to the values of habitat suitability (Vezza 2010). Common microhabitat models are PHABSIM (PHysical HABitat SIMulation Model) based on the Instream Flow Incremental Methodology (IFIM, Bovee 1982) and CASiMiR (Computer Aided Simulation Model for Instream flow Requirement, Noack, Schneider, and Wieprecht 2013). More recently, mesohabitat models have been used as they are more practical when assessing longer stretches of a river or as part of river management actions, for example in the framework of the WFD (Eisner et al. 2005; Parasiewicz 2007a; Dunbar, Alfredsen, and Harby 2012; Schneider et al. 2013; Noack, Schneider, and Wieprecht 2013). MesoHABSIM (Mesoscale HABitat SIMulation, Parasiewicz 2001; 2007a), MesoCASiMiR (Eisner et al. 2005; Noack, Schneider, and Wieprecht 2013) as well as MSC (Meso-Scale habitat Classification method, Norway, Borsányi et al. 2004) are the most commonly used mesohabitat models (see Section 3.4 for more information).

2.2.2 Fish as Indicators

As described before, river ecosystems are diverse and should be dealt with in a holistic manner. However, it is often not feasible to assess every influential factor regarding habitat suitability for all of the different species in a river and their stages of life. Therefore, most habitat models use fish as indicator species based on the assumption that the fulfilment of habitat requirements for the indicator species is sufficient for the ecosystem as a whole (Jungwirth 2003; Jorde and Schneider 2015e). In addition, approaches exists which take the whole fish community in a river into account instead of focussing on one species (Parasiewicz 2007b; Bain and Meixler 2008).

Jorde and Schneider (2015e) describe the advantages of using fish as indicators. For example, fish exist in low numbers and are therefore easy to determine in comparison to other species. Additionally, historical and current fish data is easily available as an economic interest in the fish population has existed for a long time due to the fishery industry. Furthermore, as fish form the end of the food chain, they can be used as an indicator for disturbances in other species as well. Similarly, fish depend on the lateral and longitudinal connectivity in a river and therefore they also indicate disruptions in this continuum. (Jorde and Schneider 2015e)

Fish as indicators for quality assessment of river also has some disadvantages. For one thing, fish are highly mobile and follow certain migration pattern resulting in difficulties finding and documenting fish species in their most favourable habitats (Jorde and Schneider 2015e). Secondly, the fish population and species composition have been altered due to fishery purposes (Jorde and Schneider 2015e). In addition, fish do not exist in high alpine rivers and therefore additional species need to be used as indicators in such regions (Brown, L., Milner, A., and Hannah 2008; Jorde and Schneider 2015e). Consequently, there are indicators other than fish which are used in some models, for example macroinvertebrates or macrophytes (Brown, L., Milner, A., and Hannah 2008; Jorde and Schneider 2015e).

For the setting-up of habitat models, data and knowledge about the indicator or target species are necessary to model their habitat preferences. Data collection regarding fish is a time consuming process and mostly done by electro-fishing, snorkelling or diving or by using electrofishing boats in larger rivers (Parasiewicz 2007a; Linnansaari et al. 2013; Jorde and Schneider 2015e). The sample results are then used to define habitat preferences and to calibrate the model. Additional datasets should be used to validate the established model (Jorde and Schneider 2015d).

2.2.3 Biological Habitat Models

According to Jorde and Schneider (2015b), biological habitat models describe biological processes important for the development of an individual species as well as of populations and communities. Such models include the modelling of biological processes such as metabolism, energy consumption, reproduction and the growth of individuals and communities. Additionally, food availability and competition between species, for example regarding habitats or food sources, as well as prey-predator relationships can be considered. Many of these processes are complex as they are subject to natural variabilities and sometimes not fully understood yet. Therefore, biological models are not very common as physical habitat models yet. (Jorde and Schneider 2015b)

2.2.4 Physical Habitat Models

Physical habitat models are based on the modelling of the physical characteristics of a river, so the hydraulic and morphological conditions. The results of the physical or hydraulic modelling are then linked to preference models and then transformed into values of habitat suitability (Lamouroux et al. 2017). This means that physical habitat models consist of two modules: the hydraulic modelling of the environmental conditions and the biological model which accounts for habitat preferences and calculates habitat suitability (Linnansaari et al. 2013; Lamouroux et al. 2017). Based on this, they are also called hydraulic-habitat models (Lamouroux et al. 2017).

2.2.4.1 Physical Module

A physical module includes the modelling of the hydraulic conditions, the morphology and substrate for different flow conditions (Linnansaari et al. 2013). Additionally, cover structures can be included, most often as verbal descriptions (Jorde and Schneider 2015b). However, most physical habitat models concentrate on the flow velocity, water depth and substrate (Bui, Abdelaziz, and Rutschmann 2013; Noack, Schneider, and Wieprecht 2013). The physical modelling is based on field surveys and data sampling, which is mostly done by tachymetric surveys of the riverbed topography and the use of digital terrain models or aerial photographs (Linnansaari et al. 2013; Jorde and Schneider 2015b). Cross-sectional measurements with high precision are used to achieve an accurate representation of the physical conditions of the river (Parasiewicz 2001; Vezza 2010; Linnansaari et al. 2013; Jorde and Schneider 2015b). Based on these measurements, the wetted perimeter of the observed river is divided into cells which the hydraulic conditions are calculated for (Linnansaari et al. 2013). Hence, such models provide an explicit description of the hydraulic condition in each cell (Lamouroux et al. 2017). The modelling of the hydraulic condition of a river can be achieved by considering a different number of dimensions. Zero-dimensional models do not include the calculation of hydraulic characteristics, but are based on the interpretation of measured hydraulic data (Jorde and Schneider 2015b). One-dimensional (1-D) hydraulic models only consider the horizontal component of the flow velocity and standard equations of Manning and Bernoulli are used to calculate the hydraulic conditions (Vezza 2010; Jorde and Schneider 2015b). Multi-dimensional models account for two (2-D) or three (3-D) components of the flow velocity (Poff, Tharme, and Arthington 2017). The flow conditions are then calculated based on the conservation of mass and momentum using finite element or finite volume methods and can include empirical components to take turbulences into account (Vezza 2010; Jorde and Schneider 2015b). The computational effort restricted the use of multidimensional methods in the past. Nowadays, the use of multidimensional models has increased, especially to model complex river reaches as they often need a denser and more dynamic cell-structure (Linnansaari et al. 2013). Additionally, multidimensional models are able to simulate spatial variations more accurately and therefore describe the heterogeneity of the hydraulic conditions in natural river systems in a more detailed way (Petts 2008). Nevertheless, multidimensional models require extensive field data collection and high computational effort and are therefore more expensive to apply (Acreman and Dunbar 2004; Linnansaari et al. 2013). Thus, the study site, the available data, the desired resolution and the maximal possible computational effort influence the choice of the dimension of the hydraulic model (Jorde and Schneider 2015b).

The modelling of the morphology and the substrate is also based on data collection and takes the size and composition of the substrate as well as the accessibility of the interstitial into account (Jorde and Schneider 2015b). To achieve accurate and dynamic information of the morphology, hydro-morphological models can be included in the physical habitat modelling process, which includes the simulation of morphological conditions and sediment transport (Bui, Abdelaziz, and Rutschmann 2013). Mostly, the simulation of hydro-morphological processes is simplified by using quasi-stationary conditions to reduce the complexity and amount of numerical effort (Bui, Abdelaziz, and Rutschmann 2013). This means that firstly the hydraulic conditions such as velocity and water depth are calculated based on the assumed constant conditions of the river bed (Bui, Abdelaziz, and Rutschmann 2013). Afterwards the morphological conditions, such as substrate size and composition as well as changes in the river bed level, are estimated based on the assumed constant hydraulic conditions (Bui, Abdelaziz, and Rutschmann 2013). Most physical habitat models, however, only consider substrate data collected during field surveys and do not include a simulation of the morphology itself.

2.2.4.2 Biological Module

A biological module is used to describe the response of fish to the modelled physical conditions of the environment (Parasiewicz 2007a). It creates a connection between the density or occurrence of a species within a reach and its specific hydraulic characteristics (Lamouroux et al. 2017). The goal of a biological model is to establish habitat preferences for target species, stages of life or for communities, guilds or assemblages (Jorde and Schneider 2015e; Poff, Tharme, and Arthington 2017).

A biological model uses available data obtained during data collection and fish sampling combined with the documented surrounding physical conditions to define habitat preference (Parasiewicz 2007a; Jorde and Schneider 2015e; Lamouroux et al. 2017). Additionally, expert knowledge can be used if data collection is not sufficient or not possible (Parasiewicz 2007a; Jorde and Schneider 2015e). To link the physical characteristics of a river to habitat preferences, statistical methods are mostly used. Such preference models can be univariate and consider individual habitat variables, or multivariate and account for interactions between habitat variables (Noack, Schneider, and Wieprecht 2013). In addition to statistical models, fuzzy logic approaches are used to establish habitat preferences models.

The preference models then create suitability values for different physical conditions using suitability indices SI, which are in the range of 0 to 1 (0: unsuitable habitat; 1: optimal habitat) (Bui, Abdelaziz, and Rutschmann 2013; Jorde and Schneider 2015e). Based on the simulated hydraulic conditions in each cell achieved by the physical model, suitability indices can then be calculated for each cell of the river.

Univariate models are most often used, for example in the original version of PHABSIM, and they correspond to the classic method of linking two values (Parasiewicz and Walker, J. 2007; Jorde and Schneider 2015e). This means, the suitability of a habitat is expressed as the function of a single physical variable such as water depth or flow velocity (Noack, Schneider, and Wieprecht 2013). Different methods exist to combine the univariate SI -values of different physical conditions (e.g. water depth, flow velocity and substrate) such as multiplication, arithmetic mean, geometric mean or selecting the minimum value to achieve the composite amount of habitat quality in each cell (Linnansaari et al. 2013; Noack, Schneider, and Wieprecht 2013; Jorde and Schneider 2015b). However, in order to use such mathematical operators, firstly all variables should be equally important and secondly, all variables should be independent from another (Noack, Schneider, and Wieprecht 2013). This is the major limitation of univariate preference functions as it neglects the natural interaction of physical variables.

In contrast, multivariate methods, such as logistic regression, are commonly used, for example in MesoHABSIM (Parasiewicz 2001; 2007a) and HARPHA, a more complex version of PHABSIM (Parasiewicz and Walker, J. 2007). Furthermore, multivariate fuzzy logic rules are used to establish habitat preferences as for example in CASiMiR (Noack, Schneider, and Wieprecht 2013; Jorde and Schneider 2015e). The advantage of fuzzy logic is that imprecise or qualitative data can easily be included and intermediate states can be taken into account (Noack, Schneider, and Wieprecht 2013). This is especially important when modelling ecosystems, where transitions are mostly gradual (Noack, Schneider, and Wieprecht 2013). Both multivariate statistical methods and multivariate fuzzy methods are more complex than univariate models, but we do not need to assume that the variables are independent from each other and we do not require mathematical operators to combine individual suitabilities (Noack, Schneider, and Wieprecht 2013). Additionally, interactions of habitat parameters can be considered (Noack, Schneider, and Wieprecht 2013)

Parasiewicz and Walker, J. (2007) showed the importance of the accuracy of a biological model (see also Section 3.4.1). Comparing two microhabitat models (PHABSIM and HARPHA) to one mesohabitat model (MesoHABSIM), they found out that not the difference in the scale used led to major differences in the results but the quality of the biological model. Multivariate methods and the inclusion of additional physical parameters such as cover structures and existing vegetation highly influenced the accuracy of the biological model as well as the results of the physical habitat model in general. (Parasiewicz and Walker, J. 2007)

Similarly, Noack, Schneider, and Wieprecht (2013) used a case study for modelling spawning habitats for graylings in Aare River in Switzerland when comparing univariate models to multivariate fuzzy models. The results of both model types were compared to spawning sites mapped during a field campaign. It was shown that the multivariate fuzzy approach could predict the spawning grounds better than all univariate models using geometric mean, arithmetic mean or products as mathematical operators. Additionally, the results of the different mathematical operator options showed high variabilities which presents the limitations of using mathematical operators to model naturally complex ecological processes. (Noack, Schneider, and Wieprecht 2013)

Both examples show the importance of good biological models in order to achieve accurate results in habitat modelling. Model users must understand the biological models used in their habitat simulation to correctly interpret the results and possibly identify limitations. Furthermore, we should remember that physical habitat models do not account for biological interactions such as predator pressure, habitat and food competition, metabolic processes and energy budgets, which, however, are major factors which influence habitat quality (Noack, Schneider, and Wieprecht 2013).

2.2.4.3 Outputs

In most habitat modelling approaches, the outputs of physical habitat models for a river section are expressed using Weighted-Usable-Area value (WUA) [m²] (Dunbar, Alfredsen, and Harby 2012; Poff, Tharme, and Arthington 2017). This value is the sum of the products of each area A_i of each segment or cell *i* with its corresponding SI value SI_i (Formula 1) (Bui, Abdelaziz, and Rutschmann 2013; Vezza 2010; Jorde and Schneider 2015e).

$$WUA = \sum A_i * SI_i \tag{1}$$

with WUA = weighted usable area [m²]

A_i = area of each river segment or cell i [m²]

SI_i = suitability index of each river segment or cell i [-]

The WUA values give us information about the available habitat in the river section for a specific discharge and can also be used for the presentation of research results as well as for the comparison of different management or restauration options. For methods including hydraulic modelling, the WUA values or in general the quantity of suitable habitat can easily be calculated for several different discharges which can be used to compare different situations in the river. For zero-dimensional models, such as in many mesoscale models, the habitat quantity is only known for the surveyed discharges and can only be interpolated or extrapolated for other discharge values (Dunbar, Alfredsen, and Harby 2012).

The relationship between habitat quantity and discharge can be presented in so-called habitat rating curves which allow the transformation of discharge values into habitat quantities. Additionally, the results of a physical habitat model can be linked to a hydrological time series creating a habitat time series using habitat rating curves (Linnansaari et al. 2013). Analysing the habitat quantity of each historical discharge value, for example based on WUA, gives us a basic understanding of the habitat conditions in a river such as amount and frequency as well as annual patterns of habitat quantities (Petts 2009). Habitat rating curves and habitat time series are especially valuable for river restoration planning or environmental flow assessment (Parasiewicz 2008; Linnansaari et al. 2013).

2.3 Environmental Flows

2.3.1 Term and Definition

As mentioned above, anthropogenic activities can alter the flow regime in a river. In particular, water abstraction for the municipal or industrial water supply or water impoundment and diversion for hydropower production reduce the amount of freshwater available to maintain the riverine ecosystem (Rosenberg, McCully, and Pringle 2000). Although the importance of specific flow values to sustain river ecosystems has been clear for several decades, there are numerous terms used in this field of research and for each of these terms no uniform definition even exists. Additionally, the meaning of the terms can vary among different users or usages (Horne et al. 2017). The term environmental flow (e-flow) is the most used and widely accepted term (Acreman and Ferguson 2010), however, several other terms exist such as instream flow, ecological flow, ecological demand, environmental water allocation, ecological flow requirements as well as minimum flow or compensational flow (Acreman and Dunbar 2004; Horne et al. 2017; World Meteorological Organization 2019). The latter is different to the other terms because it only accounts for the human water needs downstream (Acreman and Dunbar 2004).

As part of the Brisbane Declaration developed at the 10th International River Symposium and International Environmental Flows Conference, environmental flows were defined as "the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration 2007).

A similar definition was given by The Nature Conservancy (TNC). Here, environmental flows were defined as “the quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and sustain the goods and services they provide for people” (TNC 2018).

Both definitions firstly emphasize that environmental flows refer to a flow regime rather than a fixed flow value by using the terms quantity and timing. Secondly, in addition to its importance for a river ecosystem, the importance of the sustainability of such ecosystems for human needs is shown. According to Linnansaari et al. (2013), the definition from the Brisbane Declaration is the most inclusive definition because it includes the protection of natural ecosystems as well as the water needs of all stakeholders.

The term environmental flow is not used directly in the European Water Framework Directive (WFD), but the European Commission published a guidance document on the implementation of environmental flows as part of the framework of the WFD (European Commission 2016). In this guidance document the term ecological flow is used to emphasize its role in the assessment of the ecological status of water bodies and to avoid confusion with the broader term environmental flows used in other concepts (European Commission 2016). The document includes a working definition of ecological flows as flows which “are considered within the context of the WFD as an hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies as mentioned in Article 4(1)” (European Commission 2016). Article 4(1) regulates the objectives of the WFD, which require an at least good ecological status together with an at least good chemical status for natural surface waters (Directive 2000/60/EC, European Commission 2000). This definition does not give explicit information about how ecological flows can be characterized, as the Brisbane Declaration or TNC’s definition do. It does, however, refer to the environmental objectives of the WFD which in the opinion of WFD are sufficient enough to sustain a river ecosystem. Although, it does not directly address ecosystem needs or services provided by river ecosystems, this definition also addresses hydrological flow regimes instead of constant flow values. Furthermore, it is conceptually more limited than the term environmental flow because it excludes the requirements of additional stakeholders (Linnansaari et al. 2013). This is due to the fact that the WFD concentrates on the ecological status of river systems and not on the water needs of other stakeholders.

2.3.2 Basic Principles of Environmental Flow Assessment

The importance of environmental flows has been known about in the United States of America since the end of the 1940s and in numerous other countries in the world since the 1970s and 1980s (Tharme 2003). This process was connected to the development of environmental and water protection laws, finally leading to the development of e-flow assessment methods estimating the flow values necessary to maintain and protect an entire riverine ecosystem (Tharme 2003). Based on the definitions given above, the environmental flow assessment includes compromises between water users and ecosystem functions resulting in engineering constraints, economic and societal aspects (Lamouroux et al. 2017).

As mentioned in Section 2.1.2, river ecosystems are characterised by several different features which the native biota has adapted to as well as depends on. This implies that any change of the natural flow regime due to water abstraction or diversion will lead to changes in the natural composition of the biota. The science of e-flow assessment has the goal of maintaining and protecting riverine ecosystems (Tharme 2003), bringing with it the necessity of having methods to assess the effects of hydrological alterations and to define allowable alterations which sustain riverine ecosystems. As already mentioned, Poff and Zimmerman (2010) showed that it was not possible to generate a quantitative relationship between human alterations of the ecosystem and ecological response. In addition, Poff et al. (1997) clarified that the same human activity could cause different degrees of change when used at different locations. Based on these aspects, it becomes clear that the allowable alteration of the natural flow regime to sustain the integrity of the riverine ecosystem cannot easily be calculated. Thus, tools and methods are necessary to predict the ecological effects of water abstraction or flow regulation which can be used as a basis for decision-making (Petts 2009).

There are numerous existing strategies to assess environmental flow requirements, however, they differ in the way they consider the important characteristics of the ecosystems mentioned in Section 2.1.2. Several studies formulate basic principles within the tools used for estimating environmental flow requirements or for assessing the effects of hydrological alteration in general which need to be considered. For example, Poff et al. (1997) explains that such tools should incorporate all five components of the natural flow regime mentioned. Concentrating on only one of these components or, for example, using constant minimum flows, as well as focusing on preferences of only one species is not considered to be sufficient for ecosystem maintenance (Poff et al. 1997). Petts (2009) also realised the importance of the natural flow regime and recommends that the flow variability should be sustained by creating a flow regime which mimics the natural variability of flows including flood and droughts. This is based on the two following fundamental principles: Firstly, the evolution of aquatic biota is shaped by the natural flow regime and secondly, every river has a characteristic flow regime with associated biota (Petts 2009).

According to Bunn and Arthington (2002), there are four guiding principles, which need to be considered when analysing the effects of altered flow regimes:

1. Flow is a major determinant of physical habitat in streams which in turn is a major determinant of biotic composition
2. Aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes
3. The maintenance of natural patterns with longitudinal and lateral connectivity is essential to the viability of the population of many riverine species
4. The invasion and success of exotic and species introduced into rivers is facilitated by the alteration of its flow regime

The extent to which the existing e-flow assessment methods include and consider these basic principles differ largely. Tharme (2003) mentioned in her scientific review over 200 existing methods. The most common methods in this field of research are presented in the following sections. Several authors divide the methods into four categories: hydrological, hydraulic rating, hydraulic habitat simulation and holistic methods (Tharme 2003; Linnansaari et al. 2013; World Meteorological Organization 2019).

2.3.3 Hydrological Methods

Hydrological methods of estimating environmental flows are based on hydrological data, mostly historic discharge records and because of this they consider the flow regime (Tharme 2003; Petts 2009; Linnansaari et al. 2013; European Commission 2016; World Meteorological Organization 2019). Acreman and Dunbar (2004) defined two different groups of methods, look-up tables and desktop methods which can be considered hydrological methods (Tharme 2003). In general, hydrological methods, including look-up tables and desktop methods, are the most widely used approaches worldwide (Tharme 2003; Acreman and Dunbar 2004; Linnansaari et al. 2013; European Commission 2016). Within each group, the methods differ in the way they consider and make use of the hydrological regime.

2.3.3.1 Look-up Tables

The most simple approaches in this group use fixed values, fixed percentages or hydrological indices to set environmental flow values such as the mean annual flow (MAF) or the mean annual low flow (MALF) values (Acreman and Dunbar 2004; Linnansaari et al. 2013). Such methods assume that proportions of these hydrological indices, for example fixed percentages, are enough to sustain the riverine ecosystems (Linnansaari et al. 2013). The most commonly used method is the Tennant or Montana method (Tennant 1976), which was developed based on data collected from eleven rivers in Montana, Nebraska and Wyoming (Linnansaari et al. 2013). This method shows that 10% of the MAF is necessary to sustain the riverine ecosystem for short time periods and 30% of the MAF is needed to maintain the integrity of river ecosystems (Tennant 1976; Linnansaari et al. 2013). Additionally, numerous different percentages have been defined worldwide, often without the analysis of existing data, and several adaptions of the Tennant method exist. For example, Caissie and El-Jabi (1995) adapted the percentages of the Tennant method to 25% to maintain aquatic life in the Canadian Atlantic provinces. Furthermore, Tessman (1980) accounted for monthly changes in the flow regime using mean monthly flow values (MMF) and therefore differentiated between high-, intermediate and low-flow months (Pastor, A. et al. 2014). The following rules are recommended (Linnansaari et al. 2013; Pastor, A. et al. 2014):

- MMF, if MMF < 40% of MAF (for low-flow months)
- 40% of MAF, if 40% MAF < MMF < 100% MAF (for intermediate-flow months)
- 40% of MMF, if MMF > MAF (for high-flow months)

Similarly, Pastor, A. et al. (2014) developed another method when accounting for seasonal changes in the flow regime:

- 60% MMF, for low-flow seasons
- 45% MMF, for intermediate-flow seasons
- 30% MMF, for high-flow seasons

In addition to the use of fixed percentages of flow values, environmental flow thresholds can also be derived from flow duration curves which consider the proportion of time a certain flow value is equalled or exceeded (Tharme 2003; Linnansaari et al. 2013). Here as well, several different values are used worldwide. For example, in the UK Q90 or Q95 are used as indices of natural low flow, which accounts for flow which is equalled or exceeded 90% or 95% of the time (Acreman and Dunbar 2004). These values were also recommended by Acreman and Ferguson (2010) as threshold values for so-called hands-off flows, where water withdrawal is stopped to ensure ecosystem protection. Under the USA Federal Clean Water Act, which was brought into effect to protect water quality, the use of 7Q10 or 7Q2 is recommended which stands for the lowest flow in seven consecutive days within a 10- or 2-years return period, respectively. Even though this method was proposed in order to address water quality issues, it is used to set environmental flow values as well (Richter et al. 2012). Additionally, based on recommendation of the New England U.S. Fish and Wildlife Service (USFWS), the median monthly flow, Q50, is used to estimate environmental flow requirements for flow catchments with good hydrological data (USFWS 1981).

In general, look-up tables are based on simple percentages or statistical values. Mostly they do not account for the natural flow regime, because they reduce the hydrological data to simple hydrological indices, such as mean annual flow values (Linnansaari et al. 2013). However, there are methods, such as the Tessman method (Tessman 1980) and the method developed by Pastor, A. et al. (2014), which take seasonal changes in flow values into account. Nevertheless, these methods do not include any ecological information and are also used worldwide without any adaptions, even though they were calibrated for specific regions (Acreman and Dunbar 2004). For this reason, the results of such simple methods underlay high uncertainties (Acreman and Dunbar 2004). Additionally look-up tables eliminate the ecological importance of extreme conditions by averaging discharge values and do not consider the importance of flow timing (Richter et al. 1997). Caissie, El-Jabi, and Hébert (2007) compared the results of the use of Q50, 25% of the MAF, Q90 and 7Q2 and 7Q10 and could show, firstly, that all results vary strongly between the different methods and secondly, that Q90, 7Q10 and 7Q2 generated lower flow values then 25% of the MAF or Q50, which could lead to serious deterioration of the riverine ecosystem. Nevertheless, such methods are still widely used especially because of their easy and low cost use and the fact that detailed data is not needed (Acreman and Dunbar 2004; Linnansaari et al. 2013). To sum up, look-up values do not account for the importance of the natural flow regime nor the connection between hydrology and biology mentioned in Section 2.3.2. Hence, the methods should only be used to set preliminary flow targets or in low risk and low-controversy situations (Linnansaari et al. 2013).

2.3.3.2 Desktop Methods

In comparison to look-up tables, desktop methods take the full range of hydrological data into account and focus on the analysis of this data or data developed by hydrological simulations (Acreman and Dunbar 2004). Such methods are based on the assumption that the natural variability and seasonality of the hydrological regime need to be maintained to conserve the river ecosystem (Acreman and Dunbar 2004; European Commission 2016).

One example of this kind of method is the Range of Variability Approach (RVA, Richter et al. 1997) which is based on the method of the Indicators of Hydrologic Alteration (IHA, Richter et al. 1996). The method shows that a hydrological regime is of major importance to the sustainability of natural ecosystems and their biodiversity and therefore the natural flow paradigm is used as a basis (Richter et al. 1996; Richter et al. 1997). The IHA approach was developed to identify and quantify human-induce hydrological alteration (Richter et al. 1996). It calculates originally 32 statistical hydrological indices, or IHA parameters, for pre-impacted and post-impacted hydrological times series (Richter et al. 1996). It then compares the hydrological indices to detect anthropogenic alteration (Richter et al. 1996). The IHA parameters are classified into five groups which were chosen to provide significant ecological information of the features of river ecosystems (Richter et al. 1996). Group 1 includes the mean values of the daily water conditions for each month. The second group takes the magnitude and the duration of extreme annual water conditions into account, whereas the third group contains parameters expressing the timing of annual extreme water conditions. Group 4 identifies the frequency and duration of high and low pulses and Group 5 gives scientists information about the rate and the frequency of changes in the water condition. The IHA method is the first step in the RVA which was developed to create more appropriate river management strategies for rivers altered by human activity (Richter et al. 1997). For each IHA parameter a management target is then selected as a specific range, in which the IHA parameter can be altered (Richter et al. 1997). Hence, the river system is managed in a way that it falls into the natural variability range of the natural system (Richter et al. 1997). The management targets are chosen by management team based on available ecological information or can be set to +/- 1-times of the standard deviation, if no further information is available (Richter et al. 1997). The targets are then used to create guidelines for the river management, for example to set environmental flow rules (Richter et al. 1997). Additionally, monitoring and research programs should be implemented which allow the further adjustment of the targets in the future based on newly accumulated information (Richter et al. 1997). IHA software is available which calculates and visualizes the IHA parameters.

Newer versions of the software calculate the so-called Environmental Flow Components (EFC) in addition to the IHA parameters (TNC 2009). The EFCs consist of five different types, low flows, extreme low flows, high flow pulses, small floods and large floods. It is assumed that those components represent the full spectrum of flow conditions necessary to sustain riverine ecological integrity (TNC 2009). 34 EFCs are calculated representing their frequency, duration, peak flow timing and rise and fall rates of each EFC type (TNC 2009). The IHA method is widely used for the detection of hydrological alteration in combination with the EFCs or with the RVA method and therefore creates the basis for the assessment of environmental flows (Tharme 2003; Acreman and Dunbar 2004; Petts 2009; Linnansaari et al. 2013; Pastor, A. et al. 2014).

Similar to the Range of Variability Approach, Richter (2009) developed the Sustainable Boundaries Approach (SBA), which also limits the extent of the alteration of the hydrological regime by human activity. As with the RVA, the SBA also realises the importance of the natural flow paradigm and therefore it focusses on maintaining the natural annual flow pattern and the natural variability of a hydrological regime. This approach is a new way of expressing the desired, more natural flow regime at a river impacted by human activity. However, it was originally not considered to be an environmental flow assessment method itself, as it does not explicitly calculates discharge values, but as a method which should be applied in the environmental flow assessment process (Richter 2009). Furthermore, it only presents allowable percentages of deviation from the natural hydrograph which the altered flow regime can be changed into in order to maintain native communities (Richter 2009). Nevertheless, Richter et al. (2012) suggest the following rules to a achieve certain level of protection for natural ecosystems, which can be seen as a guideline for the setting of environmental flows (Figure 1):

- For a high level of ecological protection: avoidance of flow alteration greater than 10%
- For a moderate level of ecological protection: limitation of flow alteration between 11 and 20%
- Alteration of the flow regime by more than 20% are expected to lead to moderate or major ecological protection

However, such statistical calculations of hydrographs cannot address the impacts of short-term operations of dams (Poff, Tharme, and Arthington 2017).

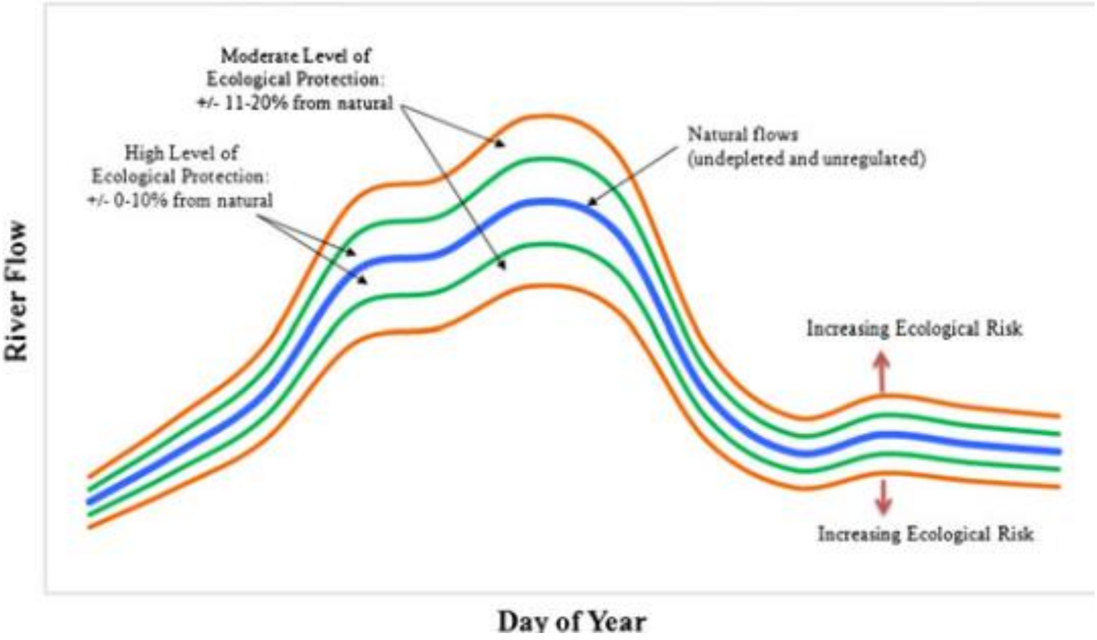


Figure 1 Suggested standards for the different levels of ecological protection based on the Sustainable Boundaries Approach (Richter et al. 2012)

In contrast to the RVA and the SBA which are both based on the analysis of hydrological data, the Lotic-Invertebrate Index for Flow Evaluation (LIFE) technique also includes ecological data (Extence, Balbi, and Chadd 1999). This method was developed to assess the impact of variable flows on the benthic populations based on British benthic macroinvertebrate data. It showed correlations between the macroinvertebrate species found during sampling at variable flow conditions. The macroinvertebrate data was used to classify species into six flow groups (from I rapid to V standing and VI drought resistant). A scoring system was then developed, which creates a connection between each flow group and each abundance class (class A estimated abundance 1-9 to class E estimated abundance 10000 and more) and a score value fs (Table 1). The sample data was transferred into the score values fs which are then used to calculate the LIFE for the river section (Formula 2 and Table 1) (Extence, Balbi, and Chadd 1999):

$$LIFE = \frac{\sum fs}{n} \tag{2}$$

with

$\sum fs$ = the sum of individual taxon flow scores for the whole sample

n = the number of taxa used to calculate $\sum fs$

Table 1 Scores fs for different abundance categories of taxa associated with flow groups I – VI (Extence, Balbi, and Chadd 1999)

Flow groups		**Abundance categories**			
		A	**B**	**C**	**D/E**
I	Rapid	9	10	11	12
II	Moderate/fast	8	9	10	11
III	Slow/sluggish	7	7	7	7
IV	Flowing/standing	6	5	4	3
V	Standing	5	4	3	2
VI	Drought resistant	4	3	2	1

In general, this calculation leads to higher LIFE values for higher discharges (Extence, Balbi, and Chadd 1999). Several studies showed the correlation between discharge values and LIFE values, which allows the use of this connection between key taxa and hydrological conditions in hydro-ecological works (Extence, Balbi, and Chadd 1999). The authors suggested using the LIFE method as part of, together with or even instead of existing environmental flow methods because information is gained on critical situation which influence the sustainability of benthic organisms. One major advantage of this method is that it uses existing macroinvertebrate data which is sampled routinely, for example, as part of the status assessment for the WFD (Acreman and Dunbar 2004).

Desktop methods are considered to be quick and easy to apply due to their use of existing data which is mostly hydrological or ecological data (Tharme 2003; Acreman and Dunbar 2004; Linnansaari et al. 2013; Pastor, A. et al. 2014). In addition, intensive field work is not needed which makes them cheap to apply (Tharme 2003; Acreman and Dunbar 2004; Linnansaari et al. 2013; Pastor, A. et al. 2014; Poff, Tharme, and Arthington 2017). Methods, such as the RVA or SBA, try to maintain the natural hydrographs and the natural variability in the hydrological regime and therefore consider the magnitude, duration and timing of natural high and low flow events (Acreman and Dunbar 2004; Linnansaari et al. 2013). This is a major advantage in comparison to look-up tables which eliminate the natural annual hydrological pattern and extreme flow events (Richter et al. 1997). Desktop methods look at the available data in much more detail and even connect ecological data to hydrological data, for example to set management targets for the IHA parameters. However, such methods do not take the hydro-morphological situation in the river into account which is an important parameter for the habitat suitability in addition to the hydrological regime (European Commission 2016; World Meteorological Organization 2019). This has created uncertainties especially regarding ecological processes (Linnansaari et al. 2013; World Meteorological Organization 2019). Furthermore, reasonable results can only be achieved if long hydrological time series of at least 12 years (Petts 2009) or 20 years (Richter et al. 1997) exist. Additionally, the results can be influenced due to the “naturalizing” effect of gauged discharges in highly impacted catchments (Petts 2009). The LIFE method, however, includes ecological data, which can be linked to flow values and therefore is more ecologically accurate. Nevertheless, the LIFE method also does not consider the morphological situation and is limited as it only accounts for benthic organisms.

Desktop methods are used to set preliminary flow targets at the planning level of water resource management or at the reconnaissance level (Tharme 2003; Poff, Tharme, and Arthington 2017). However, they can be useful tools in the process of environmental flow assessment as part of habitat simulation or holistic approaches (Linnansaari et al. 2013; Poff, Tharme, and Arthington 2017).

2.3.4 Hydraulic Rating Methods

Hydraulic rating methods assess the relationship between simple hydraulic indices, for example water depth or wetted perimeter and the discharge in a river (Acreman and Dunbar 2004; Linnansaari et al. 2013). Such methods assume that the ecosystem integrity can be maintained by ensuring some threshold values for these hydraulic indices (Tharme 2003). Therefore, they reduce the assessment of an instream habitat to some hydraulic indices which are easier to determine (Poff, Tharme, and Arthington 2017).

The most widely used approach in this group of methods is the wetted perimeter approach (Gippel and Stewardson 1998). It assumes that the instream habitat can be estimated and expressed using threshold values for the wetted perimeter. The wetted perimeter is therefore an indicator of the aquatic habitat, which must be maintained to guarantee the integrity of a river ecosystem (Poff, Tharme, and Arthington 2017). It is used to define the minimum acceptable discharges which maintain these wetted perimeter thresholds at some particular cross-sections (Poff, Tharme, and Arthington 2017). The wetted perimeter is calculated by using cross-sectional measurements of the riverbed topography and is hence used on a local scale and is specific for the particular river section (Pastor, A. et al. 2014).

Such methods need a moderate amount of data and field work and therefore they are used quickly and often (Acreman and Dunbar 2004; Linnansaari et al. 2013; Poff, Tharme, and Arthington 2017). In comparison to hydrological methods, they take the physical instream habitat into consideration. However, they do not take any other biologically relevant aspects other than water depth into account. Therefore, the habitat assessments are too simplistic and perhaps flawed, as they do not account for other important influential factors (Linnansaari et al. 2013). This means that such methods have a low resolution and result in environmental flow estimations of low confidence (Poff, Tharme, and Arthington 2017). Furthermore, these methods cannot easily be adjusted to seasonal changes or different target species (Linnansaari et al. 2013). Additionally, some studies have revealed difficulties in identifying specific thresholds (Acreman and Dunbar 2004; Linnansaari et al. 2013),

Hydraulic rating methods should only be used in situations when there is little negotiation involved or as part of habitat simulation or holistic measures (Poff, Tharme, and Arthington 2017). They were widely used some time ago and are seen as the basis of the development of habitat simulation methods (Poff, Tharme, and Arthington 2017). Then, they were superseded by habitat simulations (Tharme 2003; Poff, Tharme, and Arthington 2017).

2.3.5 Habitat Simulation Methods

Habitat simulation models developed from hydraulic rating approaches but they take the hydraulic conditions over longer river sections into account and include hydrological and ecological information. As already explained in Section 2.2, most habitat models simulate the physical habitat conditions in a river using hydraulic simulations in combination with ecological response data. Due to their ability to calculate habitat quantity and quality for different discharge conditions, several habitat models are also used to assess environmental flows. The most common examples of microhabitat models are PHABSIM and CASiMiR and the mesohabitat model MesoHABSIM, mentioned in Section 2.2.

PHABSIM was developed in North America in the early 1970s by the USFWS as part of the Instream Flow Incremental Methodology (IFIM, Bovee 1982). It was used during numerous water allocation issues in the USA and internationally and was the first widely available physical habitat model (Tharme 2003; Parasiewicz and Walker, J. 2007; Noack, Schneider, and Wieprecht 2013). In the traditional approach, the hydraulic conditions are modelled on cross-sectional velocities in combination with univariate preference models (Acreman and Dunbar 2004). Nowadays, it can also include 2-D or 3-D hydraulic models and can account for additional parameters (Acreman and Dunbar 2004). Additionally to the original univariate approach of calculating habitat preferences, multivariate models can also be used such as within the more complex version HARPHA (Parasiewicz and Walker, J. 2007).

CASiMiR was developed in the 1990s at the Institute of Hydraulic Engineering at the University of Stuttgart with the objective of creating more ecology-related minimum flow solutions (Noack, Schneider, and Wieprecht 2013). It is now used widely at an international level. Since 1998, it has been based on the multivariate fuzzy approach and since 2003, 1-D and 2-D hydrodynamic models have been included in the modelling process. It additionally includes a macroinvertebrate simulation tool. (Noack, Schneider, and Wieprecht 2013)

MesoHABSIM is a mesoscale approach for modelling instream habitats, which has been used several times to assess environmental flows as well as to develop regional environmental flow methods (Parasiewicz et al. 2013). It includes a specific data collection strategy as well as a strategy for analysing the available habitat over a time period. As this method is used in this study, it is explained in more detail in Chapter 3.

Habitat models commonly use habitat rating curves to identify discharge which leads to optimal habitat levels as well as minimum and critical habitat levels (Linnansaari et al. 2013). Taking the surrounding conditions and the economic use of the diverted water into account, a habitat threshold is a compromise between economic and environmental aspects such as habitat availability. Furthermore, a habitat times series can be used to identify important seasonal discharge patterns which the species are used to (Jorde et al. 2001). Environmental flow values and threshold values, which limit the water abstraction, can then be set for each river section to protect the sustainability of river ecosystems. (Jorde et al. 2001; Linnansaari et al. 2013).

In general, the results of habitat simulation models in environmental flow assessments are considered to be more accurate than the results of hydrological or hydraulic rating models as they take both hydraulic and ecological aspects into account (Linnansaari et al. 2013; World Meteorological Organization 2019). As such methods allow the simulation of small-scale variabilities in the hydraulic conditions and substrates, they provide information on several important aspects of riverine ecosystems (Pastor, A. et al. 2014). The results of such models have a high resolution and complexity which increases confidence in the results (Poff, Tharme, and Arthington 2017). Once a habitat model has been developed, it can easily be used to simulate the habitat conditions for several different scenarios (Poff, Tharme, and Arthington 2017) and can additionally be used in combination with morphological processes (Dunbar, Alfredsen, and Harby 2012; World Meteorological Organization 2019). Furthermore, mesoscale models use ecologically relevant scales which are linked to ecological communities and the life histories of many species (Dunbar, Alfredsen, and Harby 2012).

Nevertheless, hydraulic simulation models are based on detailed topographic and hydraulic data, which can only be attained by doing intense field work. Additionally, biological data or expert knowledge is needed to create preference models. Due to these aspects, habitat simulation models are coupled with high costs and time-consuming field work and data collection (Dunbar, Alfredsen, and Harby 2012; Linnansaari et al. 2013; Pastor, A. et al. 2014; Poff, Tharme, and Arthington 2017). As they are developed for specific river sections, their results cannot be transferred to other river stretches (Pastor, A. et al. 2014). Furthermore, habitat models are criticised because of the development of habitat preferences, which always include simplifications and uncertainties (see Section 2.2.4.2) (Dunbar, Alfredsen, and Harby 2012). Most preference models are based on empirical or simplified approaches (Acreman and Dunbar 2004). Therefore, the results of habitat simulation models highly depend on the habitat suitability model, which makes it difficult to validate or transfer the results (Dunbar, Alfredsen, and Harby 2012). Mesoscale models are only able to calculate the habitat suitability of observed conditions which means predictions for unobserved conditions are imprecise (Dunbar, Alfredsen, and Harby 2012).

Habitat simulation models are commonly used in water resource development with moderate to high conservation and strategic importance (Poff, Tharme, and Arthington 2017). Based on their ability to quantify the physical habitat of a variety of different scenarios, they are used in decision-making processes and are included in holistic frameworks (Dunbar, Alfredsen, and Harby 2012; Poff, Tharme, and Arthington 2017).

2.3.6 Holistic Methods

Holistic methods cover a broader spectrum than all of the other methods as they assess the whole ecosystem and are combinations of hydrological, hydraulic and habitat simulation methods (Tharme 2003; Acreman and Dunbar 2004; Pastor, A. et al. 2014; Stewardson, Webb, J. A., and Horne 2017). They have been developed due to the increase in research in the field of flow-ecology relationships and the need to sustain the ecosystem services as well as the structure of the entire natural ecosystem (Poff, Tharme, and Arthington 2017). Projects on river restoration and conservation have emerged leading to a change in focus from preserving individual species to protection of the whole ecosystem (Poff, Tharme, and Arthington 2017). Maintaining natural flow regimes and their natural variabilities is still a major focus of such strategies (Acreman and Dunbar 2004). However, hydrological aspects can be linked to processes and responses in the fields of ecology, geomorphology and even the economy and society (Poff, Tharme, and Arthington 2017). Such methods are therefore based on hydrological and ecological data and also include a considerable amount of expert knowledge (Acreman and Dunbar 2004; Poff, Tharme, and Arthington 2017). Holistic methods are often based on the work of panels of experts from different fields of river science as well as other stakeholders (Poff, Tharme, and Arthington 2017; World Meteorological Organization 2019). This allows the integration and incorporation of knowledge from different fields of research which then create the basis for the prediction of ecological responses to different flow regimes (Stewardson, Webb, J. A., and Horne 2017; World Meteorological Organization 2019).

One of the first holistic methods was developed on a South African workshops on environmental flow assessments in the 1990s which was attended by several most experienced river scientists in the country (King et al. 2008). After further developments and applications, the method was named the Building Block Methodology (BBM). The concept of the BBM is based on the identification of flow components of hydrological flow regimes, the so-called blocks, which are considered to be especially important for the maintenance of river ecosystems (King et al. 2008; Pastor, A. et al. 2014). The BBM assumes that the blocks can be identified and characterised using their magnitude, timing, duration and frequency, and then combined to construct a modified flow regime for a specific river (King et al. 2008). The characterisation of these blocks is then done by experts at workshops, where all the available data, such as hydrological data, hydrological indices, cross-sectional hydraulic data as well as ecological data is used (King et al. 2008). The important features of the newly modified flow regime are designed based on these workshops, such as the magnitude of the baseflow as well as the duration and timing of floods or small pulses in each wet and dry seasons (King et al. 2008). The modified flow regime is then constructed by combining the first building block, which designs the baseflow components, with several subsequent building blocks, which add higher floods which are essential in order to maintain the ecosystem (Figure 2) (King et al. 2008). Since its development, the BBM has been used numerous times in South Africa and parts of Eastern Africa (Poff, Tharme, and Arthington 2017).

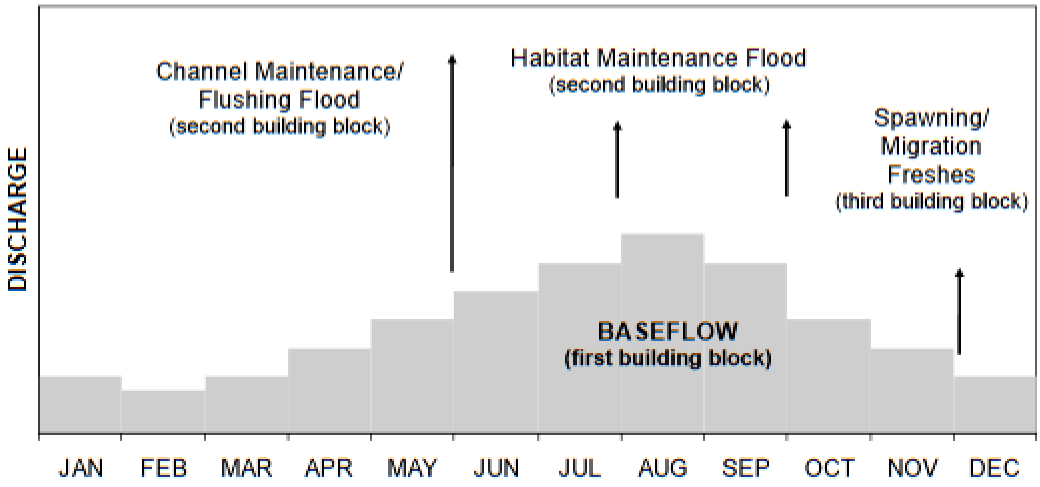


Figure 2 Theoretical environmental flow regime based on the BBM (Tharme and King 1998)

In contrast to the BBM, the Downstream Response to Imposed Flow Transformation (DRIFT) methodology is considered a top-down and scenario-based approach (Poff, Tharme, and Arthington 2017). However, it was developed using the principles from the BBM (Poff, Tharme, and Arthington 2017). It focuses on different river management scenarios and on the description of the ecological consequences of each scenario (King et al. 2008). DRIFT also uses interdisciplinary expert knowledge in addition to field data and model results to assess the potential ecological impacts or deterioration of the biotic and abiotic conditions (King et al. 2008). These different scenarios and their ecological assessments are developed based on four modules (King, Brown, C., and Sabet 2003). The first module is the biophysical module and describes the ecosystem and its expected change due to active river management (King, Brown, C., and Sabet 2003). The second module assesses the socio-economic aspects of the river resources (King, Brown, C., and Sabet 2003). In the third module, scenarios are constructed to create different potential management strategies and to estimate their ecological and socio-economic impacts of these scenarios (King, Brown, C., and Sabet 2003). Mitigation cost and compensation costs are calculated in the fourth module (King, Brown, C., and Sabet 2003). The DRIFT methodology differs from other holistic methods especially because of its explicit consideration of socio-economic aspects and has been used several times in major river basins in Africa and Southeast Asia (Poff, Tharme, and Arthington 2017).

Another widely known holistic approach is the Benchmarking Methodology, developed and largely used in Queensland, Australia (Brizga et al. 2002). It is based on the identification of hydrological indicators of high ecological importance. These indicators are then changed to different levels from their natural state and the ecological impacts are calculated for each level of change. The different levels are called benchmarks and are chosen to represent several levels of change in the flow regime. Multidisciplinary teams assess the ecological impacts of different benchmark scenarios compared to the reference state. They create relationships between hydrological indicators and the ecological response using hydrological models and risk assessment models. The results of this assessment are then used to define acceptable environmental flow regimes. This Benchmark Methodology is also a top-down approach and a multidisciplinary method which explicitly includes the determination of the risk of environmental degradation due to changes in the flow regime. (Brizga et al. 2002)

In addition to the three holistic approaches mentioned above, a group of international scientists created a new approach called the Ecological Limits Of Hydrological Alteration in 2010 (ELOHA, Poff et al. 2010). In contrast to the other approaches, ELOHA is a framework for the assessment of environmental flows on a regional scale and includes therefore the possibility of assessing many rivers simultaneously. The approach evolved from the idea of classifying rivers into groups according to their hydrological regime and geomorphic features presented in the work of Arthington et al. (2006), which can be seen as a predecessor of the ELOHA framework (Linnansaari et al. 2013; Poff, Tharme, and Arthington 2017). This classification can then be used to create connections between hydrological alterations and ecological responses for each of the group of river types based on the comparison of reference data and modified river stretches (Arthington et al. 2006). Environmental flow standards can then be developed for several rivers within one group based on the data collected for each group of rivers (Arthington et al. 2006). Finally, these standards will allow scientists to be able to set similar environmental flow rules worldwide (Arthington et al. 2006).

