Impact of Hydropeaking on Fish and their Habitat

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"Le vrai jardinier
se découvre
devant
la pensée sauvage."

Jacques Prévert

Abstract

High-head storage hydropower plants are an important renewable source of energy in alpine areas. Kinetic energy released from water, which is stored in reservoir and diverted through turbines, produces electricity. During daily peaks of energy demand, the powerhouse outflow is released in the downstream river, creating artificial flow fluctuation, so-called hydropeaking. This alters the natural flow regime of rivers and has a negative effect on ecosystems and biodiversity. As a result, water discharge, temperature, fine particle load and other abiotic factors are changed. Consequently, river organisms and their habitat are impacted.

Resulting from an increased pressure for atmospheric carbon mitigation, hydropower production is expected to increase in the future (e.g. from storage powerplants). In Switzerland this trend is further enhanced by the recent governmental decision to phase out nuclear power production. Thought, the revision of the Swiss water protection act shows the growing awareness to protect natural ecosystems downstream of hydropower facilities. However, there is a strong need for research in this field due to the lack of knowledge on the adverse impacts stemming from hydropower production.

This study is part of the interdisciplinary research project "Sustainable use of hydropower – innovative measures to reduce hydropeaking problematic" and it focuses on the impact of hydropeaking on fish and their habitat. Brown trout is used as a target species and important steps in their life cycle are studied. Three target stages of brown trout development were selected: adults, spawning and young-of-the-year. Each different life stage has specific habitat requirements. The latter can be used for identifying potential landscape filters constraining fish population renewal. Landscape filters are determined by the joint influence of river morphology and discharge regimes, such as hydropeaking.

In this work, two rivers, with different morphological characteristics, are studied, namely the Vorderrhein and the Hasliaare Rivers. Both rivers show a hydropeaking regime, are situated in alpine areas and have a comparable hydrological regime. The hydrology of the two rivers is characterized by low discharge in winter and high discharge in summer due to snowmelting. Fish species composition is similar and strongly dominated by brown trout. The Vorderrhein River is one of the few natural and morphologically intact rivers found in Switzerland, which allows to isolate the effect of hydropeaking from other potential human-induced stressors. In contrast, the Hasliaare River has been strongly channelized in the past century. Thus, the Hasliaare River system was chosen to investigate the joint effect of hydropeaking and river channelization.

In the Vorderrhein River, the seasonal impact of hydropeaking on adult brown trout habitat was modeled using the CASiMiR fish module. Therefore, different critical seasons are defined. Furthermore, the natural reproduction success was assessed and brown trout reproduction and rearing habitat were modeled. Habitat preference of spawning and young-of-the-year are established with specific Habitat Suitability Curves. The habitat model was adapted to the hydropeaking problem and indices measuring habitat dynamics were developed. Moreover, the transferability of Habitat Suitability Curves in habitat models was discussed. In addition, young-of-the-year density as well as egg to hatch survival were monitored. The results show that hydropower operations have an effect on brown trout habitat, whereat spawning and young-of-the-year life stages are more impacted than adults. The impact is seasonal and aggravated in winter. The natural river morphology provides suitable habitat areas at both peak and off-peak discharges. Although these suitable habitat areas are dewatered almost entirely or displaced on a daily basis.

In the Hasliaare River system, the joint effect of hydropeaking and channelization on young-of-the-year, lake and stream resident spawning brown trout were studied. Steady and dynamic habitat conditions were evaluated and the habitat was modeled for three different degraded morphologies. Specific preference curves for each investigated life stage were developed. Moreover, the reproduction success was monitored by egg to hatching survival experiments and young-of-the-year density surveys. The results show that channelization aggravates the impact of hydropeaking as no young-of-the-year or spawning habitat is present at peak flow. In addition, egg development was found to be impaired. Therefore, the density of young-of-the-year individuals was negligible in the hydropeaking section. The habitat model shows that in a channelized river such as the Hasliaare River, suitable habitat conditions for fish are restrained at peak flow by the riverbed width.

Finally, a tool for evaluating scenarios for mitigating the impact of hydropeaking on the downstream ecosystem was developed. The novel economic-ecological diagnostic and intervention method takes into account financial as well as environmental outcomes of hydropeaking mitigation measures for fish habitat improvement. The approach comprises (1) a hydropower operation model of flow regime generation and cost estimates for different mitigation measures, (2) a 2D hydrodynamic model to simulate the flow conditions in representative river reaches, and (3) a dynamic fish habitat simulation tool to assess the sub-daily changes in fish habitat conditions. This modeling approach gives the possibility to estimate true benefits of rehabilitation measures. The intervention diagnostic method was tested on the Hasliaare River.

The developed tools and knowledge will help implement scientifically-based solutions for a sustainable hydropower management. The study may help in supporting the application of river restoration projects at existing and newly developed hydropower facilities in alpine areas.

Keywords: Brown trout, spawning, young-of-the-year, hydropeaking, habitat suitability, habitat modeling, hydropower, sustainability, river rehabilitation, mitigation measures, economic and habitat rating.

Zusammenfassung

Wasserkraft aus Hochdruckpumpspeicherwerken stellt eine bedeutende erneuerbare Energiequelle in alpinen Gebieten dar. Die kinetische Energie des Wassers liefert Elektrizität. Hierfür wird das in Stauseen gespeicherte Wasser durch die Kraftwerksturbinen an darunter liegende Fliessgewässer abgegeben. Turbiniert wird in Anpassung an die Verbrauchsspitzen des täglichen Bedarfs. Dies führt unterhalb des Wasserkraftwerkes zu künstlich erzeugten und tagesrhythmischen Schwankungen der Wasserführung des Fliessgewässers, dem sogenannten Schwall-Sunk. Solche Schwankungen beeinflussen das natürliche Strömungsregime des Flusses und haben negative Auswirkungen auf das Ökosystem und dessen Biodiversität. Verschiedene abiotische Faktoren, darunter Wasserabfluss, -temperatur sowie Feinsedimentanteil werden verändert, wodurch die Organismen des Fliessgewässers und deren Habitat beeinträchtigt werden.

Aufgrund der steigenden Nachfrage nach Energiequellen mit geringem CO2-Ausstoss und dem geplanten Atomausstieg in der Schweiz, ist künftig mit einem weiteren Zuwachs an Wasserkraft zu rechnen. Zwar entwickelt sich ein wachsendes Bewusstsein für die Beeinträchtigung der Fliessgewässerökosysteme durch Wasserkraftnutzung, was sich zum Beispiel durch die Überarbeitung des Schweizer Gewässerschutzgesetzes zeigt. Jedoch bestehen weiterhin erhebliche Wissenslücken und Forschungsbedarf hinsichtlich der negativen Auswirkungen von Wasserkraft.

Diese Studie ist Teil des interdisziplinären Forschungsprojektes “Nachhaltige Nutzung der Wasserkraft - Innovative Massnahmen zur Reduzierung der Schwall- und Sunkproblematik“ und konzentriert sich auf die Auswirkungen von Schwall-Sunk auf Fische und ihre Habitate. Hierbei dient die Bachforelle als Modellorganismus und es werden verschiedene Phasen in deren Lebenszyklus untersucht. Drei wichtige Entwicklungsstadien wurden ausgewählt, nämlich Adult-, Laich- sowie 0+-Stadium. Jedes dieser Entwicklungstadien hat verschiedene Habitatansprüche. Letztere können dazu herangezogen werden um potentielle Faktoren zu identifizieren, welche die Regeneration von Fishpopulationen beeinträchtigen. Diese Habitat-assoziirten limitierenden Faktoren werden durch das Zusammenspiel von Flussmorphologie und Abflussregime bestimmt, inklusive Schwall- und Sunk Abflüsse.

In der vorliegenden Arbeit werden zwei Fliessgewässer mit unterschiedlicher Flussmorphologie untersucht, nämlich der Vorderrhein und die Hasliaare. Beide Gewässer sind durch einen Schwall-Sunk-Abfluss sowie ein vergleichbares hydrologisches Regime gekennzeichnet, und befinden sich in alpinen Regionen. Für beide Flüsse charakteristisch sind niedrige Abflüsse im Winter und bedingt durch Schneeschmelze, hohe Abflüsse im Sommer. Auch die Zusammensetzung der Fischgemeinschaft ist ähnlich und wird von der Bachforelle dominiert. Da der Vorderrhein eines der wenigen natürlichen und morphologisch intakten Fliessgewässer der Schweiz ist, ermöglicht er uns, die Effekte von Schwall-Sunk isoliert von anderen anthropogen verursachten Stressoren zu betrachten. Hingegen wurde die Hasliaare im vergangenen Jahrhundert stark kanalisiert. Sie wurde für diese Studie ausgewählt um die gemeinsamen Effekte von Schwall-Sunk und Flussbegradigung zu untersuchen.

Im Vorderrhein wurde der saisonale Effekt von Schwall-Sunk auf die Habitate der Bachforelle modelliert. Hierfür wurden kritische Jahreszeiten definiert und das Habitatsimulationsmodell CASiMiR verwendet. Des Weiteren wurde der natürliche Reproduktionserfolg bestimmt und sowohl Reproduktions- als auch Aufzuchtshabitate der Bachforelle modelliert. Zusätzlich wurden die 0+ Fische-Dichte sowie das

Überleben des Laichs erfasst. Präferenzen für Laich- und 0+ Fische-Habitate werden mithilfe von Habitateignungskurven bestimmt. Das Habitatmodell wurde der Schwall-Sunk-Problematik angepasst und Indizes zur Bestimmung der Habitatdynamik entwickelt. Die Übertragbarkeit von Habitateignungskurven in Habitatmodelle wird ebenfalls diskutiert. Die Ergebnisse zeigen, dass Adult-Habitate durch Wasserkraft beeinträchtigt werden, stärker betroffen sind jedoch die Habitate von Laich- und 0+ Fische-Entwicklungsstadien. Die Beeinträchtigung ist saisonal, mit verstärktem Effekt in den Wintermonaten. Zwar bietet die natürliche Gewässermorphologie geeignete Habitate während Schwall- und Sunk-Abflüssen. Jedoch werden diese geeigneten Habitatflächen aufgrund von Schwall-Sunk täglich entweder räumlich verlagert, oder sie fallen trocken.

Im Gewässersystem der Hasliaare wurde die gemeinsame Auswirkung von Schwall-Sunk und Kanalisierung auf 0+ Fische, und Laichstadien von See- sowie Bachforellen untersucht. Sowohl gleichbleibende als auch dynamische Habitatbedingungen werden bewertet und das Habitat für drei regulierte Flussabschnitte mit verschiedene degradierter Morphologie modelliert. Es wurden spezifische Präferenzkurven für jede der betrachteten Entwicklungsstadien erstellt. Ausserdem wurde der Reproduktionserfolg mittels Experimenten zur Eientwicklung und der 0+ Fische-Dichtebestimmung ermittelt. Die Ergebnisse zeigen, dass die Kanalisierung des Flusses die Auswirkung von Schwall-Sunk verstärkt, da während Schwall-Abflüssen 0+ Fische- oder Laich-Habitate vollständig fehlen. Somit ist im betroffenen Abschnitt die Dichte von 0+-Individuen vernachlässigbar gering. Zusätzlich wurde ein Beeinträchtigung der Eientwicklung festgestellt. Auch das Habitatmodell zeigt, dass während des Schwallabflusses kanalisierte Gewässer wie der Hasliaare, keine geeigneten Habitats Bedingungen für juvenile Stadien bietet. Als wichtigen limitierenden Faktor gibt das Modell die Breite des Flussbettes an.

Schliesslich wird ein Programm entwickelt welches Konzepte zur Abmilderung der Auswirkungen von Schwall-Sunk auf das Ökosystem betroffener Fliessgewässer bewertet. Das neuartige ökonomisch-ökologische Diagnose- und Interventionsverfahren berücksichtigt finanzielle und ökologische Auswirkungen von Massnahmen die der Abschwächung von Schwall-Sunk-Effekten und der Verbesserung der Fischhabitate dienen sollen. Der Ansatz umfasst (1) ein Kraftwerksmodell für die Erzeugung von Abflussregimes und die Schätzung der Kosten für verschiedene Abschwächungsmassnahmen, (2) ein 2D hydrodynamisches Modell für die Simulation von Abflussbedingungen in repräsentativen Flussabschnitten, und (3) ein dynamisches Fischhabitat-Simulationstool, um die sich innerhalb eines Tages ereignenden Veränderungen der Habitatsbedingungen zu bestimmen. Der Modellansatz ermöglicht den tatsächlichen Nutzen von Verbesserungsmassnahmen abzuschätzen. Das Diagnose- und Interventionsverfahren wurde an der Hasliaare getestet.

Die in dieser Studie erzielten Ergebnisse und entwickelten Methoden leisten einen wichtigen Beitrag für die zukünftige Umsetzung wissenschaftsbasierter Konzepte für ein nachhaltiges Management von Wasserkraft. Ausserdem bietet die vorliegende Arbeit hilfreiche Informationen, welche zur Unterstützung der Umsetzung von Flussrevitalisierungsprojekten an bestehenden und neu entstehenden Wasserkraftstandorten in alpinen Gebieten herangezogen werden können.

Schlüsselwörter: See- und Bachforelle, Laichfishen, 0+ Jährlinge, Schwall und Sunk, Habitatseignung, Wasserkraft, Speicherkraftwerke, Alpen, Nachhaltigkeit, Flussrevitalisierung, Sanierungsmassnahmen, ökonomische und ökologische Bewertung.

Résumé

Dans les régions alpines, les aménagements d'accumulations à haute chute sont une source importante d'énergie. Ce type d'aménagement permet de répondre aux pics journaliers de consommation d'énergie par le stockage saisonnier de l'eau dans des lacs réservoirs et une modulation de la production de pointe grâce à une exploitation par éclusées. Lors des pics de demande énergétique, l'eau est relâchée dans le cours d'eau, induisant une augmentation rapide du débit. Il en résulte une alternance de débit élevé (débit d'éclusée) et de débit faible (débit plancher) au cours de la journée, appelée éclusée. Ces variations de débit d'origine anthropique, induisent une perturbation du régime naturel de la rivière pouvant affecter sa structure, tout comme son fonctionnement écologique. En effet, les éclusées affectent les paramètres physiques du cours d'eau tel que le débit, la température et le transport sédimentaire. En conséquence, les organismes aquatiques ainsi que leurs habitats sont significativement impactés.

Les besoins en énergie hydro-électrique devraient augmenter dans un futur proche. Premièrement, cette source d'énergie génère peu de CO2 atmosphérique ce qui lui donne l'avantage de ne pas participer au réchauffement climatique. Deuxièmement, le parlement et le conseil fédéral Suisse ont récemment décidé d'abandonner la filière nucléaire entrainant un futur renforcement de filière compensatoire, tel que l'hydroélectricité. De plus, la révision de la loi fédérale du 24 janvier 1991 sur la protection des eaux démontre l'intérêt croissant porté à la conservation des écosystèmes naturel à l'aval des centrales d'accumulations. Cependant, l'impact écologique du auc éclusées reste toujours difficile à quantifier.

La présente étude fait partie du projet de recherche interdisciplinaire "Utilisation durable de la force hydro-électrique – Mesures innovatrices pour réduire les problèmes liés aux éclusées". Dans le cadre de ce projet de recherche, l'effet des éclusées sur la truite commune européenne (*Salmo trutta*) et son habitat est examiné de manière détaillée. L'impact des éclusées est étudié à plusieurs stades du cycle de vie de la truite (adulte, fraie, développement larvaire, alevin et juvénile) afin d'identifier les stades les plus sensibles. Chaque stade du cycle de vie de la truite présente des préférences d'habitat spécifiques. Ces préférences sont utilisés afin d'identifier d'éventuelles déficits d'habitat, qui en agissant comme un filtre, limitent le bon renouvellement de la population piscicole. Ces « habitats filtres » sont déterminés par la morphologie et le régime hydraulique de la rivière, par exemple un régime d'éclusées.

Deux rivières alpines aux caractéristiques morphologiques bien distinctes sont étudiées, le Rhein antérieur (GR) et la Hasliaare (BE). Ces deux rivières sont soumises à un régime hydraulique sous éclusées et présentent un régime hydrologique comparable, caractérisé par un débit faible en hiver et un débit élevé en été alimenté par la fonte des neiges. Dans les deux cas, le peuplement piscicole est fortement dominé par la truite commune européenne. Le Rhein antérieur présente une morphologie proche de l'état naturel permettant d'analyser uniquement l'effet des éclusées sans présence d'autres altérations physique du cours d'eau. En revanche, la Hasliaare fut fortement canalisée durant le siècle dernier ce qui permet d'étudier l'effet conjoint de la canalisation et du régime sous éclusée sur la population de truite.

Dans cette étude, l'effet des éclusées sur l'habitat des truites est modélisé sur le Rhein antérieur. Pour ce faire, le modèle d'habitat CASiMiR est utilisé et les saisons pour lesquelles le régime d'éclusées est particulièrement critique sont définies. De plus, le renouvellement de la population est étudiés grâce à la modélisation de l'habitat de fraie, des alevins et des adultes. Les préférences d'habitat pour les frayères et les alevins sont établies grâce à des courbes de préférences spécifiquement calculées pour le Rhein antérieur. Le modèle d'habitat CASiMiR est adapté à la problématique des éclusées, au travers du développement d'indicateurs d'habitat dynamique. Les résultats montrent que l'impact des éclusée sur l'habitat de la truite est aggravé en hiver principalement lors du fraie ainsi que pour les stades juvéniles de truites. Une morphologie naturelle permet de maintenir des habitats favorables aux truites pour une grande gamme de débit. Cependant, dû à l'alternance journalière entre les débits plancher et d'éclusée, la majorité des habitats est déplacé ou asséché.

Sur la rivière Hasliaare, l'effet conjoint de la canalisation et d'un régime d'éclusée sur les écotypes de la truite de lac et de rivière sont étudiée. L'habitat est modélisé pour trois différents type de morphologie dégradée, à l'aide de CASiMiR et des indicateurs dynamiques développée sur le Rhein antérieur. L'état de la reproduction naturelle est déterminée à l'aide d'incubation d'œuf jusqu'à l'éclosion et de recensement des alevins par pêche électrique. Les résultats montrent que l'effet des éclusées sur la truite de rivière et de lac est aggravé par la canalisation du cours d'eau. En effet, lorsque ces deux facteurs sont réunis, le débit d'éclusée est caractérisé par une absence d'habitat pour le fraie et les alevins. De plus, le taux de survie jusqu'à l'éclosion des œufs est diminué et le nombre d'alevins recensés dans les sections à régime d'éclusées est pratiquement nul. Dans le cas d'étude de la Hasliaare, la présence d'habitat favorable à la truite lors du débit d'éclusée est fortement limité par la largeur du lit.

Finalement, un outil numérique est développée afin d'évaluer l'efficacité de mesures d'atténuation de l'impact écologique des éclusées. Cet outil permet de comparer les coûts ainsi que les améliorations d'habitat piscicole associées à la mise en place d'une mesure d'assainissement. La méthode comprend (1) un modèle de simulation du mode d'exploitation d'aménagements hydroélectriques complexes qui génère le régime d'éclusée et les coûts associés à la mise en place de mesures d'assainissements, (2) un modèle hydrodynamique 2D simulant les conditions d'habitats physiques dans le cours d'eau et (3) un outil de simulation de l'habitat piscicole comprenant des indicateurs d'habitat stationnaires et dynamiques. L'approche heuristique est testée sur le cas d'étude de la Hasliaare. Les résultats obtenus montrent que, l'assainissement du régime d'éclusée n'est possible que par la mise en place de mesures conjointes combinant la construction de bassin de compensation, permettant une amélioration du régime hydraulique, et une amélioration significative de la morphologie du cours d'eau.

Les connaissances et outils, développés dans le présent travail, participe à l'élaboration d'un management durable de la force hydroélectrique. L'approche conceptuelle proposée est utile à la réalisation de projet d'amélioration écologique en aval d'aménagement d'accumulations à haute chute.

Mots-clés: Truite commune européenne, fraie, juvnénile, régime d'éclusées, préférence d'habitat, modélisation d'habitat, hydroéléctricité, restoration de cours d'eau, mesures compensatoires, évaluation économique et écologique.

Contents

1

Introduction

Hydropower is a leading renewable energy resource in Europe and worldwide. Especially in Switzerland hydropower use is very attractive: the steep gradient landscape combined with a high rainfall offer a great potential for this kind of energy production. High-head Hydropower Plants (HPP) produce renewable and storable energy which has a “green image” due to their low greenhouse gas emissions. However, HPP have negative impacts on aquatic ecosystems, affecting freshwater flora and fauna. During the daily high energy demand phase, the water is turbined and released back in the river downstream of the hydropower plant. This phenomenon termed “hydropeaking” induces a rapid change in discharge and leads to considerable sub-daily flow variation. Those flow alterations far exceed natural hydrological variations and have drastic biological consequences. Nowadays the demand for nuclear-free and CO2-free energy production is increasing. The current debates about abandoning nuclear power production are likely to reinforce hydroelectricity production (Schleiss 2007). Thus, the mitigation of its negative impacts on the environment is a necessity (Wüest 2012). In this work, the effect of hydropeaking on the river habitat is investigated, with a focus on brown trout. This research is conducted in river reaches with different morphological characteristics to identify how river engineering and flow regulations interact. The present work aims to gather useful knowledge and methods to solve complex river management issues rising from storage hydropower use under challenging and evolving environments.