The ELOHA framework, described by Poff et al. (2010), incorporates the idea of classifying rivers types in order to assess their ecological responses to hydrological alterations for an entire river type simultaneously. Furthermore, the ELOHA approach takes both the scientific and the social side of setting environmental flow standards into account. The scientific framework of ELOHA consists of four major steps, however, interactions as well as feedback loops and repetitions may be necessary (Figure 3). The first step creates the hydrological foundation of this concept which means the construction of a hydrologic database describing different flow regimes. Therefore, hydrological modelling is used to construct hydrographs for reference (baseline) as well as for altered (developed) conditions. This should be done for each analysis node, which means all of the locations in a region, where water management is necessary and at points in the river where ecological data is available. The hydrographs and hydrological statistics then serve as a basis for the next steps of the framework, the classification of river types and calculation of flow alteration. In this second step of the framework, flow-ecology relationships for an entire river type are established based on data from individual rivers in this group and adequate biological monitoring systems are created for each river type. The river types are classified according to similarities in the hydrological regime and in the geomorphic characteristics. The third step in ELOHA assesses the flow alteration by comparing baseline and developed hydrological conditions using available software which can calculate the deviation from baseline conditions for each analysis node. The fourth step then establishes relationships between flow alteration and ecological responses which can mostly not be quantified directly. However, they can be expressed as hypotheses based on expert knowledge. Available data and newly implemented monitoring systems can be used to prove the hypotheses which leads to the construction of flow-ecology relationships. In the social process of the framework, environmental flow standards which are developed based on the scientific process are then assessed socially and economically. (Poff et al. 2010)

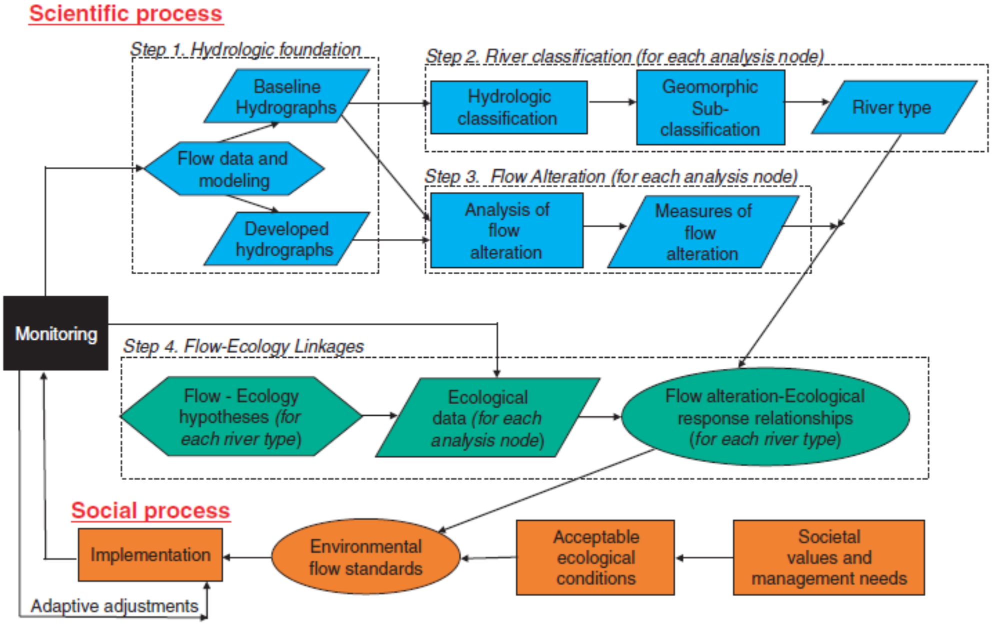


Figure 3 The ELOHA framework with its four main steps comprising a scientific and social process (Poff et al. 2010)

Finally, the ELOHA framework creates the possibility of assessing numerous rivers simultaneously and on a regional scale (Poff et al. 2010; Poff, Tharme, and Arthington 2017). Additionally, the method can be used for several different levels of resolution and by different governance and managements systems (Poff, Tharme, and Arthington 2017).

All of the holistic methods have the advantage that they use interdisciplinary knowledge from hydrology, geomorphology, biology, the society as well as the economy which guarantees that the entire ecosystem and all of the relevant water resource stakeholders have been addressed (Linnansaari et al. 2013; Pastor, A. et al. 2014; Poff, Tharme, and Arthington 2017). Therefore, solutions and compromises can be found (Pastor, A. et al. 2014; Poff, Tharme, and Arthington 2017). The holistic framework creates conceptually strong methodologies due to its use of different data sources and its interdisciplinarity (Acreman and Dunbar 2004). As some holistic frameworks even address risk and uncertainty effects, or are able to address climate change, the output for various different scenarios can be calculated and results with high flexibility and high resolution can be achieved (Poff, Tharme, and Arthington 2017).

Nevertheless, holistic methods are considered expensive and time-consuming methods (Acreman and Dunbar 2004; Poff, Tharme, and Arthington 2017; World Meteorological Organization 2019). As expert panels benefit from the supporting data, holistic methods often include other e-flow assessment methods based on extensive field work or computational effort (Linnansaari et al. 2013; Pastor, A. et al. 2014). Additionally, the consultation of experts and stakeholders can lead to time-consuming and complex processes (Linnansaari et al. 2013). Furthermore, difficulties may arise, if results or solutions must be upscaled or used in other river ecosystems, because holistic methods are mostly used and developed for specific local water management issues (Pastor, A. et al. 2014). In projects where data is no sufficient data is available, expert knowledge becomes majorly important. However, this results in a strong reliance on the experts (Acreman and Dunbar 2004; Linnansaari et al. 2013).

According to Poff, Tharme, and Arthington (2017), holistic methods are often used at large scale river management situations of high strategic importance and a high level of protection. As holistic methods consider economic and social aspects, they are often used where complex trade-offs between stakeholders must be found. If ecological and hydrological data is limited, holistic methods are especially useful as expert knowledge based on expert panels can be used instead. Thus, holistic methods are often chosen in the planning stage of new developments with a high level of protection because they address the entire ecosystem as well as socio-ecological values. (Poff, Tharme, and Arthington 2017)

2.3.7 Selection of Environmental Flow Assessment Method

According to Petts (2009), assessing environmental flow requirements is still a challenging field of research as it requires the consideration of different scales of time and space and requires the understanding of direct and indirect interactions between flows and river ecosystems. The selection of an adequate method of addressing e-flow requirements is of major importance for the conservation of river ecosystems. However, it strongly depends on the context of the river management process, the scale of analysis, the range of risk, the intensity of water use as well as on the available budget, data and timeframe which kind of assessment method is used (Tharme 2003; European Commission 2016). Furthermore, there are still numerous projects and countries which use methods with obvious negative impacts on the ecosystem, such as look-up tables, because they are cheap and easy to apply (Tharme 2003; Acreman and Dunbar 2004; Linnansaari et al. 2013). Several authors recommend a hierarchical framework for the selection of methods (Linnansaari et al. 2013; European Commission 2016; Poff, Tharme, and Arthington 2017).

As the European Commission guidance document for the implementation of ecological flows in the framework of the WFD only presents the different methods available (European Commission 2016), there is still no consistency in the use of e-flow methods in the EU. Furthermore, according to Acreman and Ferguson (2010), there is no e-flow assessment method which was has been developed to address e-flows as part of the WFD. However, as shown in Section 2.3.2, there are several major aspects which need to be addressed to achieve sustainable ecosystems, such as the natural flow paradigm. Based on this and the advantages and disadvantages of the different methods described above, river managers should choose a method which assesses the entire ecosystem and all the major processes which influence it. Therefore, habitat simulation methods or the combination of several methods in a holistic framework are recommended.

2.3.8 Regional Environmental Flow Assessment Methods

As already mentioned, research is taking place in the field of defining environmental flow rules on a regional scales. Arthington et al. (2006) stated that environmental flow assessment of specific river stretches with high scientific and social interest and enough data available, can be carried out using the methods presented above. The authors pointed out, however, that this option is not feasible for most rivers worldwide. Therefore, they suggested developing a framework to define regional rules or standards for environmental flow assessments based on the classification of rivers according to their hydrological regime (Arthington et al. 2006). As described above, this suggestion was the basis for the development of the ELOHA approach (Linnansaari et al. 2013; Poff, Tharme, and Arthington 2017).

Several methods have been developed in the last two decades which assess environmental flows on a regional scale. This includes application of ELOHA and MesoHABSIM (Vezza et al. 2012; Parasiewicz et al. 2018; see Section 3.3.4). Regional methods mentioned here all include the classification of water bodies based on their ecological, geomorphological or hydrological characteristics. This classification allows scientist to threat rivers of the same type in a similar manner and to use data gathered at representative sites for the whole river type group or region. E-flow standards are then developed for each type of river or region using information on the hydrological and ecological background of this type of river and data collected from the representative sites. These methods have certain advantages as numerous rivers can be assessed simultaneously and in a similar manner. Therefore, it is not necessary to collect detailed data for each river as data from representative sites of the same river type can be used. Furthermore, such approaches could be implemented into administrative and legal frameworks, such as the WFD, which has the objective to address European river consistently (Acreman and Ferguson 2010; Poff, Tharme, and Arthington 2017).

2.3.9 Environmental Flows in the FIThydro Project

E-flows are considered in the FIThydro project due to the fact that hydropower plants significantly alter the hydrological regime. The project identifies three major elements which need to be considered in e-flow assessments: hydrological diagnosis, geomorphological diagnosis and biological diagnosis (Fishfriendly Innovative Technologies for Hydropower (FIThydro) 2018a). Hence, an undisturbed hydrological regime with its characteristic low, frequent and high flow values is taken into account as well as the morphological situation, the fish population and the habitat diversity (FIThydro 2018a).

The Deliverable 2.1 (FIThydro 2018a) presents the e-flow values currently used in the FIThydro test cases. Despite the WFD, European countries have different rules on how to set environmental flows. However, mostly statistical values such as percentages of the mean annual flow are used. In addition, the defined e-flow values mostly represent minimum flow values instead of an environmental flow regime. This means that for most of the test cases the seasonal hydrological changes were not taken into account in the environmental flow definition. Based on these results, the Deliverable 2.1 identifies which additional tools are needed and which fields of research knowledge must be improved to assess and define environmental flows better in the future. For example, more accurate tools are necessary for measuring and surveying torrential streams. Furthermore, it is necessary to better understand the links between hydraulic or hydrological conditions and the biological targets as well as habitat preferences for species and their stages of life. (FIThydro 2018a)

The Deliverable 4.1 presents possible mitigation measures and tools (FIThydro 2018b). It shows that the flow regime is of major importance to the riverine ecosystem. Furthermore, it presents that measures to improve the flow regime have positive effects on all aspects considered in the projects such as habitat improvement, sediment management and upstream and downstream fish migration. As hydropower plants store or divert parts of the discharge, mitigation measures concerning different effects on the flow regime such as reduced annual flow, reduced flood peaks, reduced flood frequencies, rapid and short-term variation in flow, called hydropeaking, should be defined. To mitigate the effect of reduced annual flows, simple statistical approaches are mentioned but more advanced and sophisticated approaches such as habitat modelling or holistic approaches should be used. In addition, hydrological analyses should be carried out before and after flow regulation to identify changes in flood magnitude and frequency. The implementation of operational measures in the hydropower plant, physical changes in the river system and technical measures at the infrastructure are necessary in rivers which are affected by hydropeaking. (FIThydro 2018b)

To conclude, the FIThydro project shows the importance of the natural flow regime and its links to the morphological and ecological situation in a river. Similar to the results of the literature review above, it has discovered that some knowledge gaps still exist, especially regarding the link between the physical and biological aspects. Furthermore, it has identified that constant minimum flow values are still the most common method of defining e-flows because of their easy and cheap use. The project therefore collects data and knowledge in this specific field of research to help the development of improved strategies in the future.

3 MesoHABSIM

3.1 Development

MesoHABSIM is a mesoscale habitat modelling approach which uses a specific data collection technique combined with an analytical strategy (Parasiewicz 2007a). It was developed at Cornell University Massachusetts and the Rushing River Institute in 2000 and was first applied at the Quinebaug River, Massachusetts (Parasiewicz 2001). Since its first usage, the concept of the model has been revised and adapted, especially the survey method, and additional analytical approaches have been included (Parasiewicz 2007a).

MesoHABSIM is based on PHABSIM and the Instream Flow Incremental Methodology (Parasiewicz 2001; Parasiewicz and Walker, J. 2007). However, it is an enhancement of PHABSIM as it is carried out at a mesohabitat-scale instead of the microhabitat-scale used in PHABSIM (Parasiewicz 2001; Parasiewicz and Walker, J. 2007). This change in scale was necessary in order to use habitat modelling strategies for large scale river management issues. The model was developed to create a habitat assessment tool which could be incorporated into river restoration projects, where the utilisation of commonly used models is limited (Parasiewicz 2001). The change in resolution was achieved by modifying the data acquisition technique as well as the analytical approach in PHABSIM (Parasiewicz 2001). For example, mesohabitat mapping replaced detailed microscale surveys and hydrodynamic calculation (Parasiewicz 2001). The MesoHABSIM approach is implemented in the software SimStream (Rushing Rivers Institute) which can be used for data analysis and the interpretation and presentation of simulation results (Parasiewicz et al. 2013).

3.2 Application

Parasiewicz et al. (2013) presented an overview of the application of the MesoHABSIM approach in over 30 rivers. The model was used in a variety of rivers of different sizes and types. However, the methodology has been adapted several times according to the surrounding circumstances and specific research questions (Parasiewicz et al. 2013).

The main utilisation of this method is in the field of hydropower generation and when it comes to water supply issues and during river restoration and river management processes (Parasiewicz et al. 2013). As already mentioned, the first application of MesoHABSIM was in the Quinebaug River, where it was used to develop a flow augmentation and river restoration strategy (Parasiewicz 2001; 2008). Furthermore, the model was used for the development of reference habitat templates and ecological management scenarios (Parasiewicz 2007b). In addition to river restoration projects, the model can be used to assess the ecological status of rivers (Parasiewicz et al. 2013) and to quantify hydro-morphological alterations (Vezza et al. 2015). Recently, it has mainly been used to determine environmental flow values for catchments influenced by water abstraction due to water supply or hydropower. Vezza (2010) and Vezza et al. (2012) described regional methodologies to estimate minimum environmental flow values in North-Western Italy, and Parasiewicz et al. (2018) established a regional method of determining environmental flow values for Poland. Additionally, the MesoHABSIM approach is applied as a habitat assessment tool in the European research project AMBER (Adaptive Management of Barriers in European Rivers) (AMBER 2018). Furthermore, the Italian Institute for Environmental Protection and Research ISPRA (Istituto Superiore per la Protezione e la Ricerca) recommends using the model in river management processes. The numerous applications of MesoHABSIM in different fields of research can be seen as proof of the adaptability and usefulness of the model (Parasiewicz et al. 2013).

3.3 Methodology

The methodology of MesoHABSIM consists of two major parts. The first part includes surveys and data collection strategies regarding hydromorphic aspects as well as biological information. The second part deals with data analysis and interpretation in order to develop the habitat model and analyse the habitat quantity over time. These steps can be carried out using the SimStream software.

3.3.1 Survey and Data Collection

3.3.1.1 Hydromorphic Survey

As MesoHABSIM is based on the mesoscale of instream habitats, it considers hydromorphic units (HMU) as basic units for the survey. HMUs such as riffles, pools or glides can be seen as an interplay between the hydraulic conditions in a river and the topography of the riverbed which creates different riverine habitat conditions. Several studies showed the correlation in location and size between these HMUs and the mesohabitats of adult fish and therefore an HMU became a synonym for a mesohabitat. Nevertheless, the size of the mesohabitats of juvenile fish can be different to the size of the HMUs. In general, however, HMUs can be used as the basic units for the mesohabitat modelling process. (Parasiewicz 2007a)

For the MesoHABSIM mesohabitat survey, described by Parasiewicz (2007a), representative sites need to be defined in the river to be modelled. Reconnaissance surveys or aerial pictures can help to define river stretches with a representative distribution and types of HMUs. The mesohabitat survey is then carried out in these stream segments by determining and mapping mesohabitats or HMUs. In this mapping process the HMUs are delineated to estimate their extent and the types of HMU are defined. Portable GIS applications with high resolution aerial photographs or GPS devices are used to map the exact size and location of each HMU and to create geo-referenced polygons. The definition of the HMU type can be done using the descriptions in Table 2. (Parasiewicz 2007a)

Additionally, the physical attributes of the surrounding and internal environmental conditions are documented for each HMU (Parasiewicz 2007a). This part of the survey takes the abundance (> 50%), presence (≤ 50%) or absence (<5%) of instream habitat attributes such as boulders, woody debris, undercut banks and shallow margins into account (Parasiewicz et al. 2013). Furthermore, the land use of the shoreline as well as the extent of shading is documented (Parasiewicz et al. 2013). Finally, flow velocity and water depth data as well as substrate information are collected in at least seven locations within each HMU (Parasiewicz 2007a). The measurement points are selected so that all the different hydraulic conditions in the HMU are taken into consideration. Additionally, the number of measurements taken in one area of uniform hydraulic conditions within one HMU depends on its size meaning more measurements are done in larger areas than in smaller ones. In each of the seven locations, the substrate is classified based on the Austrian classification system (Austrian Standard 1997) shown in Table 3. Depending on the size of the river, this mapping survey can be carried out by walking through and along the river or by using boats or canoes (Parasiewicz et al. 2013).

Table 2 HMU types and characteristics (Parasiewicz 2007a)

HMU	Description of characteristics
Riffle	Shallow stream reaches with moderate current velocity, some surface turbulence and higher gradient; convex streambed shape
Rapid	Higher gradient reaches with faster current velocity, coarser substrate, and more surface turbulence; convex streambed shape
Cascade	Stepped rapids with small waterfalls and very small pools behind boulders
Glide	Moderately shallow stream channels with laminar flow, lacking pronounced turbulence; flat streambed shape
Ruffle	Dewatered rapids in transition to either run or riffle
Run	Monotone stream channels with well-determined thalweg; streambed is longitudinally flat and laterally concave
Fast run	Uniform fast-flowing stream channels
Pool	Deep water impounded by a channel blockage or partial channel obstruction; slow; concave streambed shape
Plunge-pool	Main flow passes over a complete channel obstruction and drops vertically to scour the streambed
Backwater	Slack areas along channel margins, caused by eddies behind obstructions
Side arm	Channels around islands, smaller than half river width, frequently at different elevation than main channel

Table 3 Choriotop types modified from Austrian Standard (1997) (Parasiewicz 2007a)

Nomenclature	Grain size range	Choriotop description
Abiotic choritop		
Megalithal	>40 cm	Upper sides of large cobbles and blocks, bedrock

Macrolithal	>20-40 cm	Coarse blocks, head-sized cobbles, variable percentage of cobbles, gravel and sand
Mesolithal	>6.3-20 cm	Fist to hand-sized cobbles with a variable percentage of gravel and sand
Microlithal	>2-6.3 cm	Coarse gravel (size of a pigeon egg to child’s fist) with percentages of medium to fine gravel
Akal	> 2 mm-2 cm	Fine to medium-sized gravel
Psammal	0.063-2 mm	Sand
Pelal	<0.063 mm	Silt, loam clay and sludge
Biotic choriotop		
Detritus		Deposits of particulate organic matter, distinguished are: CPOM (coarse particulate organic matter), as for example, fallen leave and FPOM (fine particulate organic matter)
Xylal		Tree trunks (dead wood), branches, roots, etc.
Sapropel		Sludge
Phytal		Submerged plants, floating stands or mats, lawns of bacteria or fungi, tufts, often with aggregations of detritus, moss or algal mats (interphytal: habitat within a vegetation stand, plant mats or clumps)
Debris		Organic and inorganic matter deposited within the splash zone area by wave motion and changing water levels, for examples, mussel shells, snail shells

MesoHABSIM is a zero-dimension hydraulic model, which does not include the calculation of hydraulic variables. Therefore, repetitive mappings are necessary to gain information on the different hydraulic conditions and the mesohabitat types and characteristics associated with them. The mapping survey should be carried out in three to four different discharge conditions which represent the naturally occurring discharge regime (Parasiewicz 2007a). The discharge conditions at which the mapping is carried out should be chosen according to the specific application of MesoHABSIM. For example, low discharge values should be chosen for an environmental flow assessment (Parasiewicz 2007a). The number of surveys influence the resolution of the habitat rating curve which is later constructed based on the data collected during the mesohabitat surveys (Parasiewicz et al. 2013).

3.3.1.2 Biological Survey

This part of the data collection strategy creates the basis for the biological part of MesoHABSIM. It is used to describe the habitat preferences of fish and the response of fish towards environmental conditions. The preferred ways of collecting biological data are using electro-fishing grids or electro-fishing boats and snorkelling. Fish are caught, identified and measured. Additionally, the physical conditions such as the HMU type, the substrate, the water depth and cover structures are documented. If no biological survey is carried out, literary data or expert knowledge about the habitat preferences of fish species can be used. (Parasiewicz 2007a)

3.3.2 Habitat Model Development

3.3.2.1 Identification of Biological Targets

To create a habitat model, the biological targets need to be defined, which means the selection of some aquatic elements which the model will be developed for. Parasiewicz et al. (2013) described different ways of identifying the biological target.

The simplest approach to define a target species is the selection of a representative species of interest as indicator species. In some cases, the species of interest is already defined by the investigator or agency and can not only be fish but, for example, freshwater mussels or macroinvertebrates. However, only taking one species and its habitat preferences into account is not sufficient to present the habitat requirements of the aquatic community. (Parasiewicz et al. 2013).

The most comprehensive approach to identify the biological targets is the modelling of an expected or desired community (Parasiewicz et al. 2013). Here, all the species in a community are included and their percentages within the community is defined (Parasiewicz et al. 2013). One example is the Target Fish Community approach (TFC) described by Bain and Meixler (2008). It is based on the assumption that the community structure reflects the habitat structure which means that the most common species inhabit the most common habitats (Parasiewicz 2007b). The habitat requirement for an entire community can then be developed taking the habitat preferences of the different species in the community and their percentage within the community into account.

Furthermore, the riverine community can be divided into habitat-use guilds and for each guild one or more species can be selected as representative (Parasiewicz et al. 2013). This approach is advantageous when using these applications on a regional scale as the habitat requirements of habitat-use guilds can be developed for rivers with similar hydrological and geomorphic characteristics (Welcomme, Winemiller, and Cowx 2006). In addition, abundant species which the habitat preferences can easily be defined for, can be used as representatives for the habitat-use guilds (Parasiewicz et al. 2013).

In addition, available data regarding the occurrence of riverine species or the biological classification of river systems developed for administrative processes or regional governments can be used. For example, Vezza et al. (2012) defined the target fish community in the Piedmont region based on the fish zonation defined by the regional government.

3.3.2.2 Definition of Bioperiods

Bioperiods are calendar periods which are linked to the specific biological functions of the target species (Parasiewicz 2007b, 2008). They reflect the different stages of life of these species such as spawning, rearing or growth (Parasiewicz 2008). The importance of seasonal variabilities in flow for the life cycle of species was already explained in Section 2.1.2.4. Hence, management action and the conservation of habitat during these periods are of particular importance in order to maintain a sustainable riverine community (Parasiewicz 2007b). It can be assumed that these specific periods of biological importance are triggered by changes in the flow regime (Parasiewicz 2008). This means that native species have adapted their seasonal behaviour to the natural hydrological regime of a river. Therefore, the natural flow regime is comparable to literary information about the stages of life and the seasonal behaviour of the target species (Parasiewicz 2008). Using this information, bioperiods can be identified. The habitat suitability criteria are developed for each of these bioperiods individually which reflect the biological importance of these specific periods (Parasiewicz 2007b). The habitat model is therefore developed for each bioperiod separately.

3.3.2.3 Establishing Habitat Suitability Criteria

To define whether a given habitat is suitable for the target species or not, it is necessary to identify the habitat preferences or requirements of the target species. Such habitat suitability criteria are developed using fish sampling data or, if no fish sampling is possible, using literary material or an expert opinion (Parasiewicz 2007a).

The most precise habitat suitability criteria are developed based on multivariate probabilistic models using empirical data collected from one or more rivers (Parasiewicz et al. 2013). If fish data from several rivers is available, more detailed information on habitat suitability can be gathered as a wider range of habitat availability and the species-specific response to environmental variability can be taken into account (Parasiewicz et al. 2013). This data is then used to produce a multivariate probabilistic model such as a logistic regression (Parasiewicz et al. 2013). Firstly, a cross-correlation analysis is carried out to exclude redundant parameters (Parasiewicz 2001, 2007a). Then, a stepwise forward logistic regression is applied to identify suitable habitats or habitat characteristics, which are most often linked with the presence or abundance of fish (Parasiewicz 2001, 2007a). In this process, the environmental attributes of the HMU represent independent variables, whereas the fish data are dependent variables (Parasiewicz 2007a). This application of a multivariate probabilistic model is supported by the SimStream software (Parasiewicz et al. 2013).

Using the results of a logistic regression, the probability of fish presence or high abundance can be calculated for each HMU (Formula 3) (Parasiewicz 2007a):

$$p = \frac{1}{(1 + e^{-z})} \tag{3}$$

with $z = b_1 * x_1 + b_2 * x_2 + \cdots + b_n * x_n + a$

with

p = probability of presence or high abundance

$x_{1\ldots n}$ = significant physical variables

$b_{1\ldots n}$ = regression coefficient

Probabilities calculated in this way can be classified into suitability categories in order to differentiate between suitable and optimal habitat conditions. This is done by selecting separated cut-off probabilities (Pt) for the presence and the abundance model respectively and using relative operating characteristic (ROC) curves for each presence and abundance prediction. Such curves analyse the discrimination performance of the model over a range of threshold levels according to the proportion of grids correctly or incorrectly predicted to be occupied. An HMU is then classified as suitable when the probability of presence is higher than Pt selected for the presence model or as optimal when the probability of high abundance is higher than Pt selected for the abundance model. (Parasiewicz 2007a)

For literary-based suitability criteria, information obtained from literature or experts is used to identify suitable ranges of the same five habitat descriptor used during the mesohabitat survey: water depth, water velocity, substrate, HMU type and cover (Parasiewicz et al. 2013). An HMU can be classified as suitable if the HMU attributes observed during the survey fall into the suitable ranges identified during the literary review (Parasiewicz 2007a; Parasiewicz et al. 2013). The number of fulfilled attributes can then be used to differentiate between suitable or optimal conditions (for example: 3 = suitable; ≥ 4 = optimal) (Parasiewicz et al. 2013). If some fish data is available, it can be used to calibrate the range of the developed suitability criteria (Parasiewicz et al. 2013).

The habitat suitability criteria are mostly developed for each species or habitat-use guild individually because the habitat preferences differ for different species or guilds. Additionally, different habitat preferences can be selected for each bioperiod, as the behaviour of a species and therefore their habitat requirements change seasonally. Based on this, each HMU can be defined as not suitable, suitable or optimal for each species or guild and for each bioperiod separately.

3.3.2.4 Development of Habitat Rating Curve

After the identification of suitable and optimal habitats, the results of a habitat model can be summarized in rating curves. These curves give us information about the amount of suitable or optimal habitat in different discharge conditions. Therefore, the areas of suitable and optimal habitat are summarised and expressed as a percentage of the total channel area or the wetted area at the highest measured flow. These values are then plotted on to a diagram together with the associated flow values (Parasiewicz et al. 2013). Linear curve fitting is used to interpolated between the surveyed discharge values (Parasiewicz 2007a; Parasiewicz et al. 2013). The rating curve can be created for suitable habitat conditions, optimal habitat conditions and an effective habitat separately (Parasiewicz 2007a). The latter is created by combining the results of the former two curves. Therefore, the values calculated for optimal and suitable conditions are multiplied by a weighting factor and then summarized to create an effective habitat rating curve. Most often weighting factors are 0.75 for optimal habitat and 0.25 for suitable habitat (Parasiewicz 2007a; Parasiewicz et al. 2013).

Instead of considering the habitat suitability for each species separately, habitat rating curves can also be created for an entire fish community for which two different approaches exist: the generic fish and the community habitat rating curve. The former is based on a hypothetical species, the generic fish, which uses the same habitat as all of the species in the community (Parasiewicz 2007a) and represents the habitat available for any species in a the community (Parasiewicz et al. 2013). This means, if an HMU is suitable for at least one species in the community, the area of the HMU is taken into account as available habitat. Due to this, the generic fish approach shows the total amount of habitat available (Parasiewicz et al. 2013). On the other hand, the community habitat rating curve represents the habitat available to an expected or desired fish community (Parasiewicz et al. 2013). To create this curve, the habitat of each species in the community is weighted by the proportion of this species in the fish community (Parasiewicz 2007a). If an HMU is classified as suitable or optimal for one species, the area of the HMU is weighted according to the percentage of this species in the community. This is done for all of the species in the community and the weighted habitat is added up for the entire community to calculate the values of the community habitat rating curve. Figure 4 shows an example of such rating curves where the wetted area is indicated as well as the community rating curve and the reference habitat rating curve which represent the generic fish approach.

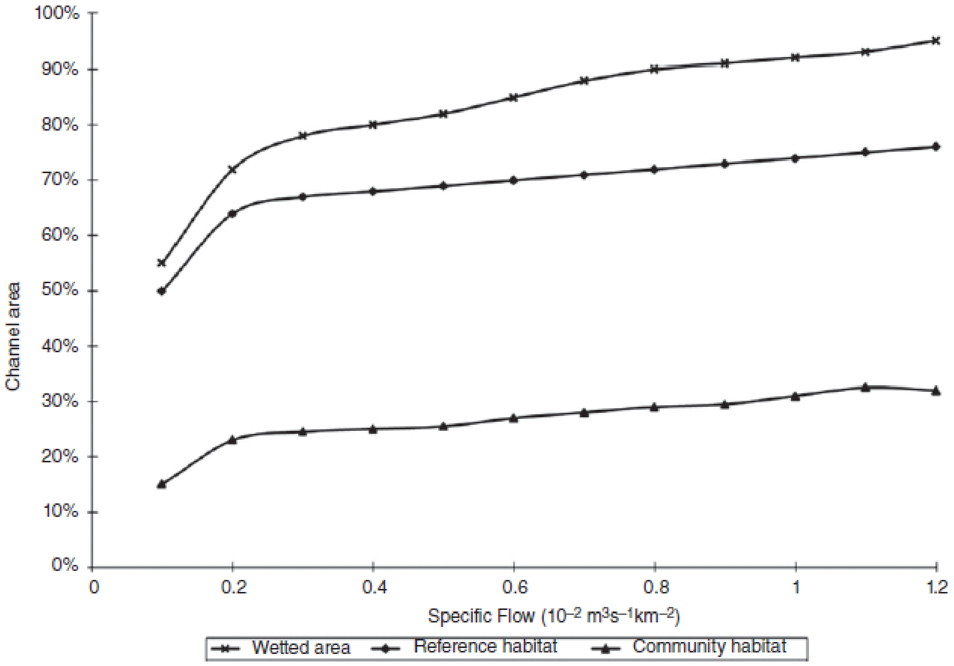


Figure 4 Example of habitat rating curves for generic fish and fish community (Parasiewicz et al. 2013)

When plotted on to one graph, the gap between the two rating curves, the generic fish and the community curve, expresses the difference between the total habitat available and the available habitat which supports the community structure. A substantial gap, as shown in Figure 4, indicates that the available habitat is not equal to the necessary habitat to support the fish's community structure (Parasiewicz et al. 2013). The graphs can also be used to identify missing habitat structures and to develop mitigation or restoration measures (Parasiewicz et al. 2013).

3.3.3 Habitat Time Series Analysis

3.3.3.1 Background and Assumptions

The aim of a habitat time series analysis is to observe the quantity and timing of available habitat which occurs in natural conditions (Parasiewicz 2007b). It especially focuses on the frequency, magnitude and duration of extreme habitat events (Parasiewicz 2007b). As it concentrates on natural conditions, undisturbed flow time series are necessary. If the surveyed river system or the hydrological regime has been anthropogenically altered, undisturbed flow time series or reference flow time series need to be created (Parasiewicz 2007b; Parasiewicz et al. 2013). Different tools exists to create such flow times series starting from a simple estimation of the flow regime in an ungauged catchment to a detailed rainfall-runoff modelling which accounts for land use changes or morphological alterations (Parasiewicz 2007b; Parasiewicz et al. 2013).

The following analysis strategy, described by Parasiewicz (2007b), assumes that the composition of native species in natural conditions is a result of the surrounding conditions which the native fauna is used to. Therefore, it can be concluded that habitat utilization is optimal in natural conditions. This means that native fauna is better adapted to common habitat conditions in a temporal sense than to rare habitat events. Analysing the frequency, magnitude and duration of naturally occurring habitat events leads, on the one hand, to information on the common conditions which the native fauna is adapted to. On the other hand, critical habitat conditions or events can be identified which only occur rarely in natural conditions and which native fauna is assumed to be less tolerant towards. Such critical habitat conditions or habitat limitations lead to environmental stress which can affect the community structure. (Parasiewicz 2007b)

According to Niemi et al. (1990), two types of stressors which affect the aquatic community can be identified and these can both be a result of habitat limitation (Parasiewicz 2007b). Pulse stressors lead to the instantaneous alteration of fish density whereas press stressors lead to a sustained alteration of species composition (Parasiewicz 2007b). Extreme habitat limitations such as the drying out of river parts or the limitation of habitats over periods of time such as long dry summers are classified as pulse stressors (Parasiewicz 2007b). Press stressors, on the other hand, are habitat limitations which occur over even longer periods of time such as for several consecutive years (Parasiewicz 2007b). Both stressors can occur naturally, however, human activity can also trigger pulse or press disturbances. Human-induced press or pulse disturbances need to be avoided by changing the actions of river management. Analysing the habitat duration pattern is therefore necessary to identify conditions which trigger pulse or press disturbances (Parasiewicz et al. 2013). The habitat time series analysis presented here focuses on the identification of natural Habitat Stressor Thresholds (HST), which show the transition between common and rare habitats conditions (Parasiewicz et al. 2013).

The result of this analysis provides scientist with detailed information on how often such critical events occur in natural conditions and for how long. Such information is valuable for the development of river management schemes because management strategies can now be developed in a way that such critical habitat events do not occur more often or for a longer duration of time or a higher magnitudes than in natural conditions. This analysis is therefore an important tool for planning river management strategies, as it shows a way to avoid an increase in environmental stress (Parasiewicz 2007b).

3.3.3.2 Uniform Continuous Under Threshold Analysis

To analyse habitat availability over time, Uniform Continuous Under Threshold curves (UCUT) are used. Based on these graphs, the duration and frequency of certain habitat events under a certain threshold can be identified (Parasiewicz 2008). This approach is based on the Continuous Under Threshold habitat duration curves (CUT) developed by Capra, Breil, and Souchon (1995). However, the approach has been modified in several ways for its use in the MesoHABSIM analysis process as described by Parasiewicz (2008). For one thing, the UCUTs were only constructed for bioperiods. Additionally, the plot of UCUT curves includes continuous durations with 0% cumulative increase and therefore they are called uniform. This modification does not significantly change the shape of the curve but it simplifies the interpretation (Parasiewicz 2008).

The development of UCUT curves is described in detail by Parasiewicz (2008). The first step to develop UCUTs is the creation of a habitat time series from a flow time series by using established rating curves. In these time series, the habitat is expressed as a percentage of the total available habitat or channel area (CA) which is a so-called relative habitat area (in %). As this analysis is done separately for each bioperiod, the habitat data for each bioperiod is extracted from the habitat time series. Then an iterative process starts and the first step is presented in Figure 5. (Parasiewicz 2008)

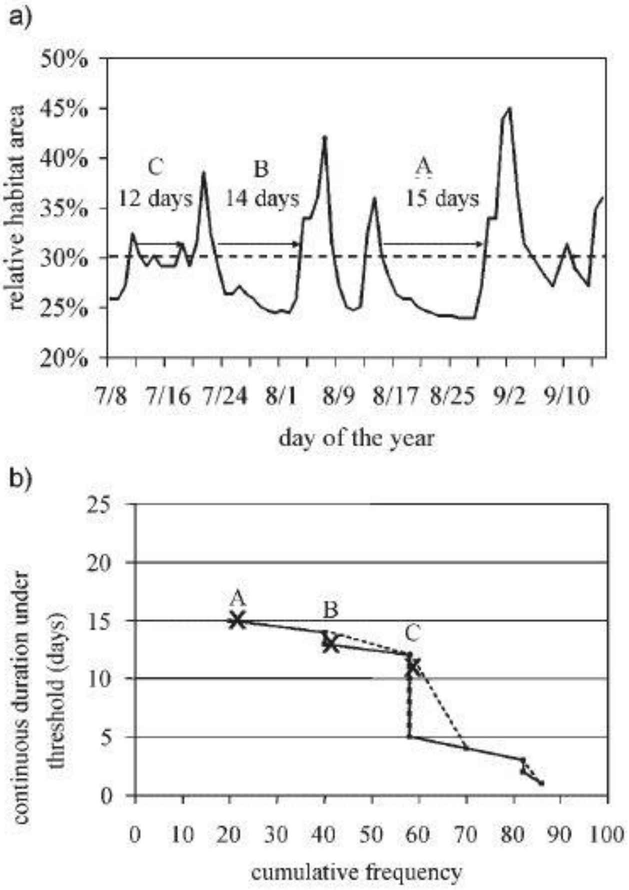


Figure 5 Schematic presentation of the UCUT curve computation (modified after Parasiewicz 2008)

Firstly, a threshold of relative habitat area is chosen and the continuous duration which the available habitat does not exceed this particular threshold for is calculated. In the example in Figure 5 part a), the selected threshold is 30% and the longest period which the habitat is under this threshold for was 15 days. The cumulative continuous duration is calculated for each duration under the threshold which presents the proportion of this duration on total length of the bioperiod. As this is expressed as cumulative duration, the proportions of shorter periods are added to the proportion of all of the longer periods (Parasiewicz 2008). In the example presented in Figure 5 this means, 15 days make up 20% of the bioperiod, which is point A in the graph in part b) of the figure. The second longest period was 14 days, which means 19% of the bioperiod and a cumulative frequency of 39%, which is shown as point B in Figure 5. To compare the different approaches of CUT and UCUT curves, the dotted lines in the graph show the CUT curves based on the approach of Capra, Breil, and Souchon (1995) and the solid lines show the UCUT curves including the continuous duration with 0% increase of cumulative duration. Continuing this process, the UCUT curve for this threshold is created not only considering one year but all the years which habitat time series have been available for. Then the threshold is changed iteratively using a constant increment to attain UCUT curves for an entire set of thresholds. Figure 6 shows an example of UCUT curves developed for a 2% habitat increment value which means the habitat thresholds which were expressed as a percentage of the channel area (CA) were increased stepwise by 2%. (Parasiewicz 2008)

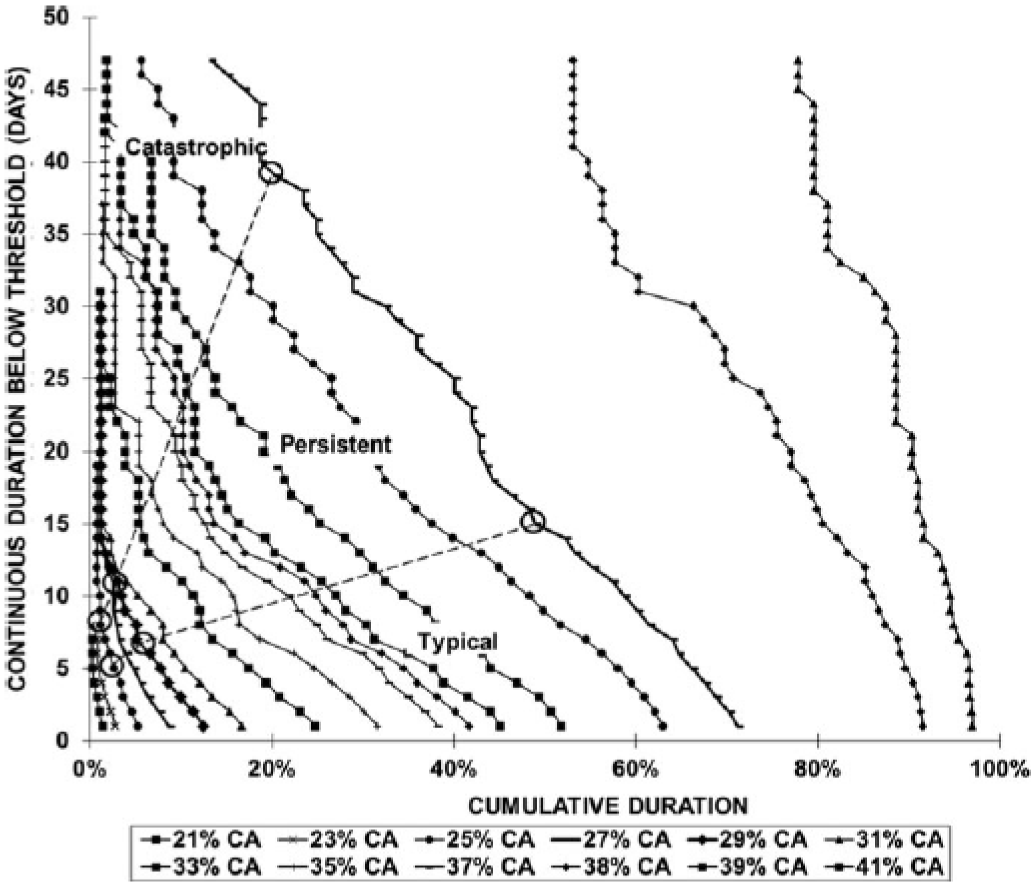


Figure 6 Example of UCUT curves used for the identification of HSTs (Parasiewicz et al. 2013)

The UCUT curves can now be interpreted to identify common and rare habitat events. This interpretation process consists of two steps. Firstly, habitat thresholds can be identified by selecting certain curves of the graphs. Secondly, critical durations can be determined by locating inflection points on these selected graphs. In general, the position of the curves gives us information on the magnitude of the habitat available, meaning for example curves in the lower left corner present rare habitat events linked to low amounts of habitat. Large distance between two curves at the same continuous duration indicate big changes in the frequency of events connected to a constant habitat increase when going on to the next threshold level. Additionally, low changes in event frequency are illustrated using by steep curves, whereas the inflection points indicate rapid changes in frequency of the continuous duration. (Parasiewicz 2008).

The Habitat Stressor Thresholds (HSTs) should identify extreme, rare, critical and common habitat conditions. Extreme conditions are the maximal environmental stress which occurs in natural conditions resulting in the lowest amount of habitat. This threshold can therefore be identified as the curve presenting the lowest non-zero habitat level, meaning the first curve in the bottom left hand corner. The other three HSTs can be found by closely observing the UCUT curves and their positions and steepness and the distance between curves. In comparison to extreme events, rare events occur for shorter periods of time and infrequently. As mentioned above, rare events can be found in the bottom left hand corner and are steep and mostly close together. This means an increase in habitat level is not really linked to an increase in frequency. As this group of rare events can be demarcated, the threshold for rare habitat events can be selected to the highest curve in this rare habitat group. Critical habitat events occur more frequently than rare events, but the habitat conditions can rapidly decrease to rare conditions. Therefore, the critical habitat threshold corresponds to the next higher curve than the rare threshold curve. The common habitat threshold indicates the beginning of normal conditions. Here larger distances between curves occur more frequently than in rare or critical conditions. Based on this, the next curve which stands out and presents rapid changes in frequency is the common habitat threshold. The selected habitat thresholds for the example in Figure 6 for rare, critical and common conditions are shown by the lines marked with the circles in Figure 6 (25% CA, 29% CA and 38% CA respectively). (Parasiewicz 2008)

In addition to the identification of habitat thresholds, the critical durations for which low habitat events occur need to be defined. As the inflection points indicate changes in frequency of habitat under-threshold durations, they can be used to identify periods in which habitat conditions are allowed to be under a specific threshold. It is possible to distinguished between persistent and catastrophic durations. Persistent events are events that are rare on an intra-annual scale but can occur every few years and affect the life cycles of one generation. To define persistent durations, the main inflection point of the associated habitat threshold curve is selected. This point shows the longest duration of a habitat under the threshold which commonly occurs. Catastrophic events, on the other hand, occur not more than once in a decade and have longer durations which affect several generations. They are defined by selecting the shortest of the longest durations which occurred only once during the investigated period or once in a decade. In Figure 6 the selected inflection points as well as the defined catastrophic durations are circled. The points divide the UCUT curves into areas of catastrophic, persistent and typical under threshold durations. (Parasiewicz 2008)

To sum up, the results of this habitat time series analysis show a combination of explicit values of relative habitat and durations which are the basis for the development of management strategies. For each bioperiod, the amount of habitat available (habitat threshold), which is expressed as the percentage of the channel area, and the common, critical, rare and extreme conditions are presented. In addition, for each of these conditions a number of consecutive days is calculated accounting for the allowable duration for which the habitat can be below the thresholds. These durations are presented as allowable durations (persistent) and as durations which trigger catastrophic events (catastrophic). Furthermore, the habitat threshold can be re-calculated into a flow value using the rating curves which makes it easier to put the information into practice in management strategy. An example of the results attained by a habitat time series analysis is presented and explained in more detail in Section 3.3.4 (Figure 8).

3.3.3.3 Applications in River Management Strategies

As explained above, the results of a habitat time series analysis including the identified thresholds for the frequency and duration of habitat stress events are the basis for developing river management strategies. Such strategies aim to avoid an increase of environmental stress. Therefore, they are built on identified natural habitat thresholds with the aim that a managed river system is not affected by more frequent, more intense or longer habitat stress than a natural one is.

Parasiewicz (2008) described the development of a flow augmentation strategy for the Quinebaug River in Connecticut and Massachusetts based on the habitat time series analysis presented above. He discovered that, in comparison to the natural flow time series, the regulated flow time series did not include peak discharge during summer low flow. These peak discharges, however, are of high importance, as they provide temporal relief during this low flow period. Using this information, he established a flow augmentation scheme to provide peak flows in order to avoid extreme habitat conditions and to limit the frequency of rare and critical events and their duration in accordance with identified persistent and catastrophic thresholds. (Parasiewicz 2008).

In addition, Parasiewicz et al. (2013) provided a way of visually summarizing the flow criteria in so-called ACTograms. These graphs are then used as a decision support system to identify times at which management plans need to be put into action. These graphs can also identify how long the flow has been below a certain threshold and whether this duration is a typical, persistent or catastrophic duration. The ACTograms are updated every day and record the number of consecutive days of flow below a certain threshold. In addition, it illustrates how long current flow conditions can exist before habitat stress occurs making management actions necessary. Stress days occur when the conditions change from typical conditions to persistent or even catastrophic conditions. If the durations become closer to catastrophic durations, flow augmentation needs to be considered. Figure 7 gives an example of an ACTogram developed for August 31, 2005 during the summer rearing and growth bioperiod in the Eightmile River. The ACTogram shows different zones representing typical (black), persistent (grey) and catastrophic (spotted) durations. Squares (present condition) and diamonds (reference conditions) are used to illustrate the fact that a flow is below a certain threshold. In this ACTogram the flow thresholds considered are 14, 8, 4 and 1 m³/s. Depending on the zone in which these indicated durations and thresholds (squares and diamonds) are found, the situation can be defined as typical, persistent or catastrophic. This ACTogram also presents the difference between the reference and current river conditions, showing that the number of stress days is distinctly higher in its current condition than it would be in its reference condition. Therefore, using this ACTogram, management action can be triggered and unnaturally high numbers of stress days and catastrophic situation can be identified and avoided. (Parasiewicz et al. 2013)

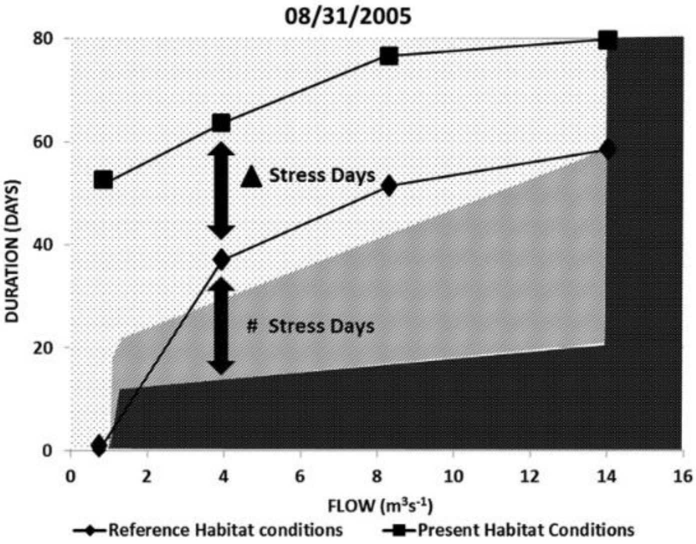


Figure 7 ACTogram for the summer rearing and growth bioperiod for the Eightmile River for August 31, 2005 (Parasiewicz et al. 2013)

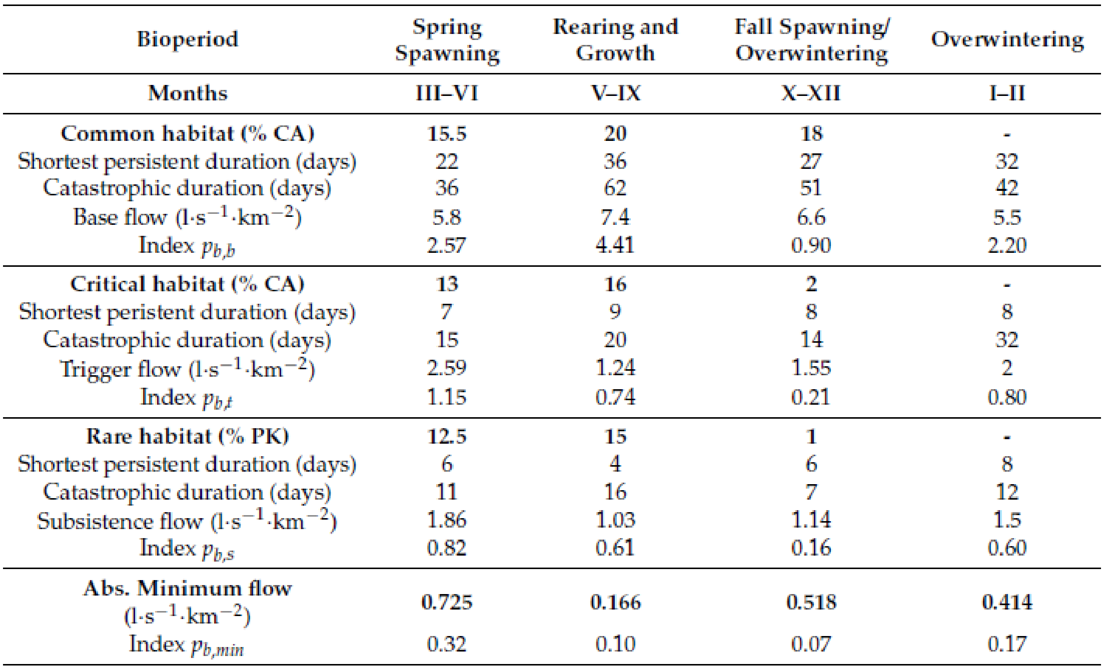
Parasiewicz et al. (2018) also used the results of the UCUT analysis to define river management rules for reference sites in Poland. The authors proposed to use the identified habitat and associated duration thresholds attained by the UCUT analysis to establish dynamic environmental flow management strategies. Management actions should be put into effect by comparing the current flow values to the thresholds and to the defined persistent and catastrophic durations. No action needs to be taken if persistent durations do not occur more than three times in a bioperiod or if catastrophic durations have not occurred in the last ten years. Otherwise, flow augmentation or water withdrawal limitations should be put into effect. (Parasiewicz et al. 2018)

3.3.4 Environmental Flow Assessment at the Regional Scale

As mentioned in Section 2.3.8, MesoHABSIM was used to establish regional environmental flow standards in the Piedmont region in Italy (Vezza et al. 2012) and in Poland (Parasiewicz et al. 2018). Both applications included the classification of river systems to identify groups of river types and to set standardised environmental flow rules for these river groups. In comparison to the approach proposed by Arthington et al. (2006), this river classification was not only created using hydrological characteristics but included hydro-ecological as well as geomorphic features in the Piedmont region and in Poland the expected fish communities were taken into consideration.

Vezza et al. (2012) presented a bottom-up approach for the definition of minimum environmental flow requirements in the Piedmont region. This work concentrates on catchments of smaller than 50 km² in size and 25 reference catchments were selected. In each of these reference catchments, representative sites were identified and MesoHABSIM surveys were carried out. In addition, regional biological models were developed using empirical fish data and logistic regression. For each reference site, effective flow habitat curves were established for each species and stage of life. The highest inflection points of the habitat rating curves were used to defined minimum flow requirements. Additionally to these site-specific observations, a catchment classification using classification and regression tree algorithms was carried out to identify rivers with similar characteristics and to upscale the obtained results to a regional scale. Four groups of rivers were detected and minimum environmental flow values from 2 to 19 l/s km² were calculated for each catchment group using the results obtained from the reference sites. This study was one of the first that presented a definition of environmental flow requirements on a regional scale. However, it only presents minimum flow values which do not account for seasonal variabilities of habitat requirements. The habitat time series analysis in the MesoHABSIM approach could not be used in this study due to the fact that flow time series were missing. Based on this, the defined minimum flow values should not be used to replace site-specific and detailed studies of setting environmental flows but to provide a range and basic guidance. (Vezza et al. 2012)

Parasiewicz et al. (2018) established regional environmental flow standards for Poland. Using fish data and clustering for large applications (CLARA) algorithms, they grouped all of Poland's water bodies into six fish ecological types (FET) and a specific target fish community were developed for each of them. For each FET, reference sites were selected and MesoHABSIM surveys were carried out. Habitat rating curves and UCUT analysis were performed as explained in the previous sections, but flow time series were used instead of habitat time series for the UCUT analysis. The flow thresholds attained were used to transfer the information obtained for the reference sites to other locations in the watershed or other water bodies of the same FET which led to the development of regional environmental flow standards. To do so, coefficients p_b were developed for each bioperiod and threshold level (common, critical and rare), which facilitate the transfer of flow thresholds to other catchments. To calculate the coefficients p_b the threshold flow values obtained for each reference site were firstly standardised in accordance with the upstream watershed areas. Secondly, the obtained specific flow value was divided by the mean specific low flow for the same bioperiod q_{MBLF}, calculated for the reference site using a flow time series and finally creating the coefficient p_b. Applying this calculation of coefficients to each reference site in one FET, a general coefficient p_b was developed for the entire FET. Figure 8 shows the results of the UCUT analysis for the Skawa river in Poland with developed coefficients p_b for each bioperiod and habitat threshold. (Parasiewicz et al. 2018)



Bioperiod	Spring Spawning	Rearing and Growth	Fall Spawning/ Overwintering	Overwintering
Months	**III–VI**	**V–IX**	**X–XII**	**I–II**
Common habitat (% CA)	**15.5**	**20**	**18**	**-**
Shortest persistent duration (days)	22	36	27	32
Catastrophic duration (days)	36	62	51	42
Base flow ($l\cdot s^{-1}\cdot km^{-2}$)	5.8	7.4	6.6	5.5
Index $p_{b,b}$	2.57	4.41	0.90	2.20
Critical habitat (% CA)	**13**	**16**	**2**	**-**
Shortest peristent duration (days)	7	9	8	8
Catastrophic duration (days)	15	20	14	32
Trigger flow ($l\cdot s^{-1}\cdot km^{-2}$)	2.59	1.24	1.55	2
Index $p_{b,t}$	1.15	0.74	0.21	0.80
Rare habitat (% PK)	**12.5**	**15**	**1**	**-**
Shortest persistent duration (days)	6	4	6	8
Catastrophic duration (days)	11	16	7	12
Subsistence flow ($l\cdot s^{-1}\cdot km^{-2}$)	1.86	1.03	1.14	1.5
Index $p_{b,s}$	0.82	0.61	0.16	0.60
Abs. Minimum flow ($l\cdot s^{-1}\cdot km^{-2}$)	**0.725**	**0.166**	**0.518**	**0.414**
Index $p_{b,min}$	0.32	0.10	0.07	0.17

Figure 8 Habitat thresholds and associated durations calculated for the Skawa River in Poland (CA—Channel Area, I–XII—month) (Parasiewicz et al. 2018)

A simple formula was developed to facilitate the calculation of flow thresholds at other locations in the watershed or for other rivers of the same FET using the coefficients p_b. The formula calculates the absolute flow threshold value $Q_{ef,b}$ at any cross section k in the catchment (Formula 4) (Parasiewicz et al. 2018):

$$Q_{ef,b} = p_b * q_{MBLF,k} * A_k \tag{4}$$

with p_b = tabulated value of index obtained from reference studies for each bioperiod and FET

$q_{MBLF,k}$ = specific mean low flow for the bioperiod at cross-section k

A_k = catchment area at cross-section k

The coefficients p_b were developed for each FET. Using this formula, the base flow, the trigger flow and the subsistence flow indicating common, critical and rare habitat thresholds respectively could then be calculated for each river in Poland. Together with the threshold durations, dynamic river management strategies such as limiting water withdrawal or releasing water from a reservoir could be developed for each Polish river. (Parasiewicz et al. 2018)

3.4 Comparison to Other Fish Habitat Models

The MesoHABSIM approach has advantages when compared to microscale physical habitat models but also in comparison to other mesoscale models. However, few research projects exist which compare different types of habitat modelling. After the development of MesoHABSIM and its first application, Parasiewicz and Walker, J. (2007) compared it to the original PHABSIM model and its multivariate version HARPHA. Eisner et al. (2005) applied the newly developed MesoCASiMiR approach with other available mesoscale habitat modelling strategies to compare the data collection strategies. The results of both studies are presented in the following sections as examples of the advantages and disadvantages of MesoHABSIM and the mesoscale approach in general.

3.4.1 Comparison to Microscale Approaches

As mentioned before, Parasiewicz and Walker, J. (2007) compared MesoHABSIM with a simplified version of PHABSIM and the multivariate HARPHA model. It was shown that only the results of the MesoHABSIM approach could be verified by the detection of a correlation between the prediction and the observation of fish. For both microscale models, however, the validation was unsuccessful. PHABSIM obviously suffered due to the use of univariate statistics, as more consistent results were identified between HARPHA and MesoHABSIM. This implies, as explained in Section 2.2.4.2, that the accuracy of the biological model influences the results more strongly than the applied scale. Furthermore, the MesoHABSIM model includes information on cover structures, which are often not represented in hydraulic models due the placement of transects. The data collection for both microscale models was less intensive, but the computational effort in the hydraulic model is greater than the processing of the MesoHABSIM data. Nevertheless, the MesoHABSIM approach is inconsistent in scale because of measurements collected at the microscale and the use of mesoscale characteristics. (Parasiewicz and Walker, J. 2007).

In addition to the work of Parasiewicz and Walker, J. (2007), several authors have discussed the advantages and disadvantages of mesoscale approaches in comparison to microscale ones. In general, the application of microscale physical models is not feasible at the longer river sections necessary for river management action (Parasiewicz 2001; Eisner et al. 2005; Schneider et al. 2013). One-dimensional physical habitat models are only useful in regular channels with steady state flow conditions, as they neglect important aspects of the hydraulic conditions (Vezza 2010). Multi-dimensional models, on the other hand, require intensive field measurements and high computational effort, especially at longer river stretches or mountainous streams with high variability in substrate and hydro-morphological conditions (Parasiewicz and Walker, J. 2007; Vezza 2010). This makes them time- and cost-intensive to use (Eisner et al. 2005). Mesoscale methods, however, do not depend on cross-sectional measurements and can therefore be applied in complex and diverse structures (Vezza 2010; Parasiewicz et al. 2013). Furthermore, mesoscale models can include more non-hydraulic variables to characterise habitat conditions, such as cover structures or land use of the banks, as they do not depend on cross-sectional measurements (Parasiewicz and Walker, J. 2007; Parasiewicz et al. 2013). Another important point is that hydraulic models are sensitive to the roughness of the riverbed and are therefore often limited when it comes to describing low flow water conditions accurately (Parasiewicz 2001). This is, however, an essential factor when estimating environmental flows. A major argument for the application of mesoscale habitat models is that fish in general are more associated to the mesoscale than to the microscale (Parasiewicz 2001; Schneider et al.

2013). This means fish can be found more easily in mesoscale habitats than in microscale habitats, because mesohabitats are areas where fish occur during several periods of their life. It is therefore less coincidental to detect fish in mesohabitats than in microhabitats (Parasiewicz 2001). Thus, mesoscale approaches to model fish habitats are easier to calibrate and validate, as fish can actually be found in mesoscale habitats with their preferred environmental condition (Parasiewicz 2001; Eisner et al. 2005; Schneider et al. 2013). The possibility of an easier calibration and validation increases the accuracy of habitat models (Parasiewicz 2001).

On the other hand, hydraulic models contain more detail when it comes to describing velocity and water depth (Vezza 2010; Schneider et al. 2013). As they describe the hydraulic conditions in the river explicitly, the data collected is less subjective than when HMU type and extent as well as measurement points need to be selected. In addition, a hydraulic model can easily simulate different discharges in the river, which can then be transformed into habitat suitability, while mesoscale models can only show the habitat quality and quantity for the surveyed conditions. Furthermore, several surveys are necessary to describe changes in habitat quantity due to changes in discharge, as no accurate method of predicting habitat values of other discharges exists (Dunbar, Alfredsen, and Harby 2012; Schneider et al. 2013).

To conclude, mesoscale habitat models have lower resolutions regarding the description of hydraulic conditions in the river and can only simulate habitat conditions for the surveyed discharges. Nevertheless, as they include more important aspects which influence habitat conditions, such as the consideration of the HMU type and available cover structures, and as habitat preferences are more easily defined and validated on the mesoscale, there are major advantages regarding the accuracy of a biological model compared to microscale physical habitat models. In general, mesoscale physical habitat models are considered to have the advantage of an holistic view of a riverine ecosystem (Schneider et al. 2013). Furthermore, they can be used in longer river sections which is important for river management action and planning processes, such as the implementation of the WFD (Eisner et al. 2005; Parasiewicz 2007a; Dunbar, Alfredsen, and Harby 2012; Schneider et al. 2013; Noack, Schneider, and Wieprecht 2013).

3.4.2 Comparison to Other Mesoscale Approaches

In general, mesoscale approaches mostly do not include calculations of the hydraulic or hydromorphologic conditions, as they are zero-dimension models. Furthermore, they do not refer to single cells in the riverbed but to stream units (Vezza 2010). These units, often referred to as HMUs, are normally mapped at different discharges to gain information on the habitat availability of different hydraulic conditions. These mapping strategies normally are able to represent larger river sections and include additional aspects such as anthropogenic disturbances (Schneider et al. 2013).

Eisner et al. (2005) compared four mesohabitat approaches in reference to ease of application, time needed, amount of detail provided and subjectivity. The authors applied the models in a stretch of the River Eyach in the upper part of the Danube catchment (Eisner et al. 2005). In addition to the MesoCASiMiR approach, the first MesoHABSIM version, MSC and Rapid Habitat Mapping (RHM) of PHABSIM were used. However, the authors stressed that RHM is considered less of a mesohabitat modelling method than an upscaling tool, as it was developed in the PHABSIM process to identify river stretches where the PHABSIM model should be applied (Eisner et al. 2005; Jorde and Schneider 2015b). Due to this, the RHM approach is not included here.

As mentioned before, MesoCASiMiR is an enhancement of the habitat model CASiMiR which is used on the mesoscale instead of the microscale like CASiMiR (Schneider et al. 2013). It includes the mapping of river stretches similar to the MesoHABSIM data collection with the use of tablet computers and GPS devices (Jorde and Schneider 2015b). This mapping process is based on units which include several different types of mesohabitat (Jorde and Schneider 2015b). For each unit, information is collected about the river use and the surrounding land use, while type, flow velocity, water depth, substrate, embeddedness and cover structures are classified for each mesohabitat (Jorde and Schneider 2015b). To improve this classification process, representative measurements may be necessary (Schneider et al. 2013). In addition, the habitat suitability is then calculated using fuzzy rules (Eisner et al. 2005; Schneider et al. 2013).

The Meso-scale Habitat Classification method (MSC) was developed as part of research projects to model habitats and help the production of juvenile Atlantic salmon in Norway (Borsányi et al. 2004). It was created to support and improve the population model NORSALMOD, which models the population development of Atlantic salmon. The goal of the development was to create a more detailed and flexible method than microscale physical habitat models and other mesoscale approaches. The MSC approach characterises mesohabitats based on classes which can be defined using a decision tree which includes surface pattern, surface gradient, surface velocity and water depth. Furthermore, the substrate composition is identified as a second layer of classification. To reduce the subjectivity, simple measurements are included in the approach to facilitate the classification using the decision tree. The results of the MSC are then used to create links between hydro-morphological units and habitat, which can be used in the NORSALMOD. (Borsányi et al. 2004).

By applying the different approaches, Eisner et al. (2005) detected that for both wadable and unwadable parts of the river, the application of the MesoHABSIM survey was the most time-consuming. For the MesoHABSIM and the MesoCASiMiR survey, it was necessary to enter and exit the river several times to select data or to carry out measurements, which increased the amount of time needed. Regarding the details considered in each strategy, however, MesoHABSIM showed the highest number of details followed by MesoCASiMIiR. Issues regarding subjectivity occurred in all methods. The influence of subjectivity on the MSC method is expected to be smallest due to the decision tree. For MesoHABSIM, subjectivity could be detected regarding the definition of the habitat type, but it could be decreased by measuring the water depth and velocity inside the habitat unit. MesoCASiMiR, additionally, showed issues of subjectivity especially regarding the beginning and end of habitat units and the description of embeddedness and cover structure. Finally, it was shown that the MSC method was the quickest and easiest method to apply, however it includes little detail and is not connected to a multivariate data interpretation process. The MesoCASiMiR and the MesoHABSIM method are both quite detailed and provide accurate information but both are time-consuming and can easily be affected by subjectivity. (Eisner et al. 2005)

Compared to other mesoscale methods, MesoHABSIM is considered to be the most time-consuming, but also the most detailed method. Due to the expert mapping process including hydraulic measurements, data collection is scientifically rigour (Parasiewicz et al. 2013). Furthermore, it includes a specific data analysis strategy based on a multivariate statistical model and considers the hydrological regime, which is unique in the field of mesoscale habitat modelling (Parasiewicz et al. 2013). The measurements of velocity and water depth are time consuming, but they reduce the subjectivity in the classification of the HMU (Eisner et al. 2005; Parasiewicz et al. 2013). Additionally, the time spent in the river during the surveys can be considered valuable, as several important aspects of the riverine habitat can be detected. It so outweighs the time spent post-processing, which is necessary for other methods including hydraulic models (Parasiewicz et al. 2013).

4 Study Objective

4.1 Aim

As shown in the sections above, research in the field of reducing the anthropogenic impacts on river ecosystems and defining mitigation actions is of major importance in order to achieve sustainable ecosystems. Numerous research projects have therefore been created such as the FIThydro project and the AMBER project funded by the European Union’s Horizon 2020. The FIThydro project concentrates on the impacts of hydropower plants on the fish population and finding innovative technical mitigation options, while the AMBER project deals with the impacts of barriers on river ecosystems in general. In addition, several ecohydraulic studies have shown that setting environmental flow rules is essential to protect and maintain riverine ecosystems. Bringing together the results of both projects, the idea of using the river classification system of AMBER based on macrohabitat types (see Section 4.2.1) to construct regional environmental flow rules and standards for different European macrohabitat regions was developed. This would allow the consistent and simultaneous assessment of environmental flows in the European Union, which could be implemented in the framework of the WFD.

With this background, the objective of this thesis is the assessment of environmental flows in the Tyrol region. This area is part of one of the recognised macro habitat types in Europe. This thesis therefore shows the application of MesoHABSIM in two case studies in Tyrol. One river stretch was located at the River Leutasch or Leutascher Ache and was selected as a reference site in order to gain information about the natural condition of rivers in this particular region. The second case study was located in the upper part of the River Inn and is part of a FIThydro test case which detailed aerial pictures, hydraulic models and instream habitat models had already been gathered for. Section 5.2 gives detailed information about the hydropower project (GKI Inn) in the Upper Inn River. This thesis generates data which can be used in order to further develop regional environmental flow assessment methods in Europe. Furthermore, it should prove the applicability of such regional environmental flow standards. In addition, the results of this thesis can be used to compare environmental flow rules for the FIThydro test case using different methodologies.

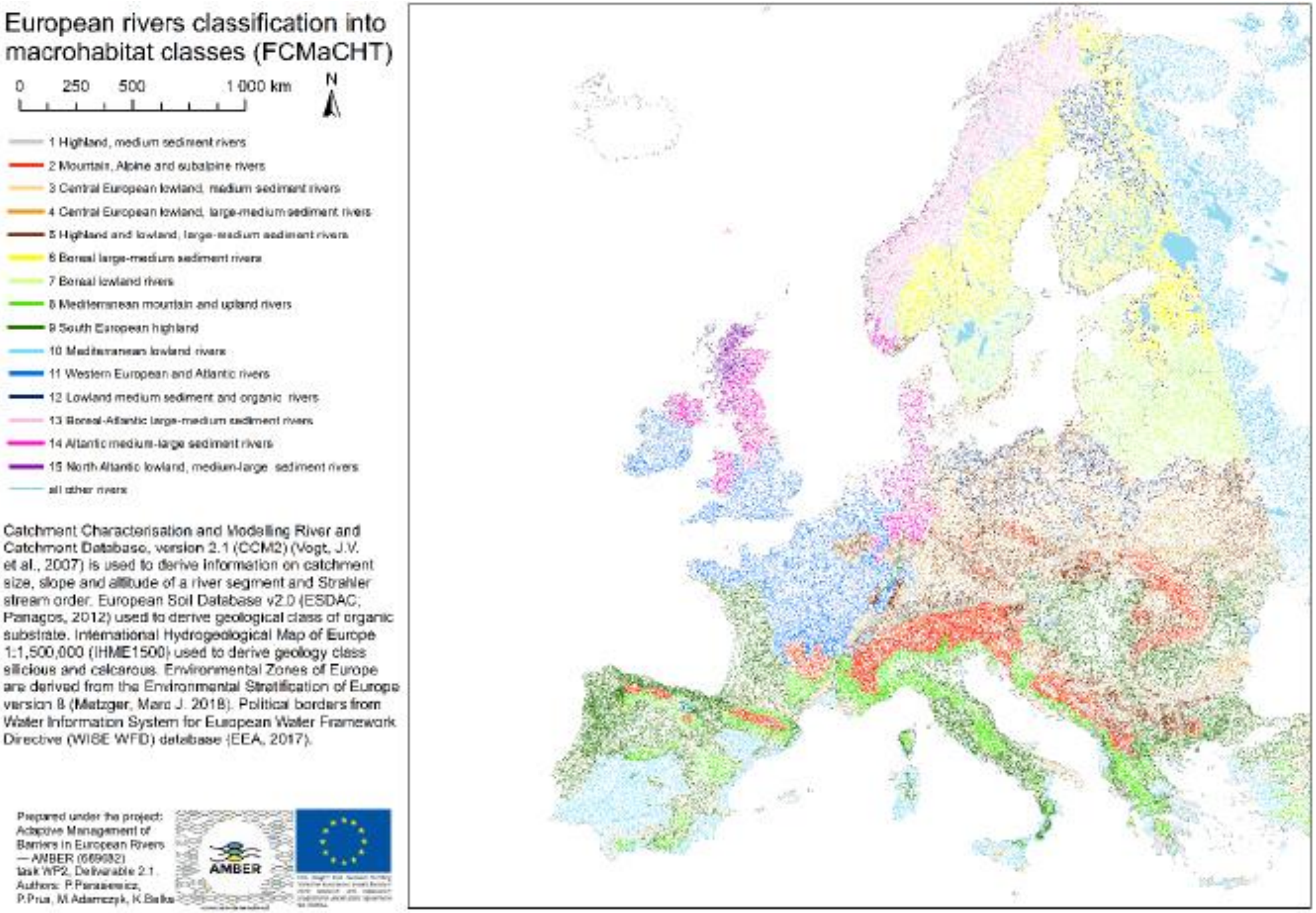
4.2 Background

The following two sections present the results gathered in the AMBER project. The development of macrohabitat types is described and explained and there is also an assessment of the impacts of barrier types on river habitat. As this thesis is based on and uses parts of these studies, the results are given as a background here in order to explain how these results were gathered.

4.2.1 Fish Community Macro Habitat Types (FCMacHT)

As part of the AMBER project, European rivers were divided into 15 Fish Community Macro Habitat Types (FCMacHT) which are based on a number of physio-geographic factors and an associated expected fish community (AMBER 2019). This classification was the result of a cluster analysis, which took the following abiotic variables: catchment size, river slope, geological type, Strahler stream order, altitude and environmental zones of Europe into account (AMBER 2019). Finally, the following 15 macrohabitat classes were identified (Figure 9) (AMBER 2019):

- 1 Highland, medium sediment rivers
- 2 Mountain, Alpine and subalpine rivers
- 3 Central European lowland, medium sediment rivers
- 4 Central European lowland, large-medium sediment rivers
- 5 Highland and lowland, large-medium sediment rivers
- 6 Boreal large-medium sediment rivers
- 7 Boreal lowland rivers
- 8 Mediterranean mountain and upland rivers
- 9 South European highland rivers
- 10 Mediterranean lowland
- 11 Western European and Atlantic rivers
- 12 Lowland medium sediment and organic rivers
- 13 Boreal-Atlantic large-medium sediment rivers
- 14 Atlantic medium-large sediment rivers
- 15 North Atlantic lowland, medium-large sediment rivers



Catchment Characterisation and Modelling River and Catchment Database, version 2.1 (CCM2) (Vogt, J.V. et al., 2007) is used to derive information on catchment size, slope and altitude of a river segment and Strahler stream order. European Soil Database v2.0 (ESDAC; Panagos, 2012) used to derive geological class of organic substrate. International Hydrogeological Map of Europe 1:1,500,000 (IHME1500) used to derive geology class silicious and calcarous. Environmental Zones of Europe are derived from the Environmental Stratification of Europe version 8 (Metzger, Marc J. 2018). Political borders from Water Information System for European Water Framework Directive (WISE WFD) database (EEA, 2017).

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Figure 9 Classification of European rivers into Fish Community Macro Habitat Types (FCMacHT) (AMBER 2019)

In addition, fish species occurring in European rivers were classified into eleven fish habitat-use guilds which combine fish species with similar characteristic habitat preferences (AMBER 2019):

- 1 Highly rheophilic, intolerant species
- 2 Rheophilic benthic species, preferring sandy-gravel bottom substrate
- 3 Rheophilic water column species, preferring sandy-gravel bottom substrate
- 4 Limnophilic benthic species of moderate tolerance
- 5 Limnophilic water column species of moderate tolerance
- 6 Intolerant, rheophilic benthic species, preferring detritus or pelal bottom substrate
- 7 Intolerant, water column species
- 8 Limnophilic lithophilic species of moderate tolerance
- 9 Limnophilic phytophilic species of moderate tolerance
- 10 Benthic species of moderate tolerance
- 11 Generalists – tolerant species

Using those fish habitat-use guilds, an expected fish community was developed for each FCMacHT. Each expected fish community was made up of several fish-habitat use guilds and the percentage of each fish habitat-use guild on the fish community was calculated explicitly (Figure 10).

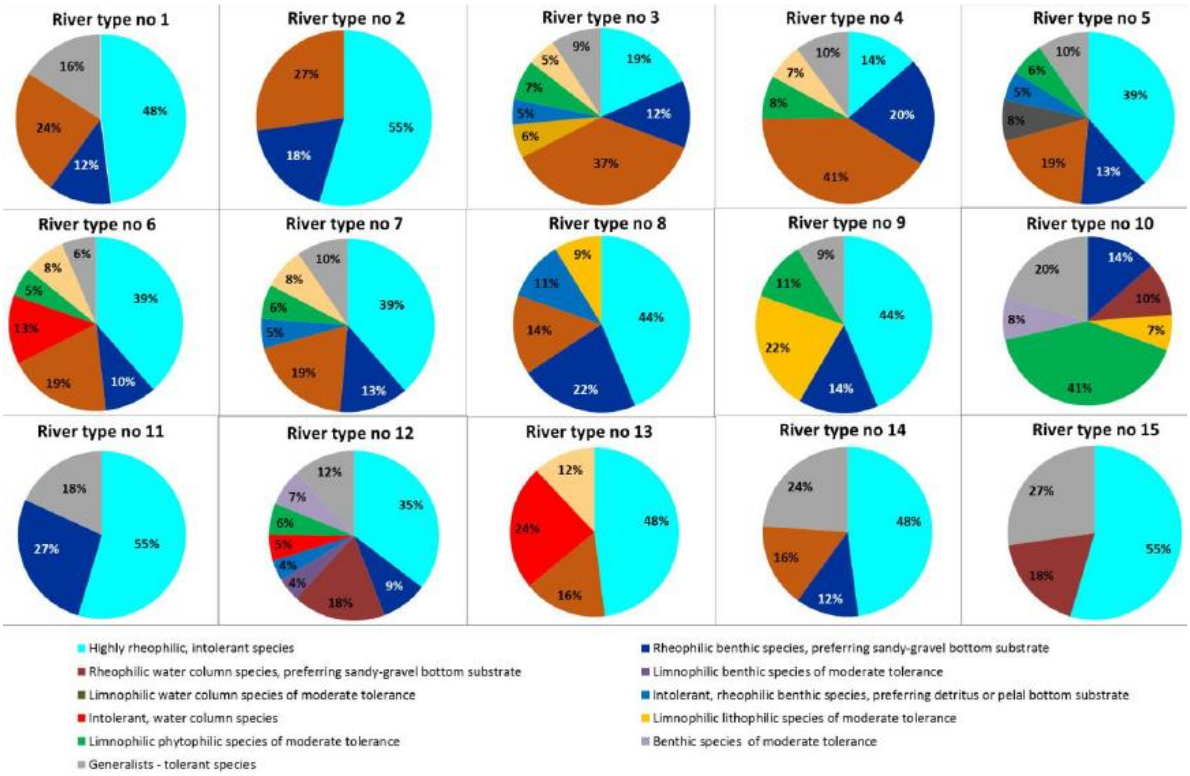
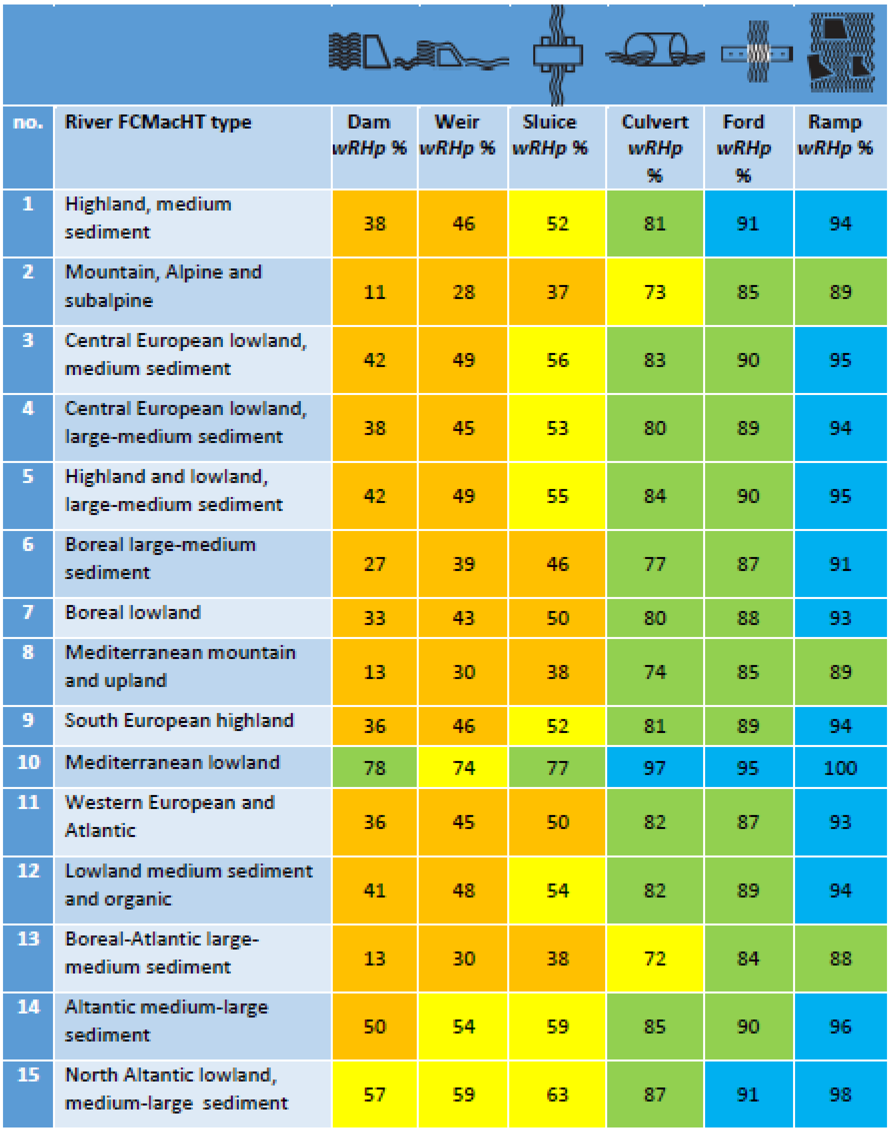


Figure 10 Expected fish community for each FCMacHT (AMBER 2019)

The river classification system developed in the AMBER project is advantageous as it provides information on each river in Europe according to its geomorphic variables as well as its expected fish community. Furthermore, rivers with similar characteristics can easily be identified and then treated similarly. For example, this river classification system was used in the AMBER project to assess the impacts of barriers on different river types (see Section 4.2.2). It was assumed that rivers which belonged to one class reacted similarly to the effects of barriers. In addition to the assessment of the impacts of barriers, other assessment methods or administrative processes, such as environmental flow rules, could be generated based on this river classification, which would facilitate the systematic management of rivers with similar characteristics in Europe. (AMBER 2019)

4.2.2 Ecological Impacts of Barriers in Europe

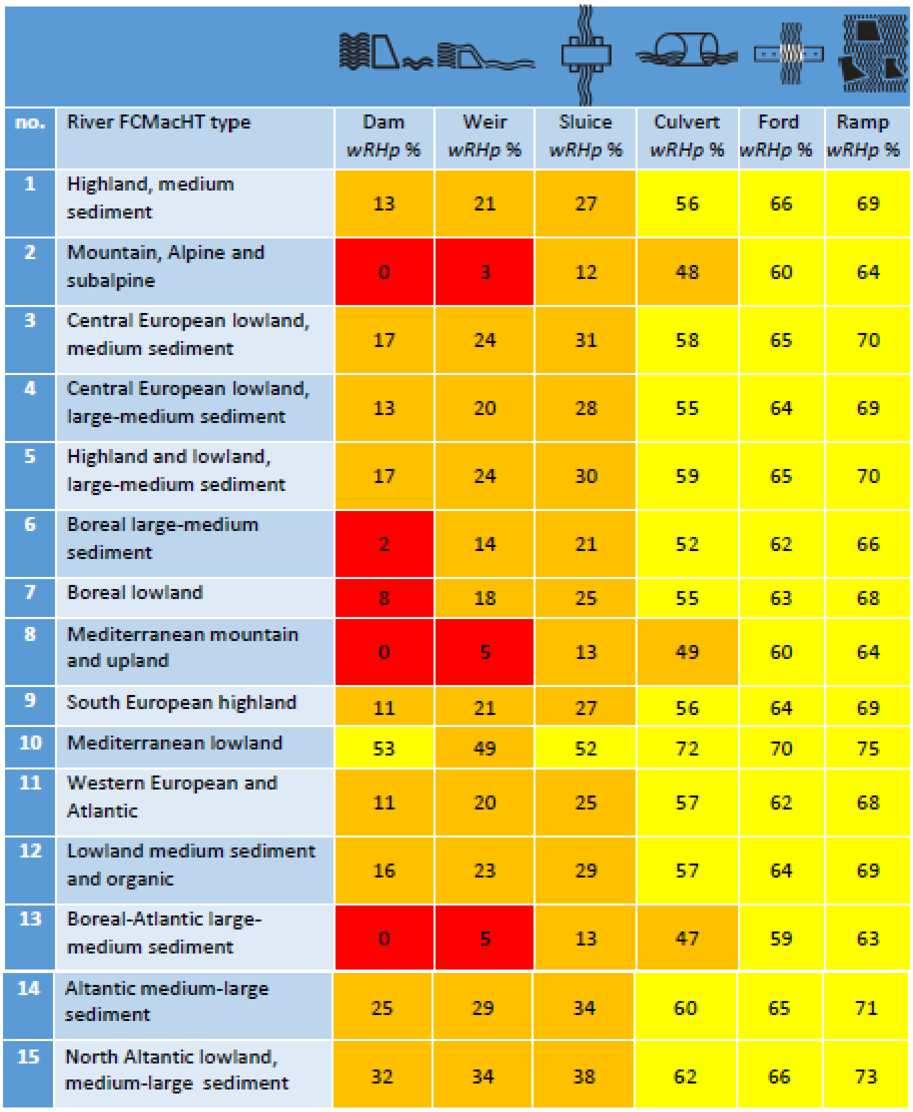
The impact of barriers on river ecosystems was assessed for each FCMacHT as part of the AMBER project (AMBER 2019). Therefore, 21 habitat attributes were identified which could be modified by the construction of barriers, including values of flow velocity and water depth, substrate composition, oxygen and trophic level, the occurrence of macrophytes and wood as well as the vegetation of river banks and habitat continuity and stability. For each barrier type considered (dam, weir, sluice, culvert, ford or ramp), it was estimated how the barrier would influence these habitat attributes. It was shown that dams have the strongest impact on instream habitat, as all of the habitat attributes are modified due to the construction of dams. Ramps, on the other hand, have the smallest impact on habitat variables. In addition, it was assessed how important the different habitat attributes are for the fish habitat-use guilds. Based on this assessment, highly rheophilic, intolerant species and intolerant, rheophilic benthic species, preferring detritus or pelal bottom substrate were identified as the most sensitive to change in the habitat attributes, while generalist species are least sensitive to habitat change. Putting together the results of these assessments, the proportion of weighted remaining habitat (wRHp in %) was calculated for each FCMacHT which gives researchers information about how much habitat will remain in the river after implementing a specific barrier type. The results of this assessment are shown in Figure 11. Habitat loss is considered to be severe and marked red, if less than 10% of the habitat remains; major habitat loss is marked orange and occurs if 11-50% of the habitat remains; significant habitat loss is marked yellow and occurs if 51-75% of habitat remains; moderate habitat loss is marked green and occurs if 76-90% of the habitat remains and finally low habitat loss is marked blue if more than 90% of the habitat remains. (AMBER 2019)



no.	River FCMacHT type	Dam *wRHp %*	Weir *wRHp %*	Sluice *wRHp %*	Culvert *wRHp %*	Ford *wRHp %*	Ramp *wRHp %*
1	Highland, medium sediment	38	46	52	81	91	94
2	Mountain, Alpine and subalpine	11	28	37	73	85	89
3	Central European lowland, medium sediment	42	49	56	83	90	95
4	Central European lowland, large-medium sediment	38	45	53	80	89	94
5	Highland and lowland, large-medium sediment	42	49	55	84	90	95
6	Boreal large-medium sediment	27	39	46	77	87	91
7	Boreal lowland	33	43	50	80	88	93
8	Mediterranean mountain and upland	13	30	38	74	85	89
9	South European highland	36	46	52	81	89	94
10	Mediterranean lowland	78	74	77	97	95	100
11	Western European and Atlantic	36	45	50	82	87	93
12	Lowland medium sediment and organic	41	48	54	82	89	94
13	Boreal-Atlantic large-medium sediment	13	30	38	72	84	88
14	Altantic medium-large sediment	50	54	59	85	90	96
15	North Altantic lowland, medium-large sediment	57	59	63	87	91	98

Figure 11 Weighted remaining habitat proportion (wRHp) for each barrier type and FCMacHT (AMBER 2019)

Dams and weirs are connected to high losses in habitat and mostly lead to major and significant habitat loss. However, these values were calculated based on the assumption that all the possible mitigation measures had been applied for all barrier types, including passability structures and options. Furthermore, not all potential impacts on habitat continuity and stability were included in this assessment. Therefore, the authors proposed a migration penalty of 25% to account for all of the additional impacts. This reduced the amount of remaining habitat for each barrier type (Figure 12). When using the migration penalty, dams and weirs even led to severe habitat loss in five and three FCMacHTs respectively and moderate or low habitat loss was not expected for any of the barrier type. (AMBER 2019)



no.	River FCMacHT type	Dam *wRHp %*	Weir *wRHp %*	Sluice *wRHp %*	Culvert *wRHp %*	Ford *wRHp %*	Ramp *wRHp %*
1	Highland, medium sediment	13	21	27	56	66	69
2	Mountain, Alpine and subalpine	0	3	12	48	60	64
3	Central European lowland, medium sediment	17	24	31	58	65	70
4	Central European lowland, large-medium sediment	13	20	28	55	64	69
5	Highland and lowland, large-medium sediment	17	24	30	59	65	70
6	Boreal large-medium sediment	2	14	21	52	62	66
7	Boreal lowland	8	18	25	55	63	68
8	Mediterranean mountain and upland	0	5	13	49	60	64
9	South European highland	11	21	27	56	64	69
10	Mediterranean lowland	53	49	52	72	70	75
11	Western European and Atlantic	11	20	25	57	62	68
12	Lowland medium sediment and organic	16	23	29	57	64	69
13	Boreal-Atlantic large-medium sediment	0	5	13	47	59	63
14	Altantic medium-large sediment	25	29	34	60	65	71
15	North Altantic lowland, medium-large sediment	32	34	38	62	66	73

Figure 12 Weighted remaining habitat proportion (wRHp) for each barrier type and FCMacHT including the migration penalty of 25% (AMBER 2019)

When using this assessment of the ecological impacts of barriers, the expected habitat loss and the associated fish fauna degradation can be estimated for a specific barrier type which can then be used in decision-making processes (AMBER 2019).

4.3 Method

The MesoHABSIM model was chosen in this study because it has certain advantages when it comes to the estimation of environmental flow rules in general as well as using them on a regional scale (see Section 3.3.4). For one thing, longer river stretches can be observed and simulated which provides a better upscaling of the obtained results to other locations in the catchment and to the catchment level. Additionally, the biological model of MesoHABSIM is detailed, accurate and flexible and therefore it can easily be adapted to the ecological conditions. As the AMBER project defines target fish communities for each particular macrohabitat type, the MesoHABSIM model is especially advantageous as it is able to take fish communities as well as individual species into account. In addition, the application of MesoHABSIM in the alpine region, especially the Austrian and German part is still rare.

MesoHABSIM has already been used to create regional environmental flow rules in Poland (Parasiewicz et al. 2018), as described in Section 3.3.4. Using this study as a background, this thesis produces data in order to create similar environmental flow rules for the alpine region. Therefore, similar strategies to the ones used in the Polish study are applied here. The MesoHABSIM model is applied in two rivers in Tyrol to gain information about the habitat characteristics in this region. Habitat models are developed which take the habitat preferences and bio-periods of the fish communities in the particular region into account. Then the obtained data is analysed as described in Section 3.3 and habitat thresholds for the frequency and duration of critical habitat events are calculated. The results of this analysis are then used to define environmental flow rules for each river stretch and the Tyrol region in general.

4.4 Study Area Selection

The two cases studies chosen for this thesis are part of the FCMacHT type two “Mountain, Alpine and subalpine rivers”. The alpine area in general was selected as study area as data and knowledge already exist from one FIThydro test case. In addition, the AMBER project shows the vulnerability of the alpine region regarding the ecological impacts which are caused by the construction of barriers (see Section 4.2.2). It identified dams and weirs, which often occur in mountainous regions, as the barrier types which have the strongest impact on the instream habitat (AMBER 2019). Furthermore, species typical for alpine rivers such as rheophilic, intolerant species are highly sensitive to change in the habitat conditions (AMBER 2019). Therefore, the alpine area is a highly interesting study area in order to develop and apply mitigation actions in order to reduce the impacts of hydropower plants and barriers in general. Furthermore, both rivers chosen here are located in the Tyrol region of Austria and therefore this thesis especially focuses on this particular part of the alpine area.

5 Study Area

5.1 Leutasch

As this thesis concentrates on the alpine river type identified in the AMBER project (Mountain, Alpine and subalpine rivers) and tries to generate data for the alpine test cases in the FIThydro project, it was necessary to find a reference site in this particular region. In addition, a river stretch was needed which hydrological data has existed for at least 20 years for. Furthermore, as the river stretch should be a reference site for the alpine or the Tyrol region, the river should not be impacted by any anthropogenic activity or the anthropogenic impacts should be minimal. Another important aspect when selecting the reference site was the size of the river and the discharge in the river stretch. For MesoHABSIM data collection, it is necessary to walk through a river with different discharge levels which means the water level and discharge should not be too high for people to stand and work in. Finally, the River Leutasch or Leutascher Ache was selected as a reference site.

5.1.1 Catchment

The source of the River Leutasch is located in Austria in the Tyrol region near the municipality of Leutasch in Tirol close to the border with Germany. 28 km after, it crosses the border with Germany near Mittenwald, where it then joins the River Isar. The river is called the Leutascher Ache in Austria and the Leutasch in Germany. In the following sections the river is referred to as the Leutasch. The catchment size is 112 km² and the length of the river is 29 km (Bayerisches Landesamt für Umwelt (LfU) 2020).

The catchment is surrounded by mountains, which reach heights of up to 2700 m a.s.l in the south-western part of the catchment (LfU 2020). The conjunction with the River Isar is located at a height of around 920 m a.s.l (LfU 2020). Based on field visits to the catchment and along the river and by using aerial picture, no major anthropogenic alterations could be identified in the catchment and in the riverbed. Only in some parts the banks are artificially stabilised mostly by boulders or riprap, when the Leutasch flows through villages or comes close to houses. However, most parts of the riverbeds and banks are natural and wide enough to form the typical features of an alpine river such as braided areas, gravel banks and islands.

Large amounts of the catchment area are covered in forest especially in the mountains and in the upper part of the catchment. In the middle and the flatter parts of the catchment, some villages can be found as well as some areas used for agriculture. In the lower part of the catchment close the border with Germany the Leutasch flows through a narrow gorge, the Leutasch-Klamm or Geisterklamm, which is a place of interest for tourists. An old hydropower plant is located upstream from the Geisterklamm. This hydropower plant is, however, not in use anymore but plans to renovate and reuse it have not been put into action yet (Schnürer, January 22, 2020). In general, the region is a touristic area used for hiking and snow sports. An aerial picture of the catchment is shown in Figure 13 with symbols indicating the size of the catchment, the river course as well as the location of the reference site, the gorge, the municipalities Leutasch and Weidach and the gauging stations (Figure 13).

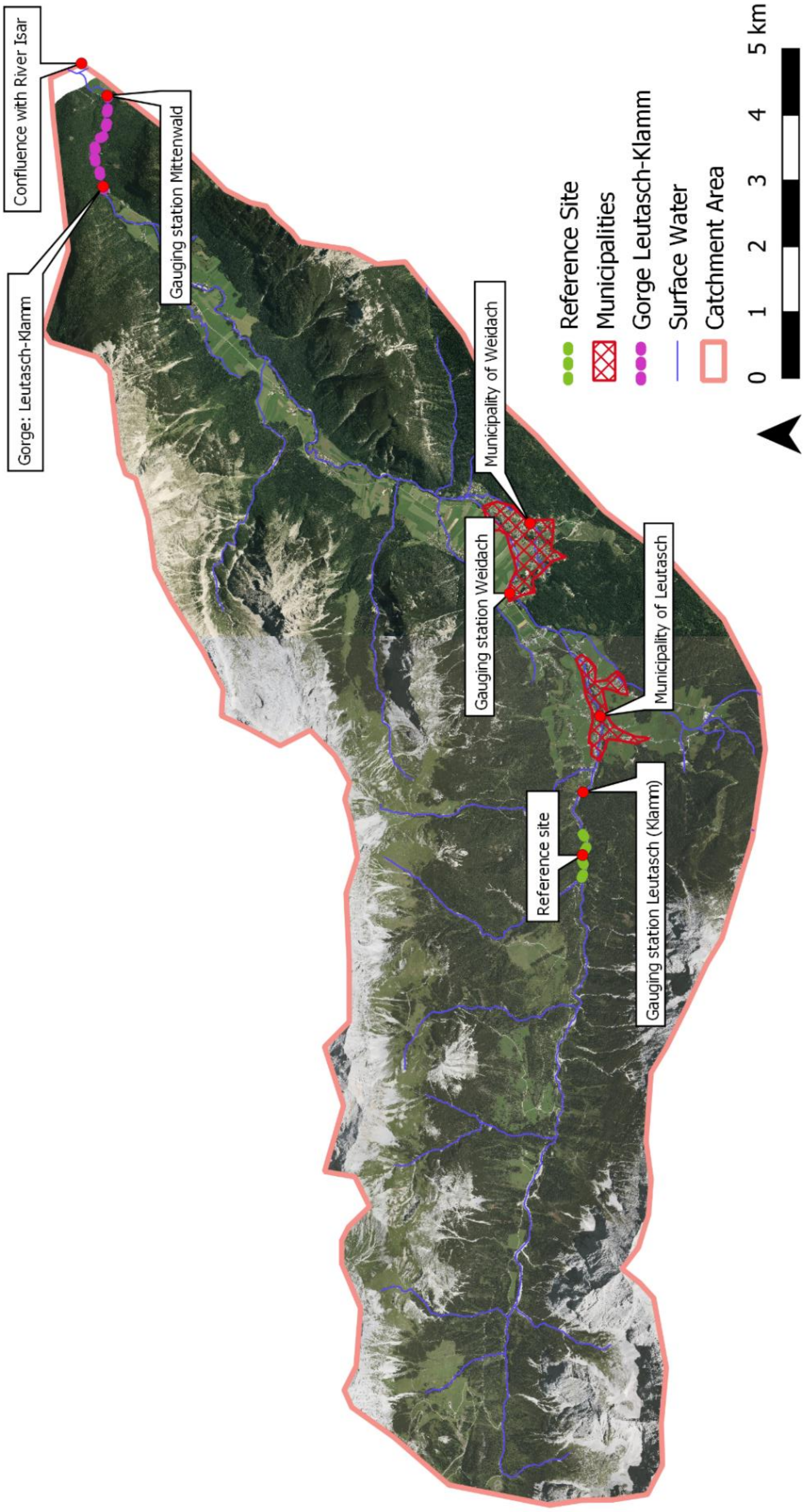


Figure 13 Aerial picture of the Leutasch catchment using geodata of Land Tirol (2020)

5.1.2 Reference Site

To use the MesoHABSIM model, it was necessary to select a river stretch of the Leutasch as a reference site. Due to the riverbed stabilisation and agricultural use in the middle part of the catchment as well as the gorge and the old hydropower station in the lower part, the selection of the reference site focused on the upper part of the catchment. In this part of the catchment, the river flows through a typical alpine valley and forms a natural river system with gravel banks, islands and erosion and deposition areas. Here, no specific anthropogenic alteration or land use could be identified. Furthermore, the area is mostly covered in forest or grass and scrubs at higher altitudes. Due to this, it is probably the case that the hydrological regime in this part of the catchment has not been altered anthropogenically. The area is a popular hiking area and therefore some streets and several parking places exist as well as hiking paths, especially in the lower part of the valley which are sometimes even close to the river. During the field work, it became clear that the hiking tracks were used frequently and the riverbanks and islands as well as the river itself were visited by hikers and tourists. The streets and hiking paths, however, made it easy to reach the river and to transport the necessary instruments to the riverbanks. During the first field trip, a river stretch was identified as a reference site (Figure 14).