In this chapter the framework, the main objectives as well as the structure of the present thesis are introduced and described.

1.1 Framework

"Sustainable use of hydropower - innovative measures to reduce hydropeaking problems" is an interdisciplinary project bringing together industrial and scientific partners. The main initiators of this project are the EPFL (Laboratory of Hydraulics Constructions), the Eawag (Department for Fish Ecology and Evolution), the Kraftwerk Oberhasli (KWO) and the Innovative Promotion Agency (CTI). The project is divided into five work packages. A) Fundamentals of fish ecology basics, B) Influence on fish and their habitat, C) Improvement of habitat conditions, D) Enhancement of complex storage hydropower plant and E) Methodology for mitigation measures of hydropeaking (Figure 1.1).

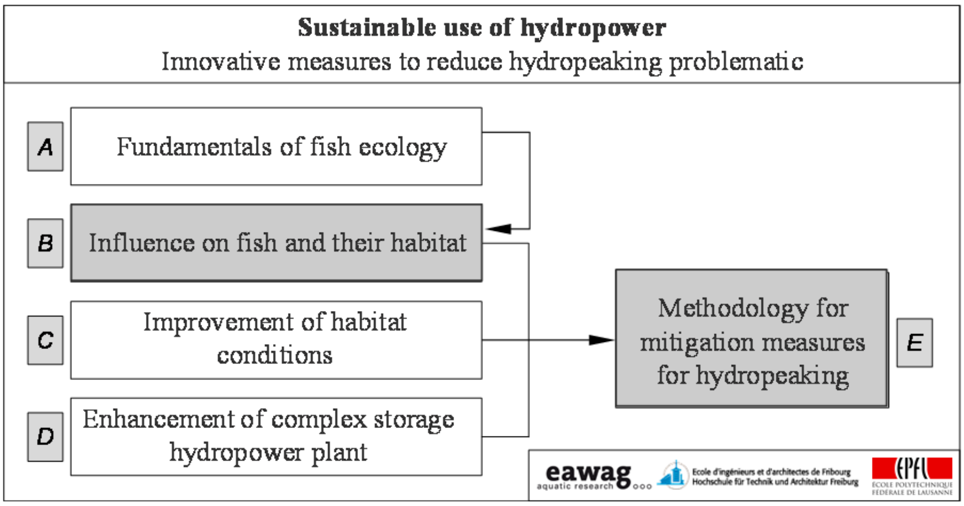


Figure 1.1: Interaction between the project work packages for handling hydropeaking problems. The grey box illustrate the topics presented in this work. Modified from Bieri (2012).

The five work packages contains the following research objectives:

- **Work package A:** Fundamentals of fish ecology documents the ecological status and current deficits in rivers influenced by hydropeaking: the Hasliaare River. Emphasis is given to the description of morphological, hydrological as well as fish populations status (Haas & Peter 2009).
- **Work package B:** Influence of hydropeaking on fish and their habitat is the present thesis. The research investigates the impact of flow regulations due to hydropower operations on fish and their abiotic habitats. Here, sensitive biota and landscape filters are defined. Tools to quantify the habitat instability resulting from hydropeaking are developed. Special emphasis is given to the interdependency between the river geomorphology and hydrology. Tools are developed to provide decision support in developing appropriate mitigation measures for fish habitat improvement.
- **Work package C:** This part deals with the improvements of habitat conditions. The design of structures at the riverbanks (flow shelter) to protect fish against excessive flow velocities due to peak discharges is

studied. Shelters are designed based on the fish swimming capacities which were assessed in flume experiments (Ribi 2011).

- **Work package D:** The package “Enhancement of complex storage hydropower plant” focuses on developing tools for modeling plant operation and predicting runoff in mountainous, glacierized alpine catchment areas. In the modeling tools are found (1) a precipitation-run-off model for long-term simulations of glacierized alpine catchment areas, (2) an operation tool for high-head hydropower HPP as well as flow regime generation and cost estimation of hydropeaking mitigation measures (Bieri 2012).
- **Work package E:** The last package “Methodology for mitigation measures for hydropeaking” develops recommendations for best practice in HPP production. Results are based on the knowledge and methods generated in packages B to D. In the present work, a tool for the assessment of cost-benefit effectiveness of mitigation measures is developed.

1.2 Research objectives

The present study investigates the effect of hydropeaking on fish and their habitats in alpine rivers. The thesis is divided into four main research objectives (A-D) described as follows:

- **Objective A** investigates habitat suitability for adult brown trout (*Salmo trutta*) in a river, affected by hydropeaking, using a habitat model.
- **Objective B** focuses on the more sensitive life stages of brown trout (juvenile, spawning and egg development) and proposes new indicators to assess the impact of hydropeaking on fish habitat. A special emphasis lies on how different river morphologies in combination with hydropeaking affect fish habitat.
- **Objective C** focuses on degraded river systems and tries to link the deficit in geomorphology and hydropeaking to their impact on fish habitat.
- **Objective D** develops a methodology to assess scenarios for fish habitat rehabilitation under hydropeaking influence using the knowledge gathered in the previous chapters. The method is applied for a hydropower plant scheme and its downstream river reach.

1.3 Case studies

To study ecological effects of hydropeaking on fish, two river systems were chosen: the Vorderrhein and the Hasliaare Rivers. The Vorderrhein River belongs to the headwater system of the Rhine catchment. It flows in the Surselva District of Kanton Graubunden and meets with another tributary, the Hinterrhein River. The two rivers flow together to form the Alpenrhein River which flows into Lake Constance. The Vorderrhein River is facing hydropeaking by a power plant scheme (operated by Kraftwerke Vorderrhein AG (KVR)), which was built between 1962 and 1968. The company operates two power plants in the Vorderrhein River and produces 790 GWh annually. The Vorderrhein River is one of the few rivers in Switzerland with a natural morphology. This allows studying the effect of hydropeaking, as the only anthropogenic stressor. The study reach, which is affected by hydropeaking is flowing in a steep canyon and shows characteristics of a braided river with dynamic restructuring gravel bed (Figure 1.2). These features provide ideal conditions to understand how morphology interacts with hydropeaking.

a)

b)

Figure 1.2: Picture of (a) the minimum flow reach in Mutteins (community of Breils/Brigels) and (b) the hydropeaking reach in Castrisch (community of Ilanz) of the Vorderrhein River. These reference reaches were used to model fish habitat. (Pictures taken in October 2010).

The second river, the Hasliaare River runs through the Berner Oberland and has a long history of human-induced modifications. It has long been used for hydropower production. The first dam and power plant “Handeck” was constructed between 1925 and 1932. Since then, the hydrological exploitation has been extended and now the hydropower network in this valley consists of a complex scheme of nine power plants and eight reservoirs. The KWO produced, generated approximately 1750 GWh in 2010. Moreover, the Hasliaare River has been strongly channelized in the downstream part, in the past century, for the purpose of flood protection and gain of agricultural land. The river is obstructed along both shores by traffic infrastructure. The hydropeaking reach is entirely channelized except for a short natural and steep canyon called the Aareschlucht (Figure 1.3). The channelized reach can be divided into three different types of engineered morphologies (Figure 1.4), allowing investigation of the joint effect of hydropeaking and degraded river morphology.

Figure 1.3: Picture of the Aareschlucht, the natural steep canyon yection section of the Hasliaare river This is the only morphologically intact section of the the hydropeaking reach of the Hasliaare River. (The picture were taken in October 2010).


a)


b)


c)

d) 

Figure 1.4: Picture of the Hasliaare River with (a) the minimum flow reach in Innertkirchen and the three types of engineered morphologies in the hydropeaking reach: (b) the groyne, (c) the gravel bars and (d) the channel (picture from Reto Haas) reaches. These reference reaches were used to model fish habitat. (All pictures were taken between October and November).

Both river catchments show similar elevation and characteristics of flow regulation. The hydrologic regime of the two rivers can be described as glacial and alpine, as they are characterized by low discharge in winter and high discharge in summer due to snowmelt. The rivers type can be described as rhithral, meaning a relatively cold water temperature in summer, a strong flow velocity and a riverbed mainly composed of gravels and stones. The study rivers belong to the "trout region" according to the Huet longitudinal fish zonation (Huet 1949).

On these two rivers systems, the impact of hydropeaking on brown trout is analyzed in the four main research objectives as previously described. Research objectives A and B focus exclusively on the impact of hydropeaking on fish habitat and fish reproduction; research has been conducted on the Vorderrhein River. Research objectives C and D investigate the effects of hydropeaking in a degraded river, the Hasliaare River and discuss possible mitigation measures. In this work, both rivers are not directly compared, even if some connections are considered in some discussion sections (see chapter 5 and 6). The choice to orient each research question on specific aspects of hydropeaking seperately was deliberate. The goal was to build an understanding of the complexity of hydropeaking effects on the river environment by first clarifying each particular aspects of the issue seperately. Therefore, each chapter is built based upon the findings and research directions resulting from the previous one.

1.4 Structure of the report

The present thesis is structured in seven chapters. A short outline of each chapter is given here:

Chapter 1: *Introduction.*

The present chapter briefly outlines the context in which the research project is embedded and its main objectives.

Chapter 2: *State of the art.*

This chapter summarizes the current knowledge in the field of interest. The motivating to perform the present work is discussed by identifying gaps in knowledge. Additionally, the research objectives are defined.

Chapter 3: *Characterization of seasonal habitat deficit in a flow regulated river with natural morphology.*

This chapter focuses on the adult life stage of brown trout and investigates seasonal differences in hydropeaking impacts on fish habitats at different times of the year. Sub-daily flow fluctuation is quantified seasonally and its effect on fish physical habitat is simulated with the help of a CASiMiR fish habitat model. The use of habitat models in assessing and quantifying the effects of hydropeaking is discussed. This chapter is a preliminary study, confirming literature results, highlighting open questions, and validating future research directions taken later in this work.

Chapter 4: *Flow instability and brown trout reproductive success. Development of new indices to model fish habitat loss.*

This chapter focuses on the sensitive life phases of brown trout related to recruitment, such as spawning individuals, the development of fertilized eggs and young-of the-year (YOY). New instability indicators are developed for describing the dynamic of habitat changes, such as shift and dewatering of habitats under fluctuating discharges. Brown trout preference for velocity, depth and substrate have been developed for the study river and integrated into habitat suitability curves (HSCs). The transferability and use of HSCs in modeling are investigated with a sensitivity analysis. The habitat conditions for young-of the-year and spawning brown trout is modeled with the newly developed, as well as classical habitat model indicators. In addition, egg survival and juvenile density under sub-daily flow conditions are assessed. The potential of river morphology to buffer negative effects from hydropeaking is discussed.

Chapter 5: *Joint effects of river channelization and flow regulation on brown trout population.*

This chapter analyzes the joint effect of hydropeaking and river channelization in the Hasliaare River. To assess the influence of morphology on the outcome of hydropower operations on fish habitat, three different aspects of degradation of the river morphology have been compared. The method, developed in the previous chapter is applied. Stream and lake resident brown trout habitat conditions are modeled with the help of instability indicators. The instability indicators quantify the loss and dewatering of habitat due to flow change. Specific HSCs for young-of the-year (YOY), lake and stream resident spawning brown trout are developed. Egg survival and post-emergent juvenile density has been assessed. The role of river geomorphology is evaluated with regard to the hydropeaking problem and potential ecological deficits in brown trout recruitment are identified. Finally, possible mitigation strategies and measures are discussed.

Chapter 6: *A tool to evaluate the cost-efficiency of mitigation measures to improve fish habitat.*

A new economic-ecological diagnostic and intervention method to assess the effectiveness of rehabilitation measures is developed and tested on the study case of the Hasliaare river system. The hydropower plant operations with and without hydropeaking mitigation and its impact on downstream fish habitat was simulated. Thus, for chosen mitigation scenarios, the costs and subsequent habitat improvement are generated and compared.

Chapter 7: *Synthesis.*

This chapter provides a general discussion, synthesis and outlook on the topic.

Chapters 3 to 6 are written as scientific articles. Chapter 3 was presented at an international conference and published in the conference proceedings. Chapter 4 was submitted for publication and chapter 6 is published in a peer-reviewed journal.

2 State of the art

This chapter provides a brief summary of current state and future challenges faced by hydropower production. It reviews the benefit and concerns of this energy source in the framework of energy strategy orientations, environmental impacts and climate change. The main focus is on high-head storage power plants whose operation results in hydropeaking.

A detailed research map of the current knowledge and mitigation of hydropeaking is provided. The knowledge assembled here aims to get a general understanding of the field of investigation.

2.1 Core issues of hydropower

A promising renewable source of energy

Renewable energy is the third largest contributor to global electricity production (18.1% of the world generation in 2001) and is mostly represented by hydropower (92 %). In today's current technological development, it is the most reliable and cost-effective renewable source of energy (Balat 2006). Hydropower is technically advanced, economically competitive with current market prices and used in over 160 countries. It represents 16 % of the worldwide electricity supply (Kumar *et al.* 2011). It is described as a key clean energy mainly because its contribution to greenhouse gas emissions is small.

High-head storage power plants (HPP) are recognized to be a driving force of socioeconomic development by substantially increasing water management options. In addition to hydroelectricity production, they provide a source of water supply, mitigate droughts and protect against flooding events. The energy is produced with a high flexibility in generation output and can be used both for base load and peak energy demand. Electricity generation can start and stop very quickly and with low costs, providing high range of generation levels in response to the market needs.

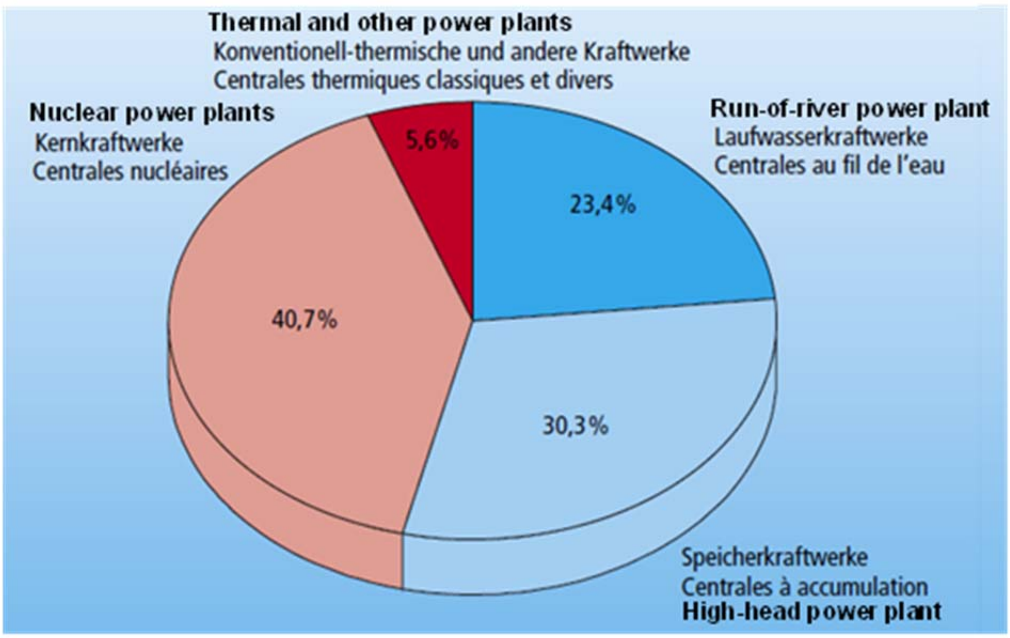


Figure 2.1: Pie chart of the sources of energy produced in Switzerland per power plant type (2011). Data from the Swiss Federal Office for Energy (Office Fédérale pour l'Energie - OFEN 2011).

Ideal conditions for hydropower production are found where precipitation and elevation differences are high. In Switzerland, where 60% of the surface is mountainous, the potential for production is substantial. The country comprises 156 large dams (> 15 m) and around 1'600 power plants (Thürler 2012). During summer when water is supplied by precipitation and snowmelt, the water is stored in the reservoir lakes in the alpine valleys. It can then be used to produce electricity for the energy network when consumption is high. Before the commissioning of nuclear power plants at the beginning of 1970s, hydropower accounted for 90 % of domestic electricity production. In 2011, actual generation ranged around 33,8 TWh. Nowadays, 40.7 % of the produced electricity comes from nuclear power, 23.4% run-of-river power plants and 30.3%, high-head power plants (Figure 2.1). In addition, hydroelectricity is an important component of the Swiss energy industry, with significant exchange to the European electricity market (OFEN 2011).

However, high-head storage power plants have several negative effects on the environment. One of the most severe concerns is the alteration of the downstream river ecosystem. The impact is mainly driven by changes in flow regime, suspended sediment load and temperature, which leads to loss of fragile freshwater habitats and biological diversity (Bruno & Siviglia 2012). Storage hydropower operations modify the volume and seasonal pattern of the river flow as well as water temperature and sediment load (IHA 2004). The growing awareness of these environmental issues led the public to understand the importance of gathering knowledge and implementing guidelines to find compromises for a sustainable management of hydropower.

Legal framework

Concerns regarding environmental aspects of hydropower production have a large impact on the development of national, regional and global policies.

The International Hydropower Association produced sustainability guidelines (IHA 2004) and the hydropower sustainability assessment protocol (IHA 2010) to provide a framework of good practices for hydropower production. In 2000, the European Union (EU) agreed on a water framework directive (WFD – European commission, 2000) committing EU members to achieve a good ecological and chemical status of all community water bodies by 2015 (WFD 2000). The promotion of sustainable water usage, the protection of the environment and aquatic ecosystems are among the objectives considered by the directive.

In Switzerland, the revised water protection act (Loi fédérale sur la protection des eaux (LEaux) modification du 11 décembre 2009) and the corresponding legal ordinance (814.201 Ordonnance sur la protection des eaux (OEaux)) came into effect on the 1st of January 2011. The goal of the modified act is to provide a framework for the protection of Swiss lakes and watercourses as habitat and biodiversity reservoirs. One of the main orientations is the reduction of the negative effects associated with hydropower production, in particular the effects on the flow regime. The act obliges the Swiss cantons to plan the necessary mitigation measures to buffer the impact of hydropeaking. The measures imposed are structural in opposition to operational measures which hinder electricity production. The planned mitigation will be financed by an increase of 0.1CHFct./kWh which will be charged to the electricity consumer.

In the legal ordinance, the damage, caused by hydropeaking to the indigenous fauna and flora and their biotopes, is considered as severe if the two following conditions are combined: 1) the ratio between off-peak and peak discharge is higher or equal to 1.5 and 2) causes drift and stranding of organisms, destruction of fish spawning redds as well as perturbation in the water temperature and turbidity (Art. 41e). The ordinance plans two phases for the implementation of mitigation strategies. First the cantons are bound to identify which power plant and downstream rivers are concerned by the article 41e and to provide a mitigation plan. In a second step, the hydropower plant holders identified by the canton must propose variants of mitigation scenarios for the concerned concessions. The chosen mitigation scenarios will be planned for implementation (Art. 41f).

The wish expressed by countries and organizations to promote sustainable use of hydropower and mitigate its impact on the ecosystem is restrained by a lack of scientific and expert knowledge which often leads to poor identification and management of the environmental impacts.

Future challenges for hydroelectricity

The world net electricity consumption is expected to double over the next two decades with an expected increase of the electricity demand of 2.3 % per year. Much of the growth is expected in developing countries, but in the industrialized nations an increase of 1.6 % is still expected (Balat 2006). Furthermore, the growing awareness about climate change leads to an adaptation of the current energy production strategies where hydropower is most likely to play a major role for is ability to reduce CO_2 emissions. The synthesis report of the intergovernmental panel on climate change (IPCC) indicates that hydropower could account for 17 % of the global electricity supply by 2030 (IPCC 2007).

Large opportunities for hydropower development are still present worldwide, with the largest growth potential in Africa, Asia and Latin America. In Europe, the estimated technically feasible capacity has now been largely exploited (WEC 2010). However, potential for growth can be achieved by renovation, modernization, expansion and upgrading of existing power plants (Schleiss 2007).