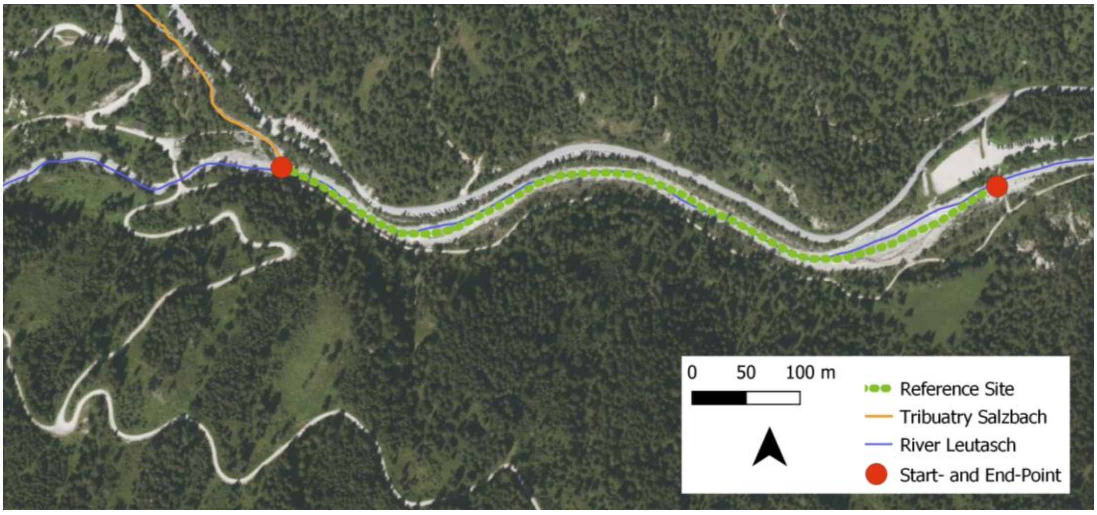


Figure 14 Aerial picture of reference site at the Leutasch using geodata of Land Tirol (2020)

The site started directly downstream from the confluence of a small tributary, the Salzbach, and stretched around 720 m downstream (Figure 14). This particular river stretch was chosen because it included several typical features of alpine rivers such as islands and gravel banks but also riffles, rapids and cascades. River stretches further upstream would not have included so many different features and the discharge would have been too low to use it to represent the entire catchment. As already mentioned, river stretches further downstream could have been subjected to bank stabilisation and hydrological alteration due to sealed and agricultural areas. In addition, a gauging station is located only a few hundred meters downstream of the selected river stretch. Therefore, this stretch was seen as representative for the entire catchment, as it included several typical features and could be assessed using hydrological data collected nearby.

5.1.3 Hydrology

There are three gauging stations in the River Leutasch (Figure 13). Two of the stations are located in the Austrian part of the catchment and are therefore part of the Hydrographic Service Tyrol (Hydrographischer Dienst Tirol). The German station is operated by the Water Authority in Weilheim (Wasserwirtschaftsamt Weilheilm). Starting downstream, the first station, which is called Mittenwald / Leutasch, is located at the border between Austria and Germany, 680 m before it joins the river Isar at a height of 922 m a.s.l (LfU 2020). The next station is located in the municipality of Weidach 13.3 km after at a height of 1122 m a.s.l (Hydrographischer Dienst Tirol 2020c). The third gauging station is Leutasch (Klamm) and can be found 16.4 km upstream from the conjunction with the River Isar at a height of 1184 m a.s.l (Hydrographischer Dienst Tirol 2020b).

The data from the gauging station Leutasch (Klamm) is mainly used in this thesis as the station is located only a few hundred meters downstream from the selected river stretch. The station has been in existence since 1983 and its catchment area is around 45 km² (Hydrographischer Dienst Tirol 2020b). The hydrological regime of the Leutasch was analysed using the IHA method (Version 7.1, The Nature Conservancy). The monthly mean values for each month are presented in Figure 15, which were calculated using parametric and non-parametric statistics. The IHA methods was based on a water year from on 1st October until the end of September the following year. In addition to the mean monthly discharge values, the median and arithmetic mean values for each day of the year were calculated to present the seasonal changes in discharge at the River Leutasch better (Figure 16). Furthermore, the daily mean discharges for the water year 2009/2010 are given as an example for the hydrological regime (Figure 17).

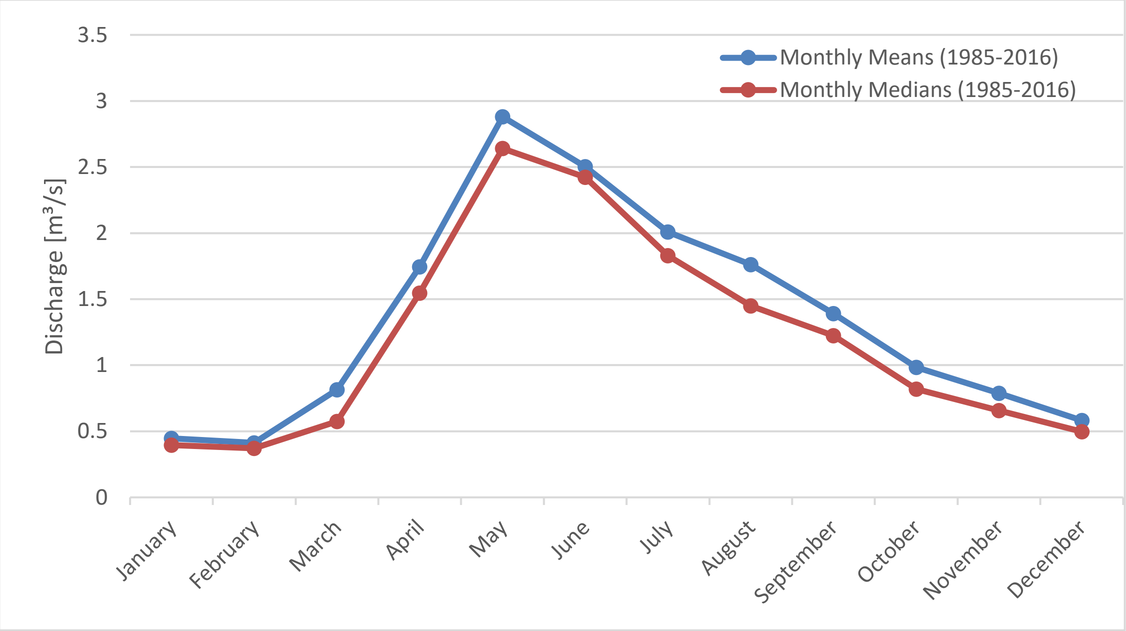


Figure 15 Mean monthly discharge values for the Leutasch at the gauging station Leutasch (Klamm) based on discharge values collected in the period from 1985 to 2016 using data of BMLRT (2020b)

Figure 16 Daily Median discharge values for the Leutasch at the gauging station Leutasch (Klamm) based on discharge values collected in the period from 1984 to 2016 using data of BMLRT (2020b)

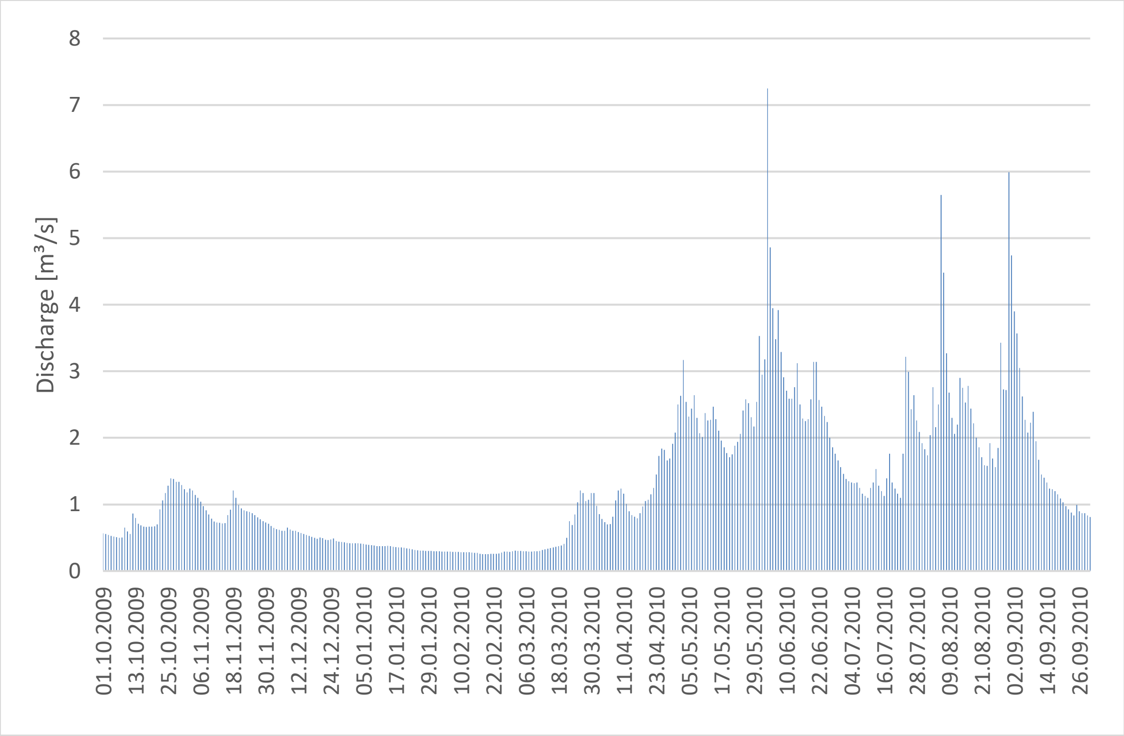


Figure 17 Daily mean discharge values collected at gauging station Leutasch (Klamm) during the water year 2009/2010 as an example for the hydrological regime of the River Leutasch using data of BMLRT (2020b)

The River Leutasch has a hydrological regime typical for the European Alps, which is formed by nival components in winter and spring and pluvial components in summer and autumn (Stahl 2016). Major factors, which influence the hydrological regime, are therefore air temperature and exposition to solar radiation (Bormann and Casper 2016). The air temperature controls whether precipitation falls as snow or as rain and the temperature and solar radiation control whether snow melts or accumulates and forms a snow cover (Bormann and Casper 2016; Stahl 2016). This normally leads to the formation of closed snow covers at altitudes above 1500 to 1700 m a.s.l. during the winter months (Stahl 2016). As precipitation falls as snow and accumulates, low discharge values occur in the river during the winter months. For the Leutasch, the low discharge values in November to March can be explained this way (Figure 15, 16 and 17). Based on the IHA analysis, minimal flow values can be expected in the middle of February. The increasing temperature and solar radiation together then start the melting process in spring, leading to higher discharge values in the valleys. This process is mainly influenced by snow distribution and altitude differences in the catchment (Stahl 2016). It influences the discharge values in several months in spring and early summer due to the gradual melting of snow at different altitudes (Stahl 2016). Based on the discharge values for the Leutasch, the snow melt and the resulting increase in discharge start around March and end in June (Figure 15 and 16). In summer and autumn, the hydrological regime is then influenced by pluvial components (Stahl 2016). The precipitation then mostly fall as rain at all altitudes and creates flood pulses in the river. The IHA methods detected that the highest flow values normally occur in July, however the monthly mean discharge is highest in May (Figure 15), possibly when the melting of snow and rainfall overlap. The runoff formation after rainfall in the alpine area is influenced by the steep topography, the low soil thickness as well as high altitudes areas without vegetation (Stahl 2016). This reduced ability of infiltration and interception together with the steepness leads to fast rising flow values creating flood pulses with high peaks and steep rising and falling limbs (Stahl 2016). This fast runoff formation can be observed during the flood peaks in June, July and August 2010 (Figure 17). The complex topographic situation in the alpine area creates a high spatial and temporal variability in precipitation, such as the formation of orographic precipitation (Stahl 2016). Therefore, the flood peaks in summer and beginning of autumn have a high variability in timing and duration. Due to decreasing temperatures in autumn, a snow cover starts to form at high altitudes again, which leads to slowly decreasing discharge values in the valley. For the Leutasch, this decrease in discharge normally starts around September or October (Figure 15 and 16). However, higher discharges can occur in autumn and early winter when the temperatures in the valley and at lower altitude are too high for snow accumulation.

It can be said that the hydrological regime of the River Leutasch is strongly affected by seasonal climatic changes which create high seasonal change in the discharge values. The mean discharge during late spring and summer caused by the melting of snow as well as rainfall is more than six times higher than the mean discharge during the low flow season from November until March. However, the hydrological regime of the River Leutasch represents the typical nivo-pluvial regime commonly found in the alpine area (Bormann and Casper 2016; Stahl 2016). This also means that the hydrological regime in the upper part of the Leutasch catchment is suitable as a reference site for alpine rivers. Furthermore, it is to be expected that riverine species typical for alpine rivers which have adapted to the specific seasonal hydrological changes exist in the Leutasch.

5.1.4 Morphology

As mentioned before, the River Leutasch can be considered a river in natural or near-natural condition. Based on the ecological assessment used in the WFD, the ecological status of the river is classified as “good” (Land Tirol 2020). Some aspects of its ecological status occur due to anthropogenic activity in the riverbed. The morphology of the river is impacted by flood risk management measures such as small barriers and riverbed ramps or stabilised riverbanks which are located near municipalities (Land Tirol 2020). Due to the riverbed and bank stabilisation action, some river stretches of the Leutasch are classified as obstructed (Figure 18 and 19). However, most parts of the riverbed and riverbanks are in natural or near-natural condition (Figure 18 and 19). The reference site is located on a river stretch which was said to be in at least near-natural morphological conditions.

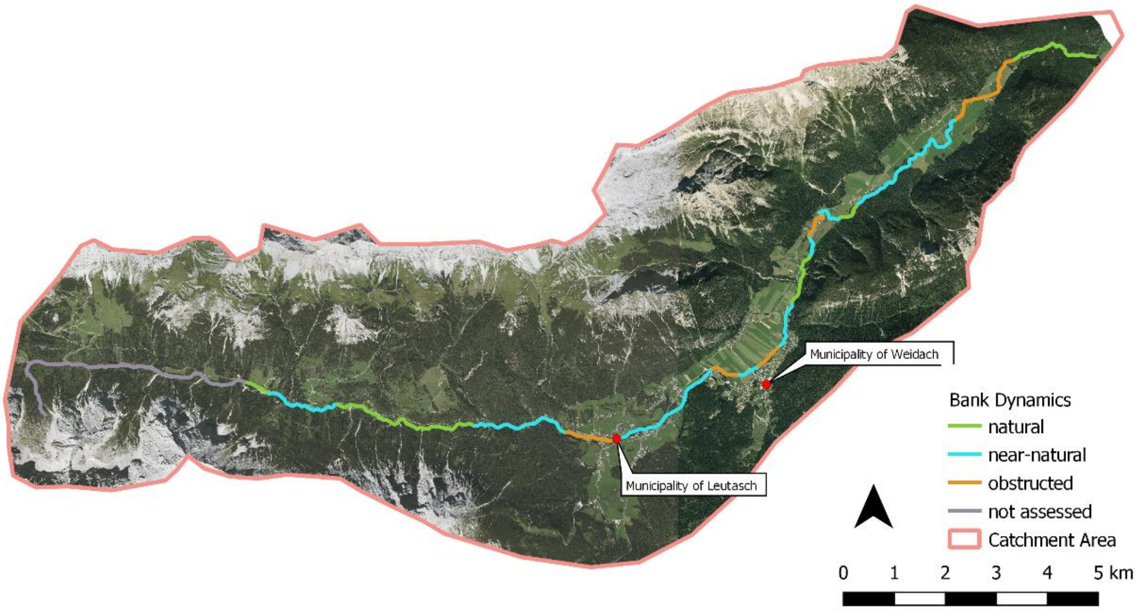


Figure 18 Morphological status in the River Leutasch regarding bank dynamics using geodata of Land Tirol (2020)

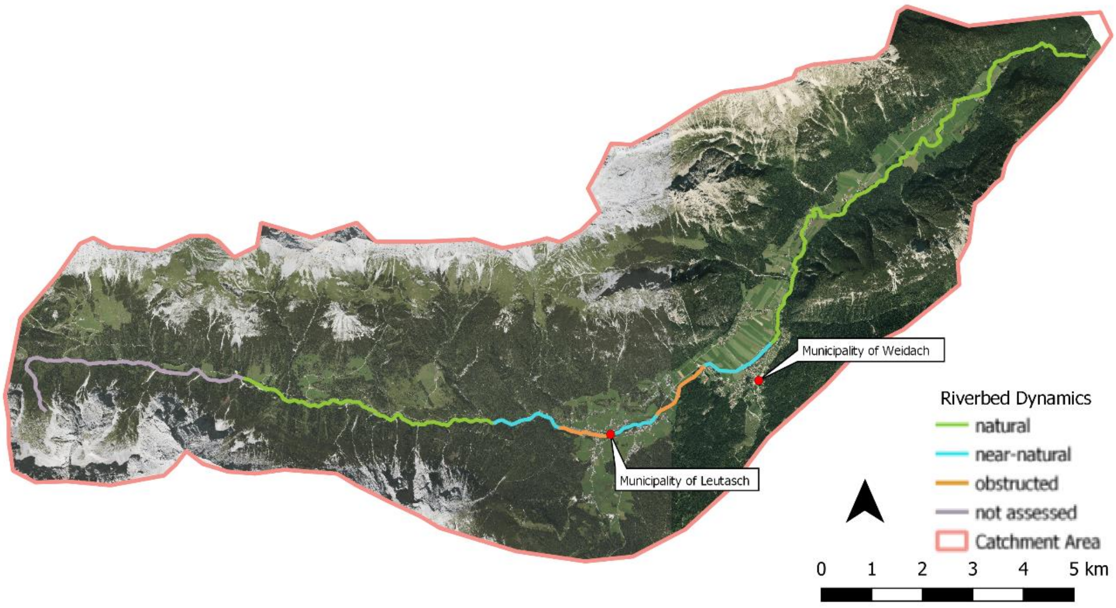


Figure 19 Morphological status in the River Leutasch regarding riverbed dynamics using geodata of Land Tirol (2020)

5.1.5 Ecology

Concerning the biological aspects in the assessment of the ecological status, Austria uses the Fish Index Austria (FIA), mentioned in Haunschmid et al. (2019), to assess the occurrence of fish in surface waters. The index was developed for fish-ecological assessments by the Institute for Water Ecology, Fisheries and Lake Research in Scharfling (Institut für Gewässerökologie, Fischereibiologie und Seenkunde) in the framework of the WFD. The index is calculated based on fish data collected during fish sampling surveys and it takes the composition of species, the fish region, regional fish guilds as well as their age structure into account. To define the expected fish community, Austria was divided into nine fish-biological regions and 12 biocoenotic regions or fish regions. The maps dividing Austria into fish-biological regions and Austrian rivers into biocoenotic regions are given in Appendix I. Using this two step classification, the expected fish species can be defined for each river stretch. The entire catchment of the River Leutasch is located in the fish-biological region “Kalkvoralpen und nördliche Kalkhochalpen” (Limestone Prealps and northern high Limestone Alps). Additionally, the River Leutasch is part of two bio-coenotic regions or fish regions, the “Epirhithral” in the upper and middle part of the catchment and the “Metarhithral” in the lower part of the catchment (Figure 20). The reference site is located in the Epirhithral-region. (Haunschmid et al. 2019)

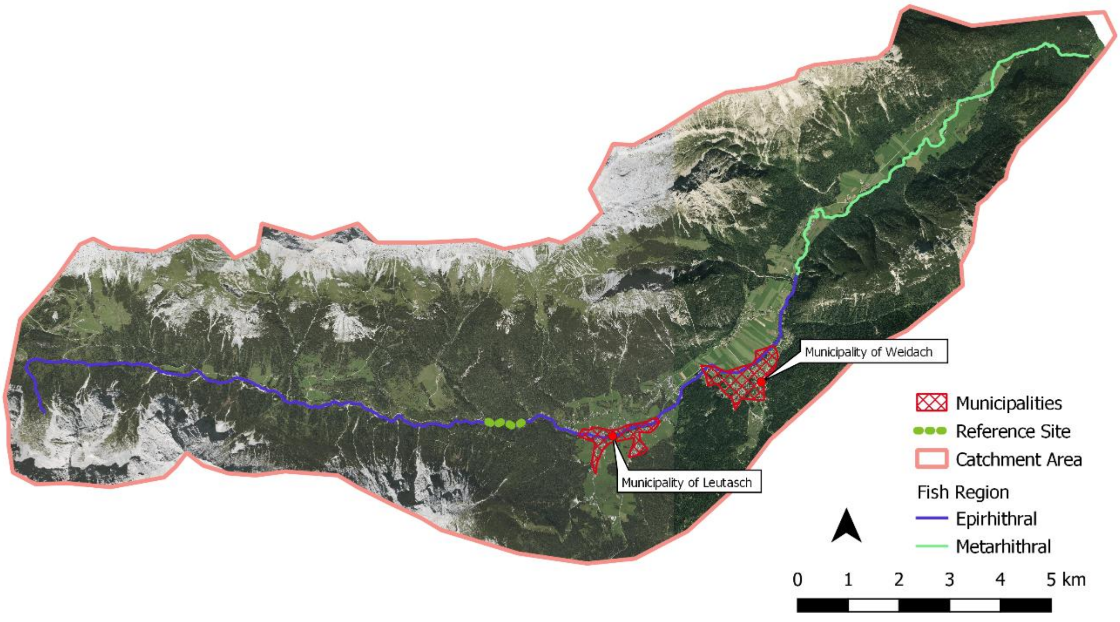


Figure 20 Fish region (biocoenotic) classification of the River Leutasch using geodata of Land Tirol (2020)

Based on this classification, the fish species expected in the Epirhithral-region are brown trout (salmo trutta fario) and bullhead (cottus gobio) (Haunschmid et al. 2019). Additionally, European grayling (thymallus thymallus) and burbot (lota lota) are expected in the Metarhithral-region (Haunschmid et al. 2019). The fish sampling surveys for the assessment of the ecological status of the River Leutasch were carried out at two points near the gauging stations Leutasch/Klamm and Leutasch/Weidach in the Epirhithral region (BMLRT 2020c; Österreichischer Fischereiverband 2020). In both locations the occurrence of brown trout, bullhead and grayling could be documented, even though grayling is not part of the expected fish community in this region (Österreichischer Fischereiverband 2020). According to information given by the fishery in Leutasch, rainbow trout (oncorhynchus mykiss) and brook trout (salvelinus fontinalis) have also been found in the Leutasch (T. Angerer, pers. comm., February 4, 2020). Based on the survey on 14th October 2010, the Fish Index Austria was calculated at 1.33 which leads to the classification of a “high” status when it comes to fish-ecological aspects (BMLRT 2020c). Hence, it can be assumed that the conditions in the River Leutasch are good enough to provide natural habitats and therefore a sustainable fish community structure.

5.2 Upper Inn

The second case study in this thesis concentrates on a bypass-section of a newly constructed hydropower plant in the Upper Inn River in Austria near the border with Switzerland. The following chapter gives some background information on this hydropower project.

5.2.1 Background GKI

The project Gemeinschaftskraftwerk Inn (GKI, joint venture hydropower plant on the River Inn) includes the construction of a new run-off-river hydropower plant on the upper part of the River

Inn near the border between Switzerland and Austria (see map in Appendix III and Figure 21). It is a joint venture project of TIWAG (Tiroler Wasserkraft AG) and EKW (Engadiner Kraftwerke AG).

The new power plant is part of a hydropower plant chain on the Upper Inn which includes plants in Pradella-Martina and Prutz-Imst (Gemeinschaftskraftwerk Inn GmbH (GKI) 2017b). The power plant consists of a water storage and a weir construction between Martina and Nauders, where parts of the incoming discharge are diverted into a piping-system. The piping-system transports a maximum discharge of 75 m³/s through a 23.3 km long tunnel system inside the surrounding mountains to the hydropower plant located in Prutz near Ried. Here the water is processed and led back into the River Inn. After its completion, the hydropower plant will produce around 414 GWh a year. (GKI 2017b)

As this hydropower plant is the biggest run-off-river plant constructed in the alpine area in recent years, it has been of great importance to take environmental aspects into consideration during the planning process. For one thing, the piping system and the power plant are not visible as they are underground (GKI 2017b). Mitigation measures which account for the ecological status of the Inn are also included, such as the widening of the riverbed and the creation of gravel banks and islands (GKI 2017a). In addition, experts have developed an environmental flow concept for the river section between the weir and the power plant to reduce the environmental effects of the reduced discharge in the bypass section (see Section 5.2.7). The environmental flow concept guarantees a constant minimum flow value during the winter months and a dynamic flow regime during the summer months using an undisturbed flow time series of one gauging station upstream from the power plant as a reference (GKI 2017c). Most importantly, the hydropower plant is constructed in a way that the currently occurring negative effects of upstream hydropower plants in Switzerland will be reduced (GKI 2017c). As these Swiss plants store a large amount of the water and process the water according to the current energy needs, the flow regime in the Upper Inn is completely altered and extremely affected by large and sudden changes in discharge, so-called hydropeaking. The storage of the new power plant is built to absorb these artificial variabilities in discharge and therefore creates a more natural flow regime downstream from the weir (GKI 2017c).

The GKI is part of the FIThydro project and is a test case for the observation of hydropeaking effects and mitigation options (M. Schletterer, pers. comm., February 11, 2020). In addition, the project includes a large monitoring program of the situation before and after the construction of the power plant (M. Schletterer, pers. comm., February 11, 2020). Therefore, several studies have already been conducted in this particular area and large amounts of data have been collected. Furthermore, a hydrodynamic model was constructed for two river stretches in the bypass section and the instream habitat model CASiMiR was applied (M. Schletterer, pers. comm., February 11, 2020). This thesis uses the results of and data from these studies as well as the results of the hydraulic models and the ecological data collected for the CASiMiR application.

5.2.2 Catchment

The source of the River Inn is Lake Lägh dal Lunghin in the Swiss Alps at an altitude of 2.484 m a.s.l.. It then flows through Switzerland, Austria and Germany and joins up with the River Danube in Passau, Germany. Around 100 km downstream from Lake Lägh dal Lunghin, the River Inn crosses the border with Austria near Nauders. As mentioned above, the GKI was constructed in this part of the Inn catchment. Based on this project, the river stretch between Martina and Prutz is considered to be a bypass section in which the discharge is artificially reduced due to the water abstraction at the weir. This study focusses on this particular stretch of the River Inn, the bypass section, which is 25.1 km long (Figure 21).

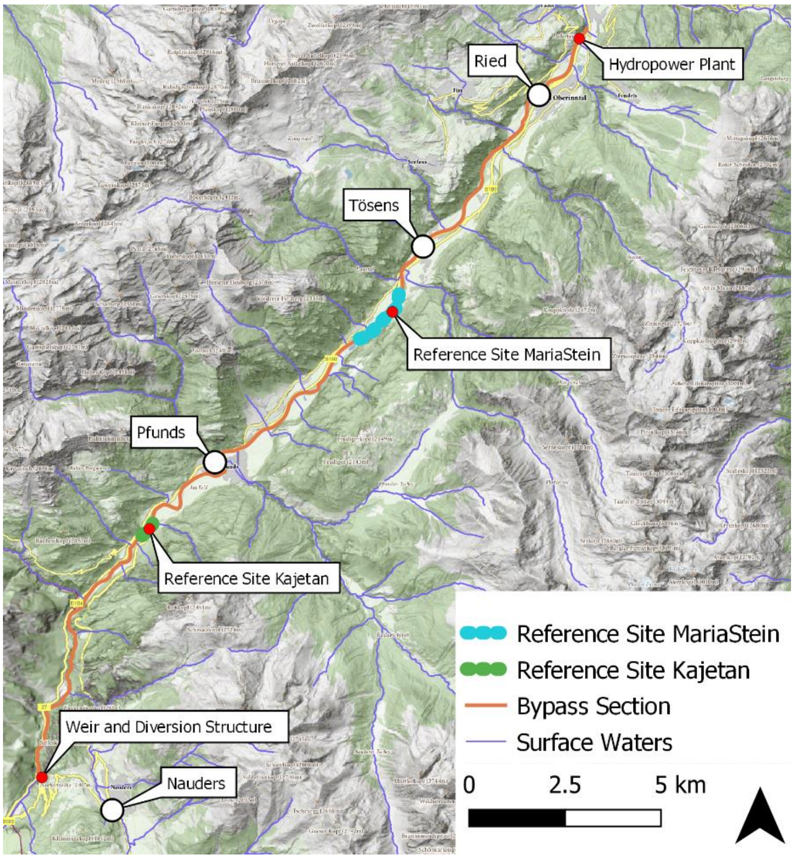


Figure 21 Overview map presenting the bypass section of the GKI using geodata of Land Tirol (2020)

There are three gauging stations in this region, one in Switzerland and two in Austria. The Swiss gauging station, Martina, operated by the Swiss Federal Office for the Environment (FOEN, Bundesamt für Umwelt BAFU) is located upstream from the bypass section. It was built at a height of 1030 m.a.s.l and the catchment of the River Inn is 1941 km² here (Federal Office for the Environment (FOEN) 2020). In addition, around 2.8% of this catchment are covered in glaciers (FOEN 2020). Further downstream, the first Austrian gauging station in the River Inn Kajetansbrücke, operated by Hydrographic Service of Tirol (Hydrographischer Dienst Tirol), is already located within the GKI bypass section. The catchment area here is 2162 km² and the station was built at a height of 967 m.a.s.l. (Hydrographischer Dienst Tirol 2020a). The third gauging station, Prutz, is situated downstream from the GKI hydropower plant and is therefore located downstream from the bypass section. It is operated by TIWAG and here the catchment is 2461.5 km² and the station is located at 862.36 m.a.s.l (Hydrographischer Dienst Tirol 2020d).

Using this data, it can be seen that the River Inn in the GKI bypass section is located at an altitude of 1000 to 860 m.a.s.l. In addition, the Inn catchment upstream from this section is around 1941 km² and the catchment of the bypass section itself around 520 km². Maximal altitudes of the surrounding mountains are around 3300 m.a.s.l in the southern area and 3000 m.a.s.l in the north-western area (Land Tirol 2020).

In this particular part of the Inn catchment, the flanks of the mountains are mostly covered in forest or grass and scrubs at higher altitudes (Land Tirol 2020). Lower altitudes and flatter parts of the valley are used for agriculture and several municipalities can be found here (Land Tirol 2020). The River Inn itself is largely affected by artificial structures such as riverbed and bank stabilisation measures (Schönlaub et al. 2007). The riverbed is only wide enough for the river to form natural riverbanks, gravel bars and islands in some of the short river stretches. Due to this river channelization in combination with the hydropeaking, the River Inn is classified as heavily modified water body in the framework of the WFD (Land Tirol 2020).

5.2.3 Reference Sites

As part of the environmental impact assessment of the GKI project, two river stretches in the bypass section were selected to provide detailed information about the instream habitat conditions in the Upper Inn River (Moritz et al. 2007). Therefore, the habitat model CASiMiR was applied at these two sites (Moritz et al. 2007). Figure 21 shows the locations of the two reference sites, Kajetan and Maria Stein. The Kajetan site is located south-west of the municipality of Pfunds with a watershed area of 2162 km² (Hydrographischer Dienst Tirol 2020a). The Maria Stein site is situated several kilometres downstream from the Kajetan site, south-west of the municipality of Tösens with a watershed area of 2277 km² (Schönlaub et al. 2007). As detailed hydraulic data and additionally the results of the habitat model CASiMiR were available for these river stretches, the two sites were also chosen as reference sites for the MesoHABSIM model.

The two river stretches have completely different physical habitat conditions. The reference site Kajetan is located in an obstructed and channelized part of the Inn (Figure 22), whereas the reference site Maria Stein represents more natural habitat conditions (Figure 23). At Maria Stein the riverbed was widened and therefore gravel banks, sidearms and islands can be found resulting in more diverse habitat conditions. The habitat model was constructed for 420 m at the Kajetan site and 1.7 km at the Maria Stein site.

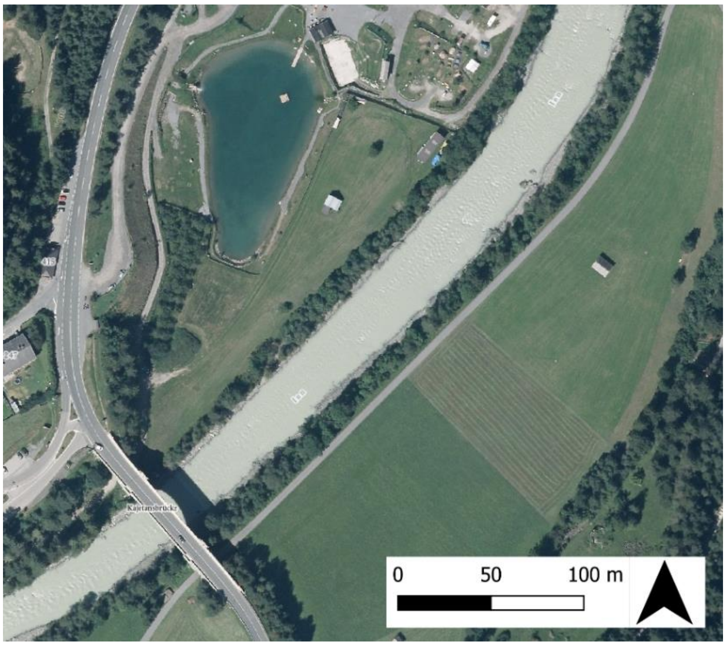


Figure 22 Orthophoto of the reference site Kajetan using geodata of Land Tirol (2020)

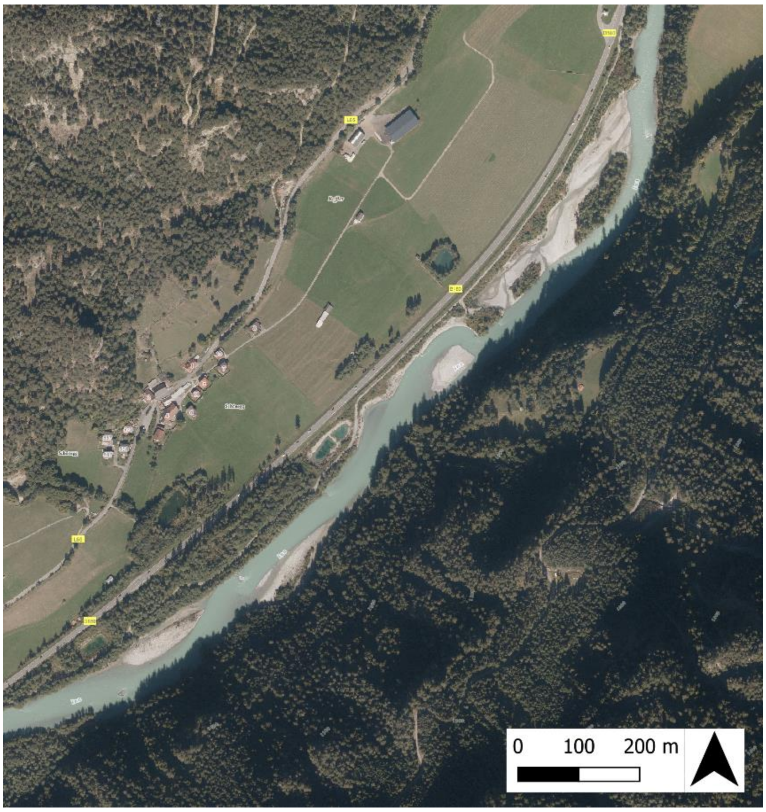


Figure 23 Orthophoto of the reference site Maria Stein using geodata of Land Tirol (2020)

5.2.4 Hydrology

As mentioned above, three gauging stations exist in this part of the Inn catchment. However, due to the Swiss hydropower plants located upstream from the GKI bypass section, none of these gauging station can reflect a natural hydrological regime (Schönlaub et al. 2007). Instead, the flow values are affected by artificial water storage and release from the hydropower plants (Schönlaub et al. 2007).

As part of the environmental impact assessment for the GKI power plant (Schönlaub et al. 2007), the natural and current hydrological conditions in the upper Inn catchment as well as the bypass section itself were analysed. Based on the analysis of meteorological data for the Inn catchment, higher precipitation values occur during summer (June to August) which is connected to convective precipitation and lower precipitation values occur during winter months. In addition to the annual precipitation pattern, the precipitation distribution is influenced by the topography of the area and therefore the precipitation is expected to be lower in some valleys within the catchment due to the shade from the surrounding mountains. The hydrological regime in the River Inn is affected by this precipitation pattern and by snow cover and glaciation at higher altitudes, resulting in a typical alpine and nival hydrological regime. The nival hydrological regime, including low discharge during winter, increasing discharge due to the melting of snow in spring and early summer and high discharge values because of the convective precipitation in summer, is described in detail in Section 5.1.3. In contrast to the Leutasch, the Inn is additionally affected by glaciation at higher altitudes increasing the discharge values in summer (July to September). The natural annual discharge pattern of the Inn is presented in Figure 24 using historic data from the gauging station Martina (1904 to 1969, blue line). (Schönlaub et al. 2007)

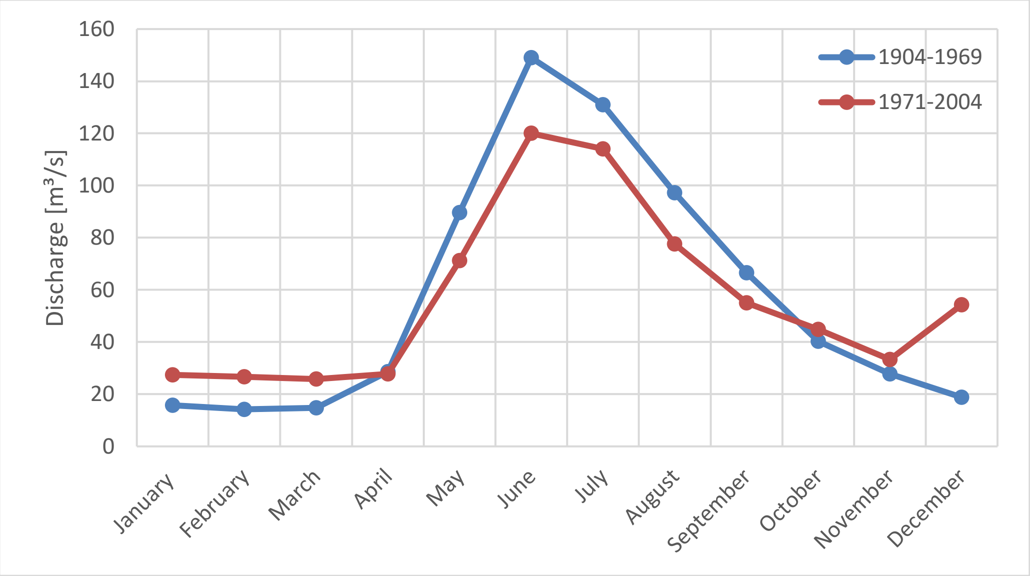


Figure 24 Monthly mean discharge values at gauging station Martina for undisturbed (1904 to 1969) and disturbed (1971 to 2004) hydrological conditions using data of Schönlaub et al. (2007)

As mentioned above, two large hydropower plants, called Pradella and Martina, exist in the upper part of the Inn catchment which have affected the hydrological regime of the Inn since 1970. They consist of intake structures and weirs in the Inn itself but also intake structures and reservoirs in tributary catchments. In addition, water has been abstracted and diverted into the Italian Adda catchment since 1964. The power plants influence the hydrological regime in two major ways. Firstly, the reservoirs are used to store large amounts of incoming discharge during the summer months, which allows the water to be processed in months with lower incoming discharge, mostly during winter. This leads to a reduction in discharge volume downstream from the reservoirs during summer and an increase in discharge during winter, affecting the monthly discharge pattern (see Figure 24, red line). Secondly, hydropeaking occurs due to the operation of the power plants resulting in high and sudden changes to the discharge conditions downstream from the plants which changes the discharge conditions on an hourly basis. Due to the operation of these hydropower plants and the water abstraction, the hydrological regime in the Upper Inn catchments has been majorly altered since 1964. (Schönlaub et al. 2007)

The missing hydrological time series representing an undisturbed hydrological condition impedes the analysis of the original hydrological conditions. For this thesis, this means that no habitat time series analysis can be constructed which further inhibits the UCUT analysis and the definition of habitat thresholds.

5.2.5 Morphology

As the considered river stretch being used is classified as a heavily modified water body, its ecological status is assessed in regard to its ecological potential. Based on data of the Land Tirol (2020), the ecological potential of the river stretch is classified as “moderate to bad”. This can be explained by the fact that the Inn is strongly affected by hydropeaking and because large parts of its riverbed and banks are stabilised and obstructed (Moritz et al. 2007). This can be seen in Figure 25 and 26, which show the status of the morphology for this river stretch in relation to riverbed dynamics and banks dynamics. Due to the river stabilisation and channelization at the reference site Kajetan, the river bed dynamics and the bank dynamics are both classified as non-natural in this river stretch (Land Tirol 2020). For the reference site Maria Stein, however, only the river banks are non-natural or obstructed whereas the riverbed has nearly natural conditions (Land Tirol 2020).

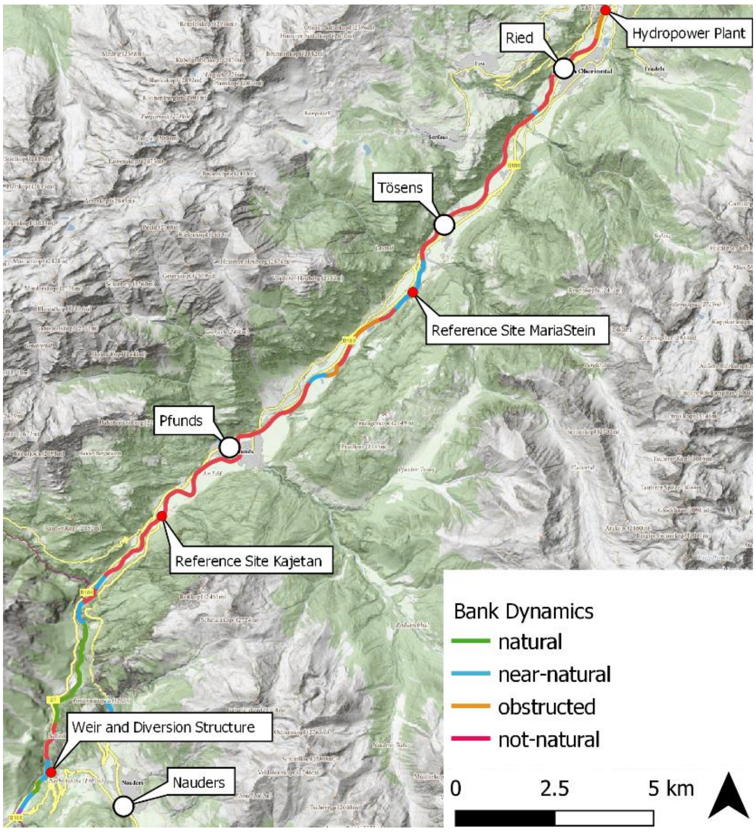


Figure 25 Morphological status in the bypass section regarding bank dynamics using geodata of Land Tirol (2020)

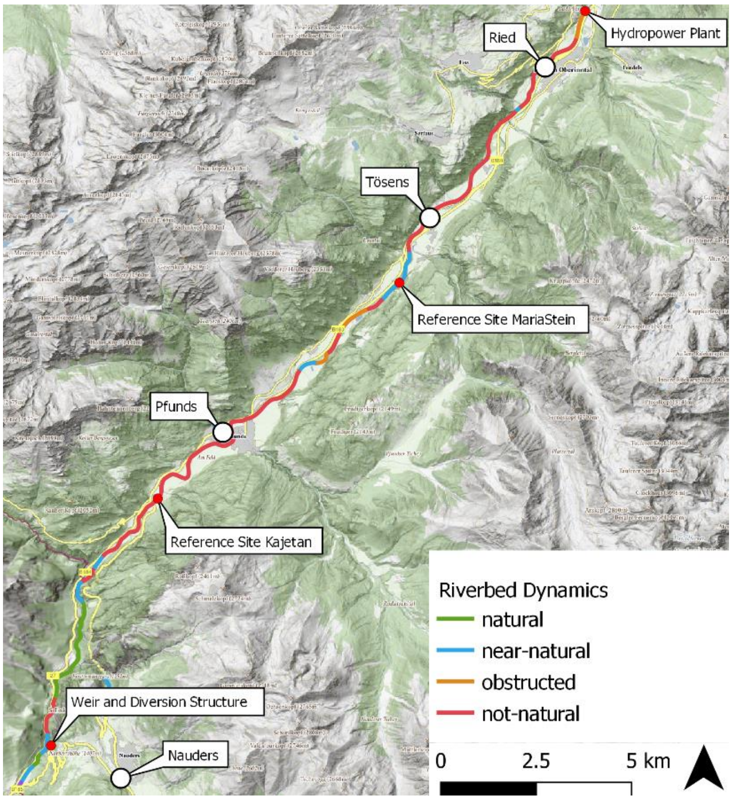


Figure 26 Morphological status in the bypass section regarding riverbed dynamics using geodata of Land Tirol (2020)

5.2.6 Ecology

According to the river classification system in Austria, this part of the Upper Inn River is located in the fish-biological region type B "unvergletscherte Zentralalpen und deren Ausläufer und Grauwacken" (unglaciated central Alps and their foothills and greywacke) (Haunschmid et al. 2019) (see Appendix I). Furthermore, the upper part of the bypass section is part of the "Metarhitral" biocoenotic region and the lower part of the "Hyporhitral large" biocoenotic region (Figure 27) (Haunschmid et al. 2019). Both reference sites are therefore located in the Hyporhitral part of the region.

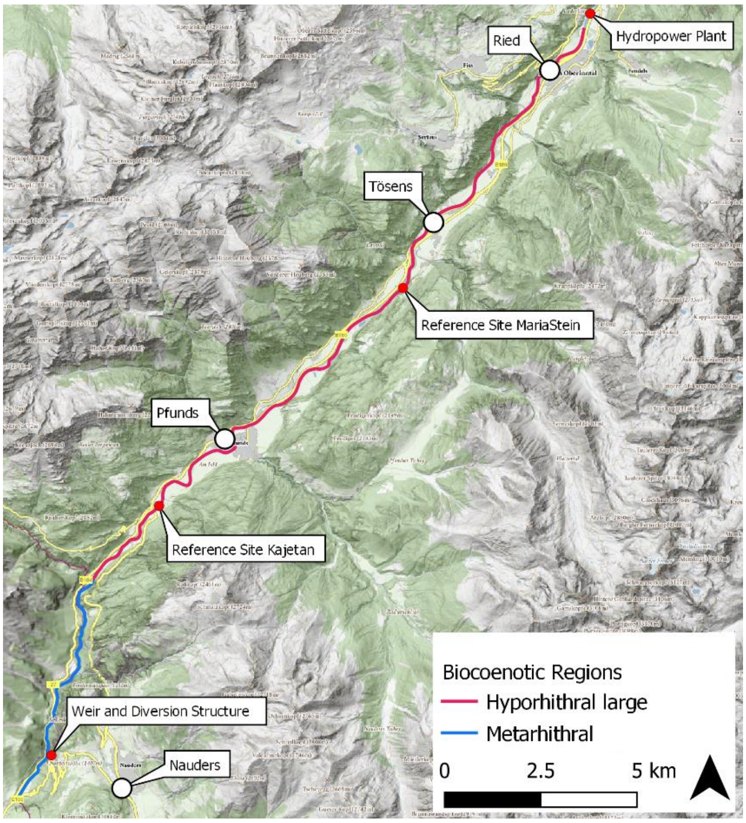


Figure 27 Fish region (biocoenotic) classification of the bypass section using geodata of Land Tirol (2020)

The expected fish community for this two step river classification can be found in Appendix IV. However, as the river stretch is a heavily modified water body, the composition of the target fish species has been adapted to the environmental conditions and the number of target species has been reduced. Therefore, the indicator fish species in both, the Metarhitral and Hyporhitral large region, are bullhead (cottus gobio) and brown trout (salmo trutta fario). For the Hyporhitral large region additionally European grayling (thymallus thymallus) is considered to be an accompanying species. Stone loach (barbatula barbatula), Eurasian minnow (phoxinus phoxinus) and squalius cephalus are rare accompanying species. (Bundesamt für Wasserwirtschaft - Institut für Gewässerökologie und Fischereiwirtschaft 2017)

As part of the environmental impact assessment for the GKI, fish sampling was carried out at four points in the Hyporhitral region (Moritz et al. 2007). Four different species were found in this river stretch of the Inn: brown trout as the dominant species, grayling as the second common species, rainbow trout (oncorhynchus mykiss) and bullheads. However, based on the fish sampling data and the habitat modelling, it can be assumed that no natural reproduction of brown trout is possible in this river stretch and that the species exists here because of stocking projects. Using the fish sampling data, the FIA was calculated at values between 4.1 to 4.5 at the sampling points which corresponds to “unsatisfactory” or “bad” status when it comes to fish-ecological aspects. (Moritz et al. 2007)

5.2.7 Environmental Flow Concept GKI

The GKI was planned as a way to reduce the negative effects of the upstream hydropower plants on the hydrological regime (Schönlaub et al. 2007). As mentioned above, an environmental flow concept was created by experts cooperating to provide more natural hydrological conditions in the bypass section. The environmental flow concept is based on minimum flow values adapted to the different seasons. It was developed to create major improvements in the current hydrological situation by increasing minimum flow values, reducing the effects of hydropeaking and creating uniform discharge conditions during winter. Therefore, a reservoir is constructed as part of the weir structure. This reservoir will be used to absorb the sudden changes in discharge due to hydropeaking and to guarantee minimum flow values. The defined minimum flow values for each season are presented in Table 4. The corresponding discharge values are calculated at the weir structure Ovella. The discharge increases in the bypass section downstream from the weir due to ajoining tributaries and the runoff of the residual catchment area. (Schönlaub et al. 2007)

Table 4 Minimum flow values according to each season at the weir Ovella (Schönlaub et al. 2007)

Season	**Minimum Flow Value [m³/s]**
16th September till 30th April	5.5
1st May till 15th May	7
16th May till 31st August	10
1st September till 15th September	7

During winter, the effects of hydropeaking are more intense, because low and mostly constant discharges occur in natural hydrological conditions. Therefore, the environmental flow concept was developed to provide more constant flow conditions during winter and a higher minimum flow value in comparison to current conditions. Hydropeaking effects are avoided during the winter period as the reservoir stores the incoming discharge peaks from the upstream power plants. The minimum flow value is then increased in two steps to account for the increase in discharge during spring and early summer (Table 4). As the new GKI hydropower plant has a lower capacity than the upstream plant Martina and as higher discharges occur during summer, it is to be expected that an overflow will occur at the weir several times during summer which will increase the discharge in the bypass section in comparison to the defined minimum flow value of 10 m³/s. Based on the historic flow time series, the overflow will occur for around 70 days in the summer period which means that the discharge in the bypass section will be higher than the defined minimum flow value for these days. (Schönlaub et al. 2007)

Additionally, the minimum flow value during the summer period is adapted according to the discharge values measured at the undisturbed gauging station at St. Moritz in the upper part of the Inn catchment (Guggi 2016). This way, natural hydrological variabilities are included in the newly defined hydrological regime (Guggi 2016). Table 5 presents the minimum flow values which correspond to the discharge values measured in St. Moritz. In addition to the definition of minimum flow values, operational rules were defined for the GKI to absorb the effects of hydropeaking by limiting the frequency and velocity at which the discharge in the bypass section is changed (Guggi 2016).