After the Fukushima incident in 2011, the Swiss Federal Council decided to decommission the Swiss nuclear power plants when they arrive at the end of their technical life. However, the “Energy Strategy 2050” (OFEN 2012) plans to maintain a high provisioning of electricity supply without nuclear power. Emphasis will be put on increasing efficiency of energy production, hydropower production and other renewable energies as wind and solar energy (Wüest 2012). Nowadays, over 85% of economically exploitable hydropower, is being utilized in Switzerland (Schleiss 2007). Thus, the plan for increasing production considers optimization, renovation and expansion of existing hydropower plants (Pfammatter 2012). The goal is to increase the mean estimated annual production by at least 2’000 GWh until 2030. In addition, market liberalization in the European Union will provide room for new activities and opportunities in the management of high-head and pumped-storage power plants.

Climate change is expected to have consequences on the distribution and management of the water resources. The main expected change will be a modification of river flow and sediment load as well as an increase in extreme events. The change in river flow will result from local modifications in precipitation and temperature, which will impact the runoff volume, the variability and seasonality of flow. Consequently, future hydropower operation will have to regionally adapt to these modifications (SGHL 2011). Nevertheless, with a harmonization in operation practice to the changing climate conditions, hydropower development is expected to remain rather stable in western and central Europe. Recently, tools and models were developed to help plan hydropower plant operations in this context (Bieri 2012; Bieri & Schleiss 2012).

New challenges for the development, planning and management of the high-head storage power plants are rising. In addition, the mitigation of its downstream environmental effect raises substantial concern. The need to understand the complex effect of hydropeaking on the river system is triggering research activity in this field.

2.2 Hydropeaking

To respond to the fluctuating energy demand, artificial discharge peaks, so-called hydropeaking, are created downstream of tailrace outlet at times of high energy production. Hydropeaking is defined as the release of water from a storage basin to generate energy. (Moog 1993; Charmasson & Zinke 2011). The water stored in reservoir lakes during summer is used in winter for electricity production consequently increasing the water level. The discharge in the receiving river varies rapidly from peak to off-peak flow depending on the energy demand. This dual nature of hydropeaking results in two ecologically different rivers (high and low flow) in which the taxa must be able to withstand the abiotic variability (Jones 2013).

a)

b)

Figure 2.2: Hydropeaking in Switzerland. a) Map of the rivers which show a hydropeaking regime (data from Limnex, 2001). b) The Vorderrhein River in Versam (Surselva district – Canton Graubunden) at off-peak discharge. The red arrow shows the difference in wetted area between peak and off-peak flow. The margin of the fluctuating water zone is clearly delimited by a layer of leaves which are deposited on the gravel shore. (Picture taken in November 2010).

In Switzerland, every fourth river is affected by a hydropeaking regime (Baumann & Klaus 2003) (Figure 2.2). During the last 30 years, a slight amplification of hydropeaking has been observed (Pfaundler & Keusen 2007b). Between two peaks events, the river water level can sink lower than the natural minimum water level (Meile *et al.* 2005). During peaks, the water level is significantly higher than naturally. These high discharge events differ from natural floods in several ways (Limnex 2004): 1) hydropeaking happens regularly and at a higher frequency. 2) discharge rises faster. 3) these artificial floods cannot be sensed by organisms by a change in water level or water chemistry (Baumann & Klaus 2003). Natural organisms are not adapted to such regular discharge changes and their reaction abilities are overcome. Thus, daily hydropeaking events, due to their unpredictability, and intensity disturb the natural abiotic structure of the ecosystems (Bruno & Siviglia 2012).

2.1.1 Abiotic effects

A flowchart of hydropeaking impacts on the river ecosystem is shown in Figure 2.3. The morphology, discharge regime and the water quality are the three abiotic characteristics directly impacted by hydropeaking. In a cascading effect, other abiotic characteristics of the river get subsequently altered such as depth, width, velocity, sediment load and water temperature, which ultimately affects the habitat of living organisms (Cushman 1985).

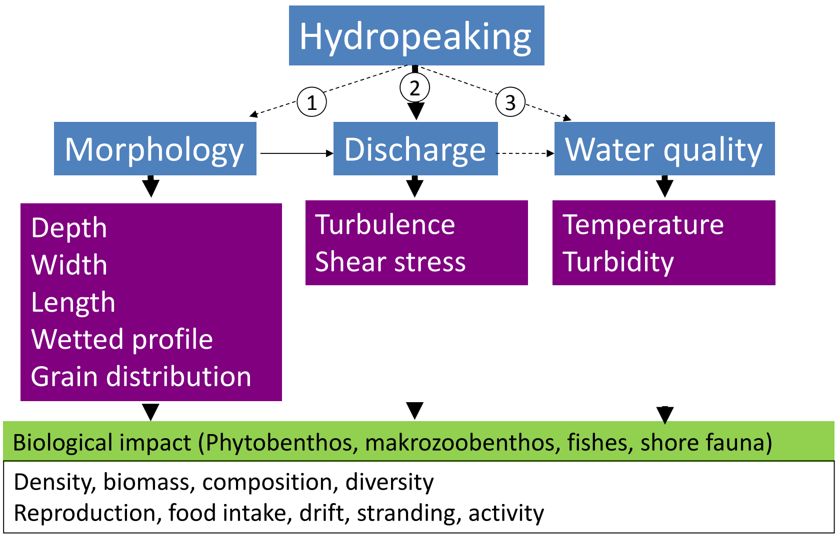


Figure 2.3: Impact of hydropeaking on river status - translated from (Meile *et al.* 2008).

Hydrology

The main alteration caused by high head storage power plant is the modification of the downstream hydrological characteristics of the river. The discharge regime which is a key factor for ecological quality of river ecosystem is dramatically affected (Poff *et al.* 1997). Several indicators and methods were developed to characterize the hydropeaking regime (Meile 2007; Meile *et al.* 2011; Baumann *et al.* 2012; Sauterleute & Charmasson 2012). The most relevant parameters for this study are:

Peak and off-peak discharge (Q_{max} and Q_{min}), amplitude ($Q_{max} - Q_{min}$), the ratio between peak and off-peak discharge so-called drawdown range (Q_{max}/Q_{min}) and the rate of flow change which is described as the flow ramping rate (Meile *et al.* 2011). The rate of hydropeaking varies a lot among power plants and rivers. In Switzerland, the drawdown range during winter season varies between 2:1 and 15,5:1 depending on the observed power plant – river system (Meile *et al.* 2006).

Temperature

The water released downstream from the powerhouse outlet has a different temperature than the receiving river. Aside from discharge peaks this phenomenom creates, temperature peaks so-called thermopeaking (Frutiger 2004a; Carolli *et al.* 2009; Zolezzi *et al.* 2011). The water in the reservoir has a rather constant temperature which can slightly warm or cool the receiving water body depending in the season. Thus, watercourse downstream of a high head storage hydropower plant show a moderate temperature regime compared to natural alpine rivers.

When looking at the dynamic of the thermopeaking and the hydropeaking wave, it was shown that, due to a difference in velocity, the two waves tend to dissociate while they propagate (Toffolon *et al*. 2010). The two asynchronous waves have distinct impacts on the biota. In high alpine floodplain rivers, the influence of flow regulation on water temperatures may impact thermal regimes of adjacent rivers even where there is no direct surface connectivity. The temperature modification can continue for periods of several weeks after the HPP operations have ceased (Dickson *et al*. 2012). As the thermal regime is a key component for freshwater ecosystems integrity, its alteration through dam operation has several ecological implications (Olden & Naiman 2010).

Sediment and water quality

The sediment carrying capacity of rivers depends on its hydrological characteristics such as slope, velocity and depth. As a consequence of flow alteration several processes of sediment transport are affected. During peak flow, the sediment is transported due to sediment abrasion and increase erosion. This resuspension of particles increases water turbidity (Anselmetti *et al.* 2007). During off-peak flow, due to low water velocities, the sediment is redeposited. This ultimately leads to clogging of the river bed (Gailiuis & Kriauciuniene 2009). This bed clogging is classified as outer and inner clogging depending on if the sediment is deposited on the surface or in the interstitial space of the bed (Schächli *et al.* 2002).

Other important processes are affected by dam operations such as ground water quality and quantity, the hydrological thermal and geochemical dynamic of riparian aquifers and their hyporheic zone (Meile *et al.* 2005; Sawyer *et al.* 2009; Casas-Mulet & Alfredsen 2012).

2.2.2 Biotic effects

The abiotic parameters, with the morphological characteristic of the river, determine the physical habitat for living organisms. As a consequence, the availability and suitability of this habitat is altered by the modification of the abiotic parameters. The riverine biological communities are consequently directly affected by hydropeaking and several studies reported this impact on fish, invertebrates or aquatic plants (Moog 1993; Smokorowski *et al.* 2011; Sanz 2012).

Shore fauna, macrophytes and benthos

Due to the high instability of the wetted area, the species richness of the riparian fauna is reduced (Paetzold *et al.* 2008) and the plant community composition is shifted toward intermittent river flora (Bernez & Ferreira 2007). Water turbidity reduces the availability of light for underwater plants and algae. Consequently, their growth is hindered due to a decrease in the rate of photosynthesis.

Macroinvertebrates, which are good indicators of river quality, were studied and the impact of hydropeaking was classified in short term and long term effects. Long term effects include shift in longitudinal zonation, communities with less diversity and reduction in taxa number and abundance (Brabec 1998; Lagarrigue *et al.* 2002; Jackson *et al.* 2007). Short term effects include drift, loss of refugia and impaired larval development (Frutiger 2004b). Organisms drift can either be behavioral or catastrophic. The behavioral drift is caused by abrupt temperature variations and happens when the temperature goes beyond the tolerability range of the organism. Larvae of Chironomidae, Simuliidae and Baetidae are most sensitive to this active drift (Carolli *et al.* 2012). Catastrophic drift is caused by an increase in water velocity and shear stress at the riverbed which flushes the organisms downstream (Cereghino *et al.* 1997; Cereghino *et al.* 2002; Cereghino *et al.* 2004; Hay *et al.* 2008; Bruno *et al.* 2010). The inner bed clogging fills interstitial space eliminating refugia zones (Bruno *et al.* 2009). Outer bed clogging impairs access to stable substrate and can embed the organisms under deposits of fine sediments (Jones *et al.* 2012).

Fish

Fish are highly valuable aquatic organisms which provide numerous essential ecosystem services (Holmlund & Hammer 1999). They are good indicators of the environmental state of the ecosystem (Harris 1995) and are often chosen as target species to study the impact of hydropower operations (Young *et al.* 2011). Several studies demonstrated that fish populations are less abundant and have reduced population sizes in hydropeaking rivers (Garcia *et al.* 2010; Costa *et al.* 2012).

Because salmonids species occur in the upper part of catchments, where the potential for hydropower is high, they are strongly impacted. Figure 2.4 shows the interaction between the abiotic processes modified by hydropeaking and their consequences on salmonids populations. The impact differs depending on the life stage or the time of the year considered. The intensity and gravity of the disturbance also depends on the river morphology.

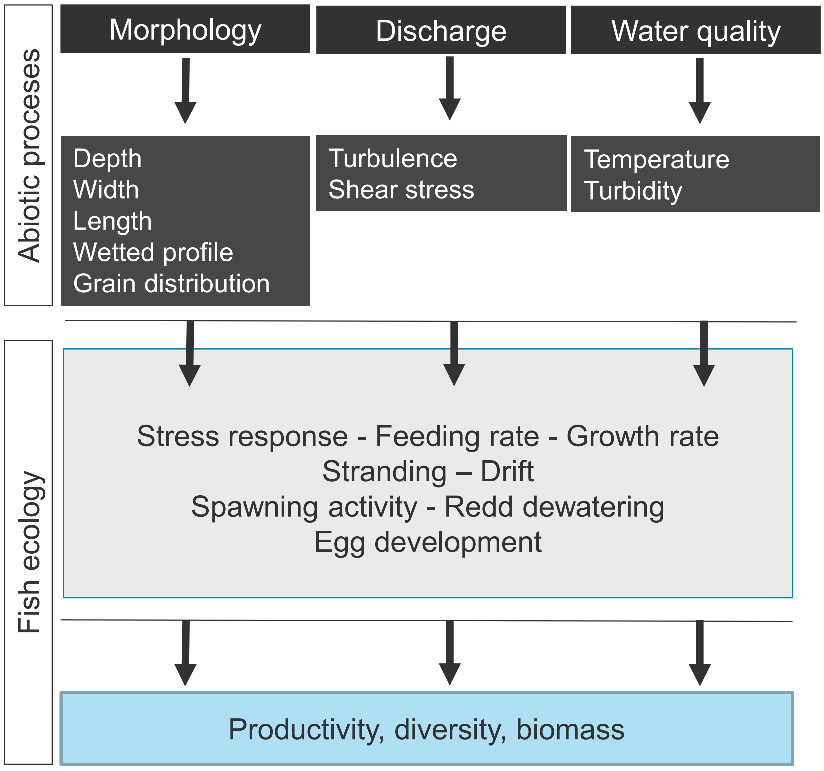


Figure 2.4: Interaction between abiotic processes impacted by hydropeaking and their consequences on salmonids population.

Native salmonid species found in Switzerland are the European trout complex (*Salmo trutta* species complex) (Keller *et al.* 2012), the European Whitefish complex (*Coregonus sp.*) (Vonlanthen 2009), the Arctic Char (*Salvelinus Alpinus*) and the Grayling (*Thymallus thymallus*). Because of its ecological requirements and occurrence pattern, brown trout is the species most impacted by dam operation in Swiss mountains and thus was chosen as the target species of this study. This fish species is easy to sample and allows for the study of different aspects of the impact of hydropeaking on the downstream river habitat mainly because of its complex life cycle. Brown trout has very specific and varied habitat requirements during its different life stages, starting from the fertilized eggs to the mature reproductive adult. Figure 2.5 shows the life cycle of the two ecotypes; lake (*Salmo trutta lacustris*) and stream (*Salmo trutta fario*) resident brown trout. The stream resident ecotype spends its entire life in the river while the lake resident brown trout migrates between growth and reproduction habitats. Lake resident ecotype lives as adult in lakes where the food availability is greater and the growth rate faster. In fall, the mature adults move great distances to spawn in small alpine rivers where the oxygen and temperature conditions for egg development are optimal. They always return to spawn to the stream where they were themselves born. This phenomenon is known as homing (Crisp 2000). Migration takes place over large distances, for example, more than 100 km between the Lake Constance and the spawning places in Vorderrhein River. Even if they do not migrate such long distances, stream resident brown trout also show a migrating behavior (Baglinière & Maisse 2002).

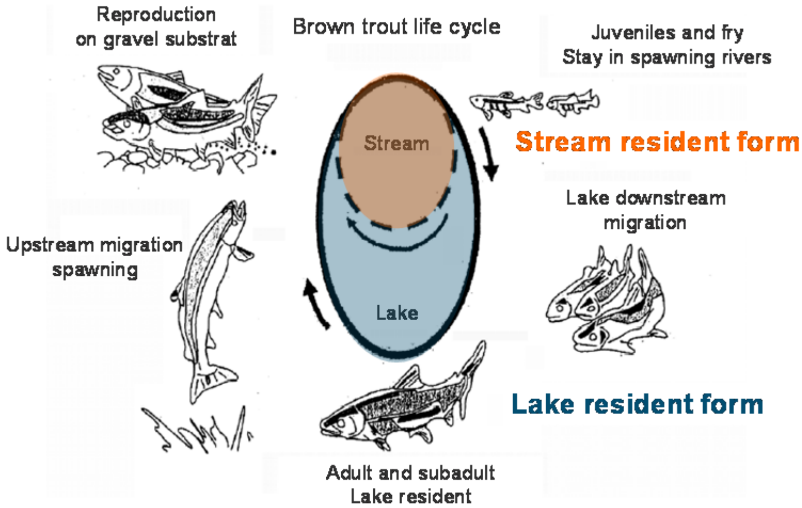


Figure 2.5 : Life cycle of stream and lake resident trout The stream and lake resident life cycles are shown in orange and blue respectivelly. Adapted from Ruhlé *et al.* (2005).

During the juvenile stages, the two ecotypes cannot be distinguished. During the first year of their life, the juveniles are called young-of-the-year and are particularly sensitive (Figure 2.6). After hatching, the alevins stay into the intragravel space and feed on their yolk sack. After resorption of the yolk sack, the fry emerges from the substrate to find a territory where to feed and grow (Elliot 1994; Roussel & Bardonnet 2002). From the emergence to the end of the first summer, mortality is very high (Baglinière & Maisse 1991).

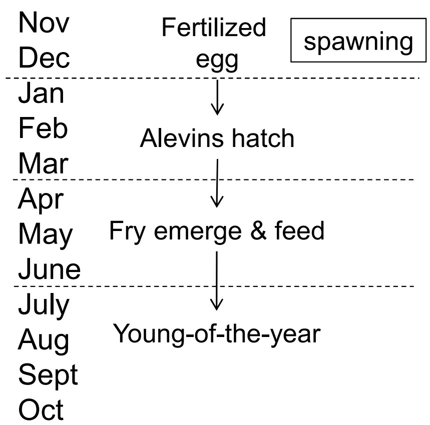


Figure 2.6: Terminology for the different life stage during the first year of life for stream and lake resident brown trout. Adapted from Elliot (1994).

The following section reviews the different impacts on fish reported in the literature with a special emphasis on salmonids. The negative effect of hydropeaking can be classified in different categories: a) fish behavior, b) fish migration, c) spawning habitat and egg development, d) juvenile life stages (0+).

Fish behavior

Fish activity fluctuates between day-night or winter-summer patterns. Experiments on adult and juveniles showed that individuals are normally less active during winter periods. However, HPP operations, fish non-migratory movement was increased and individuals showed larger home range (Heggenes *et al.* 2007; Taylor & Cooke 2012).

It was thus suggested that without appropriate flow shelter habitat, the hydropeaking regime can be energetically costly and affect over-wintering survival (Scruton *et al.* 2003; Scruton *et al.* 2008). Increased turbidity hinders fish visibility which impairs visual feeding behavior. In addition, the difficulty to find prey is increased by the deficit in macroinvertebrate density (Bruder *et al.* 2012a). All these impacts are likely to increase fish stress (Taylor *et al.* 2012). However, when looking at the effect of power plant operations on fish behavior, adults are not necessarily the most sensitive life stage (Valentin *et al.* 1996; Capra *et al.* 2012).

Fish migration

Temperature and discharge, which are both affected by peak operations, are key factors influencing spawning migration behavior (Greenberg *et al.* 1996). Telemetry experiments revealed that lake resident trout migration pattern was correlated to the hydropeaking regime, individuals achieving greater distances on the weekend when flow fluctuations were lower (Mendez 2007). However, the impact of HPP operations on fish migration is yet to be studied more deeply.

Spawning habitat and egg development

Salmon and trout spawn during the autumn and winter months and in Swiss alpine rivers, spawning occurs mainly between October and December. The female deposits the eggs in series of gravel nests known as redds. Brown trout spawn in shallow water (10 to 80cm depth) with a velocity ranging from 10 to 80 cms^{-1} and a clean gravel bed (Armstrong *et al.* 2003). Telemetry experiments provided evidence that the spawning activity takes places in hydropeaking influenced reaches (Caviezel 2006). In such conditions, dewatering of redds was observed due to the daily fluctuation in wetted area (Courret *et al.* 2012). In addition, during the peak phase, the scouring risk of redds is increased due to movement of sediment (Eberstaller & Pinka 2001). This risk is particularly high for alpine brown trout, which usually spawn in less than 4 cm substrate depth (Riedl & Peter 2013).

The water circulating through the gravel and coming from upwelling groundwater provides oxygen for egg development (Sear *et al.* 2012), thus the survival of the embryos, strongly depends on the location of the redd. In addition, fine sediment accumulation impairing dissolved oxygen consumption of eggs has severe impacts on salmonids embryos and alevins survival (Jensen *et al.* 2009; Yamada & Nakamura 2009; Louhi *et al.* 2011). Due to bed clogging and high water turbidity, the success of salmonid reproduction could be drastically reduced in hydropeaking rivers. This is supported by recent incubation experiments on the Alpenrhein River, which analyzed embryo survival until the eyed egg stage (Zarn 2008).

However, very little is known about brown trout reproduction success in rivers influenced by hydropeaking. In addition some rivers are strongly degraded and largely stocked, which increases the difficulty to evaluate the state of the natural reproduction. One of the scopes of the thesis presented here is to investigate the effect of flow fluctuation on brown trout reproduction including spawning and egg development.

Juvenile life stages (0+)

At young life stages fish have very special habitat requirements. Brown trout fry often stay near the spawning habitat were they emerged (Gaudin *et al.* 1995; Heland *et al.* 1995). After their emergence, the young-of-the-year (YOY) search for a territory where to feed and grow. They are found in shallow habitat near the riverbank, were the flow velocity is reduced. This shore habitat is very unstable in hydropeaking regimes, where the water level and wetted area are constantly moving. In hydropeaking rivers, juvenile density and growth rate is reduced and mesohabitat choice disturbed (Jensen & Johnsen 1999; Flodmark *et al.* 2006; Korman & Campana 2009). Due to the variability in wetted area and the rapid discharge increase associated to peak flow, juveniles drift or get stranded when they cannot find appropriate shelter. However, drift and stranding risks are dependent of the river morphology (Irvine *et al.* 2009; Nagrodski *et al.* 2012; Tuhtan *et al.* 2012). Studies show that the salmonid juveniles had larger home ranges and changed their habitat use in terms of velocity and depth in hydropeaking conditions (Scruton *et al.* 2005; Scruton *et al.* 2008). Juvenile reaction can be divided in two behavioral patterns; A fraction of the cohort keeps high site fidelity which might increase stranding risk, while the other fraction shows considerable movement in relationship with the flow regime which might increase body energy consumption (Scruton *et al.* 2008). In the present work, the influence of hydropeaking on juvenile habitat suitability and juvenile density will be considered. The instability of the habitat will be quantified and the effect of river morphology in habitat dynamic and availability will be assessed.

2.3 Restoring the river ecosystem

2.3.1 Rivers under multiple stressors

Since the end of the 18th century, surface water was intensively used by human societies for drinking, irrigation, energy production, waste water disposal and leisure. Intensive land use resulted in the alteration of the structure of watersheds. Numerous rivers were channelized and straightened to gain land for agriculture and protect human settlements against flood risk. The space originally allotted to surface waters has been tremendously reduced and at the same time the natural river processes have been impaired. Channel form and water flow are relevant components of river health, and their impairment threatens ecosystem functioning (Elosegi & Sabater 2012). The river morphology is a very important criterion determining habitat availability. Natural morphology offers more habitat diversity than a more homogeneous and uniform one (Cianfrani *et al.* 2009). Channelization led to the homogenization of hydraulic and sedimentary characteristics, the loss of backwaters and flow refugia, which had detrimental consequences on the river fauna (Negishi *et al.* 2002; Millidine *et al.* 2012). In the context of hydropeaking, morphology strongly influences the spatial distribution and heterogeneity of physical habitat parameters. Because of the complexity of the river's natural system, hydropeaking mitigation must be undertaken taking the entire catchment into consideration (Peter 2010).

2.3.2 Mitigation of hydropeaking

Interest in river rehabilitation is rapidly growing (Bernhardt & Palmer 2011) and the importance of flow regime as a key parameter in restoration projects for ecosystem functioning and species diversity has been recognized (Poff *et al.* 2010; Poff & Zimmerman 2010). In literature, three main directions in hydropeaking mitigation can be pointed out: operation, structural and morphological improvement measures:

- *Operational measures* imply a change in the power plant management with the setting of limitations to the operation rules e.g. slower start and stop of the turbines or anticyclic turbine activity. This can be achieved by limitating maximal discharge (Q_{max}), increasing minimum flow (Q_{min}), limitating drawdown range (Q_{max}/Q_{min}) or decreasing up- and downramping rates. For setting the appropriate operation rules in existing power plants, a methodology was proposed by Yin *et al.* (2012). However, the disadvantage of these measures are the associated severe economic consequences (Gostner *et al.* 2011).
- *Structural measures* involve measures which do not directly affect the hydropower plant operation but reduce or eliminate hydropeaking with the construction of compensation basins/caverns or bypass tunnels (Schweizer *et al.* 2008). The water is diverted and released respecting ecologically defined rules. However, these measures can sometime be constrained by land availability, the proximity of an alternative receiving water body or high level of ground water.
- *Morphological measures* deal with river engineering measures. The goal of morphology restoration is to rehabilitate the ecologically dynamic state as found in the appropriate reference systems (Palmer *et al.* 2005). In areas where land use and settlements are dense, the limited space constrains the feasibility of morphological improvements. Thus, morphological measures for hydropeaking mitigation often focus on increasing the flood evacuation capacity of the system, buffering peak flow and providing shelter habitats for fish and other organisms (Fette *et al.* 2007; Ribi 2011; Kindle *et al.* 2012; Speerli & Schneider 2012).

The two first types of measures directly target the hydropeaking regime. The third type indirectly buffers the effect of hydropower operations with the help of river morphological improvements. Being rather a new scientific area, it is hard to assess the effectiveness of such measures when the hydropeaking flow regime remains unchanged. The ecological effectiveness of direct and indirect measures applied alone is nowadays controversial (Fette *et al.* 2007). Recent studies promote a combination of measures to achieve a good ecological status of rivers under hydropeaking (Charmasson & Zinke 2011; Kindle *et al.* 2012). Such combinations of measures can be integrated in multipurpose schemes building synergies between ecological integrity, flood safety and energy production (Pellaud *et al.* 2006; Pellaud 2007; Heller & Schleiss 2011). Nevertheless, little is known about the ecological implication of hydropeaking and the effectiveness of restoration measures strongly depends on the orientation of future research (Bruder *et al.* 2012b; Melcher *et al.* 2012). In the present research study, tools are developed to assess the effectivenss of mitigation measures and understand the role that morphology plays in hydropeaking mitigation.

2.4 Environmental flow and habitat modeling

The natural flow regime is a very important parameter for the ecological integrity and species diversity in a river. The physical habitat of the river is directly and indirectly influenced by the flow regime. A mosaic of habitat features are created and maintained by hydrologic variability (Poff *et al.* 1997). These habitats support a diversity of species that evolved to adapt to this dynamic flow and habitat conditions. For example, a lot of river species life cycles require a diversity of habitat types, which fluctuate over time (Reeves *et al.* 1995; Greenberg *et al.* 1996). The need to set environmental flow (e-flow) in water management is essential (Acreman *et al.* 2009; Poff *et al.* 2010). For setting e-flow in rivers influenced by hydropeaking, several approaches and hydraulic models are developed (Alfredsen *et al.* 2012; Bakken *et al.* 2012; Hauer *et al.* 2012).

2.4.1 Instream habitat models

In the past several years, habitat modeling has been a growing field in the evaluation of altered water flow conditions on aquatic ecosystems. In the context of the Instream Flow Incremental Methodology (IFIM), methods and models have been developed to assess hydrological and morphologic impacts, on the habitat of aquatic biota, of human river management (Bovee *et al.* 1988). The collection of Physical Habitat Simulation Models (PHABSIM) quantifies the microhabitat area per unit length of stream (Bovee & Milhous 1978). A typical PHABSIM is made of three components 1) a hydrodynamic model: models the spatial and temporal variations in depth, velocity and substrate conditions, 2) biological data: consisting of the fish habitat use and preference and 3) a resulting habitat model. The habitat model combines the results of the hydraulic model and the biological data to determine the habitat available for the target fish species under a chosen flow condition.

Several models from this family, where developed worldwide over the years including RHABSIM (Payne 1994), RHYHABSIM (Jowett 1989), EVHA (Souchon *et al.* 1989), MHM (Scholten *et al*. 2003), CASiMiR (Jorde 1996) or recently SEFA (Payne & Jowett 2012). Microhabitat models are useful tools to assess the effect of hydropeaking on fish habitat (Garcia *et al.* 2010; Scholten 2012). However, such models usually do not integrate dynamic flow fluctuations. Recent developments were made toward integrating the risks associated to hydropeaking as stranding and redd dewatering (Leo *et al.* 2012; Schmidt *et al.* 2012; Schneider *et al.* 2012).

2.4.2 Fish habitat preference

Fish habitat is usually described in abiotic terms, which vary strongly with flow regime. The three most relevant abiotic parameters are substrate composition, flow velocity and depth (Armstrong *et al.* 2003).

The most used biological habitat preference descriptors in instream physical models are Habitat Suitability Curves (HSC) and fuzzy rules. Habitat Suitability Curves (HSCs) are constructed from the product of habitat use by the organism over habitat availability in the ecosystem studied. They can be built for various abiotic parameters and different life stages. The fuzzy-rule based model has been proposed as an alternative to the habitat suitability model (Jorde *et al.* 2000; Schneider *et al.* 2001). It is based on a series of verbal types IF-THEN rules similar to the way human brain thinks. They are based on expert knowledge and not on in-situ habitat suitability measurements. Recently, new fuzzy rules were developed for describing the risk associated with hydropeaking as redd dewatering, redd scouring or juvenile stranding (Kopecki *et al.* 2012; Schneider *et al.* 2012; Tuhtan *et al.* 2012).

HSC-based models are very sensitive to the accuracy and origin of preference data. Use of HSC from other regions found in literature can be inappropriate (Heggenes *et al.* 1996; Moir *et al.* 2005). Nevertheless, the uncertainty associated with fish preference and its influence on the model output is still a debated point (Ayllón *et al.* 2012; Macura *et al.* 2012; Munoz-Mas *et al.* 2012). In the univariate HSCs approach, the interaction between the physical parameters is often not taken into account. Biotic factors are not included and temporal heterogeneity in habitat conditions and preference is considered only in a limited extent (Heggenes 1996; Holm *et al.* 2001; Ibbotson & Dunbar 2002; Fukuda *et al.* 2012). To overcome this problematic, alternative methods are currently developed such as random forest (Vezza *et al.* 2012), a non-equilibrium thermodynamic model (Tuhtan 2011, 2012) or genetic models (Fukuda & De Baets 2012). However, these methods are currently not applied to the microhabitat approach.

2.4.3 CASiMiR

CASiMiR is a simulation system for the investigation of aquatic habitats. Being a member of the instream physical models family, it requires physical and biological parameters. A hydrological-physical model is coupled to biological data of the species of interest and for a particular life stage. Both HSCs or fuzzy-rules can be used (Jorde *et al.* 2000; Schneider *et al.* 2001). CASiMiR includes a fish module which models fish habitat suitability and structural characteristics at different flows (Figure 2.7). A conservation study performed in a Chilean river used CASiMiR to predict the evolution of 8 fish species habitats under varying physical habitat conditions under hydropeaking(Garcia *et al.* 2010).

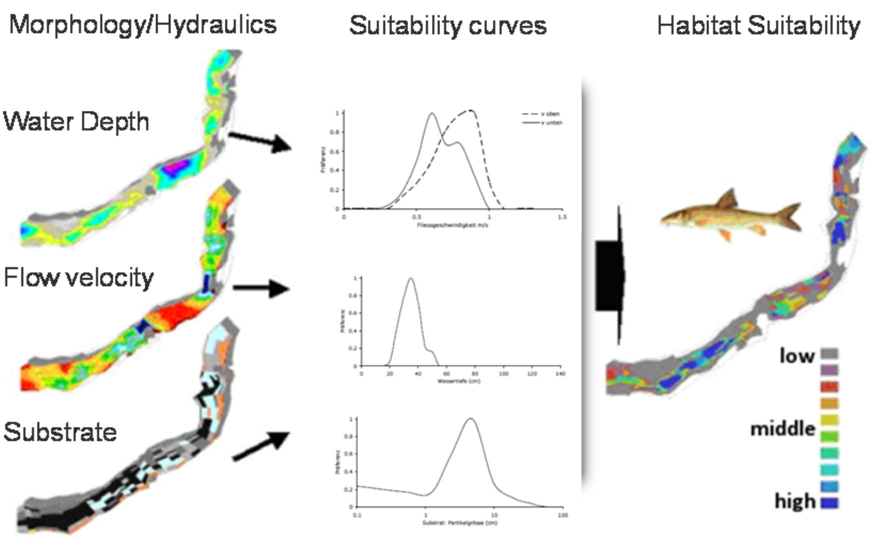


Figure 2.7: Input and output data from CASiMiR habitat model. Input data are the morphological and hydrological conditions for the studied section and suitability curves calculated for the three main abiotic parameters; depth, velocity and substrate (Schneider *et al.* 2001).

The following parameters describe the integrated distribution of habitat suitability in a river reach under on steady discharge condition:

Habitat suitability index (HSI): SI values range from 0 to 1 and can be presented on habitat suitability maps for the investigated discharges. Several mathematical methods are known to define the overall SI based on the preference values for each abiotic parameter (velocity, depth and substrate), including the product equation, the arithmetic mean, and the geometrical mean. In this study, the geometric mean was chosen for the calculation of the overall SI because the product and the arithmetic mean tend to overestimate overall suitability when one of the individual suitability of flow, velocity, depth, or substrate is very high:

$$\mathrm{SI}_i(Q) = \sqrt[3]{P(H_i(Q)) \cdot P(U_i(Q)) \cdot P(S_i(Q))} \tag{1}$$

where $\mathrm{SI}_i(Q)$ [-] represents the Suitability Index in *i*-cell for discharge Q, $P(H_i(Q))$ [-] the suitability value for flow depth H_i for discharge Q, $P(U_i(Q))$ [-] the suitability value for velocity U_i for discharge Q and $P(S_i(Q))$ [-] the suitability value for the substrate S_i for discharge Q.

Weighted usable area (WUA) [m^2]: corresponds to the total available habitat for a given discharge (Bovee 1982) and provides an absolute value for the overall habitat quality of a reach. It is the sum of the available habitat of each wetted cell regarding flow depth and velocity as well as substrate:

$$\mathrm{WUA}(Q) = \sum_{i=1}^{n} A_i \cdot \mathrm{SI}_i(Q) \tag{2}$$

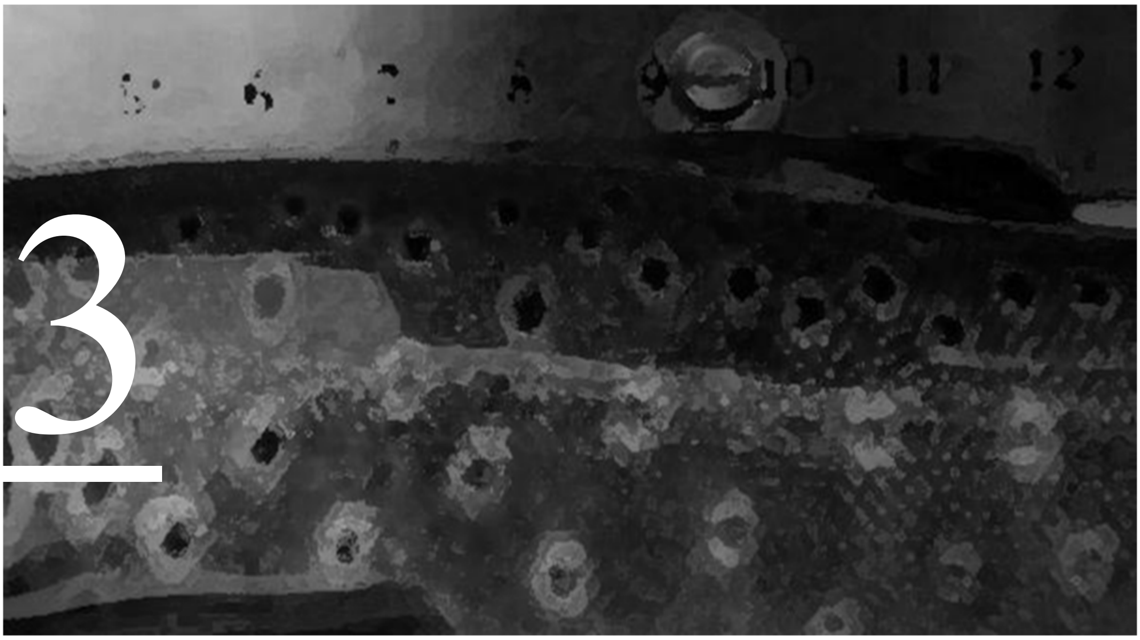
where Q [m^3/s] represents the discharge, A_i [m^2] the area of *i*-cell and $\mathrm{SI}_i(Q)$ [-] the Suitability Index of *i*-cell for discharge Q.

Habitat suitability index (HSI)[-]: is the ratio of WUA over the total wetted area (WA_{tot}) [m^2] for discharge Q. HHS represents the suitability of the physical habitat variables for the considered specie. This index defines if the overall habitat suitability in the study reach is affected by either modified abiotic parameters or changes of wetted area:

$$\mathrm{HHS}(Q) = \frac{\mathrm{WUA}(Q)}{\mathrm{WA}_{tot}(Q)} \tag{3}$$

Weighted Usable Area (WUA) and Hydraulic Habitat Suitability (HHS) were developed within the instream flow incremental methodology (Bovee 1982) to determine the minimum flow requirement for the target species. Both parameters describe habitat on a stationary mode integrating the overall habitat suitability on a reach for a steady state. Moreover, the same WUA or HHS value can represent several low-quality or a few high-quality habitat areas. To quantify instability or the dynamic changes in habitat distribution under fluctuating discharge, non-stationary parameters such as habitat time series or duration curves have to be used. Nevertheless, these non-stationary parameters do not quantify habitat dewatering or habitat displacement resulting from a hydropeaking regime.

In the present research study, the sensitivity of the model to preference data from several field sites is examined. Habitat requirement for brown trout is robustly analyzed and new indices are developed to adapt the current model descriptors to the assessment of habitat dynamics under hydropeaking. The temporal availability and suitability of the habitat is studied in relation to the magnitude and intensity of flow change, resulting from the unnatural schedule of power generation. As a result, the study quantifies habitat loss and habitat dewatering between peak and off-peak conditions. These new indices consider only highly suitable habitat (Suitability Index above a defined threshold value).



3

Characterization of seasonal habitat deficit in a flow regulated river with natural morphology

Hydropower is a promising renewable energy for developed and developing countries. However, its downstream impacts on rivers are not entirely understood. Researchers and stakeholders initiated the interdisciplinary project: “Sustainable use of hydropower - innovative measures to reduce hydropeaking effects” to find environmental solutions downstream of high storage dams and to restore suitable habitat conditions for fishes. In this research project, the impact of hydropeaking on different brown trout life stages in Swiss alpine rivers with a glacial hydrological regime was studied. Physical habitat conditions were simulated for highly degraded to almost natural stream morphologies and brown trout natural reproduction success was assessed with egg incubation experiments and juvenile density monitoring under unsteady flow conditions. In this chapter, the first results of this integrated research project are presented. The seasonal hydrological impact of hydropeaking on physical habitat conditions for adult brown trout is evaluated using CASiMiR habitat modeling. In a first step, only the adult stage is investigated, to set and validate background knowledge on the impact of hydropeaking on fish habitat. The results will help validate and focus future research directions in the following chapters. Results showed that hydropeaking has a strong impact on fish habitat mainly during winter where suitable habitat is strongly displaced under unstable flow conditions. Evidence of habitat displacement suggests that peak flow might be energetically costly to fish and decrease their physical fitness during winter.

3.1 Introduction

High head storage hydropower plants (HPP) supply most of the peak load energy demand in alpine areas where topography and high level of annual rainfall provide ideal conditions for hydropower production. This valuable energy source contributes to the security of the energy market by providing base load and peak energy as well as to the energy network stability. Due to their storage capacity, HPP enable the flexibility to deliver large amounts of energy during peak hours according to market demand. As a result, HPP produce artificial discharge peaks—known as hydropeaking—that are released in the river downstream of their reservoir dams. In Switzerland, hydropower is the most important domestic source of renewable energy, and a hydropeaking regime occurs in one out of four rivers as reported in by the Swiss Federal Office for Environment (Baumann & Klaus 2003). At the local level, hydropower plants have significant impacts on water bodies. Hydropeaking modifies seasonal temperature and discharge patterns, fine sediments concentrations, winter turbidity conditions, and bed clogging (Gailiuis & Kriauciuniene 2009). In addition, distinct changes of geochemical dynamics of riparian aquifers are observed (Sawyer *et al.* 2009). Moreover, river flow is a key ecological factor in freshwater ecosystems (Parasiewicz *et al.* 1998). Thus, daily HPP water releases disturb the natural discharge regime in the river because of their unpredictability and intensity. Discharge fluctuations occur more frequently and quickly than natural floods, and they significantly overcome the reaction abilities of natural organisms (Limnex 2004).

HPP downstream water restitution impacts salmonids species because of their habitat requirements. Daily fluctuations in flow velocity, depth and wetted area strongly affect fish habitat availability and quality. Some studies showed that salmonid populations are less abundant and have reduced population sizes in hydropeaking rivers (Moog 1993). Without appropriate flow shelter habitat, hydropeaking regime increase fish energy consumption through displacement and affect the over-wintering survival of individuals (Scruton *et al.* 2003; Scruton *et al.* 2008). Because brown trout occur in the upper part of catchments, where the potential for hydropower is high due to the steeper slope, dam operation impacts them more than other salmonid species.