Table 5 Minimum flow values at weir Ovella accoring to measured discharge conditions at St. Moritz (Guggi 2016)

Discharge Value at Station St. Moritz [m³/s]	**Adapted Discharge Value at Weir Ovella [m³/s]**
< 8.0	10.0
8.0 – 10.0	12.0
10.0 – 14.0	15.0
> 14.0	20.0

The hydrological conditions in the bypass section will be improved using this environmental flow concept as the effects of the upstream hydropower plants will be eliminated. Using an undisturbed gauging station as a reference additionally gives the hydrological regime more natural variabilities.

6 Methodology

6.1 Survey and Data Collection

6.1.1 Leutasch

In order to collect data about the hydromorphic features in a river stretch, a MesoHABSIM survey, as described in Section 3.3.1.1, was carried out at the Leutasch. The following sections describe the conditions during the surveys, the equipment used and the process of data collection and post-processing.

6.1.1.1 Dates and Conditions

The MesoHABSIM surveys were done at three different discharge levels in summer 2019 and December 2019. The first survey was carried out on 27th August at a discharge of 1.8 m³/s. The second survey took place a week later on 3rd September at a discharge of 2.4 m³/s. The survey in December was carried out on the 19th at a discharge of 0.65 m³/s. When selecting the date for the surveys, it was important to select days where the discharges were in a suitable range for a MesoHABSIM survey. This means one survey is done when the discharge is close to the mean annual flow and the other surveys are done when the discharges are higher and lower than mean annual flow. In addition, it is necessary for the discharge to be constant during the MesoHABSIM surveys and therefore the selection of date of the survey needed to take the weather conditions of the previous days and the weather forecast for the date of the survey into account. Due to the seasonal changes in discharge for the River Leutasch, low flow conditions could only be observed during winter. Table 6 shows details of the dates and times of the surveys as well as the discharge and weather conditions during the surveys.

Table 6 MesoHABSIM survey dates and conditions at River Leutasch

Date of survey	**Time of survey**	**Mean Discharge [m³/s]**	**Maximum Discharge [m³/s]**	**Minimum Discharge [m³/s]**	**Corresponding Discharge Rate [l/(s*km²)]**	**Weather conditions**
27/08/2019	8:30 am till 6:00 pm	1.83	1.86	1.81	40.7	Sunny without clouds, up to 28 °C
03/09/2019	10:30 am till 7:45 pm	2.39	2.48	2.33	53.1	Sunny with some clouds; up to 25 °C
19/12/2019	8:30 am till 4:00 pm	0.65	0.658	0.643	14.4	Sunny, without clouds, but no direct sunlight at the river due to surrounding mountains; 4 to 7 °C

6.1.1.2 Equipment

For the mapping of the mesohabitats or HMUs and the documentation of the HMU characteristics, a tablet computer with the GIS application tMap (Version 4.2.6) of the company TAXUS IT installed was used. In addition, the water depth and flow velocity data could be entered into this application. Water depth and velocity were measured using a current meter created by the chair of Hydraulic and Water Resource Engineering. It consists of a small propeller which is fixed onto a bar and a small box containing a micro-computer. The micro-computer counts the rotations of the small propeller, which are then displayed on the tablet computer using a Wi-Fi connection. The current meter was calibrated in a laboratory before its use in the field. A scale was drawn on the bar of the current meter to measure water depth easily with the same device.

For most MesoHABSIM surveys aerial pictures taken by drones are used to create orthophotos of the current conditions of the river. These pictures are then loaded up onto the tablet computer and the HMUs are mapped by drawing their shapes directly into the GIS application using the orthophotos as background information. However, at the Leutasch it was not possible for us to use a drone and therefore orthophotos provided by the Department of Geoinformation of the Federal State Government of Tyrol (Amt der Tiroler Landesregierung, Abteilung Geoinformation) were used. The pictures showing the upper part of the Leutasch catchment including the reference site were taken on 7th August 2017, at a discharge of 1.6 to 1.8 m^3/s measured at the gauging station Leutasch (Klamm) (Hydrographischer Dienst Tirol 2020b). The pictures were loaded up onto the GIS application on the tablet computer. However, the resolution of these pictures was not high enough to map the HMUs only using these pictures. Therefore, GPS devices were used to measure the exact shape of the HMUs and to get accurate data for the wetted area.

We used the GPS device Emlid Reach RS+, which can be fixed onto a bar and can be carried easily to different points of the river. The device can be controlled using the application ReachView (Version 1.5, Emlid) installed onto a tablet computer. There are two options when using the Emlid Reach RS+, as described by Emlid (2020). Firstly, only one GPS device is used and installed onto the bar which then sends the coordinates of its position to the tablet application, where the data can be saved. This stand-alone modus attains a single solution because it only uses the GPS signals received by the device itself. The expected solution in this modus is usually meter-level. However, higher solutions can be achieved by using longer timeframes in which GPS data is collected. In the second option, two GPS devices are used. One is in a fixed position and one can be carried around to collect data. The base device is installed on a tripod in a location which should not have by any obstacles such as trees or buildings. It then collects GPS data for several minutes to define its own position accurately. After that, the base starts to calculate corrections outputs, which can be used by the other device, the rover, to improve its precision. The solution of the base-rover mode is on a centimetre-level in good environments. At the reference site, however, lower precision is expected because of the surrounding mountains and trees. The tablet application presents information on the currently attained solution based on a calculated standard deviation. We only collected the GPS data if the deviation was in a range below 30 cm. This solution can be considered similar to the precision achieved by mapping onto a tablet computer using orthophotos. During the first survey the stand-alone mode was used, but in order to achieve a high enough precision, GPS data had to be collected for longer time periods of up to one minute for each point. Therefore, the rover-base mode was used for the second and the third survey. (Emlid 2020)

6.1.1.3 Data Collection

Each time, the survey started upstream from the reference site and directly downstream from the confluence with the tributary Salzbach. First, the type and the extent of the HMU were determined by walking in or along the river. For each detected HMU, the characteristics of the mesohabitat were then documented by entering the data into the tMap application. The characteristics taken into account are shown in Table 7. The characteristics are either *present, abundant* or *none* as explained in Section 3.3.1.1. In addition, some information can be given using numbers or *yes / no* options. Different descriptions can be selected for the HMU type, the choriotop type and the land use on the banks. The MesoHABSIM projects are normally named according to the name of the river, here *Leu* for Leutasch, and the HMUs are numbered using five numbers, the first number is the site number, the second two numbers are used to express the discharge condition at the time the survey was carried out and the last two numbers are the HMU number.

Table 7 Description of habitat characteristics entered into tMap during the MesoHABSIM survey for each HMU

Characteristics	Description Options
Project	name
HMU number	Number xxyyzz (xx=number of site, yy=discharge value, zz=number of HMU)
HMU type	backwater / cascade / fastrun / glide / island / plunge-pool / pool / rapids / riffle / ruffle / run / sidearm / complex high, low / highbar
Bank width	number
Wetted width	number
Choriotop	alkal / debris / detritus / gigalithal / macrolithal / megalithal / mesolithal / microlthal / pelal / phytal / psammal / sapropel / xylal
Low gradient	yes / no
Boulders	none / present / abundant
Riprap	none / present / abundant
Overhanging vegetation	none / present / abundant
Submerged vegetation	none / present / abundant
Canopy cover	none / present / abundant
Undercut bank	none / present / abundant
Woody debris	none / present / abundant
Shallow margin	none / present / abundant

Left shore use	Agriculture / field / forested / island / pasture / residential / road / shrub-brush / urban / water
Right shore use	Agriculture / field / forested / island / pasture / residential / road / shrub-brush / urban / water
Clay on left bank	yes / no
Clay on right bank	yes / no
Irregular left shore	yes / no
Irregular right shore	yes / no
Left shore stabilised	yes / no
Right shore stabilised	yes / no
Left shore eroded	yes / no
Right shore eroded	yes / no

After the characteristics of the HMU were described and saved, measurements of water depth and flow velocity were taken at at least seven randomly chosen points in the HMU. Additionally, the choriotop was defined at the point of the measurement and the status of choriotop embeddedness was classified as either *loose, embedded* or *solid*. The values were directly entered into tMap, where the exact location of the measurement could also be saved.

As described above, the size of the HMUs was measured using GPS devices. The, coordinates for each HMU were collected at several points showing the shape of the HMU. As this process has a similar precision to the manual mapping on a tablet computer using orthophotos, the shape of a HMUs measured using GPS is considered to be accurate enough.

6.1.1.4 Data Processing

After the field surveys, the data collected had to be processed and checked for mistakes. Firstly, the GPS data points were loaded up into a GIS software and used to construct the polygon-shapes of the HMUs. The area of each polygon was calculated and added up to achieve a total value for the wetted area of each observed discharge. When comparing the shapes and locations of polygons obtained by different surveys, some inaccuracies were detected at the borders of polygons. In total, the calculated wetted area increased with increasing discharge. However, at some points along the the river stretch, the polygons measured during lower discharge are wider than the polygons found during higher discharge (Figure 28). This can be explained by the inconsistencies discovered which occur due to the GPS coordinate calculation. Especially in mountainous and forested environments, such inconsistencies arise due to low satellite connection and cannot be detected during the field survey. In these situations, orthophotos were used to estimate the shape of the polygons (Figure 28 and 29).

Figure 28 HMU-polygons based on the GPS coordinates (green 19.12.19, 0.6 m³/s; orange 27.8.19, 1.8 m³/s; red 3.9.19 2.3 m³/s)

Figure 29 HMU-polygons adapted with orthophoto (green 19.12.19, 0.6 m³/s; orange 27.8.19, 1.8 m³/s; red 3.9.19 2.3 m³/s)

Secondly, the assignment of HMU type and choriotop type were reconsidered for each polygon. Pictures taken during the survey were used to check the assigned HMU type. Using these pictures and the velocity and depth measurements, the HMU type was changed for some HMUs.

6.1.2 Upper Inn

The MesoHABSIM model for the two reference sites at the River Inn was constructed based on the data collected for the GKI and the FIThydro projects. Therefore, no MesoHABSIM survey, as described in Section 3.3.1.1 and applied at the River Leutasch (Section 6.1), was carried out for these two reference sites. However, the results of the hydrodynamic models as well as orthophotos were used instead, which allowed a digital mapping process in a GIS environment.

6.1.2.1 Orthophotos

For the digital mapping process, high-resolution orthophotos are necessary to detect differences in hydraulic patterns and surface turbulences and therefore to identify different mesohabitat types. Additionally, physical attributes of the surrounding area and internal environmental conditions can be defined this way.

Three different orthophotos were necessary for each reference site showing three different discharge conditions. Orthophotos were provided by TIWAG and the government of Tyrol (Land Tirol 2020) and taken by planes or drones. Using the dates and times the photos were taken, the discharge conditions could be reconstructed using the discharge measurements from the Kajetansbrücke gauging station. The discharge values for Maria Stein were calculated using a time difference of two hours between the Kajetansbrücke gauging station and the Maria Stein site. Additionally, the discharge values measured at Kajetansbrücke were increased to account for the runoff of the catchment in between Kajetan and Maria Stein. The runoff values for the catchment in the bypass section and the discharge of the tributaries were calculated as mean values for each month as part of the environmental impact assessment (Schönlaub et al. 2007). The discharge conditions for each orthophoto and for both reference sites are shown in Table 8.

Table 8 Date and time at which orthophotos were taken of both references sites and corresponding mean discharge values

Date of flight	Time	Mean Discharge [m³/s]	Corresponding discharge rate [l/(s*km²)]
Kajetan			
10/03/2016	11:00 till 11:20 am	11.4	5.3
20/02/2017	10:00 till 10:30 am	37.4	17.3
24/09/2010	9:30 till 9:37 am	84.8	39.2
Maria Stein			
10/03/2016	11:00 till 11:20 am	15.8	6.9
17/04/2018	11:00 am till 2:00 pm	32.9	14.5
27/09/2018	12:55 till 1:30 pm	90.0	39.5

Using these discharge values, similar hydraulic conditions could be observed at both sites, reflecting low flow to mean flow conditions.

6.1.2.2 Substrate

As part of the environmental impact assessment for the GKI and the application of CASiMiR, tachymetric surveys and an assessment of the substrate were carried out for both reference sites (Moritz et al. 2007). However, no data was available regarding the embeddedness of the substrate. In CASiMiR, the substrate is classified into 10 substrate-types which are referred to using an index-number from 0 to 9. The substrate classification for the two reference sites can be seen in Figure 30.

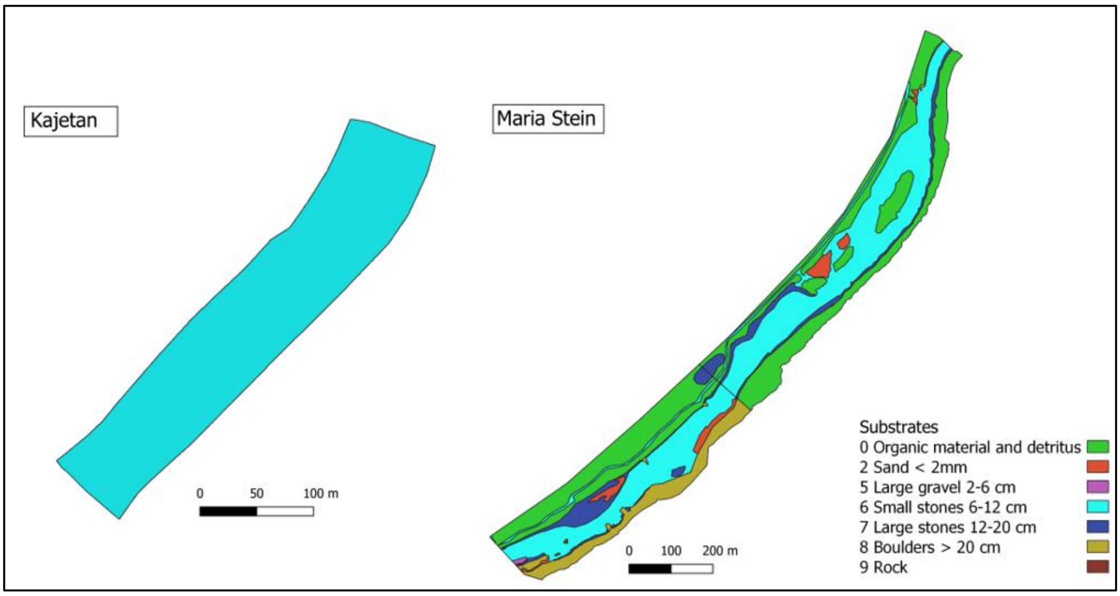


Figure 30 Substrates classification for the two GKI references sites using substrate classification of CASiMiR

This classification was then translated into the substrate classes used in MesoHABSIM (see Table 3, Section 3.3.1.1). The following table shows the substrate classification for CASiMiR (Schneider et al. 2010) and the corresponding MesoHABSIM choriotop types (Table 9).

Table 9 CASiMiR substrate classification (Schneider et al. 2010) and corresponding MesoHABSIM choriotop types

Substrate-Type	CASiMiR Index	Corresponding MesoHABSIM choriotop types
Organic material and detritus	0	Detritus
Silt, loam, clay	1	Pelal
Sand < 2mm	2	Psammal
Fine gravel 2-6 mm	3	Alkal
Medium gravel 6-20 mm	4	Alkal
Large gravel 2-6 cm	5	Microlithal
Small stones 6-12 cm	6	Mesolithal
Large stones 12-20 cm	7	Mesolithal
Boulders > 20 cm	8	Macrolithal
Rock	9	Megalithal / Gigalithal

6.1.2.3 Hydrodynamic Model

The two hydrodynamic models, for Kajetan and Maria Stein developed for the GKI and the FIThydro projects, were constructed using the Surface-Water Modeling System (SMS, Aquaveo) and HYDRO_AS-2D (Hydrotec). The computational mesh and material properties of the substrate had already been optimised and calibrated as part of those projects. To construct the MesoHABSIM model, it was necessary to obtain model results (velocity, water depth) for the discharge values mentioned above. Therefore, the boundary conditions and global parameters of the simulations were adapted using SMS (Version 12.2). The hydrodynamic simulations were then calculated in HYDRO_AS-2D (Version 4) for each site and its according discharge value. The simulation results were then checked for mistakes and loaded up into a GIS environment which makes it possible to visualise the model results and compare them to the orthophotos.

6.1.2.4 Digital Mapping

The identification and definition of different HMUs was conducted in a GIS environment using the data described above. Each reference site and each discharge condition were mapped successively. First the orthophoto was used to delineate different HMUs taking surface turbulence and hydromorphic aspects into account. Then the velocity data and water depth values were put into the orthophoto and were used to check or correct the location and size of the HMU as well as the HMU type. Additionally, characteristics and attributes as presented in Table 7 (Section 6.1.1.3) were defined for each HMU using the orthophotos and the substrate information. In the common mapping process, flow velocity, water depth and substrate data are collected at several points in each HMU. As the hydraulic model includes velocity and water depth data for each point of the grid and substrate data was available for the complete river stretch, these measurements were replaced by the simulation results.

6.2 Biological Habitat Model

The biological habitat model in MesoHABSIM is based on knowledge of the riverine species, their life cycles and reproduction strategies as well as their habitat requirements. Furthermore, bioperiods have to be defined based on the selected target species and their life cycles. The following sections described the data collected to construct the biological habitat model.

6.2.1 FCMacHT "Mountain, Alpine and Subalpine Rivers"

Using the expected fish community developed for each FCMacHT type as part of the AMBER project, one can see that there are three different fish habitat-use guilds in this study area (Figure 31):

- Highly rheophilic, intolerant species (55%, light blue)
- Rheophilic benthic species, preferring sandy-gravel bottom substrate (27%, brown)
- Rheophilic water column species, preferring sandy-gravel bottom substrate (18%, dark blue)

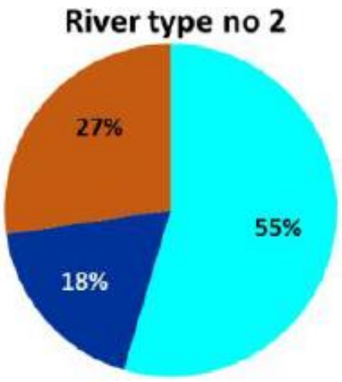


Figure 31 Fish habitat-use guild composition for FCMacHT number 2 „Mountain, Alpine and subalpine rivers" (AMBER 2019)

6.2.2 Target Fish Species

As mentioned in Section 5.1.5 and 5.2.6, brown trout, bullhead, European grayling as well as rainbow trout can be found in both rivers and additionally brook trout can be found in the Leutasch. However, rainbow trout and brook trout are non-native species to the Tyrol region and probably occur in the rivers due to stocking projects. Table 10 summarises the information on the fish species that occur in both rivers and additionally gives us information on the spawning period of these species.

Table 10 Fish species in the River Leutasch and Upper Inn River (expected and documented) and their spawning periods

Fish Species	**Species expected based on the Fish Regions of Austria** (Haunschmid et al. 2019)		**Distribution documented in the Leutasch** (Österreichischer Fischereiverband 2020; T. Angerer, pers. comm., February 4, 2020).	**Distribution documented in the Inn** (Moritz et al. 2007)	**Spawning period** (Landesfischereiverband Bayern e.V. 2020a, 2020b, 2020c, 2020d, 2020e)
	Epirhithral	Hyporhitral large			
Brown trout (Salmo trutta fario)	indicator specie	indicator specie	yes	yes	October to February
Bullhead (Cottus gobio)	indicator specie	indicator specie	yes	yes	February to May
European grayling (Thymallus thymallus)	not expected	accompanying specie	yes	yes	March to May
Rainbow trout (Oncorhynchus mykiss)	not expected	not expected	yes	yes	October to May
Brook trout (Salvelinus fontinalis)	not expected	not expected	yes	no	October to December

Brown trout and bullhead live in both rivers and are both considered to be indicator species for these particular Austrian regions (Haunschmid et al. 2019). Therefore, the two species were chosen as target species in the MesoHABSIM model as well. Additionally, European grayling was selected as a target species in this MesoHABSIM model because it also naturally occurs in both rivers and is an accompanying species in the Hyporhithral large region. Due to this, habitat requirements and life cycles for these three species are of great importance in the following habitat modelling process.

As mentioned in Section 4.4, both rivers or river stretches are part of the AMBER FCMacHT macrohabitat type two “Mountain, Alpine and subalpine rivers”. This type includes the three fish habitat-use guilds: highly rheophilic, intolerant species; rheophilic benthic species, preferring sandy-gravel bottom substrate and rheophilic water column species, preferring sandy-gravel bottom substrate. However, the three species selected as target species (brown trout, bullhead and grayling) are all classified as highly rheophilic, intolerant species (AMBER 2019). This means that only accounting for these three species would not satisfy the habitat requirements for the expected fish community in this region, according to AMBER. Therefore, the habitat requirements for brown trout, bullhead and grayling were chosen in their particular spawning periods, while the habitat requirements of the total expected fish community were taken into account in the summer period.

6.2.3 Bioperiods

The bioperiods considered in this MesoHABSIM model were defined using the spawning periods of the species of great importance (brown trout, bullhead and grayling) in correlation with the hydrological regime in the Leutasch and the Inn. Figure 32 shows the three identified bioperiods together with the hydrological regime shown in monthly mean discharge values.

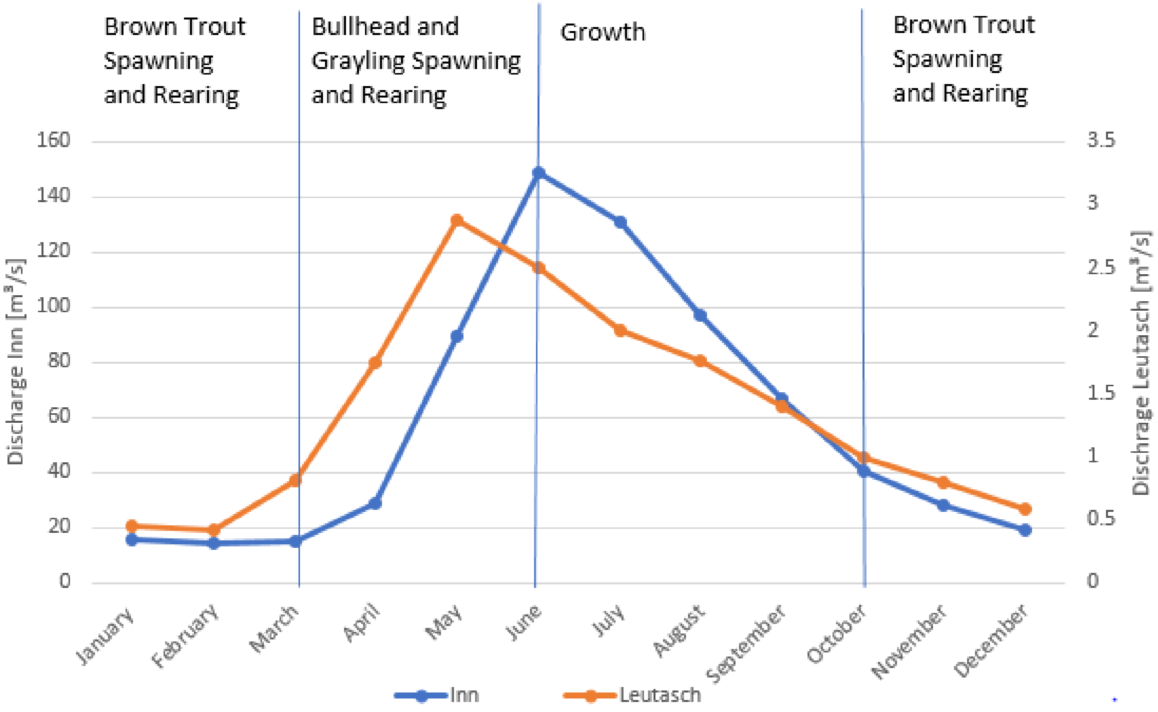


Figure 32 Identified bioperiods for the River Leutasch and the Upper Inn River based on monthly mean discharge values using data of BMLRT (2020b) and Schönlaub et al. (2007)

As brown trout spawn in autumn and winter and the larvae hatch several weeks later (Table 10), the period starting from the beginning of October to the end of February was defined as the brown trout spawning and rearing period. This period is linked to the decrease in discharge in autumn and the low discharges in winter. Bullheads as well as European graylings spawn in spring (Table 10), which correlates with the increasing discharge due to the melting of snow. Therefore, the period from March to the beginning of June is defined as the bullhead and grayling spawning and rearing period. The summer period, June to end of September, is considered as a growth period for all species in the expected fish community.

6.2.4 Habitat Preferences and Suitability Criteria

This study did not include fish sampling surveys and therefore no fish data was available to develop habitat suitability criteria. Instead, available data from literature or experts were used to define habitat requirements. To characterise the habitat requirements, the same five physical variables (water depth, water velocity, choriotop, HMU type and cover structures) used in the MesoHABSIM model and determined during the MesoHABSIM surveys were taken into account.

6.2.4.1 Growth Period

The habitat requirements for the three fish habitat-use guilds during the growth or feeding seasons had already been defined by experts as part of the AMBER project (P. Parasiewicz, pers. comm., July 11, 2020). The results of this analysis are shown in Table 11.

Table 11 Habitat requirements for the growth period (P. Parasiewicz, pers. comm., July 11, 2020)

Fish guilds	Depth [m]	Velocity [m/s]	Choriotop	HMU Type	Cover
Highly rheophilic, intolerant species	0.25-1.5	**0.3-1.2** (max. 2.0)	gigalithal, megalithal, macrolithal, mesolithal, microlithal	riffle, ruffle, cascade, rapids, fast run, run, glide, sidearm, plunge-pool, pool	boulders, undercut banks, woody debris
Rheophilic benthic species, preferring sandy-gravel bottom substrate	0.3-2.0	**0.15-0.9**	megalithal, macrolithal, mesolithal, microlithal, psammal	riffle, ruffle, cascade, rapids, fast run, run, glide, plunge-pool, pool, sidearm	boulders, undercut banks woody debris
Rheophilic water column species, preferring sandy-gravel bottom substrate	0.5-4.0	0.15-0.7	mesolithal, microlithal, psammal, alkal, debris, xylal	run, fast run, pool, plunge-pool, backwater	boulders, undercut banks woody debris, canopy cover

6.2.4.2 Brown Trout Spawning and Rearing Period

The habitat requirements for spawning brown trout are well known due to a large amount of research in this field. Based on a literature review (see Appendix II), the following habitat requirements were selected (Table 12). As brown trouts use the interstitial to protect their eggs, the substrate is of great importance to the selection of spawning habitats. Therefore, unconsolidated gravel banks with low number of fine particles are chosen as the preferred habitat.

Table 12 Habitat requirement for spawning and rearing brown trout

Species	Depth [m]	Velocity [m/s]	Choriotop	HMU Type	Cover
Brown trout spawning and rearing	0-0.75	0.15-0.75	**mesolithal, microlithal, alkal**	riffle, ruffle, pool, run, glide, sidearm	boulders, overhanging vegetation, canopy cover, shallow margins

6.2.4.3 Bullhead and Grayling Spawning and Rearing Period

Bullheads are small, benthic species which occur in cool and clear rivers with high oxygen levels (Tomlinson and Perrow 2003). The habitat requirements for their spawning period are not as well researched as for brown trout and therefore the development of habitat suitability criteria was more complicated here. However, several studies show that bullheads excavate nests under large stones or other structures and stick their eggs to the underside (Tomlinson and Perrow 2003). Using this information, the availability of such spawning substrates can be seen as the most important factor when it comes to their spawning habitat requirements. Therefore, large stones, cobbles, pebbles or other cover structures need to be available. The other habitat requirements were selected based on a literary review of the general habitat requirements for juvenile and adult bullheads (see Appendix II) and summarized in Table 13.

Table 13 Habitat requirement for spawning and rearing bullhead

Species	Depth [m]	Velocity [m/s]	Choriotop	HMU Type	Cover
Bullhead spawning and rearing	0.-0.75	0.15-1.05	macrolithal, mesolithal, microlithal	riffle, rapids, ruffle, run, glides, pool, plunge-pool, sidearm	undercut banks, **boulders,** woody debris

Graylings are rheophilic species which belong to the salmonid group and therefore also use substrate for spawning (Jungwirth 2003). In contrast to brown trout, it deposits its eggs on the substrate surface (Jungwirth 2003). Sempeski and Gaudin (1995b) saw a ontogenetic habitat shift for larval and juvenile graylings, as they live in habitats significantly different to their spawning sites. Larval grayling prefer low depths and velocities near the shore whereas young grayling move back into the main channel and so use higher depths and velocities (Bardonnet, Gaudin, and Persat 1991; Sempeski and Gaudin 1995b; Nykänen and Huusko 2003; Mallet et al. 2000). Table 14 shows the habitat requirements for spawning and rearing grayling based on a literary review (Appendix II).

Table 14 Habitat requirement for spawning and rearing grayling

Species	**Depth [m]**	**Velocity [m/s]**	**Choriotop**	**HMU Type**	**Cover**
Grayling spawning	0-0.6	0.15-0.75	**mesolithal, microlithal, alkal**	riffle, ruffle, run, glide, pool, sidearm	Undercut banks, woody debris, overhanging vegetation, canopy cover, **shallow margin**

6.2.5 Defining Habitat Suitability

The habitat requirements described in the previous sections were entered into SimStream (SimStream 8.0, Version 12, Rushing Rivers Institute) for the particular bioperiods. It was defined that suitable habitat conditions exist if three out of five habitat attributes are fulfilled and optimal conditions exist if at least four attributes are in the range described in the previous sections. In addition, some habitat requirements were defined as critical which means they must be fulfilled to be considered suitable conditions. These critical attributes are in bold print in Tables 11-14. As water depth, velocity and substrate were measured at several points in the HMUs, cut-off values were entered to define how many of these measurements have to fall into the ranges mentioned previously. Similarly, cut-off values are set for cover structures, as several cover structures can exist in one HMU. The cut-off values for water depth, velocity and substrate were set at 30% and the cut-off value for cover at 100% which means at least one type of cover must exist.

For the growth period, the three fish-habitat use guilds were combined to make one fish community according to the percentages defined by the AMBER project (see Section 6.2.1). During the spawning periods, only the habitat requirements of the spawning target species were considered. This means the habitat is only analysed during these periods to check for the habitat requirements of the spawning target species. During the bullhead and grayling spawning and rearing periods, the habitat requirements of each species were of equal importance.

7 Results

7.1 HMU Classification

7.1.1 Leutasch

47 different HMUs were identified and mapped during the field surveys at the Leutasch. The following sections show which HMU types occurred as well as their quantity and their wetted area during each survey.

7.1.1.1 Discharge 0.65 m³/s (14.4 l/(s*km²))

The lowest surveyed discharge of 0.65 m³/s occurred on 19th December 2019. During this survey, in total 15 different HMUs were identified and a total wetted area of 5483 m² was mapped. Figure 33 shows the location, extent and type of these HMUs. The mapped HMU types, their wetted area and quantity are presented in Table 15. Only four different HMU types were identified during this survey. More than 50% of the wetted area was classified as ruffle. The second most common HMU type was riffle in 22.8% of the total wetted area. Rapids occurred only in 8% of the wetted area.

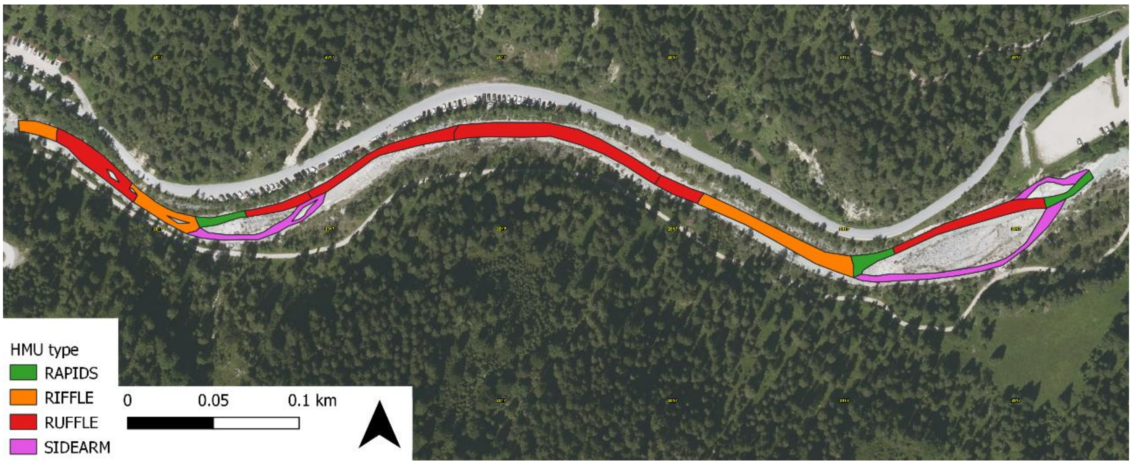


Figure 33 HMU types identified during a discharge of 0.65 m³/s on 19th December 2019 at River Leutasch

Table 15 HMU types, their quantity and wetted area during a discharge of 0.65 m³/s on 19th December 2019 at River Leutasch

HMU type	**Quantity**	**Area [m²]**	**Percentage of total wetted area [%]**
Rapids	3	438.2	8
Ruffle	6	2806.3	51.2
Riffle	3	1248.0	22.8
Sidearm	3	990.8	18.1
Sum	*15*	*5483.3*	*100*

7.1.1.2 Discharge 1.83 m³/s (40.7 l/(s*km²))

The discharge conditions of 1.83 m³/s were mapped on 27th August 2019. In total, 17 different HMUs were identified and a total wetted area of 6300 m². The extent and location as well as the HMU types are shown in Figure 34. The HMU types and their quantity as well as their wetted area are presented in the following table (Table 16). Seven different HMU types were identified during this survey. The most common HMU type was rapids in 45% of the wetted area and the second most common type riffle in 18%. In addition, several more fast-flowing HMU types occurred in comparison to lower flow condition such as two cascades, two ruffles, a run and a glide.

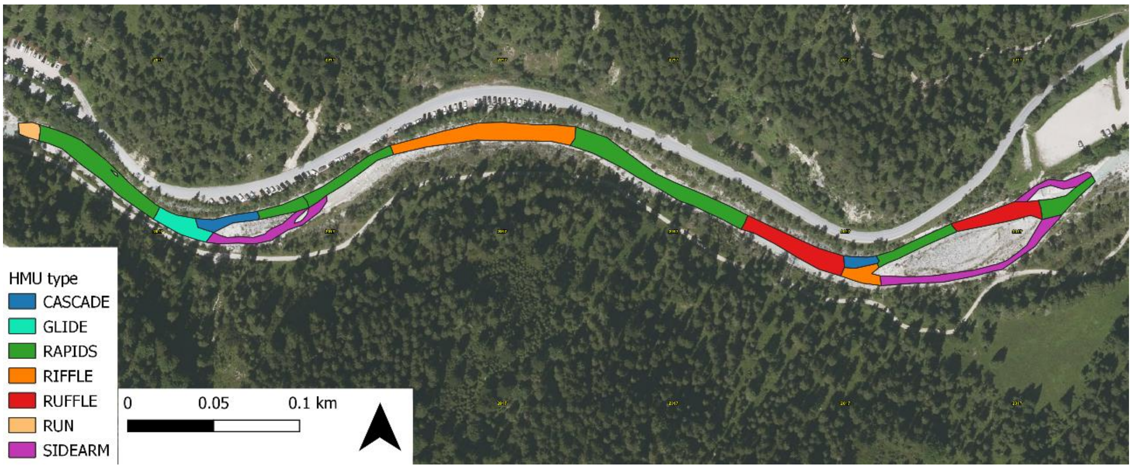


Figure 34 HMU types identified during a discharge of 1.83 m³/s on 27th August 2019 at River Leutasch

Table 16 HMU types, their quantity and wetted area during a discharge of 1.83 m³/s on 27th August 2019 at River Leutasch

HMU type	**Quantity**	**Area [m²]**	**Percentage of total wetted area [%]**
Cascade	2	312.4	5.0
Rapids	6	2841.0	45.0
Run	1	103.1	1.6
Glide	1	297.1	4.7
Ruffle	2	604.1	9.6
Riffle	2	1134.4	18.0
Sidearm	3	1016.2	16.1
Sum	*17*	*6308.3*	*100*

7.1.1.3 Discharge 2.39 m³/s (53.1 l/(s*km²))

The survey at a discharge of 2.39 m³/s was carried out on 3rd September 2019. At this discharge condition, 15 HMUs were identified and a total wetted area of 7950 m². Figure 35 shows the extent, location and type of the mapped HMUs. Table 17 shows the mapped HMU types, their area and quantity. During this survey, eight different HMU types were identified. Here, 67% of the wetted area were classified as rapids. During this survey, it was possible to identify different HMU types within one sidearm as the discharge was high enough to form typical features. Therefore, the sidearm was divided into three HMUs, a ruffle, a pool and a riffle. However, the site was generally dominated by fast-flowing HMU types such as cascades, rapids, fastruns, runs and ruffles.

Figure 35 HMU types identified during a discharge of 2.39 m³/s on 3rd September 2019 at River Leutasch

Table 17 HMU types, their quantity and wetted area during a discharge of 2.39 m³/s on 3rd September 2019 at River Leutasch

HMU type	**Quantity**	**Area [m²]**	**Percentage of total wetted area [%]**
Cascade	2	571.1	7.2
Rapids	4	5336.9	67.1
Fastrun	1	212.1	2.7
Run	1	278.1	3.5
Ruffle	1	152.4	1.9
Riffle	3	559.2	7.0
Sidearm	2	786.8	9.9
Pool	1	53.2	0.7
Sum	*15*	*7949.7*	*100*

7.1.2 Upper Inn

When using the three different orthophotos in combination with the results of the hydraulic simulations, in total eight HMUs were identified for the reference site Kajetan and 86 for the reference site Maria Stein. The HMU types, their quantity and extent are presented for both reference sites in the following sections.

Some inaccuracies were identified at the reference site Maria Stein when comparing the hydrodynamic simulation results and the orthophotos. The orthophoto taken on 17th April 2017 at a discharge of 39.2 m³/s shows a sidearm in the lower part of the reference site. This sidearm, however, does not exists in the hydrodynamic model attained for this discharge value. As the photo was taken in the high flow season, this could be a result of a previous flood event which could have led to flooding of this specific area or the modification of the morphological conditions compared to the one included in the hydrodynamic model. This flow condition was therefore mapped using mainly the simulation results of the hydrodynamic model. Otherwise, the hydraulic conditions within the main channel, water depth and velocity, would not have matched to the mapped wetted area and could not have been used in the analysis process.

7.1.2.1 Kajetan – Discharge 11.4 m³/s (5.3 l/(s*km²))

The reference site Kajetan was mapped during a discharge of 11.4 m³/s using an orthophoto taken on 10th March 2016. Four different HMU types were identified based on the hydraulic simulations. In total, a wetted area of 9465 m² was mapped. The extent, the location of the HMUs as well as the types are shown in Figure 36. Table 18 additionally shows the wetted area for each HMU type. Here, 41.2% of the wetted area was classified as run and 28.1% as ruffle. Additionally, a glide and a riffle were identified in 14% and 17% of the wetted area respectively.

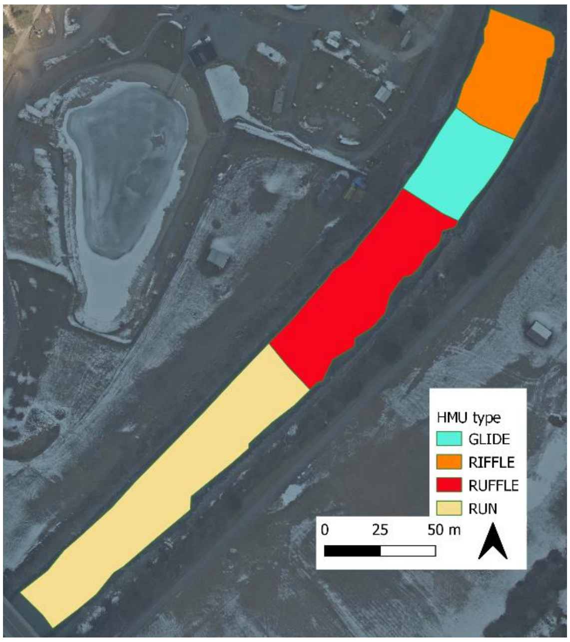


Figure 36 HMU types identified for a simulated discharge of 11.4 m³/s at Kajetan site

Table 18 HMU types, their quantity and wetted area for a simulated discharge of 11.4 m³/s at Kajetan site

HMU type	Quantity	Area [m²]	Percentage of total wetted area [%]
Glide	1	1315.8	13.9
Riffle	1	1591.4	16.8
Ruffle	1	2662.8	28.1
Run	1	3895.2	41.2
Sum	*4*	*9465.2*	*100*

7.1.2.2 Kajetan – Discharge 37.4 m³/s (17.3 l/(s*km²))

The discharge of 37.4 m³/s was mapped using an orthophoto taken on 20th February 2017. Two different HMU types were identified with a total wetted area of 11,195 m². Figure 37 shows the location, extent and type of these two HMUs and Table 19 additionally shows the wetted area for each HMU. The first part of the reference site was classified as a fastrun representing 44% of the total wetted area. The second part of the site was identified as a ruffle representing 56% of the wetted area, as lower depths and higher turbulences were visible here.

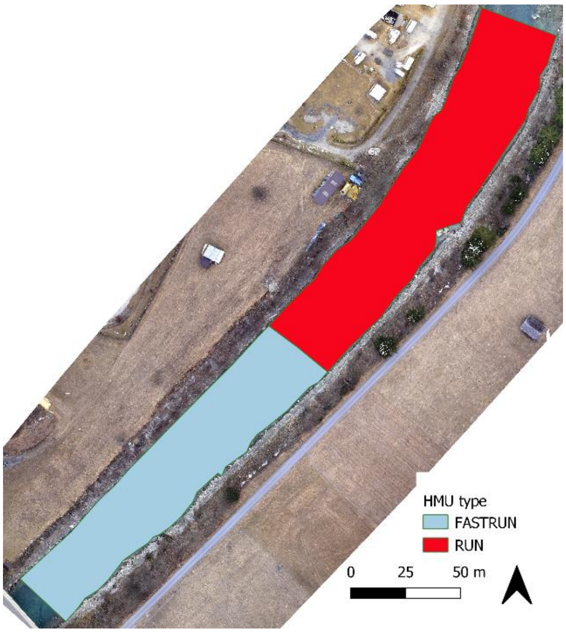


Figure 37 HMU types identified for a simulated discharge of 37.4 m³/s at Kajetan site

Table 19 HMU types, their quantity and wetted area for a simulated discharge of 37.4 m³/s at Kajetan site

HMU type	Quantity	Area [m²]	Percentage of total wetted area [%]
Fastrun	1	4954.5	44.3

Ruffle	1	6240.3	55.7
Sum	*2*	*11,194.8*	*100*

7.1.2.3 Kajetan – Discharge 84.8 m³/s (39.2 l/(s*km²))

The highest discharge was mapped using an orthophoto taken on 24th September 2010 and a hydraulic simulation of a discharge of 84.8 m³/s. Two HMUs were identified representing 13,486 m². The extent, location and HMU types are shown in Figure 38 and Table 20 shows the corresponding areas and percentages. The first river stretch was once more classified as a fastrun. The second part of the site, on the other hand, was now identified as rapids.

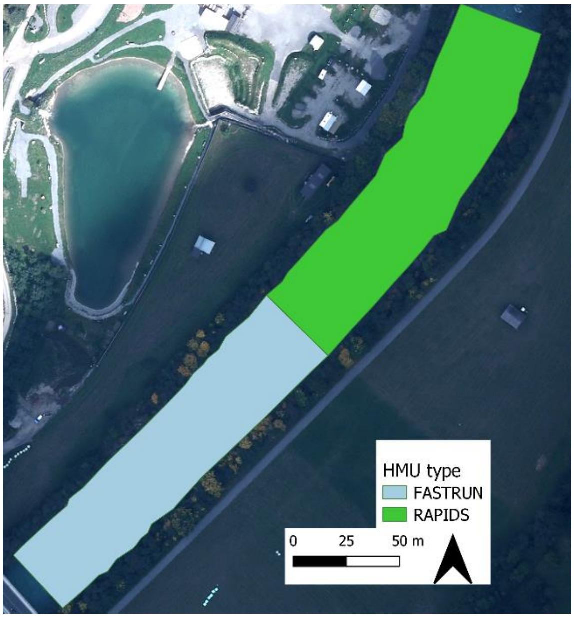


Figure 38 HMU types identified for a simulated discharge of 84.8 m³/s at Kajetan site

Table 20 HMU types, their quantity and wetted area for a simulated discharge of 84.8 m³/s at Kajetan site

HMU type	**Quantity**	**Area [m²]**	**Percentage of total wetted area [%]**
Fastrun	1	6342.5	47.0
Rapids	1	7143.5	53.0
Sum	*2*	*13,486.0*	*100*

7.1.2.4 Maria Stein – Discharge 15.8 m³/s (6.9 l/(s*km²))

The lowest discharge at the reference site Maria Stein was mapped using an orthophoto taken on 10th March 2016 and the hydraulic model simulating a discharge of 15.8 m³/s. In total, 31 HMUs were identified with a total wetted area of 61,156 m². Figure 39 shows the location, extent and types of the mapped HMUs. Table 21 shows the HMU types and corresponding areas.

Almost 40% of the site was classified as run and 14.6% as fastrun. Additionally, rapids, riffle and ruffle occurred in 10 to 11% of the area each. To smaller accounts, sidearms, backwater, pools, plunge-pools and glides were identified.

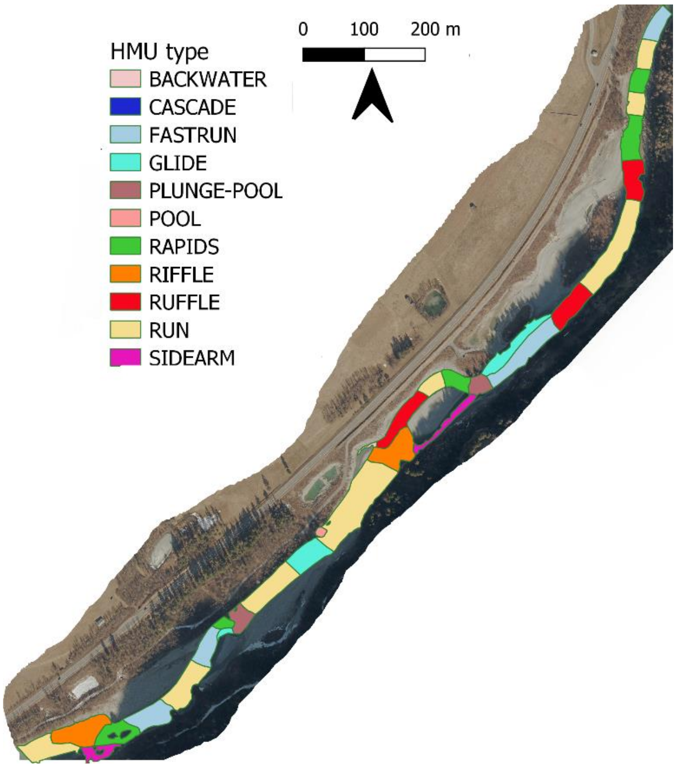


Figure 39 HMU types identified for a simulated discharge of 15 m³/s at Maria Stein site

Table 21 HMU types, their quantity and wetted area for a simulated discharge of 15 m³/s at Maria Stein site

HMU type	**Quantity**	**Area [m²]**	**Percentage of total wetted area [%]**
Backwater	1	145.3	0.2
Fastrun	4	8873.1	14.5
Glide	3	4686.8	7.7
Plunge-Pool	2	2202.6	3.6
Pool	1	229.4	0.4
Rapids	5	6496.4	10.6
Riffle	2	5914.4	9.7
Ruffle	3	6532.6	10.7
Run	8	23,878.4	39.0
Sidearm	2	2197.1	3.6
Sum	*31*	*61,156.3*	*100*

7.1.2.5 Maria Stein – Discharge 32.9 m³/s (14.5 l/(s*km²))

For a simulated discharge of 32.9 m³/s, 31 HMUs were identified and a total wetted area of 72,885 m². Here, an orthophoto taken on 17th April 2017 was used. All HMU types, their extent and locations are shown in Figure 40. Table 22 additionally shows the mapped area and quantity of each HMU type. At these discharge conditions, 30.9% of the mapped area was classified as ruffle and 23% as run. Rapids occurred in 12.6% of the mapped area. Additionally, fastruns, glides and riffles were identified and to smaller extents backwater, plunge-pools, pools, sidearms and a cacscade.