In the past several years, the field of habitat modeling for the evaluation of altered water flow conditions on aquatic ecosystems has grown. A typical instream habitat model is made of three components: 1) a hydrodynamic model, which models the spatial and temporal variations in depth, velocity and substrate conditions, 2) biological data on habitat use and preference for the target fish species, and 3) a resulting habitat model. The habitat model simulates the geographical distribution of depth, velocity and substrate classes in the study reach. Habitat suitability is determined on the organism's preference for the three abiotic parameters. Knowledge on organism preference for depth, velocity and substrate classes is based on habitat suitability curves (HSCs). HCSs are the product of habitat use over habitat availability in the ecosystem studied. They can be built for various abiotic parameters and different life stages for the specie of interest. CASiMiR evaluates aquatic habitat quality at different discharges. As a member of the instream models family, it couples a hydrological-physical model to biological data of the target species (Jorde *et al.* 2000; Schneider *et al.* 2001). CASiMiR includes a fish module, which models changes in fish habitat suitability for varying flow rates.

In this chapter, the effect of daily peak fluctuation on adult brown trout habitat was investigated using CASiMiR fish module in the Vorderrhein River: one of the few natural, morphologically intact Swiss rivers used for hydroppower production. This chapter sets and validates current knowledge on the impact of hydropeaking on brown trout and stands as the foundation and justification for the future research directions taken later on in this work. Thus, in this first step, only the adult stage is investigated here.

3.2 Method

The Vorderrhein River is a headwater of the Rhein River and is located in the Surselva District of Kanton Graubünden. It has a catchment area of 776 km^2 with a mean elevation of 2020 meter above sea level. Glaciers cover 3.8 % of its surface. Vorderrhein shows a nivo-glacial discharge regime (Hydrological atlas of Switzerland, 2009) with a mean annual discharge of 30.5 m^3/s and mean annual temperature of 6.2°C (Federal Office for Environment, 2010). The river is situated in an alpine region and shows a fish community assemblage typical for the trout zone according to Huet’s fish zonation (Huet 1949).

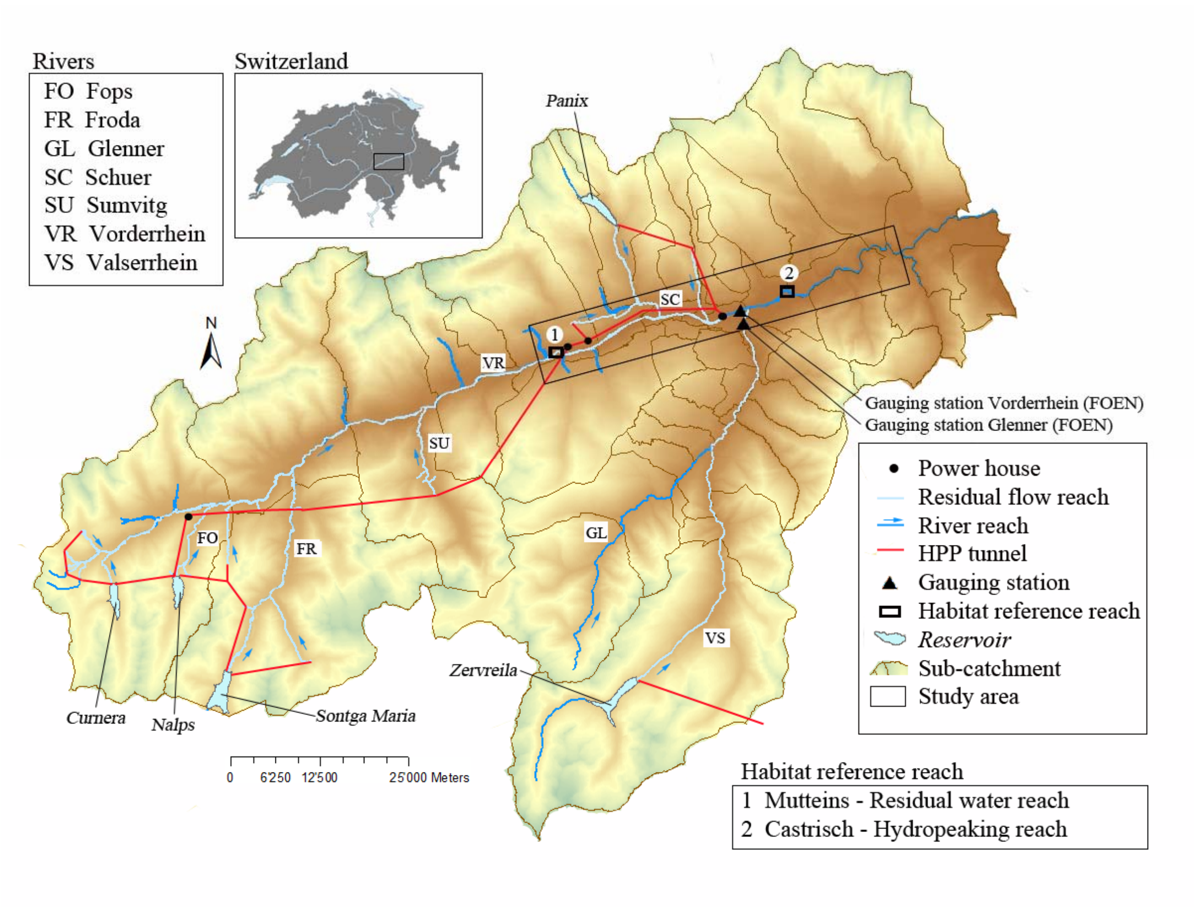


Figure 3.1: Map of the Vorderrhein catchment area in Switzerland with the hydropower scheme (reservoirs, HPP tunnels and powerhouses), the sub-catchment areas, the two river gauging stations and the river network. The residual flow river sections are shown in light blue. Box 1 and 2 indicate the modeled reaches. A picture each modelled reach is shown in chapter 1.

Two hydropower plants were constructed between 1962 and 1968 which produce 790 GWh annually. To investigate the effect of hydropeaking on brown trout habitat, a 250m long reach downstream the HPP water release in Castrisch was chosen (community of Ilanz) (average river width of 40 m). As a constant discharge control situation, a 175 m long reach of residual flow section upstream the HPP release in Mutteins was chosen (community of Breil/Brigels) (average river width of 20 m) (Figure 3.1). Both reaches are representative of the morphology and habitat available in each discharge conditions. For both sections, a two dimensional river hydraulics model was constructed. The model was based on a digital terrain model from the study reaches including riverbed elevation, which was sampled with a tachymeter LEICA TC1102 terrestrial system combined with a GPS-echosounder DESO 14. Water velocity was measured with a SEBA mini current meter type M1 and substrate was cartographied according to an internal protocol of Schneider & Jorde Engineering. Hydrological data from the Vorderrhein - Ilanz gauging station 2033 (Federal Office for Environment, 2009) were used to simulate the hydrological regime. The gauging station is situated less than one kilometer upstream from the hydropeaking modeled reach. The modeled reach stands for a standard reference reach for the hydropeaking section and was tested with a flow regime corresponding to a location close to the powerhouse outlets. The longitudinal dispersion of the peak-waves as they move from the tailwater outlet downstream is beyond the scope of this study and was not considered.

In a second step, habitat was described and modeled with the fish module of the habitat simulation model CASiMiR using a set of preference curves for adult brown (Figure 3.2). Due to sampling limitations, no specific adult suitability curves could be developed for the Vorderrhein River. Thus, curves from Souchon *et al.* (1989) were used, as they show habitat preferences similar to Vorderrhein River data for YOY and spawning brown trout (see chapter 4).

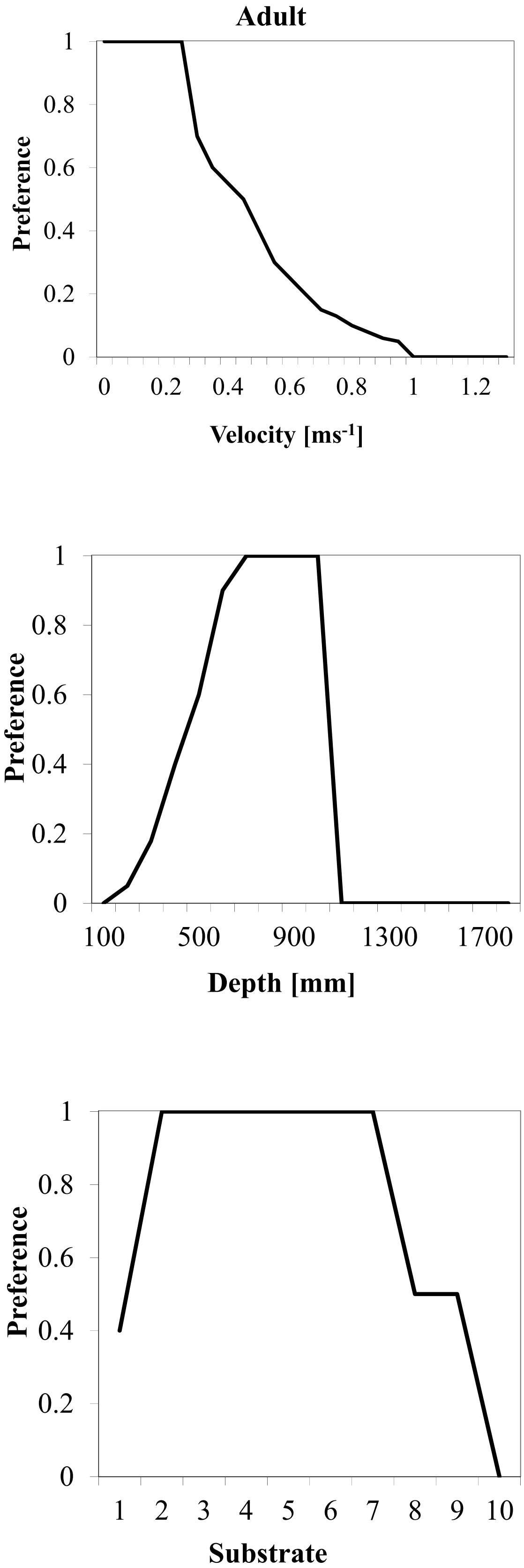


Figure 3.2: Habitat suitability curves for adult brown trout as found in Souchon et al (1989). (a) Mean water velocity, (b) Mean water depth and (c) Substrate classified according to modified Wentworth scale (1. Sand, clay < 2 mm, 2. Fine gravel 2-8 mm, 3. Middle size gravel 8-16 mm, 4. Coarse gravel 16-32 mm, 5. Very coarse gravel 32-64 mm, 6. Small stones 64-128 mm, 7. Stones 128-256 mm, 8. Big stones 256-384 mm, 9. Small boulders 384-512 mm, 10. Big boulders >512 mm).

In order to evaluate fish habitat availability and suitability, the following descriptors were used: 1) habitat suitability maps, 2) weighted usable area, and 3) hydraulic habitat suitability. Habitat suitability maps show the river wetted area according to a colour code standing for different suitability index value. Weighted usable area (WUA) shows the habitat available as a function of the discharge (Bovee 1982). For each discharge, a range of hydraulic conditions and associated suitabilities and the sum of weighted equivalent area are calculated as the summation of the available habitat in each cell:

$$\mathrm{WUA}(Q) = \sum \mathrm{A}_i \times \mathrm{P}(\mathrm{V}_i) \times \mathrm{P}(\mathrm{D}_i) \times \mathrm{P}(\mathrm{S}_i) \qquad (1)$$

Where Q represents the discharge, A_i the area of the i-th cell, $P(V_i)$ the preference value for velocity in the i-th cell, $P(D_i)$ the preference value for depth in the i-th cell and $P(S_i)$ the preference value for substrate in the i-th cell.

The weighted usable area index provides an integral view of the habitat quality over the reach.

Hydraulic habitat suitability (HHS) is the percentage of the WUA reported to the wetted area as a function of the discharge:

$$\mathrm{HHS}(Q) = (\mathrm{WUA}(Q) / \mathrm{WA}_{tot}(Q)) \times 100 \qquad (2)$$

Where $WA_{tot}(Q)$ stands for the wetted area for the corresponding discharge.

HHS represents the suitability of the physical habitat variables for the considered species. This index explains if overall habitat suitability changes because abiotic parameters changes or due to a change in wetted area. Habitat maps, WUA, HHS were calculated for adult brown trout both in hydropeaking (high and low discharge) and residual flow sections.

3.3 Results

The hydrograph in Figure 3.3.A shows the discharge regime measured by the gauging station in 2009. The main seasonal range and ratio of flows observed in the hydrograph are summarized in Table 3.1. Rare flooding events ranging up to 300 m^3/s that occurred are not taken into account. From September to March, peak regime is almost constantly fluctuating between 3 to 30 m^3/s, which corresponds to a Q_{min}/Q_{max} ratio of 1/10. During the same period, occasional stronger peak events ranging from 3 to 45 m^3/s with a Q_{min}/Q_{max} ratio of 1/15 are also registered. From April to August, base flow is higher due to seasonal glacier melt. During this time periods, off-peaks and peak discharges ranges frequently from 45 to 70 m^3/s.

Table 3.1: Seasonal hydropeaking variation is classified in three patterns: 1) September to March frequent event happening on a daily basis, 2) September to March occasional event occurring at least once per month and 3) peak event occurring during meltwater period. For each category, the peak event is described by two hydrological indicators, the Q_{min}-Q_{max} and Q_{min}/Q_{max} ratio.

Hydropeaking	Range	Ratio
1) September-March frequent	3-30 m^3/s	1/10
2) September-March occasional	3-45 m^3/s	1/15
3) April-August	45-70 m^3/s	1/1.5

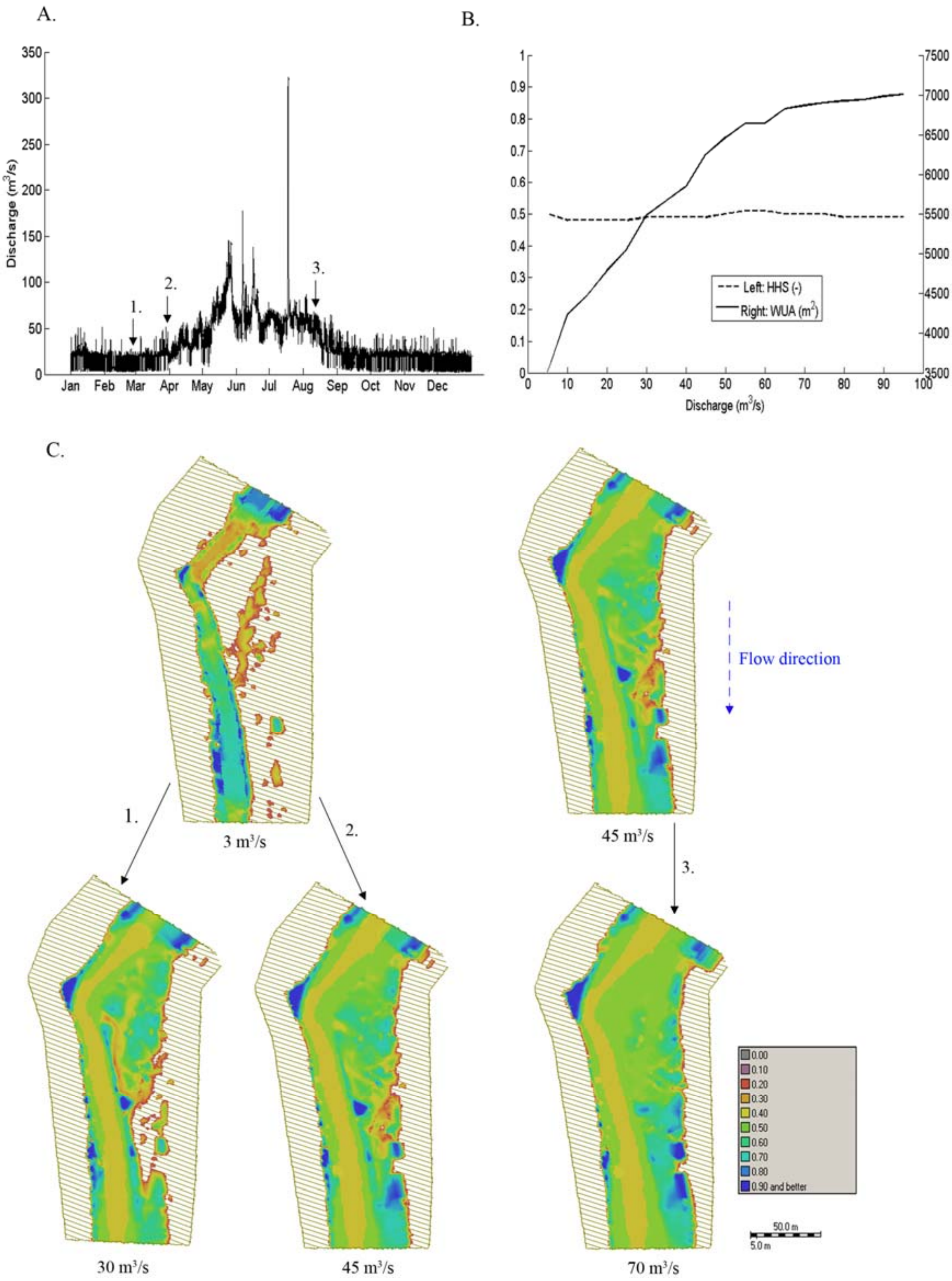


Figure 3.3: Habitat simulation results for adult brown trout in the hydropeaking reach. A) Hydrograph of the Vorderrhein River annual discharge pattern based on 10 min discharge data from the Ilanz Gauging station (Swiss Federal Office for Environment, 2009). The following three Q_{min}-Q_{max} events represent different hydropeaking situations: 1) September-March frequent event ranging from 3 to 30 m^3/s, 2) September-March occasional event ranging from 3 to 45 m^3/s, and 3) April to August event ranging from 45 to 70 m^3/s. B) WUA and HHS discharge series for adult brown trout. HHS (dotted line) is represented on the left y-axis. WUA (plain line) is represented on the right y-axis C) Habitat maps for adult brown trout corresponding to the three Q_{min}-Q_{max} situations (1-3) discussed above in the discharge hydrograph analysis. Suitability Index is expressed in a colour code. Flow direction is from the top to the bottom.

For adult brown trout, habitat suitability maps, HHS(Q) and WUA(Q) plots are calculated for both hydropeaking influenced and minimum flow reaches, based on the three peak event categories. WUA and HHS discharge series on Figure 3.3.B show that even if WUA increases with discharge, HHS index remains constantly around 0.5. This indicates that WUA increases due to stream surface increase resulting from flow rise but always stays 50 % of the total wetted area. Habitat maps presented on Figure 3.3.C show that good habitats (suitability index > 0.5) are strongly displaced from September to March between high and low flow. On the other hand, habitat availability stays more constant during April-August peak events.

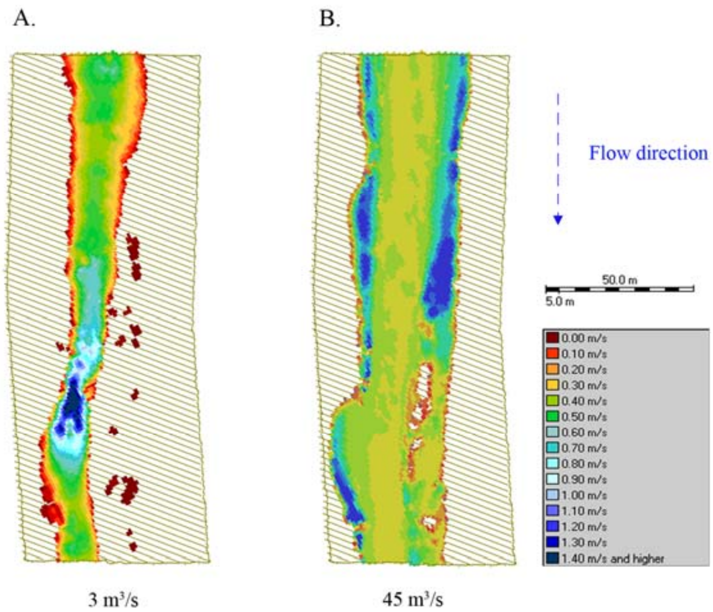


Figure 3.4: Habitat maps for adult brown trout in the residual flow reach. A) September to March situation. B) April to August situation. High basal discharge from April to August is due to snowmelt. Suitability Index is expressed in a colour code. Flow direction is from the top to the bottom.

Figure 3.4 shows habitat maps in the residual flow reach for winter (Figure 3.4.A) and summer (Figure 3.4.B) residual flow. From September to March, WUA and HHS values are 3500 m^2 and 0.5 respectively. Whereas from April to August, WUA and HHS values are 6250 m^2 and 0.5 respectively. WUA increases from 2750 m^2 during summer, however, HHS stays constant, around 0.5. HHS results in control and in the hydropeaking reaches do not differ.