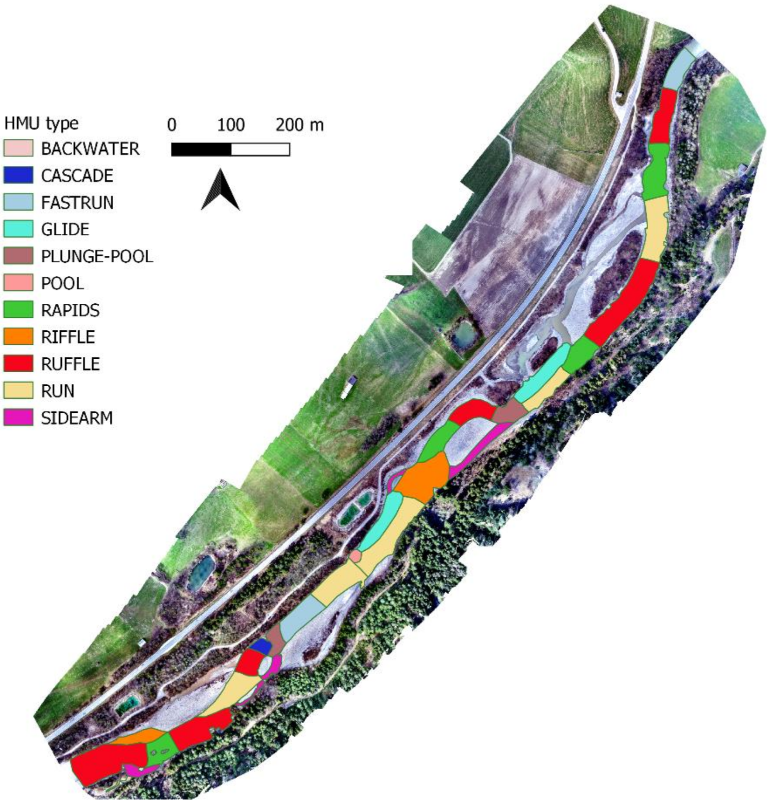


Figure 40 HMU types identified for a simulated discharge of 32.9 m³/s at Maria Stein site

Table 22 HMU types, their quantity and wetted area for a simulated discharge of 32.9 m³/s at Maria Stein site

HMU type	**Quantity**	**Area [m²]**	**Percentage of total wetted area [%]**
Backwater	1	173.4	0.2
Cascade	1	694.7	1.0
Fastrun	2	4788.2	6.6
Glide	2	5459.4	7.5
Plunge-pool	2	2744.2	3.8
Pool	1	362.6	0.5
Rapids	4	9217.1	12.6

Riffle	2	6283.9	8.6
Ruffle	6	22,489.1	30.9
Run	5	16,767.7	23.0
Sidearm	5	3904.9	5.4
Sum	*31*	*72,885.2*	*100*

7.1.2.6 Maria Stein – Discharge 90 m³/s (39.5 l/(s*km²))

The highest discharge was mapped based on an orthophoto taken on 27th September 2018 and using hydraulic simulations for 90 m³/s. 24 HMUs were mapped and their locations, extents and types are shown in Figure 41. Table 23 shows the corresponding wetted area and quantity of each HMU type. Here, fastrun was the most common HMU type in 31.6% of the wetted area followed by ruffles in 29.6%. Regarding the fast-flowing and turbulent HMU types, two rapids and one cascade occurred with 8.4% and 1.8% respectively. Furthermore, some riffles, sidearms, plunge pools and backwater were identified.

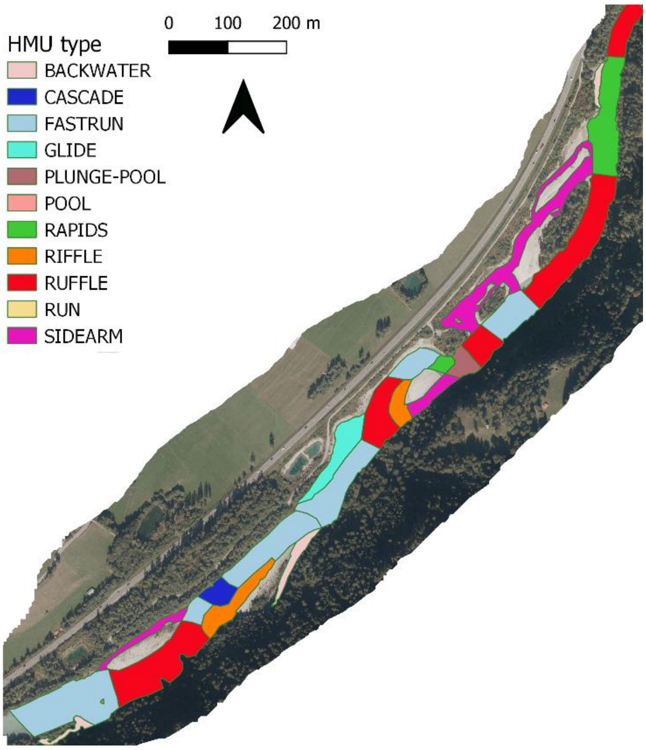


Figure 41 HMU types identified for a simulated discharge of 90 m³/s at Maria Stein site

Table 23 HMU types, their quantity and wetted area for a simulated discharge of 90 m³/s at Maria Stein site

HMU type	**Quantity**	**Area [m²]**	**Percentage of total wetted area [%]**
Backwater	3	3473.3	3.3
Cascade	1	1886.1	1.8
Fastrun	6	32947.7	31.6
Glide	1	4322.4	4.1
Plunge-pool	1	1767.4	1.7
Rapids	2	8724.4	8.4
Riffle	2	5829.3	5.6
Ruffle	5	30,866.3	29.6
Sidearm	3	14,354.5	13.8
Sum	*24*	*10,4171.3*	*100*

7.2 Habitat Rating Curves

The habitat rating curves were created using the software SimStream 8.0 (Version 12, Rushing Rivers Institute). The curves were constructed based on the effective habitat which takes habitat defined as suitable and habitat defined as optimal into account (see Section 3.3.2.4). The HMU data (HMU type, attributes and area) and the velocity, depth and substrate point measurements can be loaded into SimStream as spreadsheets. Using the habitat suitability described in Section 6.2.4, discharge values are then transformed into values of habitat quantity. The values in-between the measured discharge conditions are interpolated using linear-curve fitting.

7.2.1 Leutasch

The habitat rating curves for the Leutasch were constructed based on specific flow values (l/(s*km²)) in the range of 1 to 60 l/(s*km²) with an increment of 1 l/(s*km²). The total channel area was assumed to be 10,000 m² which represents around 1.25 times the highest value of the wetted area measured (here wetted area measured as 7950 m² on 3rd September 2019 at a specific discharge of 53.1 l/(s*km²), see Section 7.1.1.3). In the following, the rating curves are presented for each bioperiod separately. In addition, the wetted area curve is shown which represents the total amount of potential habitat at each discharge level.

7.2.1.1 Growth Period

The habitat during the growth period was analysed regarding the habitat suitability of each fish habitat-use guild as well as for the community in total (Figure 42). The available habitat for highly rheophilic species in the Leutasch is very high, almost the total amount of the wetted area is suitable for these species. On the other hand, only small parts of the riverine habitat are suitable for rheophilic water column species. The amount of suitable habitat for rheophilic benthic species first increases with increasing discharge, then decreases slightly before it increases again. Additionally to the guild rating curves, the habitat rating curve was created for the fish community taking into account the proportions mentioned in Section 6.2.1. The available habitat for the community increases with increasing discharge and therefore the highest amount of suitable habitat for the community is found at the highest surveyed discharge, here 65% of the channel area at 60 l/(s*km²).

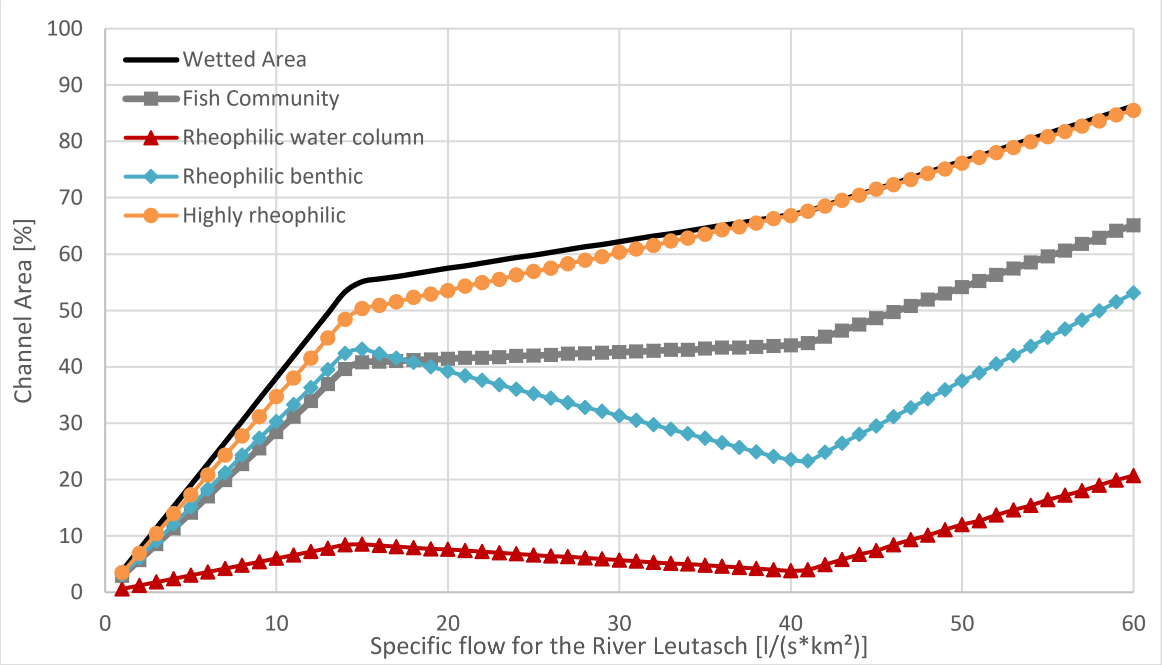


Figure 42 Rating curves at the River Leutasch during the summer growth bioperiod

7.2.1.2 Brown Trout Spawning and Rearing Period

The habitat available for spawning and rearing brown trout is shown in Figure 43. The amount of suitable habitat for spawning and rearing brown trout first increases with increasing discharge, reaching the highest amount of suitable habitat at a specific flow of 15 l/(s*km²). At discharges higher as these 15 l/s *km², the suitable habitat decreases again. However, 30% of the channel area is suitable for spawning and rearing brown trout even at high discharges conditions (60 l/s *km²).

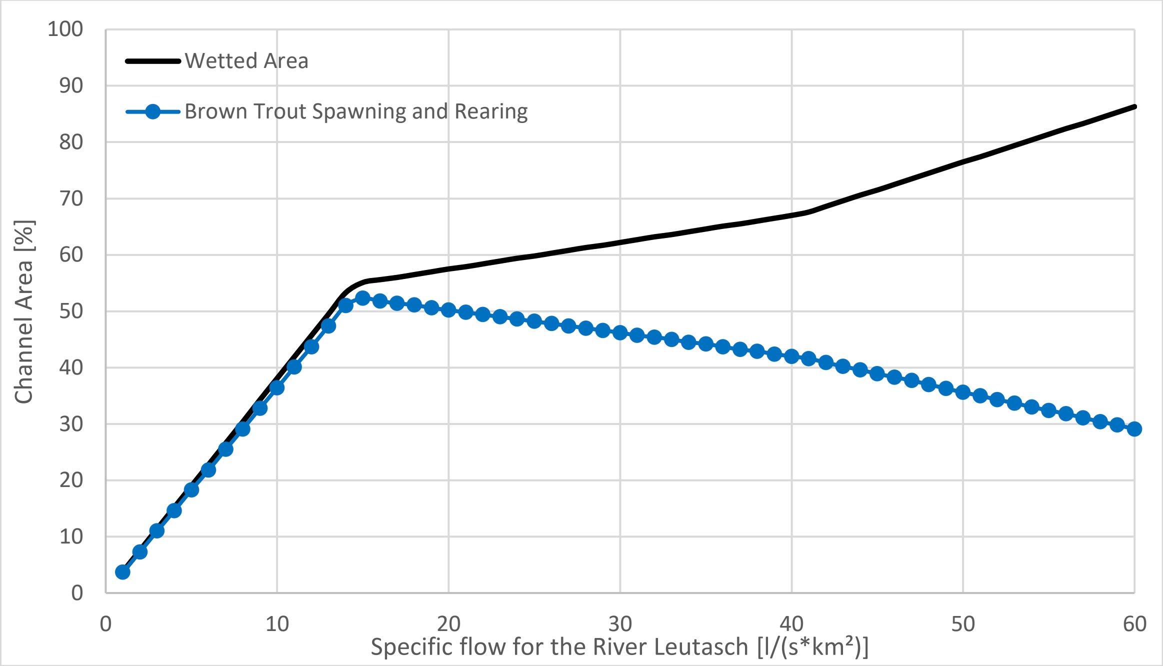


Figure 43 Rating curves at the River Leutasch during the brown trout spawning and reaing bioperiod

7.2.1.3 Bullhead and Grayling Spawning and Rearing Period

The habitat rating curves for spawning and rearing bullhead and grayling are presented in Figure 44. The total available wetted area is suitable as habitat for spawning and rearing bullhead. The habitat rating curve for spawning and rearing grayling increases until it reaches its maximum at 15 l/(s*km²) similar to the curve of spawning and rearing brown trout.

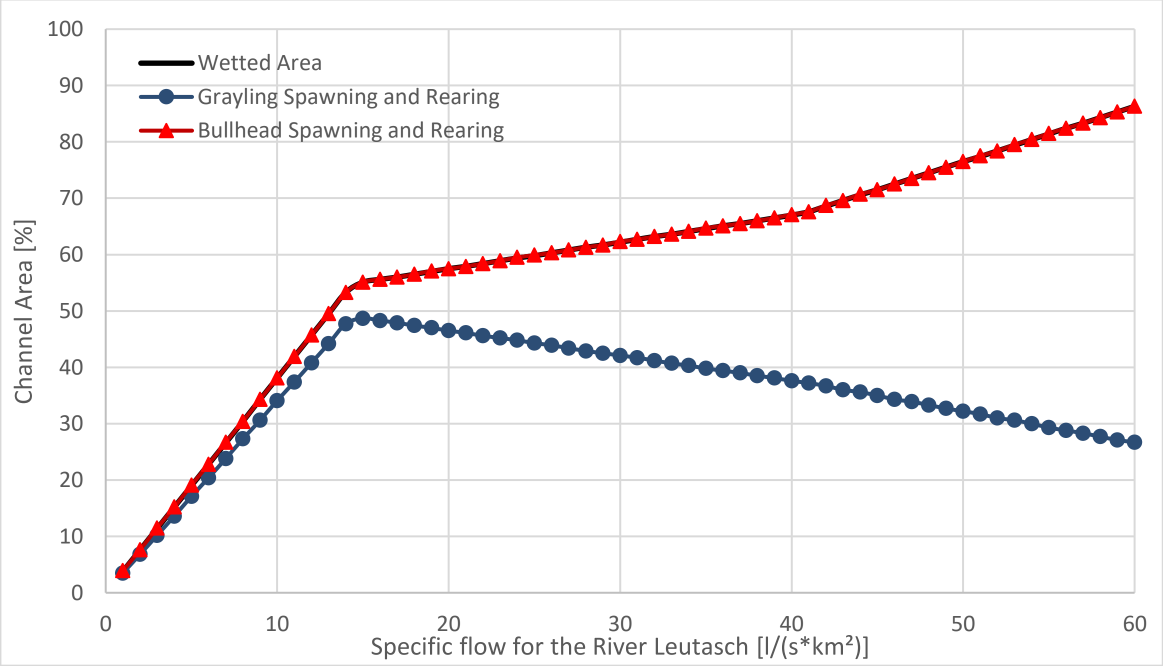


Figure 44 Rating curves at the River Leutasch during the bullhead and grayling spawning and rearing bioperiod

7.2.2 Upper Inn

The habitat rating curves for the Upper Inn were created based on specific flow values in the range of 1 to 45 l/(s*km²) with an increment of 1 l/(s*km²). For the Kajetan site, the total channel area was assumed to be 16,200 m² which represents around 1.2 times the highest value of the wetted area measured (here wetted area measured as 13,486 m² on 24th September 2010 at a specific discharge of 39.2 l/(s*km²), see Section 7.1.2.3). The total channel area for the Maria Stein site was calculated to 125,000 m² (here wetted area measured as 104,171 m² on 27th September 2018 at a specific discharge of 39.5 l/(s*km²), see Section 7.1.2.6). The following sections show the rating curves together with the wetted area for each reference site and each bioperiod separately.

7.2.2.1 Kajetan – Growth Period

In general, the Kajetan site represents an obstructed and regulated river stretch which means that a low diversity in habitat structure occurs. Additionally, increasing discharge values are strongly connected to increasing flow velocity and water depth as no flood plains or sidearms can be flooded to extend the wetted area laterally. This can also be seen by the curves presenting the wetted area for increasing discharge conditions.

The following graphs show the rating curves developed for the growth period taking into account the habitat for highly rheophilic, rheophilic benthic and rheophilic water column species as well as the fish community (Figure 45). The total wetted area is suitable for highly rheophilic species during the summer period. Suitable habitat for rheophilic benthic species, however, only exists for flow conditions below 15 l/(s*km²). The suitable habitat for rheophilic water column species increases with increasing discharge. Summarizing the habitat suitability for all species, the fish community rating curve shows that more than half of the wetted area is suitable for the fish community during the summer growth period.

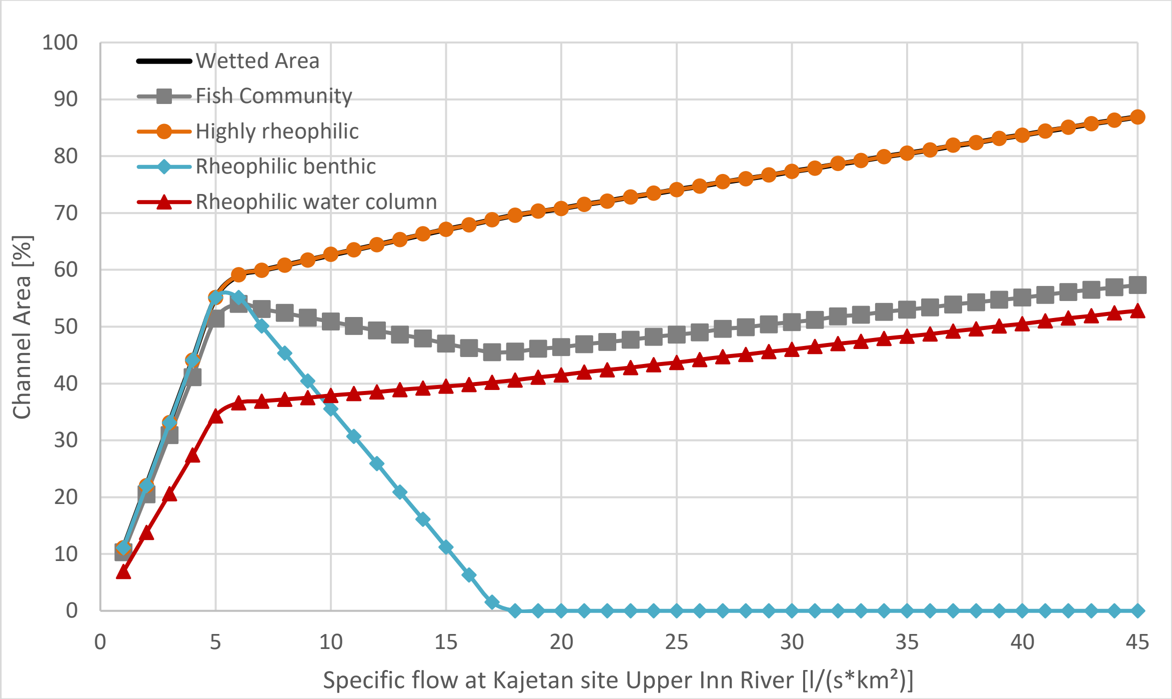


Figure 45 Rating curves at the Kajetan site at the Upper Inn River during the summer growth bioperiod

7.2.2.2 Kajetan – Brown Trout Spawning and Rearing Period

Figure 46 shows the habitat rating curve for spawning and rearing brown trout during. According to the model results, suitable habitats for spawning and rearing brown trout exist at the Kajetan site for discharge conditions below 40 l/(s*km²) with a maximum of suitable habitat at around 5 l/(s*km²).

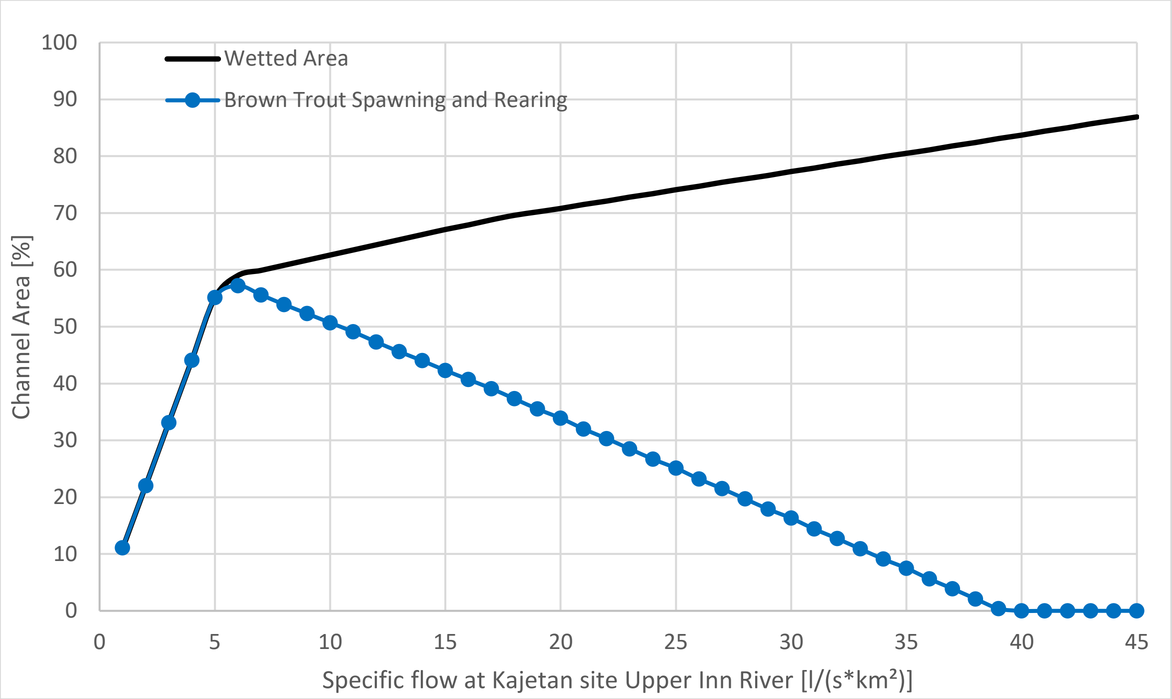


Figure 46 Rating curves at the Kajetan site at the Upper Inn River during the brown trout spawning and rearing period

7.2.2.3 Kajetan – Bullhead and Grayling Spawning and Rearing Period

The habitat rating curves for bullhead and grayling during their spawning and rearing period are shown in Figure 47. For both fish species, the habitat maximum can be found at around 5 l/(s*km²). After that point, the amount of suitable habitat for graylings decreases steadily with no suitable habitat at the highest surveyed discharge at around 40 l/(s*km²). The rating curve for spawning and rearing bullhead decreases slightly and then increase slightly again due to the increase in the wetted area from one surveyed discharge to another.

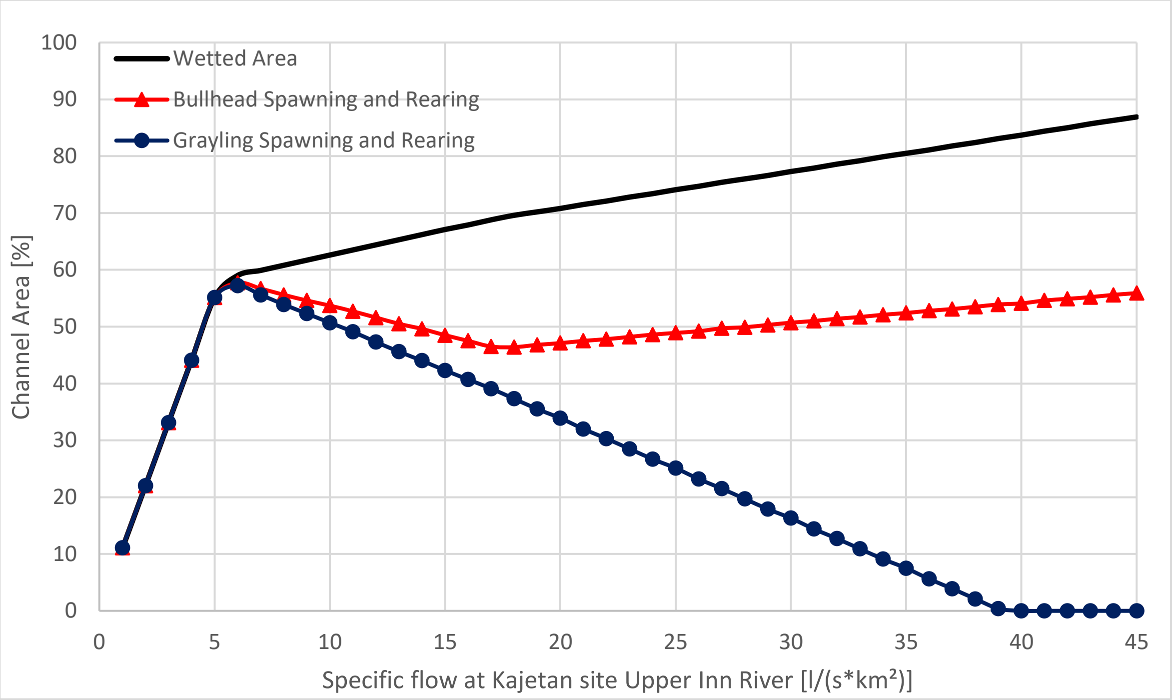


Figure 47 Rating curves at the Kajetan site at the Upper Inn River during the bullhead and grayling spawning and rearing period

7.2.2.4 Maria Stein – Growth Period

The rating curves developed for the Maria Stein site for the growth period are shown in Figure 48. Almost the total wetted area is classified as suitable habitat for highly rheophilic species. The suitable habitat for rheophilic water column species first increases up to 35% of the channel area at 7 l/(s*km²). It then decreases slightly and then increases again. The habitat suitable for rheophilic benthic species reaches its maximum for 7 l/(s*km²) with 35% of the channel area and then decreases with increasing discharge. Summarizing the results, the suitable habitat for the fish community increases with increasing discharge with a fast increase untill values of 7 l/(s*km²) and then a smooth increase for higher discharges.

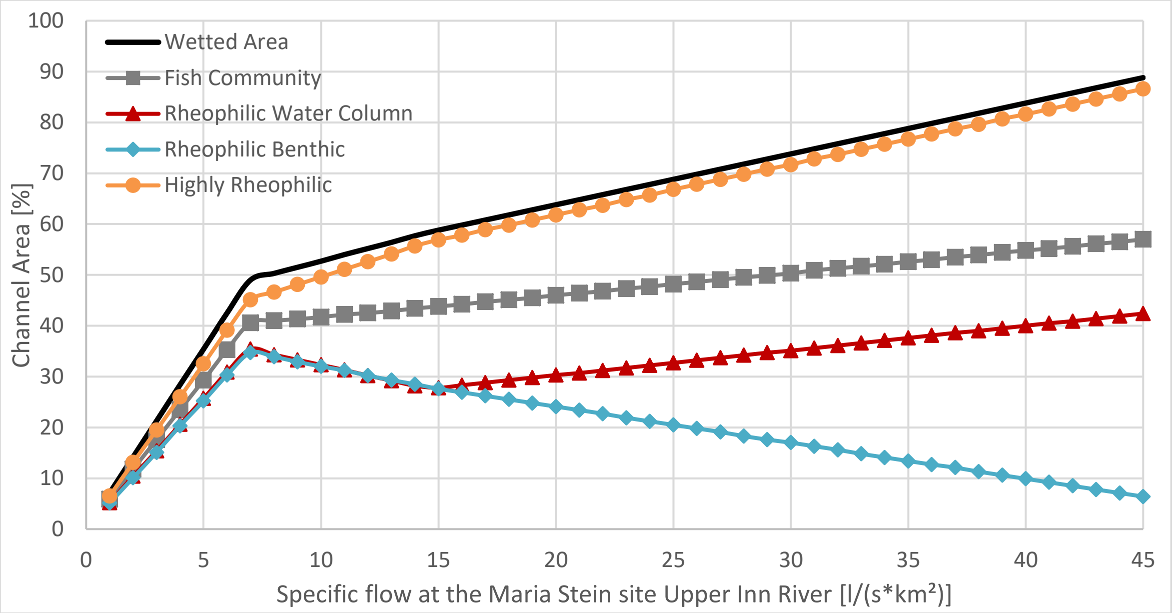


Figure 48 Rating curves at the Maria Stein site at the Upper Inn River during the summer growth bio-period

7.2.2.5 Maria Stein – Brown Trout Spawning and Rearing Period

Figure 49 shows the habitat rating curves for spawning and rearing brown trout. The suitable habitat for spawning and rearing brown trout has its maximum value for 7 l/(s*km²). However, after that point, the amount of suitable habitat only decreases slightly with increasing flow reaching a value of suitable channel area of 35% for a specific flow of 45 l/(s*km²).

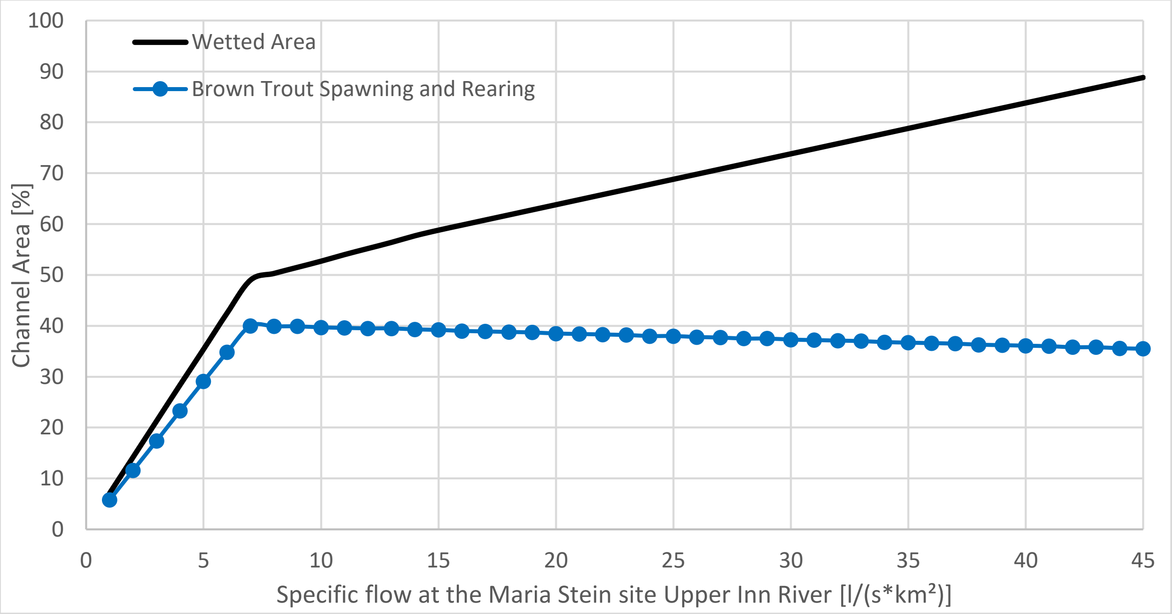


Figure 49 Rating curves at the Maria Stein site at the Upper Inn River during the brown trout spawning and rearing period

7.2.2.6 Maria Stein – Bullhead and Grayling Spawning and Rearing Period

The habitat suitable for spawning and rearing grayling and bullhead are shown by the rating curves in Figure 50. The amount of suitable habitat for both species reaches its maximum value at 15 l/(s*km²) and even for higher discharges still large areas are classified as suitable habitat for both species during this period.

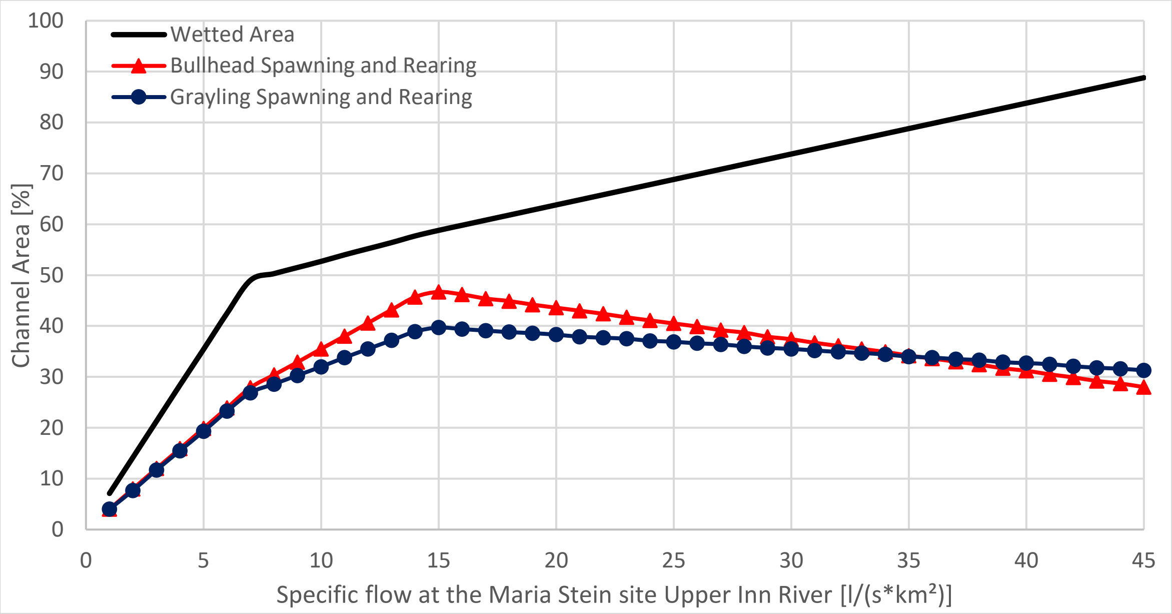


Figure 50 Rating curves at the Maria Stein site at the Upper Inn River during the bullhead and grayling spawning and rearing period

7.3 Habitat Time Series Analysis (UCUT)

As part of the habitat time series analysis, discharge records were transformed into habitat values using the corresponding rating curves presented above. Then the habitat time series analysis using UCUT curves was performed for each bioperiod separately using the software SimStream 8.0 (Version 12, Rushing Rivers Institute). The range of channel area considered in this analysis was selected based on the rating curves presented above. The different habitat thresholds for rare, critical and common habitat conditions as well as the corresponding allowable and catastrophic duration could be identified using the developed UCUT curvess. The selection criteria to identify the habitat thresholds (baseflow, trigger flow and subsistence flow) as well as the corresponding durations are described in Section 3.3.3.2. This analysis was conducted for the Leutasch only because for the Upper Inn no undisturbed flow time series was available (see Section 5.2.4). Analysing the habitat using influenced and altered hydrological conditions would not have led to reliable habitat thresholds.

The habitat time series was developed using a discharge time series measured at the gauging station Leutasch/Klamm (BMLRT 2020b, see Section 5.1.3). A flow time series from 1984 to 2016 was used and therefore the habitat time series analysis is based on 32 years of flow data.

The catastrophic durations were then defined by selecting the longest durations where the habitat was below the particular habitat threshold which occurred not more than three times (approximately once in a decade).

7.3.1 Growth Period

The UCUT curves with an increment of 1% channel area (CA) were selected for the growth period analysis because the habitat thresholds were better recognisable in these graphs (Figure 51).

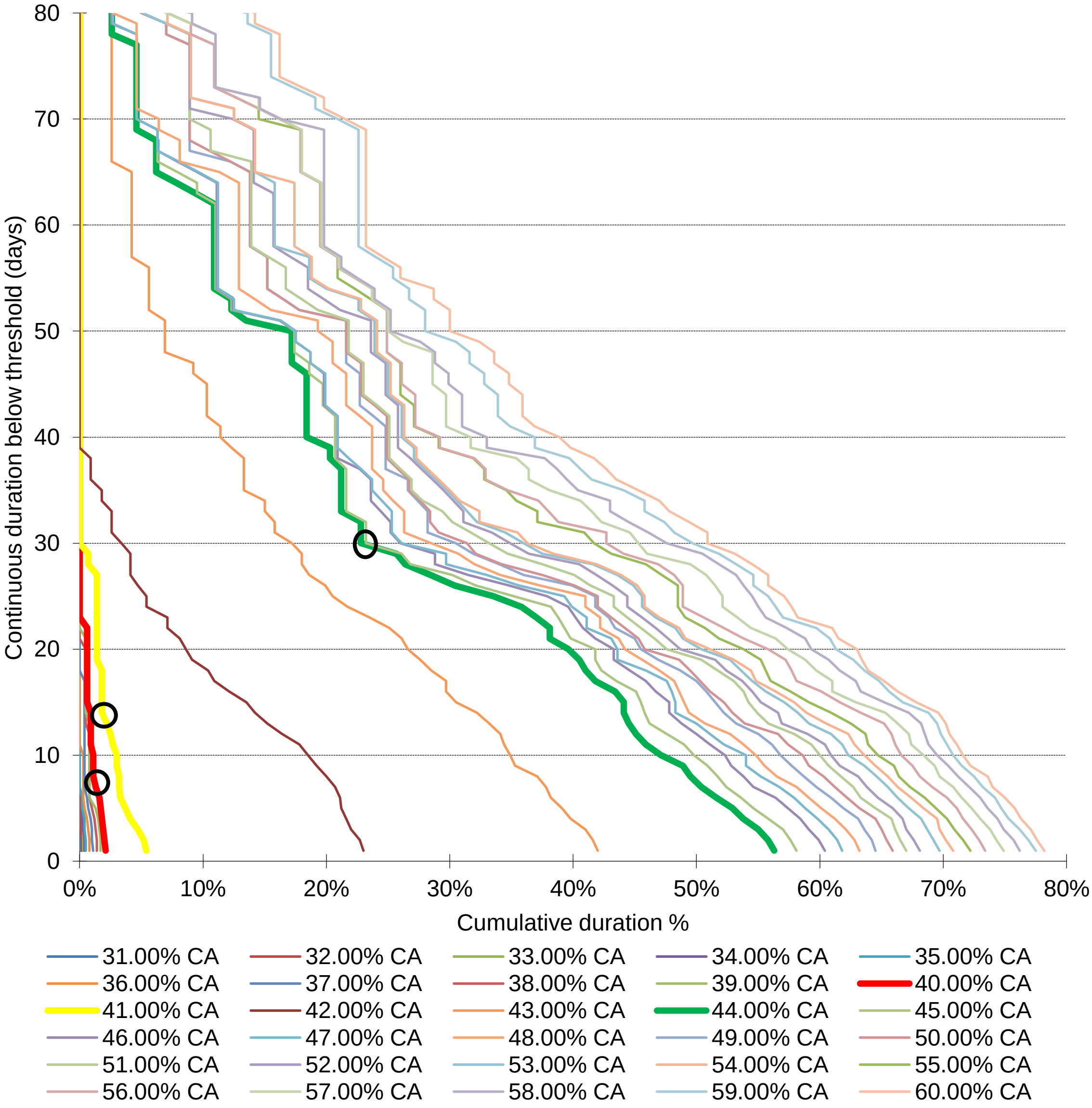


Figure 51 UCUTs for the River Leutasch during the summer growth period

Rare habitat conditions could easily be identified in the graphs in the lower left corner (Figure 51). The red line (40% channel area) marks the rare habitat threshold (Figure 51). The next higher line (41% channel area, yellow) shows the critical habitat threshold and the green line shows the beginning of normal conditions (44% channel area) (Figure 51).

The allowable duration could be identified by selecting the main inflection point at each habitat threshold curve. The points selected are marked with a black circle in Figure 51. The allowable duration for events with habitat values below the rare habitat threshold is 8 days, below the critical habitat threshold 14 days and below the common habitat threshold 30 days (Figure 51). The catastrophic durations for each habitat threshold were defined as 10, 18 and 68 days for rare, critical and common conditions respectively.

7.3.2 Brown Trout Spawning and Rearing Period

The habitat time series analysis for the brown trout spawning and rearing period is based on UCUT curves with an 2% increment for the channel area (Figure 52).

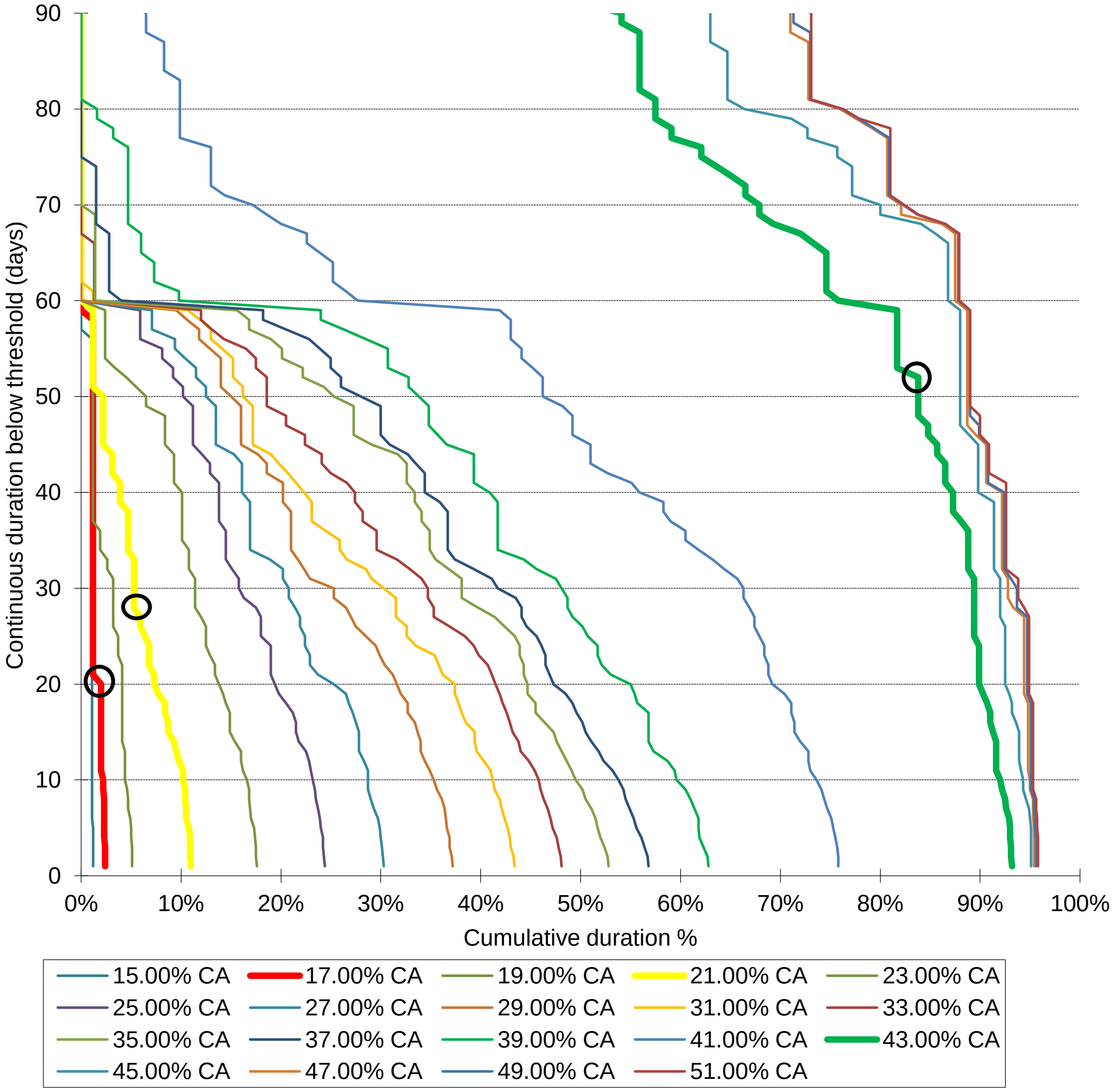


Figure 52 UCUTs for the River Leutasch during the brown trout spawning and rearing bioperiod

Rare habitat conditions occur for habitat values below 17% of the channel area (red line, Figure 52). The critical habitat threshold was selected as 21% CA (yellow line, Figure 52) and the common habitat threshold as 43% CA (green line, Figure 52). The allowable durations for which the habitat can be below the thresholds are marked with black circles in Figure 52 presenting 20, 28 and 52 days for rare, critical and common conditions respectively. The catastrophic durations were calculated as 20, 44 and 140 days for rare, critical and common conditions respectively.

7.3.3 Bullhead and Grayling Spawning and Rearing Period

The UCUT curves with an increment of 2% of channel area were chosen for the bullhead and grayling spawning and rearing bioperiod because they better showed the habitat thresholds.

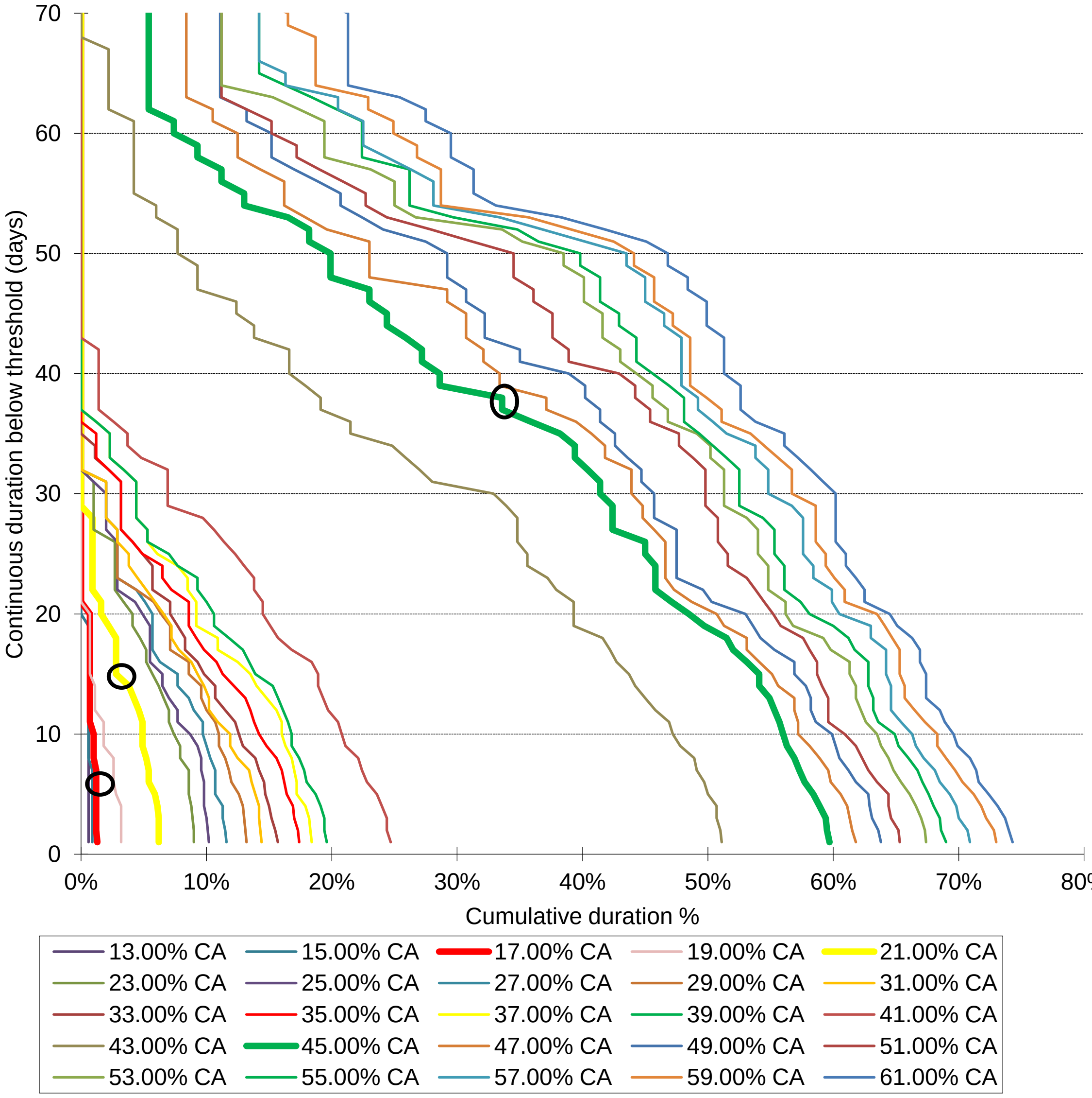


Figure 53 UCUTs for the River Leutasch during the bullhead and grayling spawning and rearing bioperiod

The threshold for rare habitat conditions was identified as 17% of the channel area (red line, Figure 53) and for critical habitat conditions as 21% of the channel area (yellow line, Figure 53). 45% of the channel area mark the transitions to common habitat conditions (green line, Figure 53). The allowable durations were defined as 6, 15 and 39 days and the catastrophic durations as 7, 19 and 61 days for rare, critical and common habitat events respectively.

7.4 Environmental Flow Assessment

7.4.1 Environmental Flow Criteria

Environmental flow criteria can be developed for the Leutasch using the results obtained by the UCUT analysis presented in the previous sections. Table 24 summaries the selected and identified habitat thresholds and durations for the three bioperiods in the River Leutasch. In addition, it shows the corresponding flow conditions for each habitat threshold (baseflow, trigger flow and subsistence flow). The absolute minimum habitat value represents the lowest measured habitat which was identified by the lowest discharge value which occurred in the period 1984 till 2016 during the particular bioperiod (BMLRT 2020b).

Table 24 Environmental flow criteria for the River Leutasch

Leutasch	**Growth**	**Brown Trout Spawning and Rearing**	**Bullhead and Grayling Spawning and Rearing**
	June to September	October to February	March to May
Common habitat (%CA)	**44**	**43**	**45**
Allowable duration under (days)	30	52	39
Catastrophic duration (days)	68	140	61
Corresponding baseflow (l/(s*km²))	40.4	33.4	41.6
Corresponding baseflow (m³/s)	1.820	1.510	1.870
Critical habitat (%CA)	**41**	**21**	**21**
Allowable duration under (days)	14	28	15
Catastrophic duration (days)	18	44	19
Corresponding trigger flow (l/(s*km²))	16.8	7.4	7.4
Corresponding trigger flow (m³/s)	0.758	0.332	0.332
Rare habitat (%CA)	**40**	**17**	**17**
Allowable duration under (days)	8	20	6
Catastrophic duration (days)	10	20	7
Corresponding subsistence flow (l/(s*km²))	14.3	6.0	6.0
Corresponding subsistence flow (m³/s)	0.644	0.270	0.270
Absolute minimum (l/(s*km²))	**10.49**	**4.38**	**4.16**

During the summer growth period, higher discharges occur in comparison to the two spawning periods. Here, the absolute minimum discharge value was identified as 10.5 l/(s*km²). Rare habitat conditions exist if the less than 40% of the channel area is available as habitat, which can be recalculated as 644 l/s or 14.3 l/(s*km²). If the flow falls below 758 l/s or 16.8 l/(s*km²) corresponding 41% of the channel area, critical habitat conditions occur. Common habitat conditions correspond to 1.82 m³/s or 40.4 l/(s*km²) or higher.

The absolute minimum discharge value connected to extreme habitat conditions during the brown trout spawning and rearing period was identified as 4.4 l/(s*km²). Rare habitat conditions occur for discharges below 270 l/s or 6.0 l/(s*km²) corresponding to 17% of the channel area and critical habitat conditions occur for discharges below 332 l/s or 7.4 l/(s*km²). If the flow is 1.52 m³/s or 33.4 l/(s*km²) or higher, common habitat conditions exist.

For the bullhead and grayling spawning and rearing period, extreme habitat conditions occur for flow values of 4.16 l/(s*km²) or less. Rare habitat conditions are connected to 270 l/s or 6.0 l/(s*km²). The flow values triggering critical conditions during the spawning and rearing period of bullhead and grayling are the same during the brown trout period (332 l/s or 7.4 l/(s*km²)). Common habitat conditions, however, exist at higher discharge values (1.87 m³/s or 41.6 l/s *km²).

7.4.2 Standardization

The environmental flow criteria developed for the Leutasch (Table 24) can be used to create environmental flow criteria for the FCMacHT region "Mountain, Alpine and subalpine rivers" in general. In order to achieve this transformation process, the coefficients p_b explanied in Section 3.3.4 are calculated by dividing the mean specific low flow value for one bioperiod by the corresponding habitat threshold value expressed as specific flow. The coefficients attained using the results of the Leutasch are shown in Table 25. They were calculated using mean low flow values identified for each bioperiod based on the historic flow time series of the Leutasch (BMLRT 2020b). The coefficients p_b vary widely with bioperiod and habitat threshold. In general, highest values occur for the common habitat thresholds. In addition, the coefficients p_b are highest for the brown trout spawning and rearing period.

Table 25 Coefficients p_b developed for the River Leutasch

	Growth	Brown Trout Spawning and Rearing	Bullhead and Grayling Spawning and Rearing
q_{base} Leutasch [l/(s*km²)]	40.4	33.4	41.6
q_{MBLF} Leutasch [l/(s*km²)]	27.8	10.6	23.6
p_{base} FCMacHT 2	1.45	3.15	1.76
q_{trig} Leutasch [l/(s*km²)]	16.8	7.4	7.4
q_{MBLF} Leutasch [l/(s*km²)]	27.8	10.6	23.6
p_{trig} FCMacHT 2	0.60	0.70	0.31
q_{subs} Leutasch [l/(s*km²)]	14.3	6	6
q_{MBLF} Leutasch [l/(s*km²)]	27.8	10.6	23.6
p_{subs} FCMacHT 2	0.51	0.57	0.25

7.4.3 Upper Inn

Using the Formula (4) in Section 3.3.4, the environmental flow criteria meaning the baseflow, trigger flow and subsistence flow can be calculated for the two reference sites in the Upper Inn.

The coefficients p_b then need to be multiplied by the catchment area of each site and the corresponding mean low flow value for the particular bioperiod. As no undisturbed flow time series for the Upper Inn was available, the low flow values were calculated using the measured flow time series of the gauging station Kajetansbrücke (BMLRT 2020a). In addition, the so calculated low flow values were used for both reference sites because no information about the runoff or groundwater discharge during low flow conditions was available for the catchment area between the two sites. Table 26 presents the low flow values calculated for the Kajetansbrücke station and the flow values for the baseflow, trigger flow and subsistence flow for the Kajetan and the Maria Stein sites as well as the corresponding allowable and catastrophic durations.

Table 26 Environmental flow criteria for the Upper Inn River at Kajetan site and Maria Stein site

Upper Inn	**Growth**	**Brown Trout Spawning and Rearing**	**Bullhead and Grayling Spawning and Rearing**
	June to September	October to February	March to May
q_{MBLF} Kajetansbrücke [l/(s*km²)]	22.1	4.9	8.7
q_{MBLF} Kajetansbrücke [m³/s]	47.8	10.7	18.9
Baseflow [l/(s*km²)]	**32.2**	**15.5**	**15.4**
Baseflow Kajetan [m³/s]	69.5	33.6	33.3
Baseflow Maria Stein [m³/s]	73.2	35.4	35.1
Allowable duration under (days)	30	52	39
Catastrophic duration (days)	68	140	61
Trigger Flow [l/(s*km²)]	**13.4**	**3.4**	**2.7**
Trigger Flow Kajetan [m³/s]	28.9	7.4	5.9
Trigger Flow Maria Stein [m³/s]	30.4	7.8	6.2
Allowable duration under (days)	14	28	15
Catastrophic duration (days)	18	44	19
Subsistence Flow [l/(s*km²)]	**11.4**	**2.8**	**2.2**
Subsistence Flow Kajetan [m³/s]	24.6	6.0	4.8
Subsistence Flow Maria Stein [m³/s]	25.9	6.4	5.1
Allowable duration under (days)	8	20	6
Catastrophic duration (days)	10	20	7

For the growth period, the habitat baseflow was calculated for the Kajetan site as 69.5 m³/s and for Maria Stein as 73.3 m³/s. The trigger flow and subsistence flow were calculated as 28.9 m³/s and 24.6 m³/s for the Kajetan site and 30.4 m³/s and 25.9 m³/s for the Maria Stein site, respectively.

The environmental flow criteria for the brown trout spawning and rearing period are lower than for the growth period. Here, the baseflow, trigger flow and subsistence flow were identified as 33.6 m³/s, 7.4 m³/s and 6.0 m³/s for the Kajetan site and 35.4 m³/s, 7.8 m³/s and 6.4 m³/s for the Maria Stein site, respectively.

During the bullhead and grayling spawning and rearing period, the lowest environmental flow values occur. The baseflow was calculated as 33.3 m^3/s for the Kajetan site and 35.1 m^3/s for the Maria Stein site. The trigger flow and the subsistence flow were defined as 5.9 m^3/s and 4.8 m^3/s for the Kajetan site and 6.2 m^3/s and 5.1 m^3/s for the Maria Stein site, respectively.

8 Interpretation

8.1 HMU Classification

The results of the mapping process showed that several different HMU types could be identified for the Leutasch and the reference site Maria Stein. This indicates that diverse habitat conditions representing natural or near natural habitat conditions occur at these two sites. At the Kajetan site, on the other hand, the hydromorphic conditions are more monotone as expected for a channelized and stabilised river stretch. Nevertheless, the reference site Maria Stein which was renaturated and widened still includes some characteristics of a channelized river stretch. Backwater or sidearms which represent important habitat for juvenile or spawning fish exist only to small amounts for low discharge conditions. For a river of this size which is associated with high discharge values and therefore also high water depths and velocities, refuge areas should exist for low flow conditions as well as high flow conditions. The renaturation at Maria Stein could therefore be optimised by connecting the sidearms and the main channel even at lower discharge conditions.

8.2 Habitat Rating Curves

8.2.1 Growth Period

The rating curves at all the three sites show that more than half of the available habitat is suitable for the expected fish community according to FCMacHT. In particular, large amounts of or nearly the whole wetted area is defined as suitable habitat for highly rheophilic species. Highly rheophilic species were the only species found at all the reference sites during fish sampling surveys which proves that these stretches are a suitable habitat for this guild. Habitat suitable for rheophilic benthic species mostly only exists in lower discharge conditions. The velocity is a critical factor for these species and should not exceed 0.9 m/s which is probably why no suitable habitat occurs at higher discharges. However, the shape of the habitat rating curve for this guild developed for the Leutasch is different as it first increases then decreases and then increases again. This shape occurs because of a long HMU classified as rapids which was mapped at the highest discharge and was identified as a suitable habitat for rheophilic benthic species. As explained before, the suitable area for benthic species would be low for high discharge values as high velocities and turbulence are not good for these species. The rating curve shows therefore how easily the results can be influenced by the classification of one HMU. The rating curves of rheophilic water column species show high amounts of habitat in the Upper Inn but lower amounts in the Leutasch in low discharge conditions. This can be explained by the fact that these species prefer higher water depths which do not appear in the Leutasch during low or medium discharges.

To conclude, all three river stretches have habitat conditions which are suitable for the expected fish community even though some guilds do not occur here or have not been documented upto this point. The reference sites at the Leutasch and Maria Stein representing natural or near natural conditions show a constant increase in the habitat for the fish community which means the habitat conditions are stable with varying discharge conditions. Kajetan, on the other hand, shows instable habitat conditions with an increasing flow as the habitat rating curve first increases, then decreases and then increases again. Unstable habitat conditions are typical for regulated and obstructed river stretches and this shows a decrease in habitat quality and quantity which occurs due to stabilization and channelization measures.

8.2.2 Brown Trout Spawning and Rearing Period

The habitat suitable for spawning and rearing brown trout mainly occurs in low flow conditions at all three sites. However, suitable habitat at the Leutasch and at the Maria Stein site exits in larger amounts in higher discharge conditions as well. This can be explained by the fact that additional sidearms are then flooded or backwater or shallow margins occur near the main channel which provide suitable conditions. In Kajetan, on the other hand, no such hydromorphic features exist in high discharge conditions as this river stretch is channelized and stabilised. Nevertheless, the results for Kajetan and Maria Stein are contradictory to the fish sampling data which showed that no reproduction of brown trout takes place in the main channel of the River Inn (Moritz et al. 2007). However, additional aspects might have influenced the availability of spawning sites in this case such as the status of choriotop embeddedness and hydropeaking effects which are not included in this model.

8.2.3 Bullhead and Grayling Spawning and Rearing Period

Large amounts of suitable habitat for spawning and rearing bullhead exist at all three reference sites. The total wetted area in the Leutasch is even classified as suitable. The range of suitable water depths, velocities and HMU types for spawning and rearing bullheads is wide and only boulders as cover structure are critical. These high values of habitat suitability are due to the abundance of boulders which can be found in the Leutasch and boulders are also present at both sites in the Upper Inn.

The rating curves obtained for spawning and rearing grayling have a similar shape to the one for spawning and rearing brown trout. Both species are salmonids and therefore have similar preferences regarding the substrate as well as the velocity and water depth. Suitable habitats occur at all reference sites in low flow conditions and at the Leutasch and the Maria Stein site also in backwater, shallow margins and sidearms during high discharge conditions. Similar to the brown trout spawning habitat, additional aspects might influence the habitat availability which are not considered here and which inhibit the reproduction of these species in the Upper Inn.

8.3 Habitat Time Series Analysis and Environmental Flow Criteria

8.3.1 Growth Period

During the growth period in summer, high discharge values normally occur which are reflected in the selected rare and critical habitat thresholds which are both higher than during the two spawning periods. In addition, the absolute minimum habitat value is much higher than during the two other bioperiods, which is the lowest discharge value which occurred during the monitored time period. However, habitat thresholds connected to higher discharge values indicate that high discharges are of great importance for the riverine community during this time. The riverine community relies on these high discharge values and can only survive a few days if the habitat falls below the identified thresholds. This is reflected in the short durations defined as allowable and catastrophic durations for each threshold.

8.3.2 Brown Trout Spawning and Rearing

A characteristic of a typical alpine hydrological regime is a low discharge value during the winter months. This is reflected in the selected habitat thresholds for the brown trout spawning and rearing bioperiods which are associated with low discharge values. Riverine species are adapted to and rely on these low discharge values during this bioperiod. For example, brown trout spawning habitats occur in areas with constant low values of velocity and water depth. Furthermore, the allowable and catastrophic durations defined here are longer than for the other two bioperiods. This shows that habitat limitations due to low discharge values occur commonly and that the species adapted to it and can survive such conditions for several days.

8.3.3 Bullhead and Grayling Spawning and Rearing

The habitat thresholds defined for the bullhead and grayling spawning and rearing bioperiods are similar to those defined for the brown trout spawning and rearing periods. However, during these months, particularly April and May, high discharge values also occur because of the melting of snow and rainfall. Therefore, the common habitat conditions are connected to the higher discharge conditions in this period and the allowable and catastrophic durations are much shorter than in the brown trout spawning and rearing bioperiod. This shows that the riverine species can survive low discharge values during this bioperiod but only for few days and that they also rely on higher discharge values and even flood events during this time.

8.4 Environmental Flow Assessment

The habitat time series analysis based on UCUTs allows the definition of environmental flow criteria. For the Leutasch, habitat thresholds for baseflow, trigger flows and subsistence flow in connection with common, critical and rare habitat conditions could be defined this way. In addition, durations representing allowable or catastrophic conditions were identified. Thus, explicit values were obtained which were used as a basis for the environmental flow assessment.

The environmental flow criteria obtained for the Leutasch could be standardised by calculating coefficients p_b. The coefficients p_b for the common habitat thresholds are higher than during the other bioperiods which is because these habitat thresholds are associated with the highest discharge values. The coefficients p_b defined for the brown trout spawning and rearing bioperiod are higher than for the other two periods because the mean low flow value is much lower in this bioperiod than the other two.

The standardisation of the environmental flow criteria developed for the Leutasch means that environmental flow criteria can be defined in other catchments with similar characteristics.

Therefore, such criteria could also be developed for the Upper Inn. However, it must be kept in mind that an undisturbed flow time series is necessary to calculate the exact low flow values defined for each bioperiod. The environmental flow criteria for the Upper Inn also reflect the seasonal changes in the hydrological regime which have been described for the Leutasch. Here, the habitat thresholds in the growth period are three to four times higher than in the two spawning periods.

In general, environmental flow criteria do not present minimum flow values but define a concept of dynamic flow augmentation. The defined thresholds and durations are used to identify times when a management action becomes necessary. This means it is necessary to compare the discharge conditions currently occurring to the defined habitat thresholds and corresponding durations as explained in Section 3.3.3.3. For the Upper Inn this means that no constant minimum values occur in the bypass section, but the discharge values need to be increased if the habitat thresholds are not reached or the allowable durations are exceeded.

9 Discussion

The discussion of the results obtained in this thesis is divided into four parts. Firstly, the MesoHABSIM model and its data collection and analysis strategy in general are analysed taking possible limitations into account. Then, the results of the habitat modelling approach MesoHABSIM for the Leutasch and the Upper Inn are discussed. Thirdly, the results of this thesis are compared to the data and results obtained by the GKI project. Finally, the applicability of the concept of regional environmental flow criteria based on FCMacHTs is analysed.

9.1 Methodology of MesoHABSIM

9.1.1 Data Collection and Data Analysis

The MesoHABSIM data collection strategy is based on the repetitive mapping of a river stretch. During the data collection, some aspects of subjectivity might occur especially regarding the size and type of HMUs. However, due to the additional measurements of water depth and velocity as well as the classification of the substrate and as the HMU type is only one of five criteria considered in this analysis process, the influence of subjectivity on the overall results of the habitat model is low.

Furthermore, the water depth and velocity values are only collected at at least seven locations within each HMU. Therefore, the entire hydraulic pattern cannot be taken into account. In addition, the hydraulic data collected is influenced by the selection of measurement locations and therefore also influenced by subjectivity. Additional measurements, however, would have extended the duration of the surveys. A fast data collection strategy is one of the main advantages of mesoscale approaches as they allow the application of habitat models over longer river stretches than microscale models do. If more detailed hydraulic data is available, for example due to the application of hydraulic simulations, such data should be included in the analysis process.

The data collected during a MesoHABSIM survey is then analysed taking the habitat suitability for the target species into account. Five attributes are considered in the definition of habitat suitability so far in the SimStream software: HMU type, velocity, water depth, choriotop type and cover structure. This means some of the data collected during the survey cannot be included in the analysis process yet such as the status of embeddedness and the condition and use of the shorelines. The inclusion of these additional habitat attributes would improve the accuracy of the results of the habitat suitability analysis.

As many mesohabitat models do not include the calculation of hydraulic conditions, discharge conditions and their corresponding habitat values need to be interpolated and extrapolated to obtain habitat suitability values for discharge conditions which are not mapped. This can lead to inaccuracies in the calculation of habitat suitability values. Furthermore, the UCUT analysis and the development of habitat thresholds and their corresponding durations can also include aspects of subjectivity as the specific curves and inflection points need to be selected by the user. Here, additional rules for the selection of specific UCUT curves and durations might be useful.

Finally, none of the biological or chemical aspects which influence the habitat suitability such as intra- and interspecies competition or water quality issues are taken into account, because MesoHABSIM is a physical habitat model. Overall, the MesoHABSIM has many advantages as described in Section 3.4. The MesoHABSIM strategy was applied successfully in this thesis and generated important information about the instream habitat of the two rivers which can be used in further research projects.

9.1.2 Application at Leutasch and Upper Inn

The habitat preferences for the target species were obtained using literary data on both rivers. This brings uncertainties with it because the data was collected for different river types and sometimes with different research questions in mind. Additionally, the literary data might have focussed on different attributes of the riverine habitat which then needed to be transferred into aspects of the MesoHABSIM approach. A more precise biological model could have been constructed using fish sampling data and the simultaneous documentation of the attributes and conditions of the riverine habitat at the reference sites. This would mean the application of multivariate probabilistic models as described in Section 3.3.2.3 which has been proven to generate more accurate results.

The application of MesoHABSIM in the two rivers differed in how the data about the instream habitat was collected. The advantages and limitations of these processes are discussed briefly in the following sections.

9.1.2.1 Leutasch

At the Leutasch, the commonly applied data collection strategy of MesoHABSIM was performed. Instead of orthophotos taken by drones, orthophotos taken from planes with lower resolutions were used. Therefore, additional GPS data had to be collected which extended the time spent at the site. High resolution aerial pictures taken by a drone would have facilitated the data collection process and would have allowed us to survey longer river sections.

In general, one could argue whether the size of the catchment at the reference site in the Leutasch (45 km²) as well as the length of the reference site (700 m) were sufficient enough to develop regional environmental flow standards for the complete alpine region which includes much larger catchments and rivers. Additional reference sites and reference rivers are necessary to define more accurate environmental flow standards for the alpine region.

9.1.2.2 Inn

The data collection in the Upper Inn was carried out using a digital mapping process. The inaccuracies found comparing the orthophotos and the hydraulic models have already been mentioned in Section 7.2.2. In addition, the orthophotos were taken in different years and during different seasons, which is why the resolution and details of the riverine conditions were different from one orthophoto to another. In addition, some attributes such as submerged vegetation, undercut banks or woody debris were difficult to identify from the pictures. Furthermore, the mapping process very much depends on the accuracy of the hydraulic model which, however, can also contain computational errors. The results of the hydraulic simulation are linked to the morphological conditions in the river stretch which can easily be altered by flood events.

The MesoHABSIM data collection commonly applied would not have been possible in the Upper Inn as the water depths and velocities are too high for people to work in. Furthermore, drones are becoming more and more important in many scientific fields which will make it easier to gain more detailed and high-resolution aerial photos in the future. Similarly, hydraulic models are applied in many rivers providing detailed hydraulic data which can be used in the MesoHABSIM model. Therefore, a digital mapping process is advantageous for many rivers and will be a valuable alternative to traditional data collection strategies in the future. Such digital mapping processes, however, should include field visits as some of the attributes of a riverine habitat can only be detected after close observation.

9.2 Results Achieved by the MesoHABSIM Model at Leutasch and Upper Inn

The application of MesoHABSIM in the Leutasch and the Upper Inn led to reliable results. However, some limitations and uncertainties in the results need to be discussed.

9.2.1 Habitat Diversity

The results show that a river stretch in natural or near natural condition as at the Leutasch or the Maria Stein sites includes a variety of different habitats. However, the channelization and stabilisation of rivers as at the Kajetan site reduce the habitat diversity within a river. Additionally, as shown by the rating curve for the fish community, river channelization leads to unstable habitat conditions meaning the habitat quality varies greatly depending on the discharge. In general, renaturation measures and the widening of the riverbed of channelized river stretches as done at the Maria Stein site can improve both the habitat availability and habitat quality again. Nevertheless, such management measures have to be planned using detailed knowledge of riverine species and their preferences. The planning process should also include hydraulic and hydrological information about the river stretch in order to be able to analyse the habitat conditions spatially and temporally and to optimise the habitat availability. In addition, monitoring programmes should be used to observe the development of habitat structures and to identify possible methods of optimisation.

9.2.2 Habitat Rating Curves

Additional surveys would have led to a greater accuracy in the shape of the habitat rating curves and inaccuracies which occurred due to the interpolation and extrapolation process would have been reduced. In particular, the rating curve for rheophilic benthic species in the Leutasch shows inaccuracies which occur due to the low number of surveys and the corresponding interpolation process. Here, the habitat at a specific flow of 40.7 $l/(s*km^2)$ was probably underestimated whereas the habitats at 14 $l/(s*km^2)$ and 53 $l/(s*km^2)$ might have been overestimated. Additional surveys could have led to more information on the habitat conditions in between the surveyed discharge values. This would have facilitated the identification of an over- or underestimation of the habitat and therefore could have reduced inaccuracies in the rating curves.

Furthermore, the rating curves for the highly rheophilic species show an increase in the habitat with an increase in discharge. However, the habitat rating curves are expected to level out or decline again at high discharge values because high discharge conditions or even floods do not normally provide a suitable habitat for the riverine species. As this effect is not shown in the rating curves developed for the Leutasch or the Upper Inn, it becomes clear that the surveyed discharge conditions were not high enough to cause such high discharge conditions and show their effect on the habitat suitability. Additional surveys may have been necessary here as well to show the habitat availability during high discharges. This was especially the case for the Upper Inn where the highest discharge conditions surveyed were around 40 l/(s*km^2). In addition, inaccuracies in the orthophotos and the corresponding hydraulic simulation results may have influenced the shape of the rating curves for the Upper Inn as well. As this thesis concentrates on the development of environmental flow criteria connected to low flow conditions, the uncertainties in the habitat suitability during high flow conditions do not have a big influence on the overall results.

The MesoHABSIM model identified suitable spawning grounds for salmonids (brown trout and grayling) at all three reference sites although such conditions only occur at Kajetan when there are low discharge values. Nevertheless, the results of the fish sampling survey showed that no natural reproduction of brown trout is possible in the Upper Inn. Therefore, the reproduction process is probably inhibited by aspects other than habitat limitation. As this stretch is heavily influenced by hydropeaking, this might be the crucial factor which prevents natural reproduction processes. If the negative effects on the habitat availability caused by hydropeaking are reduced in the Upper Inn in the future due to the construction of the GKI power plant, the Upper Inn might also have suitable spawning grounds for brown trout and grayling, in particular at the Maria Stein site. However, other influential factors such as choriotop type and embeddedness must also be considered.

9.2.3 Habitat Time Series Analysis

The shape of the UCUT curves developed for the Leutasch differ for each bioperiod. This is mainly due to the hydrological regime which varies greatly between the bioperiods, but it is also due to the different shapes of the rating curves constructed for that particular bioperiod. However, this makes the identification of threshold curves and inflection points more difficult. Common habitat thresholds in particular were difficult to define as the location of these curves in the diagram as well as the distance between the curves differed greatly. Therefore, the identification of threshold curves and the inflection points must be done in combination with the corresponding flow values and with the shape of the rating curves in mind. As mentioned in Section 9.1.1, a simplified and less subjective way of identifying the thresholds would have been of advantage here as well.

It was not possible to perform the UCUT analysis on the Upper Inn as there was no undisturbed flow time series available. The results of such an analysis would have been advantageous, firstly, to compare the results obtained for the Leutasch to those from the Inn. Secondly, more exact environmental flow criteria for the alpine region would have been obtained as two reference sites would have been included in the development of environmental flow standards. Due to this, further research is necessary to establish a flow time series for the Upper Inn.

9.2.4 Environmental Flow Assessment

The standardisation of the environmental flow criteria developed for the Leutasch meant that is was also possible to develop such criteria for the Upper Inn. The advantages of using such a standardised method to define environmental flows are described in Section 9.3.1. However, the criteria developed here are only based on one reference river which might not include all the necessary features of the habitat structure in the alpine region. The allowable and catastrophic durations in particular were only developed based on hydrological data available for the Leutasch. Further research is necessary to define how the durations are influenced by the catchment size and the hydrological regime in order to transfer the allowable and catastrophic durations from one catchment to another. In general, as mentioned above, additional reference sites and additional reference rivers should be included in the development of such standards. This would lead to a more exact definition of environmental flow criteria in the Upper Inn.

In addition, the environmental flow criteria developed for the Upper Inn were calculated using low flow values from a flow time series which included hydrological alterations due to hydropower production. Hydropeaking particularly alters the hydrological regime in this part of the catchment which influences the flow values on a daily basis. This means lower discharge values occur when the power plants are in operation and high discharges occur when hydropower production is not taking place. As these operational changes mostly occur on the same day, it cannot be determined whether the effects of hydropeaking lead to lower or higher mean daily low flow values than expected for natural hydrological conditions. However, by comparing the specific low flow values developed for Leutasch and Upper Inn, it can be seen that lower values were estimated in the Upper Inn, in particular for the two spawning periods. This means the low flow values for the Inn are probably underestimated which reduces the calculated habitat thresholds. Therefore, the baseflow, trigger flow and subsistence flow in the Upper inn might be underestimated. In particular, the environmental flow criteria developed for the bullhead and grayling spawning period seem to be extremely low. Flow time series showing the natural regime are necessary to calculate exact low flow values and would also make a UCUT analysis of the Upper Inn possible. As mentioned above, further research is necessary to gain an undisturbed flow time series of the Upper Inn.

9.3 Comparison to Results and Data Collected in the GKI Project

The results of this study can be compared to the data and results previously obtained in the GKI project. Firstly, the environmental flow values developed in the GKI project and the environmental flow criteria for the Upper Inn are compared and then the results of the CASiMiR model and the results of the MesoHABSIM model are analysed.

9.3.1 Environmental Flow Concept for GKI

Section 5.2.7 describes the environmental flow concept which was developed for the GKI bypass section by cooperating experts. This concept will now be compared to the environmental flow criteria developed for the Upper Inn using the MesoHABSIM model. Table 27 presents the minimum flow values defined by the GKI project and the trigger flow and baseflow values determined for Kajetan for each month as part of this thesis. The GKI project determined the minimum values at the Ovella weir at the beginning of the bypass section. Therefore, the discharge values for the Kajetan site are higher due to the additional runoff and inflowing tributaries (Schönlaub et al. 2007).

Table 27 Comparison of minimum flow values defined for the GKI and environmental flow criteria developed for the Upper Inn using the MesoHABSIM results

Season	**Corresponding Meso-HABSIM bio-period**	**Minimum flow value defined in the GKI project [m³/s]**		**Corresponding trigger flow [m³/s]**	**Corresponding habitat baseflow [m³/s]**
		At weir Ovella	At Kajetan	At Kajetan	At Kajetan
January	Brown trout spawning and rearing	5.5	7.0	7.4	33.6
February	Brown trout spawning and rearing	5.5	6.9	7.4	33.6
March	Bullhead and grayling spawning and rearing	5.5	7.5	5.9	33.3
April	Bullhead and grayling spawning and rearing	5.5	9.1	5.9	33.3
1st May to 15th May	Bullhead and grayling spawning and rearing	7	17.8	5.9	33.3
16th May to 31st May	Bullhead and grayling spawning and rearing	10	20.8	5.9	33.3
June	Growth	10	23.3	28.9	69.5
July	Growth	10	20.1	28.9	69.5
August	Growth	10	16.4	28.9	69.5
1st September to 15th September	Growth	7	11.6	28.9	69.5
16th September to 30th September	Growth	5.5	10.1	28.9	69.5

October	Brown trout spawning and rearing	5.5	9.0	7.4	33.6
November	Brown trout spawning and rearing	5.5	7.9	7.4	33.6
December	Brown trout spawning and rearing	5.5	7.3	7.4	33.6

The values presented in Table 27 show that the minimum flow values are much closer to the trigger flow values than to the habitat baseflow values. This can be explained by the fact that the GKI project determined minimum flow values which have to be reached in the bypass section in order to sustain the instream habitat during the times when the hydropower plant is in operation. However, due to water abstraction at the Ovella weir, the discharge in the bypass section will be reduced in comparison to normal conditions and therefore habitat conditions associated with the common habitat threshold will only occur rarely.

In addition, it can be seen that the trigger flow values are in the same range as the minimum flow values for the brown trout spawning and rearing period. This shows some similarities in the results of the two concepts. The minimum flow values for the GKI were developed with its focus on creating better habitat conditions during the winter months. The results of the MesoHABSIM model confirm that the minimum values during for this period are within an acceptable range for the riverine community. Furthermore, the allowable durations which the discharge conditions can be below the common habitat threshold for was defined as 54 days. This means that the riverine community can survive such conditions even if the minimum flow values are not exceeded for several days or weeks.

The minimum flow values determined for the summer period are much lower than the corresponding trigger flow values. However, as explained in Section 5.2.7, the minimum flow values are exceeded for around 70 days during the summer period due to overflow at the Ovella weir. This leads to higher discharge conditions in the bypass section in comparison to the defined minimum flow values for more than half of the time. In addition, the discharge in the bypass section is increased during the summer months according to discharge values measured at an undisturbed upstream gauging station. Therefore, the minimum flow concept of the GKI is probably in the same range than the environmental flow criteria calculated by the MesoHABSIM model. Nevertheless, further research is necessary here to see if the environmental flow concept developed for the summer months is able to avoid the rare and extreme habitat conditions identified in the MesoHABSIM model.

The trigger values developed for the bullhead and grayling spawning and rearing period are much lower than the minimum flow values. This means that particularly during this period the developed minimum flow values are high enough to sustain the riverine ecosystem. However, as previously mentioned, the habitat thresholds developed for the Upper Inn especially for this period were probably too low because altered hydrological conditions were used in the calculation process.

In general, the MesoHABSIM environmental flow criteria define a dynamic flow augmentation concept in the Upper Inn which means that the discharge in the bypass section only needs to be increased if the allowable durations are exceeded. This is a great difference and also an advantage when compared to the minimum flow concept of the GKI where constant values need to be maintained over long periods of time. For one thing, such dynamic flow augmentations mimic the natural hydrological conditions which includes variabilities in discharge. In addition, the hydropower company could probably process more water as no constant minimum flow value need to be obtained for the whole time. However, this concept might lead to more operational effort at the power plant and the weir structure as discharge values need to be compared to the defined environmental flow criteria every day.

To conclude, according to the results of the MesoHABSIM model, the defined minimum values for the GKI bypass section are mostly within an acceptable range which could sustain the riverine community. As the GKI project additionally reduces the hydropeaking effects, the habitat condition in the bypass sections are likely to improve in comparison to the current conditions. Nevertheless, we need to remember that the environmental flow criteria for the Upper Inn were calculated using altered hydrological time series which probably influenced the habitat threshold values. The criteria should be optimised and recalculated using the low flow values naturally occurring in the Upper Inn.

9.3.2 Results of the Habitat Model CASiMiR

As mentioned previously, the habitat model CASiMiR was used at the two reference sites in the Upper Inn as part of the environmental impact assessment for the GKI project. The results will now be compared to the results obtained by the MesoHABSIM model. However, this comparison is restricted to the analysis of the habitat of adult and juvenile brown trout, as the CASiMiR model was developed using only brown trout as an indicator. In addition, no results of the CASiMiR model were available for the reference site Maria Stein because the site had not been renaturated and widened at the time the environmental impact assessment was carried out. Furthermore, CASiMiR analyses the habitat quality expressed using the suitability index (0 not suitable, 1 suitable, see Section 2.2.4.3). The results of the MesoHABSIM model, on the other hand, are expressed using the habitat rating curves which present the amount of effective habitat as a percentage of the channel area.

The results of the CASiMiR model for the Kajetan site are presented in Figure 60 (Appendix V). Suitable habitat conditions for adult brown trout occur in discharges of up to 6.5 m^3/s (3 $l/(s*km^2)$) with suitability indices of 0.7 to 0.9 (Moritz et al. 2007). At discharges conditions from 10 to 15 m^3/s (4.6 to 6.9 $l/(s*km^2)$), the suitable habitat decreases continuously and habitats with suitability indices of 0.7 or higher only occur near the shores (Moritz et al. 2007). The amount of suitable habitat for juvenile brown trout is very small and can only be found near the shorelines (Moritz et al. 2007).

In the MesoHABSIM model, adult brown trout are only taken into account as part of the highly rheophilic habitat-use guild. The habitat rating for this guild was constructed at discharge values of up to 45 l/s*km (97 m³/s) and shows that the suitable habitat increases with increasing flow values. It is expected, however, for the suitable habitat to then soon reach a constant value or even decrease again as higher flows lead to velocity and water depths which are not in the suitable range anymore, especially in this channelized part of the river. The habitat for juvenile brown trout is shown on the habitat rating curve of spawning and rearing brown trout which shows the highest amount of suitable habitat conditions at discharge conditions of 6 l/(s*km²) (13 m³/s).

The CASIMIR model determines suitable habitat conditions for adult brown trout at lower discharge values whereas the MesoHABSIM model shows an increase in suitable habitat with increasing flow. However, this is mainly due to the different focus of the analysis strategy in both models. The CASiMiR results show suitable habitats conditions also in high discharges even in the highest discharge included in this analysis at 160 m³/s but the suitability indices here are only moderate (0.3 to 0.6). As the CASiMiR model focuses on habitat quality and the MesoHABSIM model and the rating curves mostly take the total suitable area in general into account, the overall results of both models are similar.

Both models show that the suitable habitat for juvenile brown trout is limited to lower flow conditions. The CASiMiR model shows the highest suitability at discharge values of 15 m³/s and lower and the MesoHABSIM model shows that the best conditions for spawning and rearing habitat occur at discharge values of 6 l/(s*km²) (13 m³/s). Therefore, the results of both models regarding the habitat for juvenile brown trout correlate well.

In addition, both models show that the defined minimum flow values of the GKI lead to suitable habitat conditions. The CASiMIR model proves that sufficient habitat for adult brown trout and even suitable habitat for juvenile brown trout exists for the minimum flow value determined for the winter period (Moritz et al. 2007). The MesoHABSIM model also shows that the minimum flow values during the winter months are of an acceptable range (see Section 9.3.1)

Both models also show the limitations connected to physical habitat models. The models do not include the effects of hydropeaking and do not take the stabilised and obstructed riverbed into account which are two of the major factors inhibiting the reproduction of brown trout.

This comparison of the results of CASiMiR and MesoHABSIM cannot be generalised or transferred to other fields of use because both models were used in a river stretch which had been heavily altered by human activity and therefore did not represent natural habitat conditions. Secondly, both habitat models do not show the real habitat conditions as they are limited to the physical habitat and do not include the impacts of hydropeaking. Additional research is necessary to compare the two models in more detail as the comparison of the two models was not the focus of this thesis. In particular, the differences in their biological models, which means the definition of the habitat preferences of the target species, should be analysed. This would allow further detection and the explanation of differences in the obtained results.

9.4 Regional Environmental Flow Standards for Europe based on FCMacHT

9.4.1 Concept

The development of European standards for the determination of environmental flows would be advantageous in many ways. First of all, it would mean that all European rivers are addressed consistently which is the main goal of European environmental laws and regulations such as the Water Framework Directive. In addition, it would simplify the definition of environmental flows as only one simple formula would need to be applied which would replace intensive data collection as well as expert discussions. Furthermore, a dynamic flow augmentation can be carried out as this environmental flow strategy does not refer to minimum flow values but to threshold values which can trigger management action. This could address the problem of water scarcity which is already occurring in some parts of Europe and will increase due to climatic changes and the expansion of hydropower production. The existence of several European research projects such as AMBER and FIThydro, which focus on establishing sustainable river ecosystems in Europe, shows that the European Union has realised the importance of standardised and consistent solutions for European rivers. This creates the basis for further research in this scientific field on a European scale.

The MesoHABSIM approach, which creates the basis of this regional environment flow assessment, is especially useful in this context as it is based on the physical instream habitat and includes a detailed analysis of important features such as cover structures and hydromorphic conditions. Furthermore, it addresses different seasons and therefore different habitat preferences of fish by defining bioperiods. In addition, it includes a habitat time series analysis which is based on a flow times series and therefore takes the natural flow regime into account. These are important aspects which need to be considered in the definition of environmental flows as highlighted by many authors (see Section 2.3.2) and within the FIThydro project (see Section 2.3.9). In addition, as it is a mesoscale approach it assesses the riverine habitat at a scale which is relevant for the fish community and can also be used in longer river stretches.

Nevertheless, the AMBER project has identified 15 macrohabitat types for Europe which results in large regions which are then treated similarly. Differences in hydrological or ecological aspects from one catchment to another within the same group are therefore not considered. Some adaptations regarding macrohabitat types as well as the fish communities might be necessary during the application of this concept. Furthermore, several reference sites need to be found in one region to include as many different conditions as possible. However, it is difficult to find characteristic reference sites with undisturbed hydrological and ecological conditions as many European rivers are altered by human activity. In addition, hydrological time series representing the natural flow regime are needed for the reference rivers as well as the river stretches which the environmental flows should be developed for. This can be difficult as shown by the Upper Inn in this thesis which has been majorly altered for centuries and no undisturbed flow time series exists.

9.4.2 Expected Habitat Structure According to FCMacHT

The concept of regional environmental flow standards uses the river classification system based on macrohabitats, FCMacHT, defined in the AMBER project. It gives us information about the expected fish community in each European river (AMBER 2019). Based on the assumption that the fish community structure reflects the habitat structure (see Section 3.3.2.1), the percentages of available suitable habitat for one guild in rivers in natural condition is expected to be similar to the percentages of the guilds within the fish community. It can now be analysed if this is the case for the three reference sites in order to find out if the FCMacHTs really represent riverine habitat conditions within one type. However, this analysis can only be carried out for the habitat which occurs in the summer growth period as this was the only period that was analysed using the habitat preferences of the expected fish community defined by AMBER.

Figure 54, 55 and 56 show the proportions of the available habitat for the different fish habitat-use guilds at different flow conditions at the Leutasch, Kajetan and Maria Stein sites respectively together with the expected habitat structure based on the FCMacHTs. Table 28 shows the correlation between the expected and the available habitat structure.

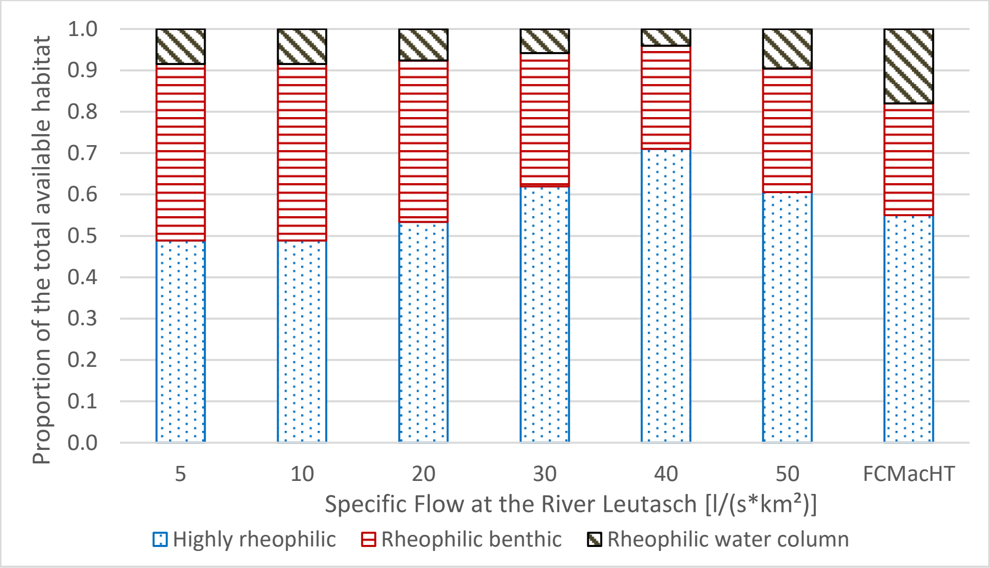


Figure 54 Habitat suitable for the fish habitat-use guilds for different flow conditions at the Leutasch expressed as proportions of the total available habitat

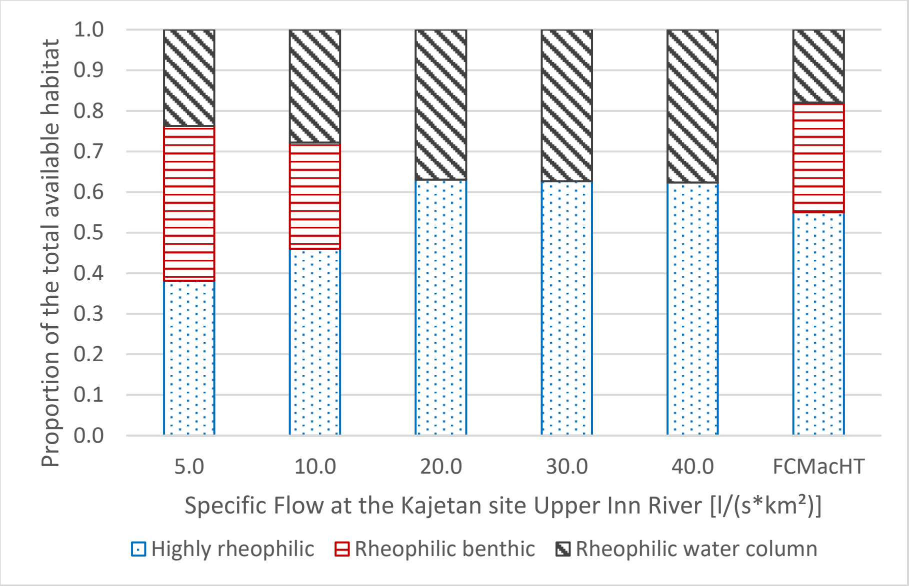


Figure 55 Habitat suitable for the fish habitat-use guilds for different flow conditions at the Kajetan site expressed as proportions of the total available habitat

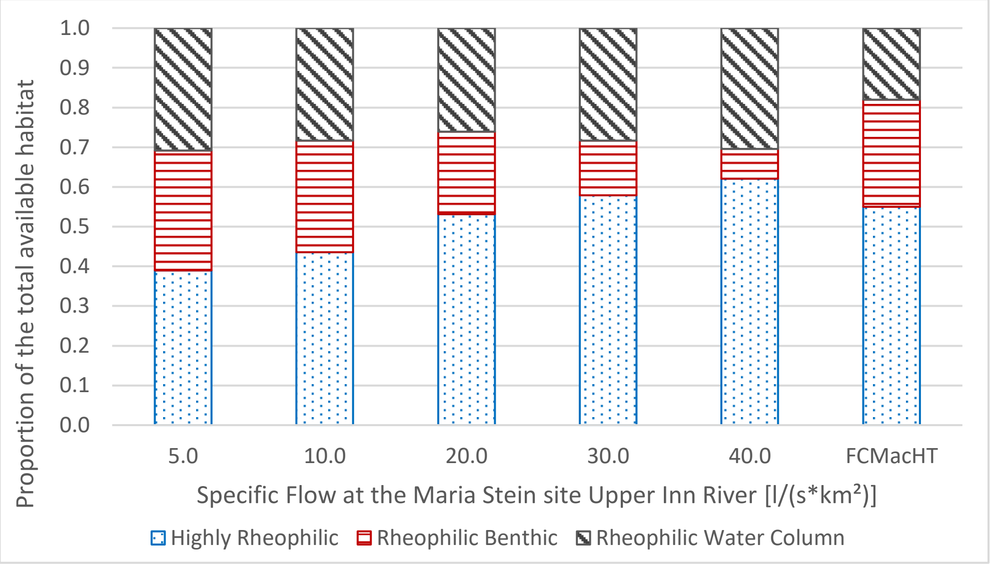


Figure 56 Habitat suitable for the fish habitat-use guilds for different flow conditions at the Maria Stein site expressed as proportions of the total available habitat

Table 28 Correlation [%] between the available habitat structure at the reference sites and the habitat structure defined for the “Mountain, Alpine and subalpine rivers” type (AMBER 2019)

Specific Flow [l/(s*km²)]	5	10	20	30	40	50
Leutasch	84.3	84.3	87.9	87.9	84.0	91.6
Kajetan	81.1	90.2	73.0	73.0	73.0	-
Maria Stein	84.5	88.5	91.9	83.5	80.5	-

The habitat structure in the Leutasch is very similar to the habitat structure expected according to FCMacHT. The highest correlation of almost 92% is obtained for the highest specific flow which the analysis was carried out for (50 l/(s*km²)). During lower discharges, the amount of habitat for rheophilic water column species is lower than expected for this river type (see Section 8.2.1) However, discharges commonly fall into a range of 40 to 50 l/(s*km²) during the growth bioperiod in summer. This means the habitat structure available during the growth period matches the habitat structure of the FCMacHT. Similar results were discovered for the Maria Stein site. Here, lower discharges from 10 to 20 l/(s*km²) lead to the highest correlations of 88.5 and 91.9% but even for higher discharge values the habitat structure was similar to the expected one.

At the Kajetan site, higher differences between the available and the expected habitat structure could be detected. For discharge conditions higher than 15 l/(s*km²), no habitat is available for rheophilic benthic species as already shown on the habitat rating curves (Section 7.2.2.1). Therefore, high values for the correlation between the available and the expected habitat structure only occur for the discharge conditions from 5 to 10 l/(s*km²). Such flow conditions, however, are lower than the discharge which is expected during the summer months. This means that the Kajetan site does not provide sufficient suitable habitat for the expected fish community in this region during the summer period. This can be explained by the channelization and stabilisation of the riverbed and the riverbanks which were established at this site and have led to unnatural habitat conditions.

The reference site Leutasch and the reference site Maria Stein, which had natural or near natural conditions, provide suitable habitats for the expected fish community. Therefore, the results of this thesis prove that the river classification of FCMacHT based on macrohabitat types as well as the associated fish community is valid for these two rivers within the alpine region. Nevertheless, no rheophilic water column species nor rheophilic benthic species were found in the Leutasch or the Upper Inn. As the habitat for these species is available, this must have different reasons other than habitat limitation. One option for the Leutasch might be that such species have never existed here, for example due to the isolation of this river stretch from other rivers and catchments in this region. Another explanation is that these species occur in the Leutasch but no documentation of these fish species exists. Fish sampling in the bypass section of the GKI could also not document any rheophilic water column or rheophilic benthic species. However, as this section is heavily affected by hydropeaking and stabilisation and channelization measures, the species currently occurring in the Upper Inn do not reflect the natural fish community. The fish community expected for the Upper Inn River based on the Austrian classification system for rivers which are not classified as heavily modified water bodies includes rheophilic water column and rheophilic benthic species (see Appendix IV). To conclude, the habitat structure in both rivers correlates well with the habitat structure which was defined for this macrohabitat type even though some fish habitat-use guilds do not occur in these rivers. This proves the validity and applicability of FCMacHT for the alpine region.

10 Conclusion

This thesis shows that the assessment of environmental flows is still an important part of ecohydraulic studies. Several different methods of setting environmental flows exist and no consistent regulations or standards exist within a state or region or even in the European Union. Environmental flow methods should cover the riverine biota and should take the natural flow regime into account to maintain a sustainable river ecosystem. The development of consistent standards which account for these two factors would facilitate the application of consistent and reliable environmental flow rules. Therefore, research in this scientific field should be encouraged.

The MesoHABSIM model was successfully applied in two rivers in Tyrol and generated detailed and reliable information about the riverine habitat conditions. A digital mapping process was used in the Upper Inn which also produced good results. This shows that digital mapping based on pictures taken by drones together with hydraulic simulations will be a valuable alternative in future studies.

The results obtained in this thesis can be summarised into three main points which provide a basis for further research in the field of ecohydraulics when focusing on sustaining river ecosystems and establishing regional environmental flow standards.

Firstly, the stabilized and channelized river stretch Kajetan does not provide sufficient habitat for the riverine community especially for benthic species, juvenile fish and spawning species. This can be seen in the results of the CASiMiR model applied in the GKI project as well and from the comparison of the available habitat structure at this site to the habitat structure expected according to the FCMacHT. In addition, this site provides unstable habitat conditions as a variable habitat quality occurs with varying discharge. Generalising the results obtained for the Kajetan site, the channelization of rivers always means a loss of instream habitat and changes to the riverine community structure. The example of the Maria Stein site shows that renaturation processes improve the habitat conditions within the river and therefore it shows how effective such management action can be. Renaturation processes should be put into practice more often and at several sites in highly impacted rivers because they are effective mitigation measures which reduce the negative effects on the riverine biota caused by water abstraction or diversion.

Secondly, the environmental flow values obtained by experts within the GKI project and the ones developed as part of this study are in the same range even though the two concepts are different. Hence, the application of MesoHABSIM as part of an environmental flow assessment is useful and effective. In addition, the MesoHABSIM model proves that the minimum flow values of the GKI project provide sufficient habitat to sustain the river ecosystem. However, an undisturbed flow time series for the Upper Inn could optimise the results and would make further research on environmental flow standards for this region possible.

Finally, the habitat structure of the two rivers is the same as the expected habitat structure according to the AMBER project. This proves the concept of FCMacHT and the definition of expected fish communities on a regional scale. Therefore, the development of regional environmental flow standards based on FCMacHT also seems reasonable. The successful application of regional environmental flow standards in the Upper Inn shows the potential of this concept. In order to apply this concept in Europe and especially in the alpine area, additional reference sites are necessary in order to optimise the results and to prove the overall applicability and validity of this concept. The dynamic flow augmentation associated with this concept would be of advantage in Europe as it is able to take water scarcity due to droughts and the expansion of hydropower production into account.