3.4 Discussion & conclusions

The present study investigates the effect of hydropeaking on adult brown trout habitat in a morphologically intact alpine river. Seasonal flow regime analysis showed that peak events are greater in winter when discharge is naturally low. CASiMiR habitat simulations revealed that hydraulic habitat suitability for adult brown trout remains constant when calculated over the total wetted area (HHS) and is independent of discharge. However, even if habitat availability stays proportional to the wetted area, the habitat areas are decreased from high to low flow during winter (a WUA decrease of 2750 m^2 when discharge changes from high to low flow). Habitat maps showed that area with a high suitability (SI>0.5) is strongly displaced, forcing the fish to move between geographically changing suitable areas. These findings extend those of previous work suggesting that fish movement in hydropeaking influenced rivers due to habitat displacement could be energetically costly and affect over-wintering survival of individuals (Scruton *et al.* 2003; Scruton *et al.* 2008). Yet, CASiMiR simulation and resulting WUA(Q) series did not reveal substantial habitat loss for adult brown trout.

The results provide evidence that hydropeaking impact on brown trout is greater in winter, during which habitat is strongly unstable and might impair fish physical fitness. However, some limitations are worth noting. Although, adult brown trout habitat is impacted by flow change, this might not be the most sensitive life stage to habitat change or displacement, and therefore, not a useful indicator of hydropeaking impacts on brown trout. Juveniles, which need shallow shore habitat or spawning adults, might be more impacted by hydropeaking operations. It was previously documented that juveniles are exposed to drift and stranding risks (Liebig *et al.* 1998; Saltveit *et al.* 2001; Halleraker *et al.* 2003). Moreover, spawning which occurs during winter months when the effect of hydropeaking is aggravated might be strongly impaired by fast displacement of spawning places and dewatering of redds. Therefore, the use of juveniles and individuals at spawning and their habitats is recommended as indicators of hydropeaking impacts. However, first investigating the adult stage was essential in order to provide reference results to compare with other data and validate the relevance of concentrating future research efforts on other aspects of brown trout life cycle.

Another important limitation is the choice of HSCs curves used as biological descriptors of fish habitat preference. HSCs present in the literature are currently used in habitat modeling works for example by Ovidio *et al.* (2008) or Valentin *et al.* (1996). However, habitat preference differs regionally and modeling of habitat is more accurate when described by preference curves established especially for the study river.

4

Flow instability and brown trout reproduction success. Development of new indices to model habitat loss and dewatering.

High-head storage power plant operations drastically alter the natural flow regime of rivers and thus fish habitat conditions. A lot of effort has been invested in mitigating the impact of hydropeaking on the downstream ecosystem, mainly by reducing the magnitude and rate of flow change. However, the role of morphology - which generates variability in velocity, depth and substrate distribution for a given discharge – has been poorly investigated in hydropeaking studies thus far. In the present chapter, a natural braided river subjected to hydropower operation is studied. Brown trout reproduction and rearing habitat availability and dynamic under flow fluctuating conditions was modeled. In addition, young-of-the-year (YOY) density as well as egg to hatch survival was monitored in the field. Results showed that habitat is available but undermined by instable conditions under hydropeaking. Habitat is substantially shifted or dewatered, which might have detrimental consequences on fish population recruitment. However, the presented results suggest that braided morphologies are able, to a certain extent, to "buffer" hydropeaking impacts in displaying abiotic conditions that meet fish habitat requirements for a large range of varying discharges.

4.1 Introduction

Hydroelectricity is a dominant source of renewable energy, which has the main advantage of quickly adapting to fluctuating market-dependent energy demand. During peak demand periods, high head storage hydropower plants (HPP) produce artificial discharge peaks, so-called hydropeaking, released into the river downstream. Though hydropower has a "green image" as it produces energy with low contributions to atmospheric CO2 emission, the unsteady water release from the tailwater outlet has severe cascading effects on the ecosystem downstream. In alpine regions like Switzerland, where hydropower production is economically highly relevant, every fourth river is affected by hydropeaking. This corresponds to approximately 1000 km of river reaches (Baumann & Klaus 2003). These unsteady water releases from reservoirs alter the diurnal and seasonal natural discharge regime of the rivers. A natural flow regime is a key factor for the ecological integrity of riverine ecosystem (Poff *et al.* 1997; Parasiewicz *et al.* 1998; Bunn & Arthington 2002). Hydropeaking cycles differ from natural floods because disturbance occurs sub-daily and at high amplitude (Limnex 2004). As a consequence, rivers with hydropeaking influence differ significantly in their species community compared to unimpaired rivers (Smokorowski *et al.* 2011; Young *et al.* 2011; Sanz 2012). To help in quantifying hydrological alteration of the natural flow regime caused by hydropeaking, hydraulic indicators have been developed. They describe sub-daily flow fluctuations in terms of intensity, frequency and the rate of flow changes (Meile *et al.* 2011). In addition to flow disturbance, hydropeaking also affects other abiotic conditions of the downstream sections. Water stored in high head reservoirs often has a different temperature than the receiving river, which results in daily intermittent temperature shifts, so-called thermopeaking and alters the seasonal temperature regime of downstream reaches (Zolezzi *et al.* 2011). Furthermore, particle transport is altered as a consequence of the sediment retaining capacity of reservoirs (Zwahlen 2003; Finger *et al.* 2006; Anselmetti *et al.* 2007). Cascading effects affect other abiotic processes such as bed clogging, water turbidity, stream bed particle size, velocity distribution, wetted area and hyporheic flow exchange (Gailiuis & Kriauciuniene 2009; Sawyer *et al.* 2009).

The hydrology, sediment regime, hydraulics and morphology determine the physical habitat available for stream organisms. In hydropeaking conditions, these parameters are strongly modified and exceed tolerance abilities of organisms, leading to drastic consequences on species diversity and abundance (Cushman 1985). Thus, the distribution of sensitive invertebrate taxa, macrophytes and fish are reduced (Moog 1993; Bernez & Ferreira 2007; Smokorowski *et al.* 2011). Healthy fish populations contribute to freshwater biodiversity and are essential for ecosystem functioning. They furnish valuable ecosystem services, firstly by organism consumption which regulates food web dynamics, sediment bioturbation on stream bottoms, or as gene, energy and nutrient reservoirs (Holmlund & Hammer 1999). Secondly, healthy fish populations are vital for generating resources for human society through food production and recreational fishing. Due to their body size and sensitivity to many stressors, fish are a suitable indicator to study anthropogenic stress on natural ecosystems (Harris 1995). Several studies of hydropeaking influences report a reduction in fish population size due to a loss of habitat availability and quality compared to natural rivers (Moog 1993; Smokorowski *et al.* 2011). As high head storage dams are situated in the mountainous regions, where steep and fast flowing headwaters dominate, some fish families are more strongly impacted. Headwaters are typically inhabited by salmonid species, in Switzerland by brown trout (*Salmo trutta*). Fish movement is increased to adapt to sub-daily flow fluctuations (Scruton *et al.* 2003; Scruton *et al.* 2008). These extra movements lead to an increase in fish activity, which reduces energy reserves and impacts over-wintering survival of individuals. During winter, the spawning period for salmonids, natural discharge is usually low. Therefore differences between peak and off-peak discharge is high. Under these conditions, spawning behavior is altered (Chapman *et al.* 1986), redds and egg pockets are exposed to dewatering which may result in the death of the eggs (McMichael *et al.* 2005). It is known that fine sediment accumulation reduces oxygen supply to the embryo either by bed clogging or reduction of egg oxygen exchange through the membrane and thus affects embryo survival (Greig *et al.* 2005a; Jensen *et al.* 2009; Yamada & Nakamura 2009). However, egg survival under altered particle transport, resulting from HPP operation, is still poorly understood. From emergence to the end of their first winter, young-of-the-year (YOY) stay in shallow riverbank habitat, where flow velocity is low (Crisp 2000). In rivers influenced by hydropeaking, the growth rate, density and mesohabitat choice of juveniles is affected (Jensen & Johnsen 1999; Flodmark *et al.* 2006; Korman & Campana 2009). In addition, a physiological stress response was observed to fish after exposure to hydropeaking. However, Flodmark *et al.* (2002) showed that juvenile can adapt to such conditions and stress response decreases with increased exposure time. Shallow and irregular riverbanks combined with high discharge peaks lead to extra movements as well as drift and the risk of stranding of young fish (Liebig *et al.* 1998; Halleraker *et al.* 2003). However, stranding and drift risks strongly depend on riverbank slope, substrate type, shelter availability as well as amplitude, magnitude, duration, frequency and speed of up and down ramping (Liebig *et al.* 1998; Saltveit *et al.* 2001; Halleraker *et al.* 2003; Berland *et al.* 2004).

In the past years, habitat modeling has become an important tool for evaluating the impact of human-altered flow regime to the fish fauna. Such modeling studies reported unsteadiness in adult fish habitat under hydropeaking conditions (Valentin *et al.* 1996; Person & Peter 2012) (see chapter 3). Instream models are based on: 1) hydrodynamic model: simulating spatial and temporal variations in abiotic parameters (depth, velocity and substrate conditions), 2) abiotic preferences for the target fish species, 3) physical habitat model, combining the results of the hydrodynamic model and the biological preference (Bovee *et al.* 1988). Habitat suitability for the target fish species is modeled for varying flow conditions. CASiMiR is a habitat simulation system from the instream model family, including a fish module especially developed to model habitat suitability at different flow rates (Jorde *et al.* 2000; Schneider *et al.* 2001). This module was applied to study habitat evolution of 8 Chilean endemic fish species under hydropeaking regime and suggest appropriated habitat improvement measures (Garcia *et al.* 2010). These studies were mainly focused on adult fish and therefore lack in considering other life stages (Valentin *et al.* 1994; Valentin *et al.* 1996).

Weighted Usable Area (WUA) and Hydraulic Habitat Suitability (HHS) are used to quantify the amount of suitable habitat in PHABSIM habitat modeling approaches. They integrate the overall habitat suitability on a reach scale, under a steady discharge regime. WUA and HHS were first developed to determine minimum flow requirements

(Bovee 1982) and thus were not adapted to express dynamic habitat conditions, as induced by hydropeaking. The suitability of a given habitat for fish is commonly calculated based on the abiotic preferences of those species. This preference is described by habitat suitability curves (HSCs). The product of habitat use by the organisms over habitat availability, in the ecosystem is calculated. Habitat preferences of the same fish species differ between regions due to regional adaptation and plasticity. Therefore, habitat modeling results rely strongly on the chosen HSCs (Heggenes *et al.* 1996). As HSCs are commonly not available for the studied river or are not known, most studies rely on expert based knowledge or published HSCs of other catchments, which are subsequently adapted for a specific geographic area (Valentin *et al.* 1996; Ovidio *et al.* 2008).

In the "Green Hydropower" assessment procedure for river management, hydropeaking was identified as one of the future research priorities. This is because of the lack of knowledge concerning its interactions with the river ecosystems downstream and thus the difficulty to identify appropriate mitigation approaches (Bratrich *et al.* 2004). The importance of mitigating human impacts on river ecosystems has been recognized and resulted in the initiation of water protection policies such as the Water Framework Directive of the European Union and the new water protection law in Switzerland (LEaux (OFEV 2009)). In the Swiss water protection law, hydropeaking is recognized to cause serious infringement on the downstream river. A harmful threshold of 1:1.5 was defined for the off-peak:peak ratio. Different mitigation measures are proposed in a strategic plan to reduce negative effects resulting from hydropeaking (Sanierung Schwall/Sunk – Strategische Planung, 2012). This involves operational measures (change in turbine operation) as well as structures that buffer flow peaks, such as compensation basins or multipurpose schemes (Heller & Schleiss 2011). Both strategies should reduce the hydrological impact of HPP operation. Morphological measures, such as river revitalisation are also considered, as far as they mitigate hydropeaking effects by increasing natural retention capacities of rivers (Church 1995). Such morphological habitat enhancement measures performed on the Oulujoki River in Finland contributed to the maintenance of a grayling population under HPP operation (Vehanen *et al.* 2003). However, Weber *et al.* (2007) argued that morphological improvements are not sufficient for a successful rehabilitation if the hydrological regime remains altered. There is a clear need for quantitative framework studies, incorporating simulation and modeling approaches as well as biological monitoring methods.

This chapter focus on the hydropeaking effects on the early and sensitive life stages of brown trout (spawning and young-of-the-year). The effect of sub-daily flow fluctuation on the natural reproduction is studied in a morphologically natural river. The role of natural morphology as hydropeaking mitigator by directly influencing velocity, depth and grain size distribution in the river bed and consequently sustain fish spawning and nursery habitat is investigated. A theoretical habitat model approach was combined with observation and field experiments. Habitat suitability and stability is modeled with the CASiMiR fish module. For this purpose, specific HSCs have been developed for the investigated river for spawning and YOY life stages. Habitat changes are quantified with dynamic habitat descriptors developed by Person *et al.* (2013) (see chapter 6) assessing habitat loss (WHL) and habitat dewatering (DAR) especially developed for modeling fluctuating flow conditions. Natural reproduction success is investigated with in situ egg to hatching incubation experiments and YOY density sampling surveys.

4.2 Study area

The Vorderrhein is one of two main river branches, which constitute the mainstream of the river Rhine, before it enters into Lake Constance. The Vorderrhein runs through the Surselva District of Canton Graubunden in Switzerland.

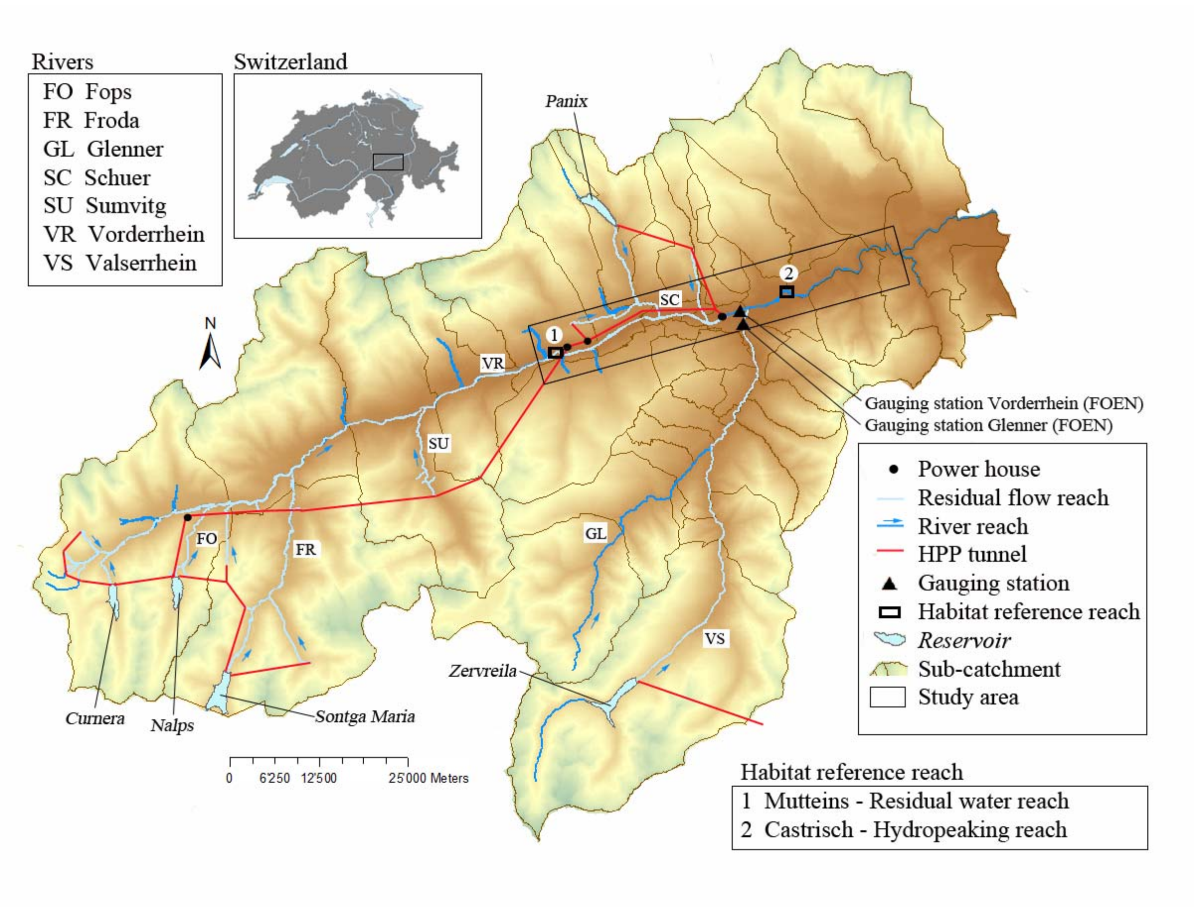


Figure 4.1: Map of the Vorderrhein catchment area in Switzerland with the hydropower scheme (reservoirs, HPP tunnels and powerhouses), the sub-catchment areas, the two river gauging stations and the river network. The residual flow river sections are shown in light blue. Box 1 and 2 indicate the modeled reaches.

The catchment size is 776 km^2 with a mean elevation of 2020 m.a.s.l, 3.8 % of the catchment area are covered by glaciers. The river shows a nivo-glacial discharge regime, influenced by snow and glacier melt (Hydrological Atlas of Switzerland, 2009). As a result, discharge is high (65 m^3/s) in early summer and low (17 m^3/s) in winter with a mean annual discharge of 30.5 m^3/s and mean annual temperature of 6.2°C. Seasonal water temperature ranges from 1-4°C in winter and 7-11°C in summer (Federal office for environment, 2010). The Vorderrhein River is one of the few remaining rivers in Switzerland showing a natural morphology, with a fish community according to the trout region (Huet 1949). Between 1962 and 1968, hydropower plants were constructed, which produce 790 million kWh annually (Figure 4.1).

To investigate the effect of hydropeaking on spawning grounds and habitat utilized by brown trout YOY, a 15 km long section was studied. This section contains an upstream residual flow reach, from where water is extracted to feed the HPP and a downstream hydropeaking reach. For both sections upstream and downstream of the HPP, two 200 m sections, one situated in Castrisch (community Ilanz) and another one in Mutteins (community of Breil/Brigels) were modeled. The latter is defined as a constant discharge control (residual flow reach). Both modeled sections show a typical morphology and habitat availability representative for residual flow and hydropeaking conditions. The residual flow reach is dominated by alpine riffle-pool sequences, while the hydropeaking section shows a braided river morphology with transverse bars and eroding banks.

4.3 Methods

Habitat suitability

To study spawning habitat use, brown trout redds were measured along a 6 km section of the residual flow reach (November 2010). In total 87 redds were sampled. For each redd, water depth, mean water velocity and dominant substrate were recorded at five points within each redd (front, back, center, left and right). Substrate was classified according to modified Wentworth scale (Krumbein & Sloss 1963). To estimate habitat use, young-of-the-year (YOY) brown trout were sampled along a 200 m section of the residual flow reach by point electrofishing (according to Bain *et al.* (1985)), using a portable 1.5 KW generator. In total 165 brown trout juvenile got caught. Sample locations were spaced sufficiently to avoid fish frightening. Field work was conducted in October 2010, after the period of density dependency YOY mortality (Crisp 2000). In autumn, YOY body size ranges between 60-110 mm. This size spectrum can be fished efficiently by electrofishing. To avoid biases due to drifting fishes facing galvanotaxis from electrofishing, fish position was recorded, in the very first moment after the anode entered the water. The location was documented, where fish was spotted first. This allowed fish position to be recorded precisely right at the beginning of the anodic reaction. Numbered tags were dropped on the stream bed to mark fish positions.

Habitat availability data were collected concurrently with redd and fish sampling. Water depth, mean water velocity and dominant substrate were measured every 2 m along transects perpendicular to river flow. The transects were taken with a distance of 10 m in between.

Univariate preference curves for water depth, flow velocity and substrate were developed according to standard procedure based on use and availability field sampling data (Bovee *et al.* 1988). Use and availability data were clustered into classes, in order to calculate frequency histograms. The latters were normalized according to their corresponding maximum value and a preference index was calculated for each class, as the ratio between use and availability. The preference index was normalized so that habitat suitability values range between 0 and 1.

To compare data from the Vorderrhein River with other regional HSCs, published curves for spawning and YOY were extracted from literature (Bovee 1978; Raleigh *et al.* 1986; Belaud *et al.* 1989; Souchon *et al.* 1989; Grost *et al.* 1990; Bullock 1991; Johnson *et al.* 1995; Lamouroux & Capra 2002; Louhi *et al.* 2008; Ayllon *et al.* 2009).

The suitability curves where considered when sampling and data analysis methods were available and comparable to the method applied to the Vorderrhein River. HSCs from the Hasliaare River in Switzerland (see Chapter 5) were also used for comparison. All curves are listed in Table 4.1.

Table 4.1 : Sources of brown trout habitat suitability curves reviewed for young-of-the-year (YOY) and spawning life stages.