11 Summary

This thesis describes the development of environmental flow criteria in the Tyrol region based on three reference sites located in the River Leutasch or Leutascher Ache and in the Upper Inn River. It is based on a new method developed for Poland which uses the habitat modelling tool MesoHABSIM and a river classification system to define regional environmental flow standards (Parasiewicz et al. 2018). This methodology is transferred and applied to the alpine region. This thesis includes a literary review about ecohydraulic principles, habitat modelling and environmental flows assessment methods. Furthermore, it describes the applied habitat modelling approach MesoHABSIM and the corresponding analysis strategy. Then it shows the application of MesoHABSIM in the two alpine rivers and the environmental flow criteria developed for this region.

Ecohydraulic is an interdisciplinary science focussing on the link between hydraulic engineering and environmental aspects such as the sustainability of ecosystems (Jorde and Schneider 2015c; Maddock et al. 2013). Methods in this scientific field assess the effects of anthropogenic impacts on the ecosystems and help to find environmentally friendly mitigation options. The modelling of riverine habitat and the definition of environmental flows are two major fields of ecohydraulics. River ecosystems are highly complex, diverse as well as dynamic systems and therefore it is difficult to assess them entirely as part of ecohydraulic studies (Wood, Hannah, and Sadler 2008; Patt, Jürging, and Kraus 2011). A river ecosystem can be described using physical, chemical and biological features. Physical features include the flow regime, water temperature and insolation. Chemical features consist of oxygen concentration as well as the distribution of other inorganic substances (Patt, Jürging, and Kraus 2011). Biological features encompass the animals and organisms living in the river as well as their interactions (Patt, Jürging, and Kraus 2011). These features are also the main features that influence a riverine habitat. This is why riverine species are adapted to the physical, chemical and biological features in the river they live in and are dependent on these specific conditions (Jorde and Schneider 2015a). River ecosystems are, however, influenced and altered by anthropogenic activities such as hydropower production, water abstraction for the supply of drinking water or for industrial and agricultural purposes. These anthropogenic activities alter a riverine habitat and reduce the ecosystem diversity. The main effects of such activities are the reduction of high flows responsible for dynamic processes, the reduction of low flows resulting in habitat limitation and unnatural seasonal changes which influence the life cycles of all of the species (Petts 2008). The quantification of anthropogenic effects in the river ecosystem is difficult and depends on the specific conditions which make assessment tools such as habitat modelling approaches necessary (Lamouroux et al. 2017; Poff and Zimmerman 2010).

Habitat models create a relationship between the physical conditions in an river, most often water depth and flow velocity, and the riverine habitat (Linnansaari et al. 2013). They are used to assess the impacts of anthropogenic changes on the ecosystem by modelling the response of riverine biota (AMBER 2018; Noack, Schneider, and Wieprecht 2013). Habitat models can simulate a riverine habitat using different scales such as micro-, meso- and macroscale which take different aspects of habitat attributes into account. Mostly, habitat models are based on fish as the indicator species which the habitat model is developed for because data on fish occurrence is easily available and has existed for several centuries (Jorde and Schneider 2015e). Habitat models can simulate the biological or physical aspects of the instream habitat, but most habitat models are based on physical habitat characteristics which is why they are called physical habitat models. Such models consist of two modules, the physical module describing the hydraulic conditions of a river and the biological module transforming the physical characteristics into values of habitat suitability. Habitat models are able to quantify the suitable habitat in rivers and are therefore valuable tools in river management processes.

The Brisbane Declaration defines environmental flows as quantity, quality, as well as the timing of flows which are necessary to sustain the riverine ecosystems as well as human water needs (Brisbane Declaration 2007). This definition shows firstly that the temporal and spatial variability of the flow regime needs to be considered. Secondly, it realises that a balance between ecosystem and human water demands needs to be found. Four main groups of environmental flow assessment methods exist: hydrological, hydraulic rating, habitat simulation and holistic methods. Hydrological methods include look-up tables which use fixed values, fixed percentages or hydrological indices and desktop methods which include the analysis of hydrological and sometimes even biological data. Hydraulic rating methods are based on the relationship between the discharge in a river and simple hydraulic indices such as the wetted perimeter. Habitat simulation methods use habitat models such as PHABSIM, CASiMiR and MesoHABSIM to quantify the instream habitat and find habitat threshold values which need to be maintained in the river. Holistic methods include interdisciplinary expert knowledge and include environmental flow concepts which take several different stakeholders into account. Examples of this group include the Building Block Methodology (BBM, King et al. 2008), the Downstream Response to Imposed Flow Transformation (DRIFT, King, Brown, C., and Sabet 2003), the Benchmarking Methodology (Brizga et al. 2002) and the Ecological Limits Of Hydrological Alteration (ELOHA, Poff et al. 2010). It depends on the river management process, the availability of data, the range of risk and the available budget which method is applied. However, simple and inexpensive methods such as look-up tables or desktop methods are still the most common methods used worldwide which often threaten the sustainability of a river ecosystem as they are developed without considering biological aspects (Tharme 2003; Acreman and Dunbar 2004; Linnansaari et al. 2013). In addition, several new approaches have emerged defining regional environmental flow values which facilitate the application of environmental flow standards in regions or states.

As this thesis includes the application of MesoHABSIM as tool defining environmental flows, MesoHABSIM data collection and its analysis strategy are described in detail. The MesoHABSIM model is applied worldwide to support different river management processes. It consists of a mesoscale data collection and mapping approach which takes hydromorphic conditions, cover structures as well as substrate, flow velocity and water depth in the river into account (Parasiewicz 2007a). In addition, a biological model is constructed using fish sampling data and regression models or expert knowledge and literary data. The habitat preferences of the selected target species are considered using so called bioperiods which divide the hydrological year into seasons of great biological importance regarding specific stages in the lives of species. Analysing the collected data together with the defined habitat preferences of the target species, habitat rating curves are developed showing the available habitat for different discharge conditions. These curves can then be used to transform discharge series into habitat series which leads to a habitat time series analysis based on Uniform Continuous Under Threshold curves (UCUT) (Parasiewicz 2008). Different habitat thresholds and allowable as well as catastrophic durations when it comes to certain habitat events can be identified based on these UCUT curves. The habitat thresholds defined in this way show environmental flow criteria which need to be considered when determining water management strategies. Parasiewicz et al. (2018) applied this methodology in different regions in Poland and developed regional environmental flow standards based on river types classified according to fish ecological aspects. Due to the definition of coefficients p_b, the environmental flow criteria can be adapted and applied to all Polish rivers. In comparison to microhabitat models, MesoHABSIM has the advantage that it simulates the riverine habitat at a scale which is used by the entire fish community. Furthermore, it can be used for longer river stretches. Compared to other mesoscale approaches, it goes into a great amount of detail and includes an analysis strategy to interpret and assess the collected data.

The aim of this study was the development of environmental flow criteria in the alpine region using data collected by the AMBER project. According to results of AMBER, European rivers can be classified into 15 Fish Community Macro Habitat Types (FCMacHT) which means it is possible to analyse rivers of one type simultaneously (AMBER 2019). Using the study of Parasiewicz et al. (2018) in Poland as a basis, we decided to use AMBER's river classification system to define regional environmental flow standards in Europe. The "Mountain, Alpine and subalpine rivers" were selected as the study area of this thesis because hydropower plants often occur in mountainous regions and the rheophilic species connected to alpine rivers are especially affected by river regulation measures and the construction of dams and impoundments.

Two rivers located in Tyrol, Austria, were selected as case studies for this thesis. Firstly, the River Leutasch or Leutascher Ache was chosen as it represents a typical alpine river in a natural condition when it comes to river morphology, hydrology and ecology. Here, the MesoHABSIM model was applied at a reference site which had a length of around 700 m and was located in the upper part of the catchment. Secondly, the Upper Inn River was selected as a study case as it is located in the bypass section of a newly constructed hydropower plant and is a test case in the FIThydro project. This part of the Inn is greatly affected by anthropogenic activities especially hydropower production and river straightening. As part of the environmental assessment process of the new hydropower plant GKI (Gemeinschaftskraftwerk Inn), an environmental flow concept using minimum flow values was established based on expert knowledge and the results of the habitat model CASiMiR. Two sites, Kajetan and Maria Stein, were used as reference sites here. The Kajetan site is a straightened, regulated river stretch whereas the Maria Stein site shows natural conditions.

At the Leutasch site, the data for the MesoHABSIM model was collected in the usual way by mapping the reference site in three different flow conditions (0.65 m^3/s or 14.4 $l/(s*km^2)$, 1.8 m^3/s or 40.7 $l/(s*km^2)$, 2.4 m^3/s or 53.1 $l/(s*km^2)$). The data for the two reference sites in the Inn were obtained by using a digital mapping process with orthophotos, hydraulic models and the substrate data collected for the CASiMiR model. Three different discharge conditions were mapped at both sites (11.4 m^3/s or 5.3 $l/(s*km^2)$, 37.4 m^3/s or 17.3 $l/(s*km^2)$, 84.8 m^3/s or 39.2 $l/(s*km^2)$ at Kajetan and 15.8 m^3/s or 6.9 $l/(s*km^2)$, 32.9 m^3/s or 14.5 $l/(s*km^2)$, 90 m^3/s or 39.5 $l/(s*km^2)$ at Maria Stein).

Three target fish species (brown trout, bullhead and European grayling) were selected using fish sampling data as well as the Austrian river classification system to define indicator species. In addition, the fish community defined in the AMBER project was taken into account during the summer period. Three bioperiods were observed (growth in the summer, brown trout spawning and rearing in autumn and winter, bullhead and grayling spawning and rearing in spring and early summer). The habitat preferences of the corresponding target fish species were defined for each of these bioperiods using literary data.

At the Leutasch and Maria Stein sites, a diverse habitat structure was identified with different hydromorphic features whereas more monotone hydromorphic conditions occurred in the stabilised river stretch Kajetan. The identified habitat structure was then transformed into values of habitat availability using the defined habitat preferences for the different species during each bioperiod. It was shown that large parts of the riverine habitat at all sites were suitable for highly rheophilic species and lower amounts were suitable for rheophilic benthic and rheophilic water column species. Suitable habitats for spawning and rearing brown trout and grayling occurred mostly at lower discharge values although at the Leutasch site and at the Maria Stein site even high discharges provided some suitable spawning grounds. At the Leutasch site, the entire instream habitat was suitable for spawning and rearing bullhead and large parts of the instream habitat in the Upper Inn are suitable as well. The rating curves developed for the Leutasch were used in a habitat time series analysis which led to the identification of common, critical and rare habitat thresholds and the corresponding allowable and catastrophic durations for each bioperiod. The trigger flows associated with the transition towards critical habitat conditions were identified as 758 l/s during the growth period and 332 l/s during the two spawning and rearing periods. Common habitat conditions are said to be 1.82 m^3/s during the growth period, 1.51 m^3/s during the brown trout spawning and rearing and 1.87m^3/s during the bullhead and grayling spawning period. The identified thresholds were then standardised into coefficients p_b which meant that the determination of environmental flow criteria in other parts of the alpine area was possible. Such criteria were then used to develop habitat baseflow values, trigger flow values and subsistence flow values for both river stretches in the Upper Inn. The habitat thresholds presenting common habitat conditions (baseflow) for the Kajetan site were then calculated at 69.5 m^3/s during growth period, 33.6 m^3/s during the brown trout spawning and rearing period and 33.3 m^3/s during the bullhead and grayling spawning and rearing bioperiod and habitat thresholds associated with critical habitat conditions were calculated at 28.9 m^3s, 7.4 m^3/s and 5.9 m^3/s respectively.

Some limitations of the MesoHABSIM model were discussed such as aspects of subjectivity which might occur during the survey as well as the fact that additional surveys could have improved the obtained information about the habitat availability. Then the obtained results of this thesis were compared to results obtained in the GKI project. It was shown that the environmental flow criteria developed for the Upper Inn using MesoHABSIM had similar values to the defined minimum flow values. In addition, the MesoHABSIM model also showed similar results to the applied CASiMiR model and showed that these minimum flow values provide sufficient habitat to sustain the riverine community. Furthermore, the habitat structure observed in the two alpine rivers was very similar to the habitat structure defined by FCMacHT in the AMBER project. However, it is necessary to create undisturbed flow time series for the Upper Inn in order to prove the environmental flow criteria developed and additional references sites in this region are necessary to optimise these standardised values.

To conclude, this thesis has proven that river channelization leads to a reduction and destabilisation of the instream habitat whereas river renaturation processes can lead to major improvements in the instream habitat structure. Secondly, the MesoHABSIM model provides environmental flow criteria which are in the same range as the minimum flow values developed for the GKI showing the applicability of the MesoHABSIM model in this scientific field. Thirdly, the concept of FCMacHT which defines expected fish communities and their associated habitat structures for regions in Europe was valid for the two alpine rivers and therefore also shows the potential of this concept as part of the development of regional environment flow standards.

12 References

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List of Abbreviations

1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
7Q2	Lowest flow in seven consecutive days within a 2-years return period
7Q10	Lowest flow in seven consecutive days within a 10-years return period
am	Ante Meridiem
AMBER	Adaptive Management of Barriers in European Rivers
BAFU	Bundesamt für Umwelt Federal Office for the Environment
BAW	Bundesamt für Wasserwirtschaft Federal Office for Water Resources Management
BBM	Building Block Methodology
BMLRT	Bundesministerium für Landwirtschaft, Regionen und Tourismus Federal Ministry for Agriculture, Regions and Tourism
°C	Degree Celsius
CA	Channel Area
CASiMiR	Computer Aided Simulation Model for Instream flow Requirement
CLARA	Clustering Large Applications
cm	Centimetre
cm/s	Centimetres per second
CUT	Continuous Under Threshold
D90	Particle size which is equalled or exceeded by 10% of the sample
DRIFT	Downstream Response to Imposed Flow Transformation
e.g.	Example given
e-flow	Environmental flow
EFC	Environmental Flow Components

EKW	Engadiner Kraftwerke AG Engadine Hydropower Plants
ELOHA	Ecological Limits of Hydrological Alteration
EU	European Union
FCMacHT	Fish Community Macro Habitat Types
FET	Fish Ecological Types
FIA	Fish Index Austria
FIThydro	Fishfriendly Innovative Technologies for Hydropower
FOEN	Federal Office for the Environment
FPOM	Fine Particulate Organic Matter
GIS	Geographic Information System
GKI	Gemeinschaftskraftwerk Inn Joint Venture Hydropower Plant on the River Inn
GPS	Global Positioning System
GWh	Giga watt hour
HMU	Hydromorphic unit
HST	Habitat Stressor Thresholds
IFIM	Instream Flow Incremental Methodology
IGF	Institut für Gewässerökologie und Fischereiwirtschaft Institute for Water Ecology and Fisheries
IHA	Indicators of Hydrologic Alteration
ISPRA	Istituto Superiore per la Protezione e la Ricerca Italian Institute for Environmental Protection and Research
km	Kilometre
km^2	Square kilometre
$l/(s*km^2)$	Litres per second and square kilometre
LfU	Bayerisches Landesamt für Umwelt

	Bavarian Environment Agency
LfV Bayern	Landesfischereiverband Bayern e.V. Bavarian Fisheries Association
LIFE	Lotic-Invertebrate Index for Flow Evaluation
m	Metre
m^2	Square mete
m^3	Cubic metre
mm	Millimetre
m/s	Metre per second
m^3/s	Cubic metre per second
m.a.s.l	Metre above sea level
max.	Maximum
MAF	Mean annual flow
MALF	Mean annual low flow
MBLF	Mean low flow for a particular bioperiod
MesoHABSIM	Mesoscale Habitat Simulation
MMF	Mean monthly flow
MSC	Meso-Scale Habitat Classification
ÖNORM	Österreichische Norm Austrian Standard
pm	Post Meridiem
pers. comm.	Personal communication
Q50	Median monthly flow
Q90	Flow value which is equalled or exceeded 90% of the time
Q95	Flow value which is equalled or exceeded 95% of the time
RHM	Rapid Habitat Mapping
ROC	Relative Operating Characteristic

RVA	Range of Variability Approach
S	Second
SBA	Sustainable Boundaries Approach
SC	Size Class
SI	Suitability Index
TFC	Target Fish Community
TIWAG	Tiroler Wasserkraft Arbeitsgemeinschaft Tyrol Hydropower Syndicate
TNC	The Nature Conservancy
UCUT	Uniform Continuous Under Threshold
UK	United Kingdom
U.S.	United States
USA	United States of America
USFWS	United States Fish and Wildlife Service
WFD	Water Framework Directive
Wi-Fi	Wireless Fidelity
WMO	World Meteorological Organization
WUA	Weighted usable area
wRHp	Proportion of Weighted Remaining Habitat

List of Symbols

Symbol	Denotation
%	Percent
WUA	Weighted Usable Area [m²]
$\sum$	Sum
i	Segment or cell i
A_i	Area of each river segment or cell i [m²]
SI_i	Suitability index of each river segment or cell i
$LIFE$	Lotic-Invertebrate Index for Flow Evaluation
fs	Individual taxon flow scores
n	Number of taxa used to calculate $\sum fs$
p	Probability of presence or high abundance
$x_{1 \ldots n}$	Significant physical variables
$b_{1 \ldots n}$	Regression coefficient
$Q_{ef,b}$	Absolute flow threshold value
p_b	Tabulated value of index obtained from reference studies for each bio-period and FET
$q_{MBLF,k}$	Specific mean low flow for the bioperiod at cross-section k
A_k	Catchment area at cross-section k
q_{base}	Specific baseflow
q_{trig}	Specific trigger flow
q_{subs}	Specific subsistence flow
p_{base}	Baseflow Index
p_{trig}	Trigger flow index
p_{subs}	Subsistence flow index

Appendix I – Fish Regions of Austria

Biocoenotic Regions Austria

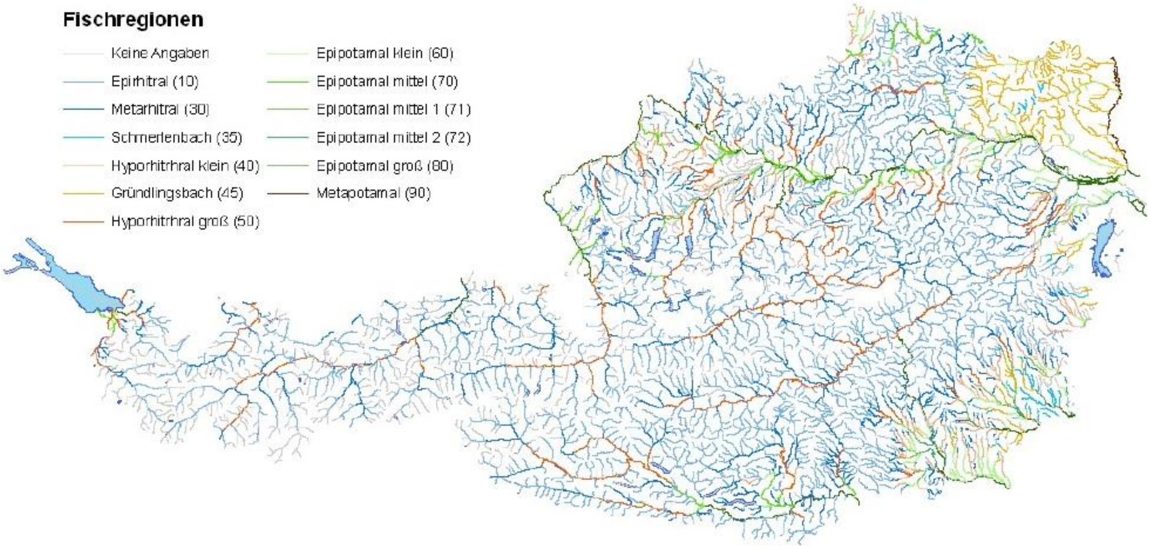

Figure 57 Biocoenotic Regions in Austria (Haunschmid et al. 2019)

Fish-Biological Regions Austria

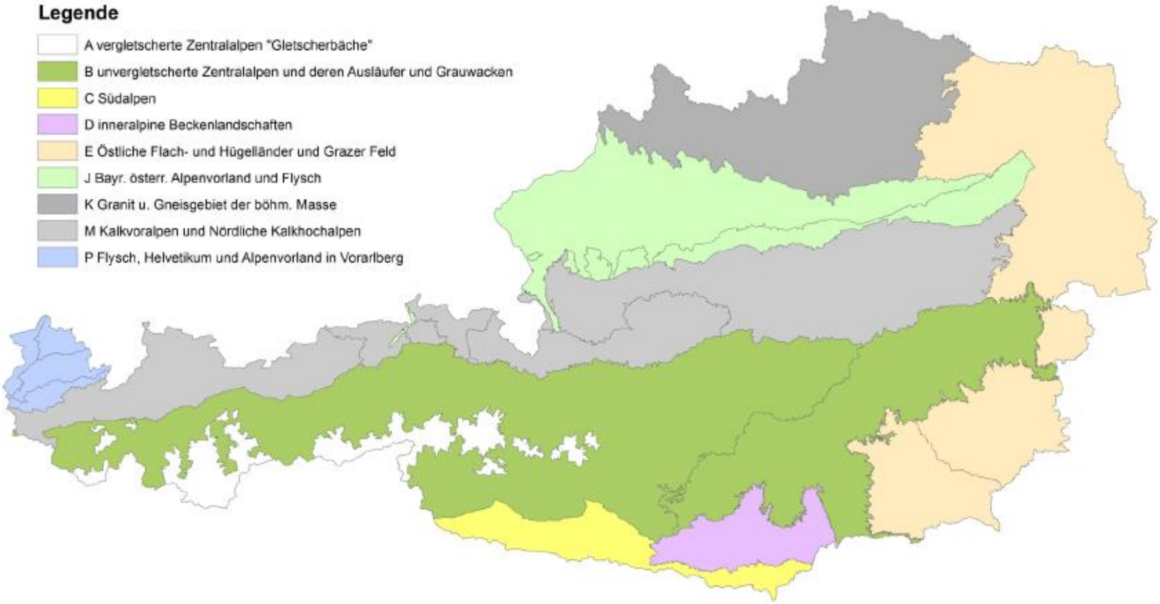

Figure 58 Fish-Biological Regions in Austria (Haunschmid et al. 2019)

Appendix II – Literature Review: Habitat Suitability

Spawning and Rearing Habitat of Brown Trout

Table 29 Results of the literature review on habitat requirements and preferences of spawning and rearing brown trout

Reference	Method	Water Depth	Water Velocity	Substrate	Fine particles	Cover	HMU type / geomorphology
Jungwirth (2003)	Literature review (Ottaway et al. 1981; Nihouarn 1983; Shirvell and Dungey 1983; Witzel and Maccrimmon 1983; Fragnoud 1987; Heggberget, Hansen, and Næsje 1988; Beard and Carline 1991; Grost, Hubert, and Wesche 1991)	Minimum: 10cm Maximum: 50cm Median: 30cm 50% Percentile: 25 -45cm	Minimum: 28cm/s Maximum: 48cm/s Median: 40cm/s 50% Percentile: 35-42cm/s	Minimum: 8mm Maximum: 82mm Median: 50mm 50% Percentile: 15-65mm	Percentages < 1mm around 6-17% (Ottaway et al. 1981) Percentages < 0,8mm around 7% (Beard and Carline 1991)	-	Overflown gravel bars, scours (Ottaway et al. 1981) Egg and yolk sac period: intact interstitial important
Pulg (2009)	Literature review	0.46cm (Ingendahl et al. 1995) 10-50cm (Jungwirth 2003) 0.08 bis 0.51cm, mean: 0.24cm	Mean value around 0.5m/s (0.18 bis 0.83m/s, n 43) (Walker, A. and Bayliss 2006)	Gravel, unconsolidated and stable	During incubation and for emerging: If >15mm similar oxygen levels reached as in river	-	Gravel bars with high currents Levies in riverbed, riffles (Rubin, Glimsater, and Jarvi 2004)

		(Walker, A. and Bayliss 2006)	Mean value around 0.43m/s (Ingendahl et al. 1995)		water (Rubin, Glimsater, and Jarvi 2004) Kondolf (2000): fine sediment percentage around 12% to 14%; percentage of grainsizes between 1mm and 6.3mm smaller than 30%		
Gauthey et al. (2017)	Surveys in two rivers in Pyrenees Mountains	3 to 77cm	0.1 to 0.8m/s	D90 of particle size ranged from 2.223 to 6.34cm	-	-	-
	Citing: Riedl and Peter (2013)	2 to 77cm	0.1 to 0.8m/s	D90: 2.22 to 6.34cm			
Riedl and Peter (2013)	Surveys in seven Swiss rivers in alpine ad pre-alpine rivers	10 to 20cm	30 to 40cm/s	16 to 32mm	-	-	-
Zimmer and Power (2006)	Literature review (Ottaway et al. 1981; Shirvell and Dungey 1983; Witzel and Maccrimmon 1983; Crisp and Carling 1989; Grost, Hubert, and Wesche 1990; Essington,	6 to 82cm	6 to 80cm/s	2-256mm	-	-	-

	Sorensen, and Paron 1998)						
	Survey in Credit River, Ontario	27 to 51.9cm	23.4 to 49.6cm/s	-	-	Reed size independent of cover features	Pools and riffles habitats
Louhi, Mäki-Petäys, and Erkinaro (2008)	Literature review	15 to 45cm	20 to 55cm/s	16 to 64mm	If depositing sediment are finer than 2mm, results in reduction of permeability of redd and lower oxygen supply (Chapman 1988; Lisle 1989; Sear 1993; Pauwels and Haines 1994)	-	pool-riffle zones (Gaudemar, Schroder, and Beall 2000); Avoid step pool systems and cascades (Moir et al. 2004)
Garbe, Beevers, and Pender (2016)	Literature review	0.15 to 45cm (Witzel and Maccrimmon 1983; Louhi, Mäki-Petäys, and Erkinaro 2008)	0.2 to 0.55m/s (Witzel and Maccrimmon 1983; Louhi, Mäki-Petäys, and Erkinaro 2008)	Gravel, sand bus mostly pebbles, median grain size 20 to 30mm (Crisp and Carling 1989)	Unconsolidated	Important (Armstrong et al. 2003)	-
Armstrong et al. (2003)	Literature review	Mean 31.7cm (Shirvell and Dungey 1983) Range 6-82cm (Shirvell and Dungey 1983)	Mean 39.4cm/s (Shirvell and Dungey 1983) Range 15-75cm/s (Shirvell and Dungey 1983)	Mean 6.9mm (Witzel and Maccrimmon 1983) Range 8-128mm (Ottaway and Clarke 1981;	Material <1mm: 8-12% (Crisp and Carling 1989)	important requirement for brown trout during spawning 84% of the redds were recorded within 1.5m of	-

		Mean 25.5cm (Witzel and Maccrimmon 1983)	Mean 46.7cm/s (Witzel and Maccrimmon 1983) Range 10.8 to 80.2cm/s (Witzel and Maccrimmon 1983)	Shirvell and Dungey 1983; Chapman 1988)		cover (Witzel and Maccrimmon 1983)	
Armstrong et al. (2003): Nursery habitat	Literature review	Preference <20-30cm (Bohlin 1977; Kennedy and Strange 1982; Bardonnet and Heland 1994; Mäki-Petäys et al. 1997) Range 5-35cm (Mäki-Petäys et al. 1997)	Range for fry 0-20cm/s (Bardonnet and Heland 1994) Range for 0+ parr: 20-50cm/s (Crisp 1993; Heggenes 1996)	Range 50-70mm (Heggenes 1988b) Range 10-90mm (Bardonnet and Heland 1994)	-	very important for brown trout (Heggenes 1996)	riffle margins offering both suitable refuges and nearby feeding areas may represent the best combination of habitat conditions for juvenile brown trout in many stream (Mäki-Petäys et al. 1997)
Armstrong et al. (2003): Rearing habitat		Preference >50cm (Heggenes 1988a) Mean preference 65 cm (Shirvell and Dungey 1983) Range 14- 122cm (Shirvell and Dungey 1983) Range 40-75cm (Mäki-Petäys et al. 1997); Minimum <5.1cm (Baldes and Vincent 1969)	Range 10-70cm/s (Heggenes 1988a) Range 0-65cm/s (Shirvell and Dungey 1983) Mean 26.7cm/s (Shirvell and Dungey 1983)	Range 8-128mm (Eklov et al. 1999) Maximum >128mm (Heggenes 1988a)	-	Overhead cover and aquatic vegetation important (Binns and Eiserman 1979; Heggenes 1988a; Mäki-Petäys et al. 1997)	-

Spawning and Rearing Habitat of Bullhead

Table 30 Results of the literature review on habitat requirements and preferences of spawning and rearing bullhead

Reference	Method	Water Depth	Water Velocity	Substrate	Spawning	Cover	HMU type / geomorphology
Tomlinson and Perrow (2003)	Literature review	Shallow (Perrow, Punchard, and Jowitt 1997; Punchard, Perrow, and Jowitt 2000) 20 to 40cm (Roussel and Bardonnet 1996)	Moderate velocities (Smyly 1957; Crisp 1963; Gaudin and Caillere 1990)	Coarse substrates with large stones for breeding (Smyly 1957; Crisp 1963; Mills and Mann 1983)	Excavate nest under suitable large stone, or other media (woody debris, tree roots)	Shade and cover important components of habitat Shelter: woody debris, tree roots, leaf litter, macrophytes, large stones (Perrow, Punchard, and Jowitt 1997)	Stony riffles (Perrow, Punchard, and Jowitt 1997; Punchard, Perrow, and Jowitt 2000)
Knaepkens et al. (2004)	Using ceramic tiles as spawning enhancement in lowland degraded rivers in Flanders	Appeared to be of no importance in canalised parts In meandering parts, tiles in deeper parts where chosen	Appeared to be of no importance in canalised parts	-	-	-	
Gosselin, Petts, and Maddock (2010)	Literature review	From 0.05 (Legalle et al. 2005a) to 0.4m (Roussel and Bardonnet 1996)	0.1m/s (Carter, Copp, and Szomlai 2004) to 1 m/s (Knaepkens et al. 2002)	Gravel, pebble and boulder beds	-	-	Riffle (Langford and Hawkins 1997; Perrow, Punchard, and Jowitt 1997)

	Surveys at the Upper Severn, England	0.05 to 0.2m	Below 0. m/s most frequently used	Strong association with cobbles providing shelter			Strong association with glides (deep, slow flowing)
Vezza et al. (2014)	Using Random Forest and Logistic regression models to predict distribution of bullhead using data of reference streams of the Alps (NW Italy)	0.15 to 0.3m positive influence on abundance 0 to 0.15m/s negative influence on adult presence and abundance	0.3 to 0.45m/s: positive influence on abundance 0.6 to 0.75m/s: negative effect on abundance	Most important habitat attribute: mesolithal 6-20mm and macrolithal 20-40mm non-cohesive gravel, pebbles, cobbles and boulders (Davey et al. 2005; Legalle et al. 2005b; Legalle et al. 2005a; van Liefferinge et al. 2005; Knaepkens, Baekelandt, and Eens 2006; Gosselin, Petts, and Maddock 2010) Adults: coarser substrates than juvenile (Davey et al. 2005; van Liefferinge et al. 2005)	-	-	Bullhead found in pool, riffle, rapid, ruffle, run

Legalle et al. (2005a)	Comparing microhabitat preference curves for bullheads of different size classes (SC) in a piedmont stream in Southwest France	SC1: shallow habitats 11-20cm SC2 and 3: deeper areas 21-30cm SC4: deepest areas >25cm	Similar for all stages: 5 to 35 cm/s	SC1: preference for cobbles SC2 to SC4: association with both fine and coarse material; Non-cohesive	-	Take refuge under pebbles	-
Legalle et al. (2005b)	Survey in southwestern France	5 to 20cm	<40cm/s	Non-cohesive substrates coarse mineral particulates, pebbles, cobbles, and boulders deposited on sand	-	Take refuge under pebbles or cobbles or largest particulates	-
Adamczyk et al. (2019)	Development of deductive conditional habitat suitability criteria based in literature review (Starmach 1972; Gaudin and Caillere 1990; Prenda, Rossomanno, and Armitage 1997; Utzinger, Roth, and Peter 1998; Brylińska 2000; Tomlinson and	25-75cm	30-105cm/s	Microlithal, Mesolithal, Macrolithal	-	Undercut bank, boulders, woody debris	Rapids, Riffle, Ruffle

	Perrow 2003; Kotusz 2012; Junker et al. 2012; Fischer and Kummer 2012)						
	Survey on the Stura di Demonte River (NW Italy)	10 to 50cm	0 to 122cm/s	-	-	Large stones, woody debris	Mostly found rapid mesohabitats: rapid, riffle, ruffle and plunge-pool; lower percentages found in slower mesohabitats: glides, pools, sidearms, backwater
Langford and Hawkins (1997)	Surveys in lowland forest stream, Hampshire, England	-	-	-	-	Often found under or in shelter of single logs or branches and among gravel	Shallow riffles
van Liefferinge et al. (2005)	Surveys in upper course of River Over, Flanders	Use deeper water in winter than in summer Adults use deeper parts than juveniles	Velocity near substratum: Optimal utility range for summer: 0.08 to 0.5 (juveniles) 0.09 to 0.37m/s (adults) Optimal utility range for winter: 0.13 to 0.5m/s (juveniles) and 0.12 to 0.38m/s (adults)	Adults: more coarsely grained substratum 5 to 250mm (gravel to cobbles) Juveniles: smaller fractions (0.062 to 100mm)			

			Stream velocity near surface: Optimal utility range for summer: 0.07 to 0.56 (juveniles) and 0.22 to 0.57m/s (adults) Optimal utility range for winter 0.33 to 0.81 (juveniles) and 0.29 to 0.66m/s (adults)				
Davey et al. (2005)	Literature review	-	-	Stony substrata (Welton, Mills, and Rendle 1983; Copp, Warrington, and Bruine 1994; Roussel and Bardonnet 1996; Knaepkens et al. 2002; Copp, Spathari, and Turmel 2005)	-	Seek shelter during day, physical protection and visual isolation ((Smyly 1957; Mills and Mann 1983; Knaepkens et al. 2002)	Prefer fast-flowing riffle habitats (Mann 1971; Roussel and Bardonnet 1997; Carter, Copp, and Szomlai 2004)
	Survey in a southern English chalk stream	-	Moderate water velocities	-	-	Strong preference for cover in the form of macrophytes and coarse substrata	-
Knaepkens et al. (2002)	Literature review	-	Moderate-to-high water velocity (between 0.2 to 1.0m/s) (Bless 1982, 1990)	-	Stones important for successful reproduction because they are used as spawning substrate (Morris	Seek shelter underneath loose stones (Smyly 1957; Welton, Mills, and Rendle	-

					1955; Smyly 1957; Korolev 1991)	1983; Korolev 1991)	
	Survey at a regulated lowland river in Flanders	-	-	-	Use cavities underneath stones for nesting	-	-
Carter, Copp, and Szomlai (2004)	Surveys on field side channels and tributaries of River Avon, Hampshire England	0+ bullhead preferred shallower depths (10-20cm)	0+ bullhead associated with moderate to high water velocities (>15cm/s)	Associated with areas of coarse substrata (gravel and cobbles)	-	-	
Stahlberg-Meinhardt (1994)	Surveys at two anthropogenically influence rivers in Lower Saxony	0.2 to 0.5m, no specific preference	0.2 to 0.7m/s	Substrate size similar to size of individuum's; Amount of substrate > 5mm: 50% heterogenic, mosaic-structure	-	Cover-structures, shade	Riffle, especially for 0+ and 1+ individuals
Smyly (1957)	Field studies in Windermere	-	-	Lives under stones before breeding begins, male enlarges space under its stone	-	Lives under stones	-

Spawning and Rearing Habitat of European Grayling

Table 31 Results of the literature review on habitat requirements and preferences of spawning and rearing European grayling

Reference	Method	Water Depth	Water Velocity	Substrate	Cover	HMU type / geomorphology
Gönczi (1989)	Field studies at two Swedish river (Indalsälven and Ammeran) considering spawning sites	Mean: 36 cm (range of 30-50cm)	Mean: 54 cm/s (range 23-90 cm/s)	10-20% sand, 50-70% gravel (<2cm), 20-30% stones (2-10cm), a few bigger stones (>10cm)	-	Bottom structure caused water turbulence maintaining good aeration
Guthruf (1996)	Field studies at three Swiss rivers (Aare, Belper Giesse and Glane) considering spawning sites and larval phase	Larval phase: low depths	Spawning: >20cm/s Larval phase: low velocities	-	-	Spawning: riffles and transitions between pool and riffles
Sempeski and Gaudin (1995a)	Field studies at two French rives (Pollon and Suran) regarding spawning sites	Pollon: 27.2cm (range 13-57cm), no spawning in <10cm and >60cm Suran: 26.3cm (range 15-40cm), no spawning in <10cm and >40cm Similar to Müller, K. (1961) (20-40cm) and	Pollon: 47.8cm/s (range 25.8-91.7cm/s) Suran: 50.2 (range 30.3-67.7cm/s), strong selection of >40cm/s Mean: 48.9cm/s (range 25.8-91.7 cm/s), strong selection of 40-70cm/s	Pollon: composed of fine pebble and fine gravel Suran: coarse pebble, coarse gravel and fine cobble Consistent with literature data: Müller, K. (1961) (hazelnut size), Fabricius and Gustafson (1955) (pea size 1-3cm)	Tree roots, overhanging branches	Pool: important resting place for females during spawning activity (low velocities and high depths)

		Gönczi (1989) (30-50cm)				
Sempeski and Gaudin (1995b)	Field studies at River Pollon, France, regarding larval and juvenile habitats	Larvae: 0-40cm, high selection for <20cm Juvenile: 40-60cm	Larvae: 0-20cm/s, strong preference for low velocities 0-10cm/s Juvenile: 15-50cm/s, high selection for 30-30cm/s	Larvae: sand, silt, fine gravel Juvenile: fine pebbles, coarse gravel, fine gravel	-	Riparian habitat, dead zones, marginal positions along the channel
Nykänen and Huusko (2002)	Field study at River Kuusinkijoki in north-eastern Finland considering spawning habitat	Mean: 61cm, optimal 30-40cm	Mean: 53cm/s, preferred 40-70cm/s, optimal 50-60cm/s	Dominated by coarse gravel and fine pebble: 3% sand, 14% fine gravel (2-8mm), 44% coarse gravel (8-16mm), 26% fine pebble (16-32mm), 11% coarse pebble (32-64mm), 2% fine cobble (64-128mm), optimal 16-31mm	-	-
Nykänen and Huusko (2003)	Field study at River Kuusinkijoki in north-eastern Finland considering habitat for larval grayling	Water depth increased with fish size Smaller larvae: strong preference for 20-30cm Middle-sized larvae: 30-90cm Large larvae: 80-110cm	Small larvae: 10cm/s Middle-size larvae: <10cm/s Large larvae: 10-50cm/s	Small larvae: preferred substrates dominated by organic matter, silt and sand Middle-sized larvae: coarse and fine substrates Large larvae: boulders and sand	Small larvae near shoreline vegetation and submerged vegetation Vegetation cover	-

Mallet et al. (2000)	Field study at the Ain River in France considering all age-classes	Differed between age-classes: 0* strong preference for shallow water (optimal range 50-60cm), larger individuals prefer deeper waters (80-200cm) Spawning: 30cm Larveas: 10cm (Sempeski and Gaudin 1995a, 1995b) Juveniles: 60cm	Spawning: 55cm/s Larvaes: 5cm/s (Sempeski and Gaudin 1995a, 1995b) Juveniles: 100cm/s	Similar for all age-classes: 0.5-16mm	-	-
Darchambeau and Poncin (1997)	Field study at River Ourthe in Belgium regarding spawning behaviour	20-55cm	-	Fine gravels (1-2cm) with larger pebbles (5-10cm) and stones (15-25cm)	-	-
Fukuda et al. (2013)	Comparison of results of different species distribution models using data of Mouton et al. (2008)	Water depth important variable	Flow velocity important variable	-	-	-
Bardonnet, Gaudin, and Persat (1991)	Field study at river Suran in France regarding young grayling	Low depth (10-30cm)	Low velocities (25cm/s), chief factor affecting distribution	-	-	-
Mouton et al. (2008)	Construction of a fuzzy physical habitat model for spawning grayling in the Aare	Observed at 1.9-2.3m, significantly higher as described by other authors (Gönczi 1989;	10-40cm/s, consistent with (Gönczi 1989; Sempeski and Gaudin	Preferring fine to medium sized gravel, results strongly correspond with previous	-	-

	River, Switzerland, using data collected during field studies	Sempeski and Gaudin 1995a; Nykänen and Huusko 2002)	1995a; Nykänen and Huusko 2002)	research (Gönczi 1989; Sempeski and Gaudin 1995a; Nykänen and Huusko 2002)		

Appendix III – GKI

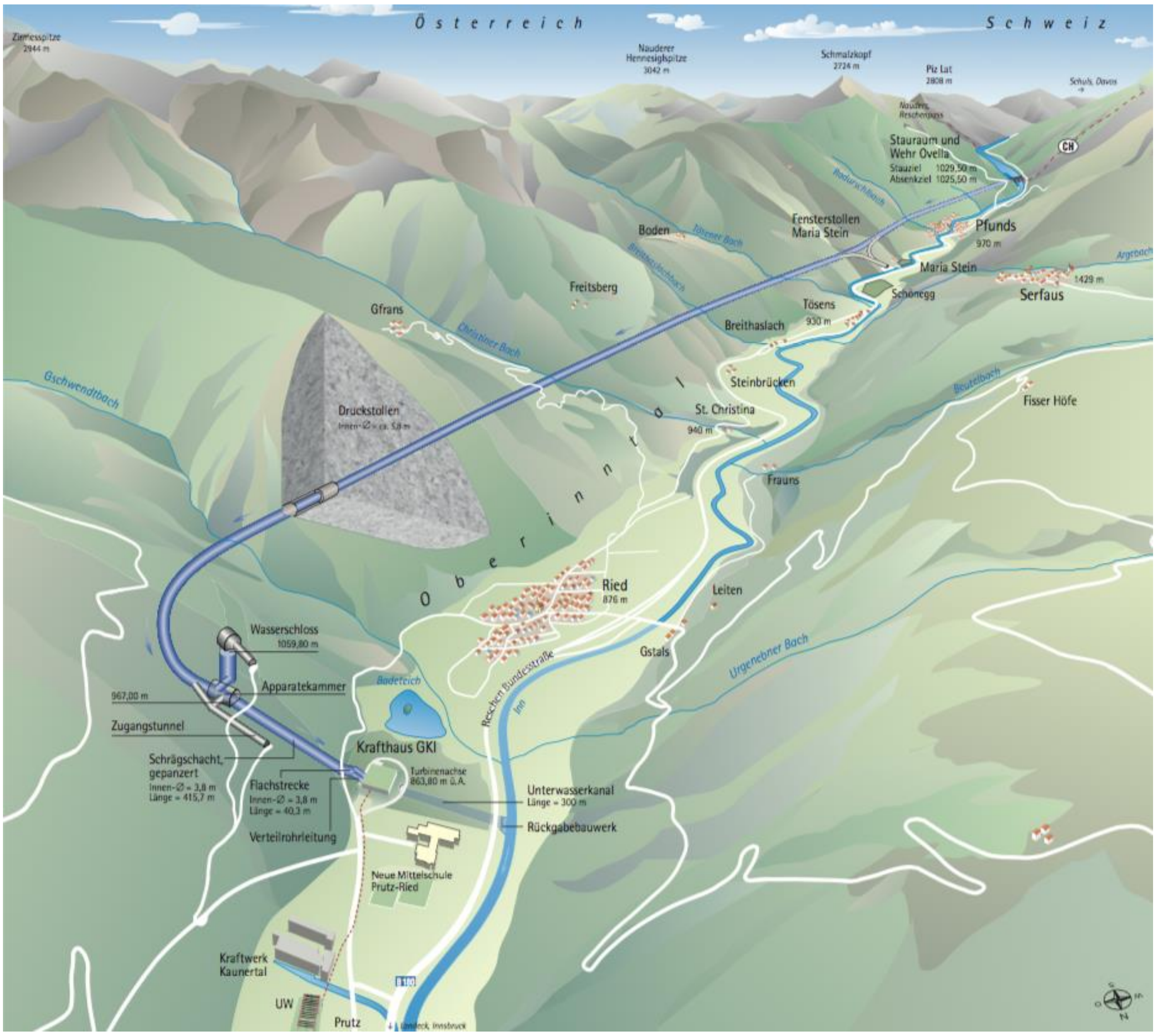

Figure 59 Overview map for the GKI project (GKI 2017b)

Appendix IV – Expected Fish Community Inn

Metarhithral

Table 32 Expected fish community for the Metarhithral region at the River Inn (Haunschmid et al. 2019)

Target Fish Species	Brown trout	Salmo trutta fario
	Grayling	Thymallus thymallus
	Bullhead	Cottus gobio
	Huchen	Hucho hucho
Accompanying Species	Grayling	Thymallus thymallus
	Bullhead	Cottus gobio
	Ukrainian brook lamprey	Eudontomyzon mariae
Rarely accompanying Species	Squalius cephalus	Squalius cephalus
	Common minnow	Phoxinus phoxinus
	European perch	Perca fluviatilis

Hyporhithral large

Table 33 Expected fish community for the Hyporhrithral large region at the River Inn (Haunschmid et al. 2019)

Target Fish Species	Brown trout	Salmo trutta fario
	Grayling	Thymallus thymallus
	Bullhead	Cottus gobio
	Huchen	Hucho hucho
Accompanying Species	Burbot	Lota lota
	Squalius cephalus	Squalius cephalus
	Common barbel	Barbus barbus
	Gudgeon	Gobio gobio
	Common nase	Chondrostoma nasus
	Ukrainian brook lamprey	Eudontomyzon mariae
Rarely accompanying Species	Stone loach	Barbatula barbatula
	Common minnow	Phoxinus phoxinus
	European perch	Perca fluviatilis
	Pike	Esox lucius
	Schneider	Alburnoides bipunctatus

	Danube barbel	Barbus balcanicus
	Soufiia	Telestes souffia

Appendix V – Results CASiMiR Model

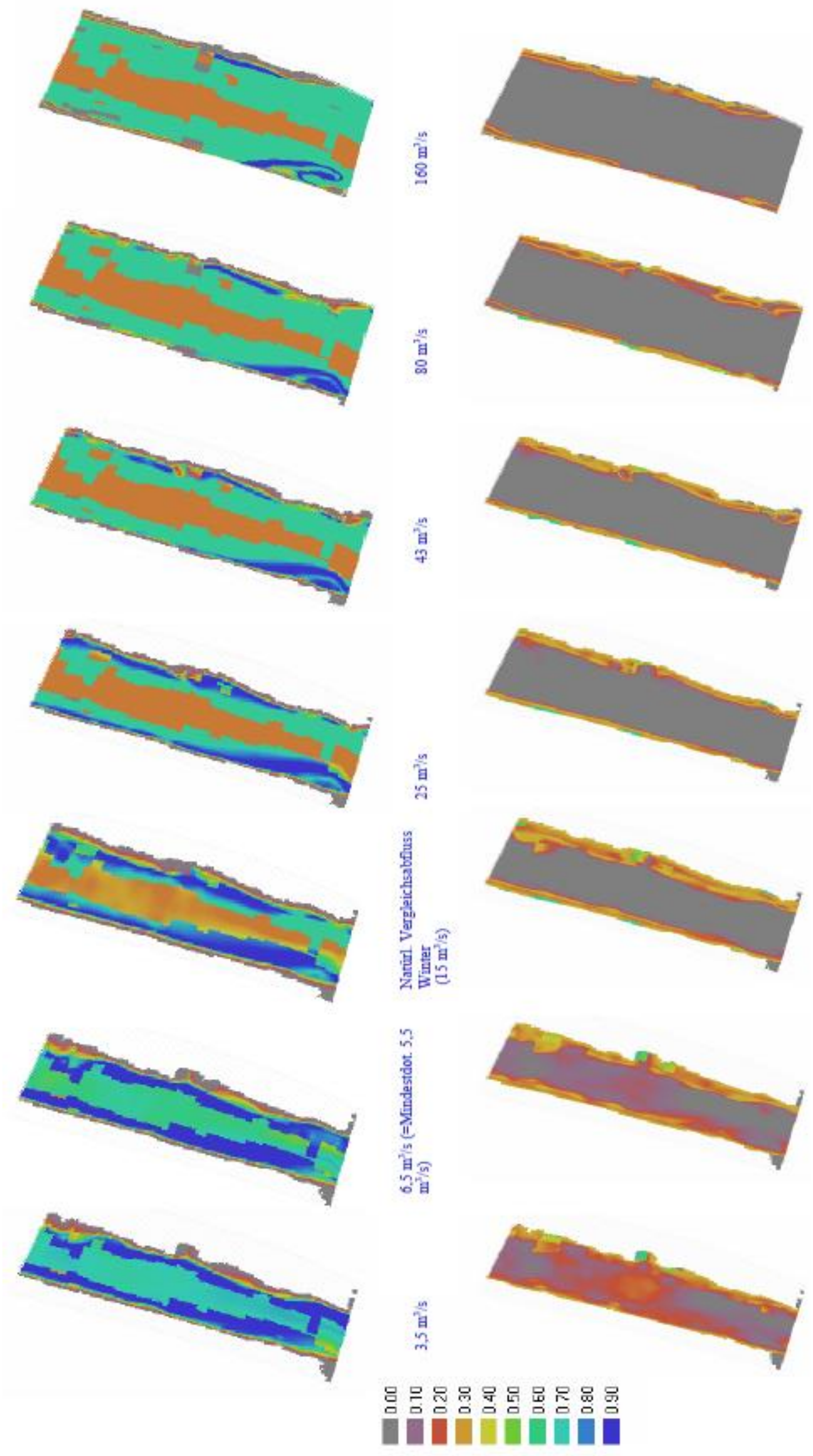

Figure 60 Habitat suitability for different discharge conditions developed using CASiMiR for the reference site Kajetan Upper Inn River for adult brown trout (upper part) and juvenile brown trout (lower part) (Moritz et al. 2007)