Reference	0+ Juvenile			Spawning			Location
	Velocity	Depth	Substrate	Velocity	Depth	Substrate	
Bovee (1978)	+	+	+	+	+	+	USA
Raleigh (1986)	+	+	+	+	+	+	USA
Belaud et. al (1989)	+	+	+				France
Souchon et. al (1989)	+	+	+	+	+	+	France
Grost et. al (1990)				+	+	+	USA
Bullock et. al (1991)	+	+	+	+	+	+	Great Britain
Johnson et. al (2002)				+	+	+	Great Britain
Lamouroux et. al (1999)	+	+		+			France
Louhi et. al (2008)				+	+	+	Constructed*
Ayllon et. al fast water (2009)	+	+					Spain
Ayllon et. al slow water (2009)	+	+					Spain
Person (Hasliaare River data) (see chapter 5)	+			+			Switzerland

* Constructed suitability curves are generated based on published information

Fish habitat modeling

River bed elevation was sampled for the two 200 m river sections, Mutteins (Breil/Brigels commune) and Castrisch (Ilanz commune). Measurements were collected combining tachymeter LEICA TC1102 terrestrial system with a GPS-echosounder DESO 14. Points were taken every 0.5 seconds which corresponds to a distance of a few decimeter between points. This allows a very precise replication of the channel bed. In the meantime, water velocity was measured with a SEBA mini current meter type M1 and substrate was mapped. A digital terrain model was computed from the topographic and bathymetric data. Hydrological data from the Vorderrhein River - Ilanz gauging station 2033 and the Glenner river – Castrisch gauging station 2498 (Federal Office for Environment, 2009) were used to simulate flow regime. Discharge hydrographs of November (spawning) and October (YOY) months were used. Based on these discharge patterns, section topography and substrate field data, a 2D hydraulic model was calculated for a range of discharge between 4 and 90m^3/s. Q_{min} and Q_{max} for hydropeaking characterization correspond to the 90th and 10th percentile for the investigated month. The dates of 5th October and 9th November showed a typical hydropeaking discharge pattern and thus were chosen as representative to model sub-daily temporal habitat variation.

In a second step, habitat was modeled with the fish module of CASiMiR habitat simulation model. To test the sensitivity of habitat suitability, the model was first run with a selection of literature curves from Table 4.1, where information for the three abiotic parameters (velocity, depth and substrate) was available. In a second step, habitat suitability was calculated based on the set of preference curves for spawning and YOY brown trout specifically developed for the Vorderrhein River. To evaluate fish habitat availability and suitability, three CASiMiR outputs were used as described in Garcia *et al.* (2010): 1) Habitat suitability maps, 2) Weighted Usable Area and 3) Hydraulic Habitat Suitability. Suitability index values are displayed on habitat suitability maps. SI values range from 0 to 1 and can be presented on habitat suitability maps for the investigated discharges Several mathematical methods are known to define SI from the different preference values, whereas the geometric mean is a commonly applied one:

$$\mathrm{SI}_i(Q) = \sqrt[3]{P(H_i(Q)) \cdot P(U_i(Q)) \cdot P(S_i(Q))} \qquad (1)$$

where SIi(Q) [-] represents the Suitability Index in i-cell for discharge Q, P(H_i(Q)) [-] the preference value for flow depth H_i for discharge Q, P(U_i(Q)) [-] the preference value for velocity U_i for discharge Q and P(S_i (Q)) [-] the preference value for the substrate S_i for discharge Q.

Weighted Usable Area (WUA) [m^2] shows the wetted area of a river reach weighted by its suitability as a function of discharge (Bovee 1982):

$$\mathrm{WUA}(Q) = \sum_{i=1}^{n} A_i \cdot \mathrm{SI}_i(Q) \qquad (2)$$

where Q [m^3/s] represents the discharge, A_i [m^2] the area of i-cell and SI_i(Q) [-] the Suitability Index of i-cell for discharge Q.

Hydraulic Habitat Suitability (HHS) [-] is the ratio of WUA over the total wetted area (WAtot) [m^2] for discharge Q. HHS represents the suitability of the physical habitat variables for the considered species:

$$\mathrm{HHS}(Q) = \frac{\mathrm{WUA}(Q)}{\mathrm{WA_{tot}}(Q)} \qquad (3)$$

Suitable habitat dynamics were described with indicators developed by Person *et. al* (2013) (see chapter 6): 1) Suitable Area (SA), 2) Suitable Habitat Ratio (SHR), 3)Weighted Habitat Loss (WHL) and 4) Drained Area Ratio (DAR). Suitable Area (SA) [m^2] considers habitat only if the associated SI achieves a defined threshold value $\mathrm{SI_{lim}}$. SA for discharge Q corresponds to the total surface area, where SI is greater or equal to $\mathrm{SI_{lim}}$. Here, $\mathrm{SI_{lim}}$ is set to 0.5, which includes middle to high SI areas. Suitable Habitat Ratio (SHR) [-] is the ratio of SA over the total wetted area for discharge Q. Wetted Habitat Loss (WHL) [-] stands for the percentage of suitable habitat lost between two steady flow regimes. It calculates the relative area where habitat conditions change from suitable ($\mathrm{SI} \geq \mathrm{SI_{lim}}$) at discharge Q_1 of steady state 1 to unsuitable ($\mathrm{SI} < \mathrm{SI_{lim}}$) at discharge Q_2 of steady state 2. Drained Area Ratio (DAR) [-] corresponds to the percentage of suitable area falling dry, when discharge switches from Q_1 to Q_2. It calculates the relative area where habitat conditions change from suitable ($\mathrm{SI} \geq \mathrm{SI_{lim}}$) at Q_1 to drained at Q_2. The formulas and detailed description of each indicator are to be found in chapter 6. Habitat maps, WUA, HHS, SA and SHR were calculated for spawning and YOY brown trout both in hydropeaking as well as residual flow conditions. Moreover, WHL and DAR were calculated for Q_{min} and Q_{max} in the hydropeaking reach to assess sub-daily change in habitat conditions.

Natural reproduction success

Success of egg development under hydropeaking conditions was investigated from November 2010 to March 2011. Fertilized brown trout eggs were exposed up to hatching time under two different conditions: one replicate under sub-daily flow fluctuation (hydropeaking), another one under steady flow conditions (residual flow). In the same time, a control batch of eggs was incubated in the lab. Eggs were obtained from native ripe brown trout, originating from Vorderrhein River. A pool of fertilized eggs was produced from eggs and sperm from 5 females and 5 males mixed all together. After an hour, non-fertilized or dead eggs were removed. Remaining eggs were placed on a layer of the Vorderrhein River gravel in Vibert boxes (20 eggs per box). Vibert boxes were burried 10 cm deep in the river gravel. Eight Vibert boxes were buried together, simulating an artificial redd. Three artificial redds were constructed at each study site (hydropeaking and residual flow reach). Study sections were selected for being known as spawning sites for brown trout either by direct redd observations or previous spawning observations with radiotracked trout (Caviezel 2006). As a control for mortality due to egg or female quality, 300 eggs were placed in a lab incubator. Temperature loggers were installed in the two study sites, which recorded water temperature every minute during the whole experimental period. Vibert boxes were retrieved at hatching time. Number of dead eggs and hatched alevins were counted. Living eggs were left in oxygenated water until they all hatched which happened after 6 hours; they were than recorded as hatched alevins. Due to the low number of replicates in each reach descriptive analysis of the results was chosen over a statistical approach.

YOY density was investigated in 24 sections distributed upstream and downstream of the HPP (July 2010). For each section, 100 m shore line was electrofished according to the semi-quantitative electrofishing sampling method (Bohlin *et al.* 1989). All brown trout caught in each section were counted and measured. Based on a frequency length class distribution, the number of YOY per section was assessed. Variation in body length and density of YOY between residual and hydropeaking flow conditions was statistically tested with a non-parametric randomization test and a wilcoxon test respectively.

4.5 Results

Habitat suitability

Figure 4.2 shows habitat suitability curves (HSCs) for the Vorderrhein River for spawning and young-of-the-year (YOY) brown trout. Spawning activity surveys in the Vorderrhein River conducted in winter 2009 and 2010 revealed that most spawning places were found at the interface of the pool riffle habitat. Brown trout redds were mainly located in areas with velocities of 0.4 to 0.8 m s^{-1} (Figure 4.2a), depths of 200 to 700 mm (Figure 4.2c) and consisted of substrate between 2 and 64 mm (Figure 4.2e). Although the entire cross section of the river has been systematically electrofished, almost all YOY brown trout were caught in shore habitats or along gravel banks islands. These shallow habitat were characterized by velocities of 0 to 1 cms^{-1} (Figure 4.2b) depths of 100 to 400 mm (Figure 4.2d) and fine substrates (Figure 4.2e).

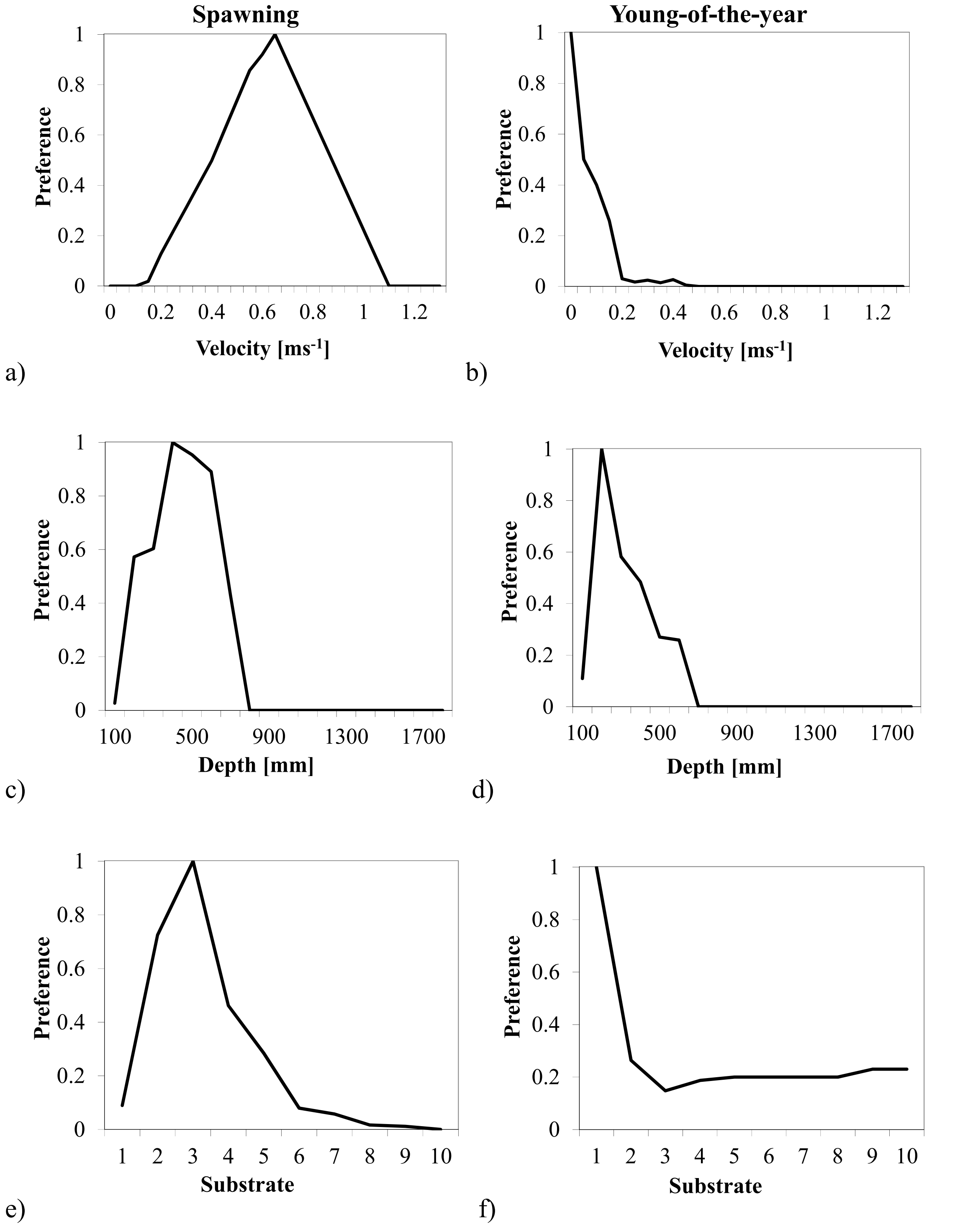


Figure 4.2: Habitat suitability curves for (a)(c)(e) spawning and (b)(d)(f) young-of-the-year (YOY) brown trout in the Vorderrhein River. (a-b) Mean water velocity, (c-d) Mean water depth, (e-f) Substrate is classified according to modified Wentworth scale (1. Sand, clay < 2 mm, 2. Fine gravel 2-8 mm, 3. Middle size gravel 8-16 mm, 4. Coarse gravel 16-32 mm, 5. Very coarse gravel 32-64 mm, 6. Small stones 64-128 mm, 7. Stones 128-256 mm, 8. Big stones 256-384 mm, 9. Small boulders 384-512 mm, 10. Big boulders >512 mm).

Habitat suitability curves (HSCs) from the Vorderrhein river were compared to brown trout HSCs from the literature listed in Table 4.1. Figure 4.3 shows the comparison among the Vorderrhein River HSCs and the selected literature HSCs with respect to velocity, depth and substrate. Velocity preference by brown trout at spawning grounds can be grouped in four velocity preference patterns: 1) large range of preference from 0.2 to 0.9 ms^{-1} (Bullock 1991), 2) low velocity preference ranging from 0.3 to 0.5 ms^{-1} (Souchon *et al.* 1989; Grost *et al.* 1990; Johnson *et al.* 1995; Louhi *et al.* 2008), 3) middle velocity preference ranging from 0.5 to 0.65 ms^{-1} (Bovee *et al.* 1988) and 4) high velocity preference ranging from 0.65 to 0.8 ms^{-1} for the Hasliaare (see chapter 5) and Vorderrhein rivers.

Water depths at spawning sites are similar among the literature. Data suggest an optimum ranging between 200 to 400 mm except for Bullock (1991) and Raleigh (1986) who found a preference for deeper water and Grost (1990) who found a depth preference, which is opposite to the other HSCs (Figure 4.3b). Preference on spawning substrate shows a bigger variance, ranging from small gravel to stones according to the source of data (Figure 4.3e). YOY HSCs show similar velocity preferences, with an optimum between 0 and 0.4 ms^{-1}, except for the fast and low flow HSCs, published by Ayllon (2009) (Figure 4.3b). The same is observed for depths preference, with an optimum between 100 and 500 mm, except for Raleigh (1986), Johnson (1995) and Souchon (1989) HSCs, where preference is higher in deeper water (Figure 4.3d). On the contrary, YOY substrate preferences were very divergent for all HSCs reported (Figure 4.3f).

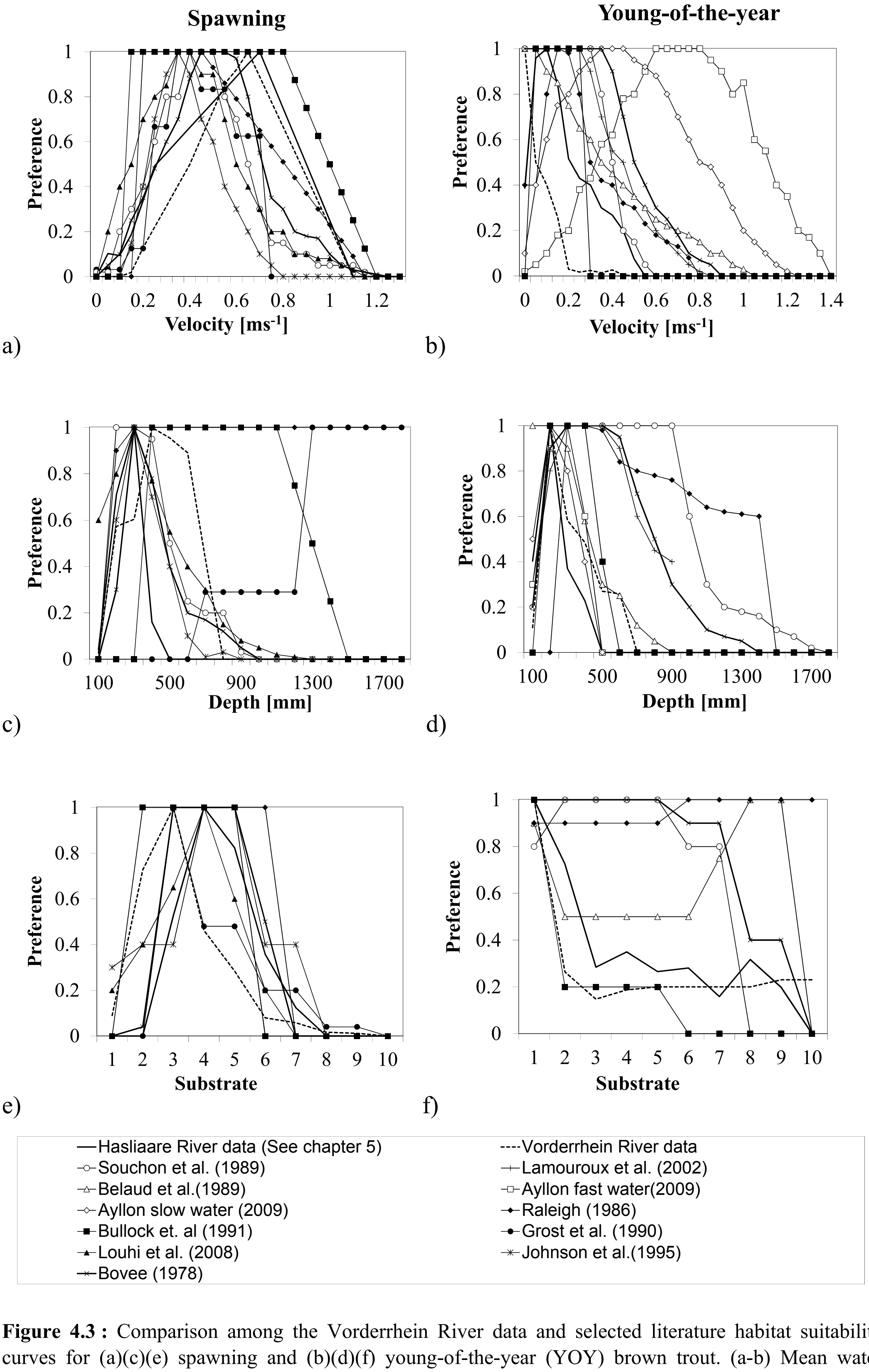


Figure 4.3 : Comparison among the Vorderrhein River data and selected literature habitat suitability curves for (a)(c)(e) spawning and (b)(d)(f) young-of-the-year (YOY) brown trout. (a-b) Mean water velocity, (c-d) Mean water depth, (e-f) Substrate is classified according to modified Wentworth scale (1. Sand, clay < 2 mm, 2. Fine gravel 2-8 mm, 3. Middle size gravel 8-16 mm, 4. Coarse gravel 16-32 mm, 5. Very coarse gravel 32-64 mm, 6. Small stones 64-128 mm, 7. Stones 128-256 mm, 8. Big stones 256-384 mm, 9. Small boulders 384-512 mm, 10. Big boulders >512 mm).

Fish habitat modeling

Hydraulic Habitat Suitability (HHS) and Suitable Habitat Ratio (SHR) sensitivity to origin of Habitat Suitability Curves (HSCs) of brown trout are shown in Figure 4.4. HHS and SHR at peak and off-peak flow vary with the origin of HSCs given as input.

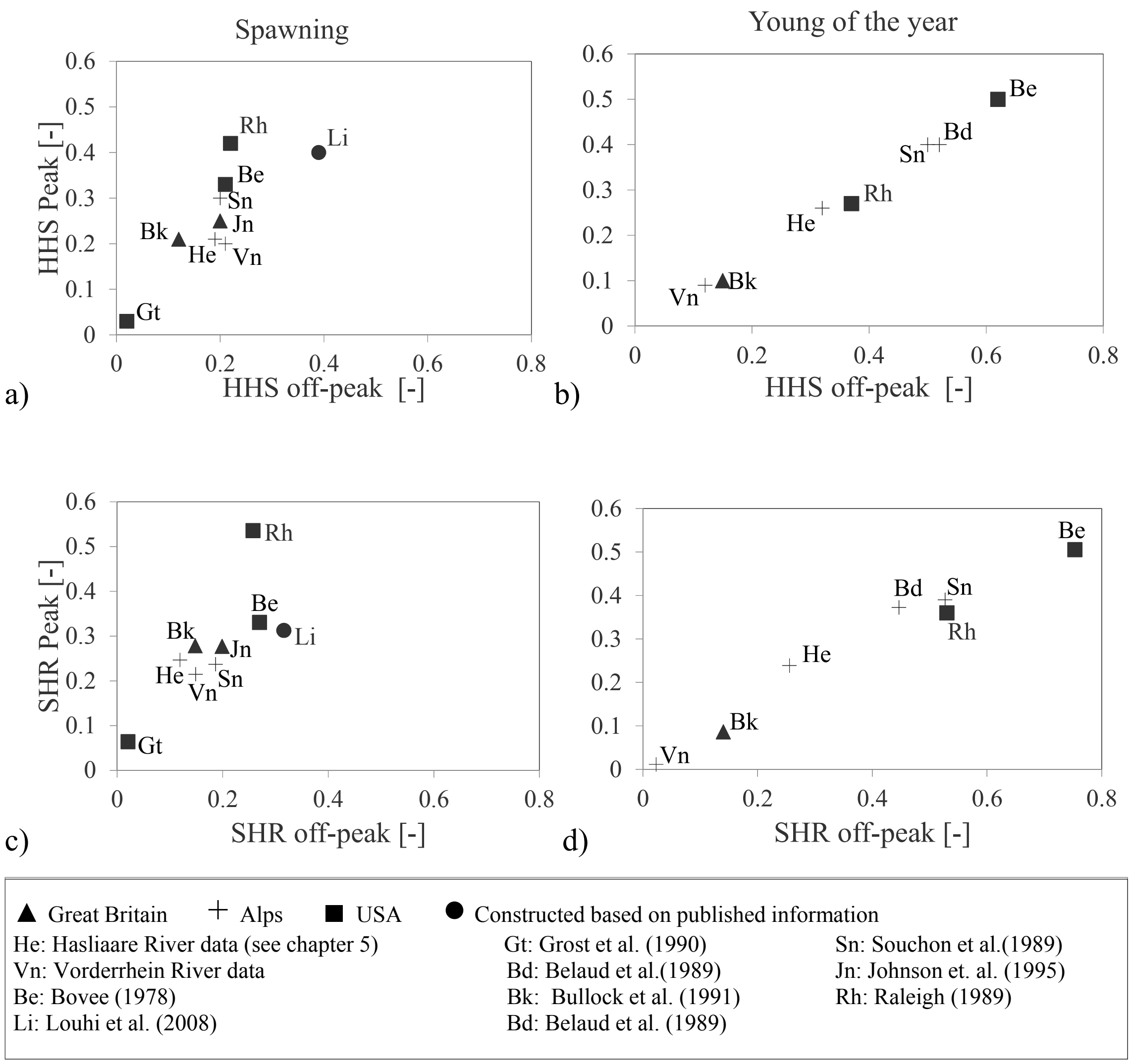


Figure 4.4 : Sampling-based sensitivity analysis of Hydraulic Habitat Suitability (HHS) and Suitable Habitat Ratio (SHR) for Habitat Suitability Curves (HSCs) of brown trout from various origins. On the two upper plots, HHS at peak (y-axis) and off-peak (x-axis) for spawning (a) and young-of-the-year (b) is represented. On the two lower plots, SHR at peak (y-axis) and off-peak (x-axis) for spawning (c) and young-of-the-year (d) is represented.

Results show that HSCs curves, which predict a high amount of suitable habitat area at off-peak conditions, tend to predict a high area of suitable habitat at peak flow and inversely. For spawning habitat prediction, HHS and SHR vary from 10% to 50% of the total wetted area, depending on the HSCs origin. However, spawning habitat prediction for alpine HSCs shows a lower uncertainty in habitat outputs. Difference in prediction ranges only from 10% of the total wetted area (Figure 4.4a and c). Prediction for juvenile habitat suitability varies strongly with HSCs origin (Figure 4.4b and d). Even, HSCs from similar origin show very divergent HHS and SHR output values.

Figure 4.5 shows Weighted Usable Area (WUA), Suitable Area (SA) as well as HHS and SHR for the whole range of 2D simulated discharge in the downstream HPP release reach. Maximum WUA and SA values for spawning are achieved for 60 m^3/s (Figure 4.5a). However, according to HHS and SHR indexes, suitable habitat remains relatively constant proportionally to the wetted area, corresponding to approximately 30% to the total wetted area (Figure 4.5b). Predictions on spawning habitat differ between the classical instream habitat indexes WUA and HHS and the newly developed indices, SA and SHR. This is mainly due to differences in habitat calculations. Classical instream habitat indexes are based a sum of stream areas first weighted by their suitability whereas the new indexes sums only instream areas where SI is greater than SI limit (SI_{lim} = 0.5) and does not weight them by their corresponding suitability. Maximum area of YOY habitat is achieved for the lowest flow values independently of the index used. SA and SHR indexes are always lower than WUA and HHS indexes, which is due to the low amount of high suitability habitat and a majority of low suitability habitat in the modeled reach.

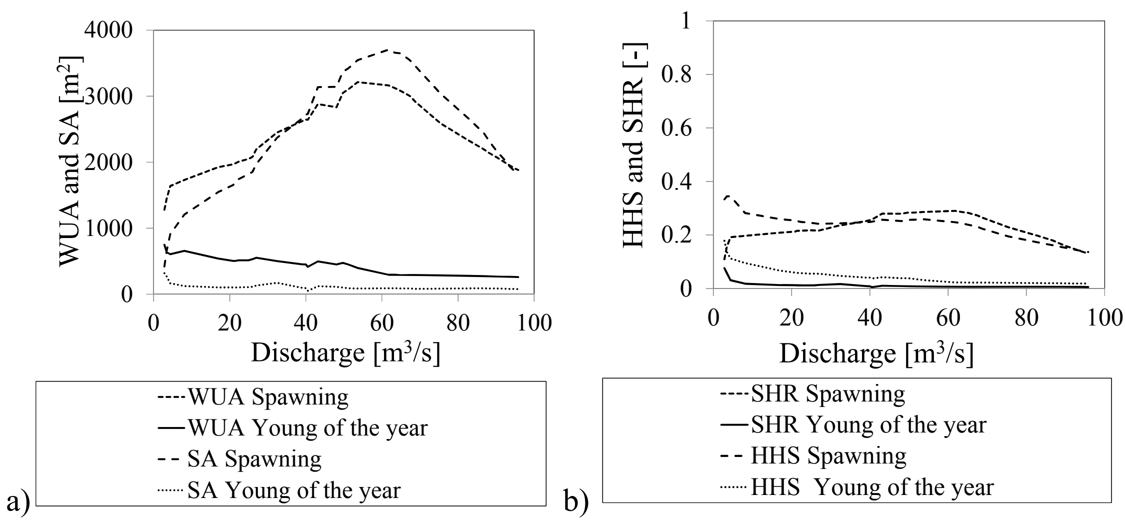


Figure 4.5 : Weighted Usable area (WUA), Suitable Area (SA), Hydraulic Habitat Suitability (HHS) and Suitable Habitat Ratio (SHR) for the Vorderrhein River as a function of discharge. (a) WUA values for spawning (dashed line) and young-of-the-year (YOY) (solid line). SA values for spawning (long dashed line) and young-of-the-year (YOY) (dotted line). (b) HHS values for spawning (long dashed line) and young-of-the-year (YOY) (dotted line). SHR values for spawning (dashed line) and young-of-the-year (YOY) (solid line).

Sub-daily temporal habitat variation was investigated for spawning for a representative November hydropeaking day. During the day, SA and SHR vary proportionally to discharge change (Figure 4.6). In October, Q_{min} and Q_{max} are 5 and 25m^3/s, respectively, which corresponds to a 1/5 drawdown range. At peak conditions, 1000 m^3 of the SA is lost, which corresponds to a 7 % loss of SHR. Spawning habitat suitability maps for the reference reach Mutteins upstream HPP water release as well as the hydropeaking influenced reach downstream HPP water release at off-peak and peak conditions are shown on Figure 4.7. SHR is 12 % (residual flow), 14 % (hydropeaking off-peak) and 21 % (hydropeaking peak) of the total wetted area respectively. In the hydropeaking section, habitat is strongly displaced with discharge changes. Suitable spawning grounds are located in the central part of the river cross sections during off-peak. During peak flow, they are close to the shores, where they will fall dry under off-peak conditions.

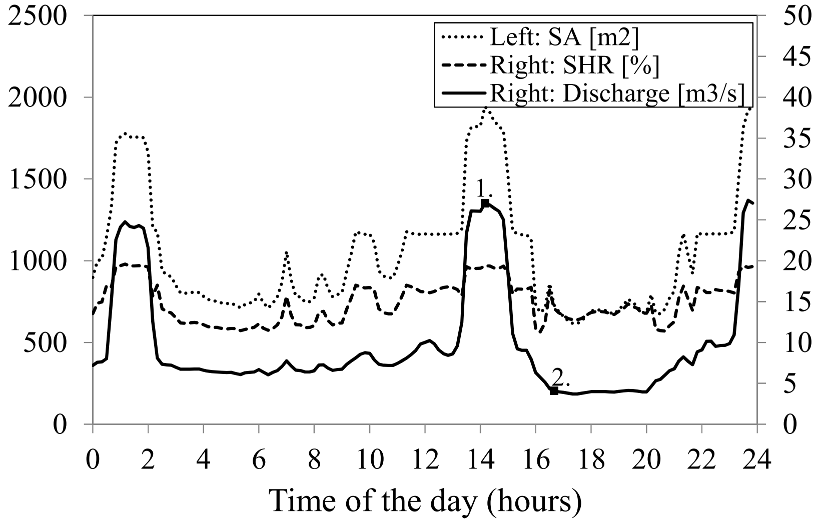


Figure 4.6 : Discharge (solid line, right y-axis), Suitable Area SA (dotted line, left y-axis), and Suitable Habitat Ratio SHR expressed in % of the wetted area (dashed line, right y-axis) for spawning as a function of time for the Vorderrhein River. Discharge was measured by Ilanz gauging station on the 9th November 2009 chosen as representative days to study sub-daily temporal spawning habitat variation. Locations 1. and 2. on the discharge time series refer respectively to peak and off-peak discharge conditions which are modeled on habitat maps in Figure 4.7.

Comparing the habitat suitability and habitat instability maps of the Vorderrhein River for both spawning and juvenile life stages showed a reduced wetted area in the instability map (Figure 4.7 and 4.10). This difference was caused by the difference in wetted area calculations. For the instability map, wetted area was defined by the Effective Wetted Area (WA_{eff}) [m^2] for discharge Q, which only considers water levels H achieving H_{lim}, the threshold water depth at which flow is too shallow to sustain the life stage of interest. According to the habitat preference curves and field observations of the habitat use of brown trout in Vorderrhein River, H_{lim} was set to 5 cm for YOY and 10 cm for spawning individuals. In the instability map, the present H_{lim} criteria excludes areas from the suitability maps which are considered too shallow to sustain the fish. The habitat suitability results cannot be directly compared between the two maps and the difference is stronger for YOY as the majority of their habitat is found on the river shores (Figure 4.10).

This is confirmed by the instability maps of Figure 4.7. Almost all the suitable habitats are displaced with flow fluctuation. A negligible amount of suitable habitat (SI> 0.5) persists at off-peak and peak discharges (0.06 and 0.02% respectively). Moreover, 65% of the total suitable habitat present at peak flow is dewatered during off-peak conditions (Figure 4.8). Due to redd dewatering and thus potential egg mortality, if spawning took place at peak flow conditions in shore part of the river, the potential suitable habitat area at Q_{max} is reduced to an effective suitable area of 45% of the potential suitable area at Q_{max}.

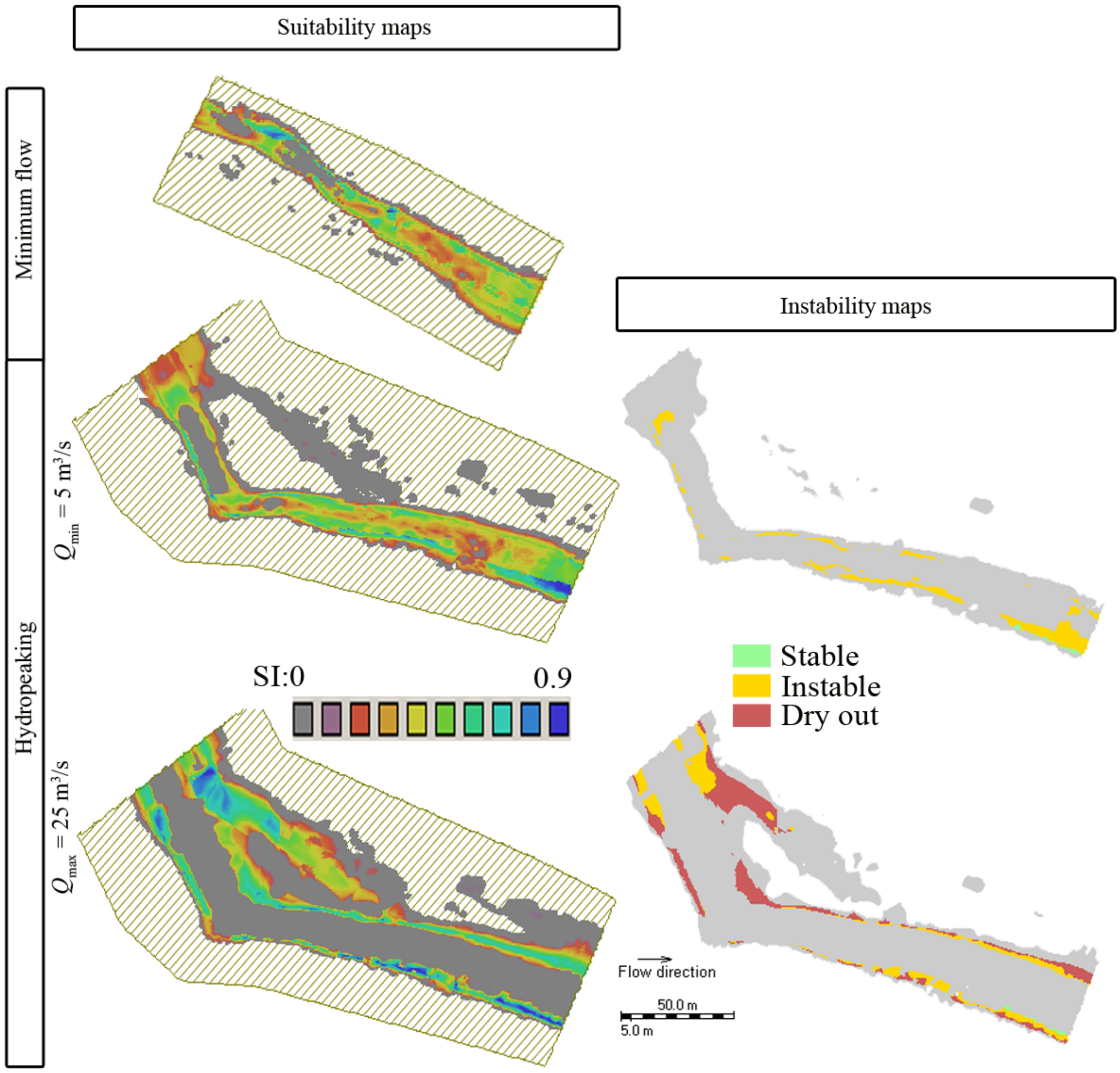


Figure 4.7 : Habitat suitability (SI) maps and habitat instability maps for spawning brown trout resulting from habitat modeling for residual flow, hydropeaking at off-peak ($Q = 5$ m^3/s) and hydropeaking at peak ($Q = 25$ m^3/s) river reaches for November. Left panels show habitat suitability (SI) maps where grey stands for low habitat quality, whereas blue for high habitat quality. SHR is respectively 12, 14 and 21% of the total wetted area for minimum flow, hydropeaking at off-peak ($Q = 5$ m^3/s) and hydropeaking at peak ($Q = 25$ m^3/s) river reaches. Right panels show habitat instability maps where grey shows the effective wetted area (where water depth > 10cm), green shows the areas where habitat conditions stays stable between the two steady states Q_{min} and Q_{max}, yellow where habitat conditions change from suitable to unsuitable and redd where habitat conditions change from suitable to dewatered. The arrow indicates flow direction (from left to right).

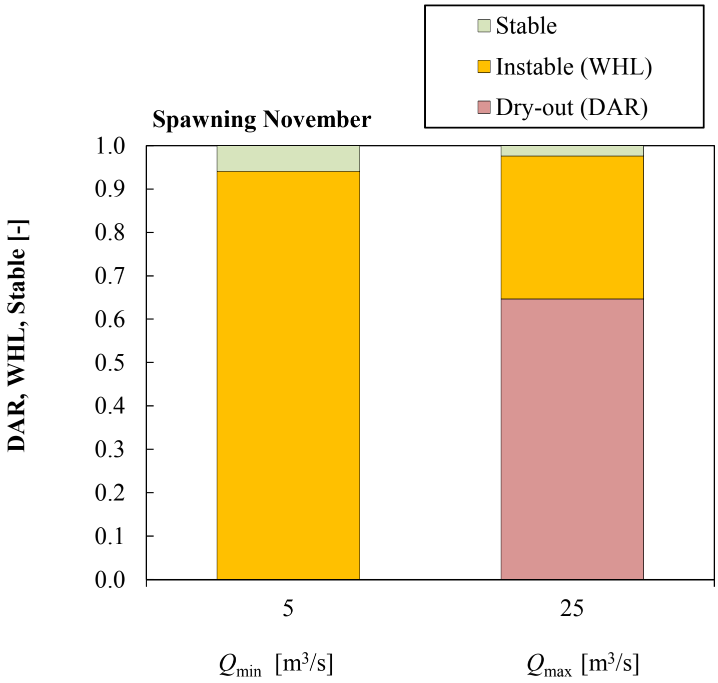


Figure 4.8 : Fate of the suitable habitat (SI > 0.5) when discharge changes from off-peak to peak and from peak to off-peak for spawning brown trout for the off-peak Q_{min} and the peak Q_{max} discharge of November 2009. For discharge changes from Q_{min} to Q_{max} (left box) and Q_{min} to Q_{max} (right box) respectively, percentage of stable (green), instable (yellow) and dewatering (red) habitat is indicated.

Sub-daily temporal habitat variation for YOY for a representative October day are shown on Figure 4.9. SA and SHR time series show frequent and inversely proportional variations to discharge change. Drawdown ratios are the same in October as in November. At peak conditions, 150 m^2 of the SA is lost, which corresponds to a 5% loss of SHR.

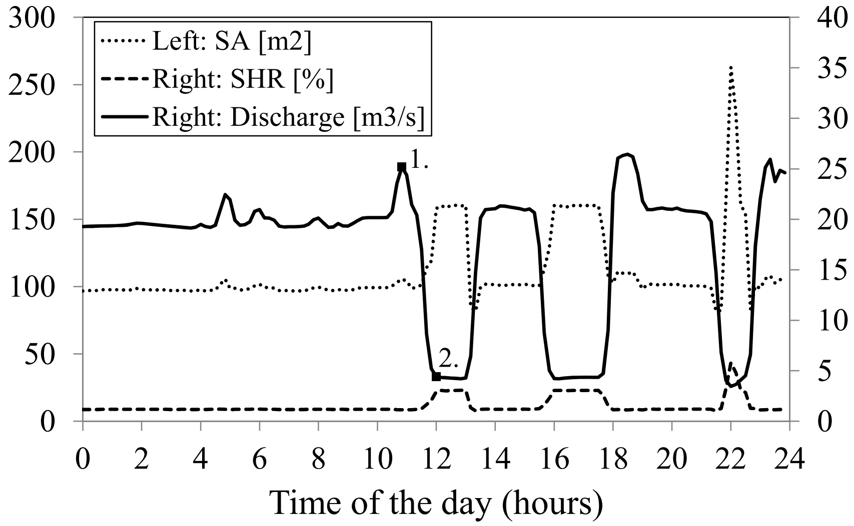


Figure 4.9 : Discharge (solid line, right y-axis), Suitable Area SA (dotted line, left y-axis), and Suitable Habitat Ratio SHR expressed in % of the wetted area (dashed line, right y-axis) for young-of-the-year (YOY) as a function of time for the Vorderrhein River. Discharge was measured by Ilanz gauging station on the 5th October 2009 chosen as representative days to study sub-daily temporal YOY habitat variation. Locations 1. and 2. on the discharge time series refer respectively to peak and off-peak discharge conditions which are modeled on habitat maps in Figure 4.10.

Figure 4.10 shows YOY habitat suitability and instability maps. SHR is 1, 2 and 1% of the total wetted area for minimum flow (reference reach Mutteins), the hydropeaking influenced reach at off-peak and peak conditions, respectively (reference reach Castrisch). In the hydropeaking section, suitable habitat is restricted to shore areas and thus strongly displaced during flow fluctuation. Seventy percent of the suitable habitat (SI > 0.5) is displaced with flow fluctuation. The remaining 30% persists at peak and off-peak discharges, resulting mainly from a pool frequently disconnected from the main channel. Moreover, as most of the suitable habitat is restricted to shore areas, 60% of this habitat is dewatered during flow decrease (Figure 4.11).

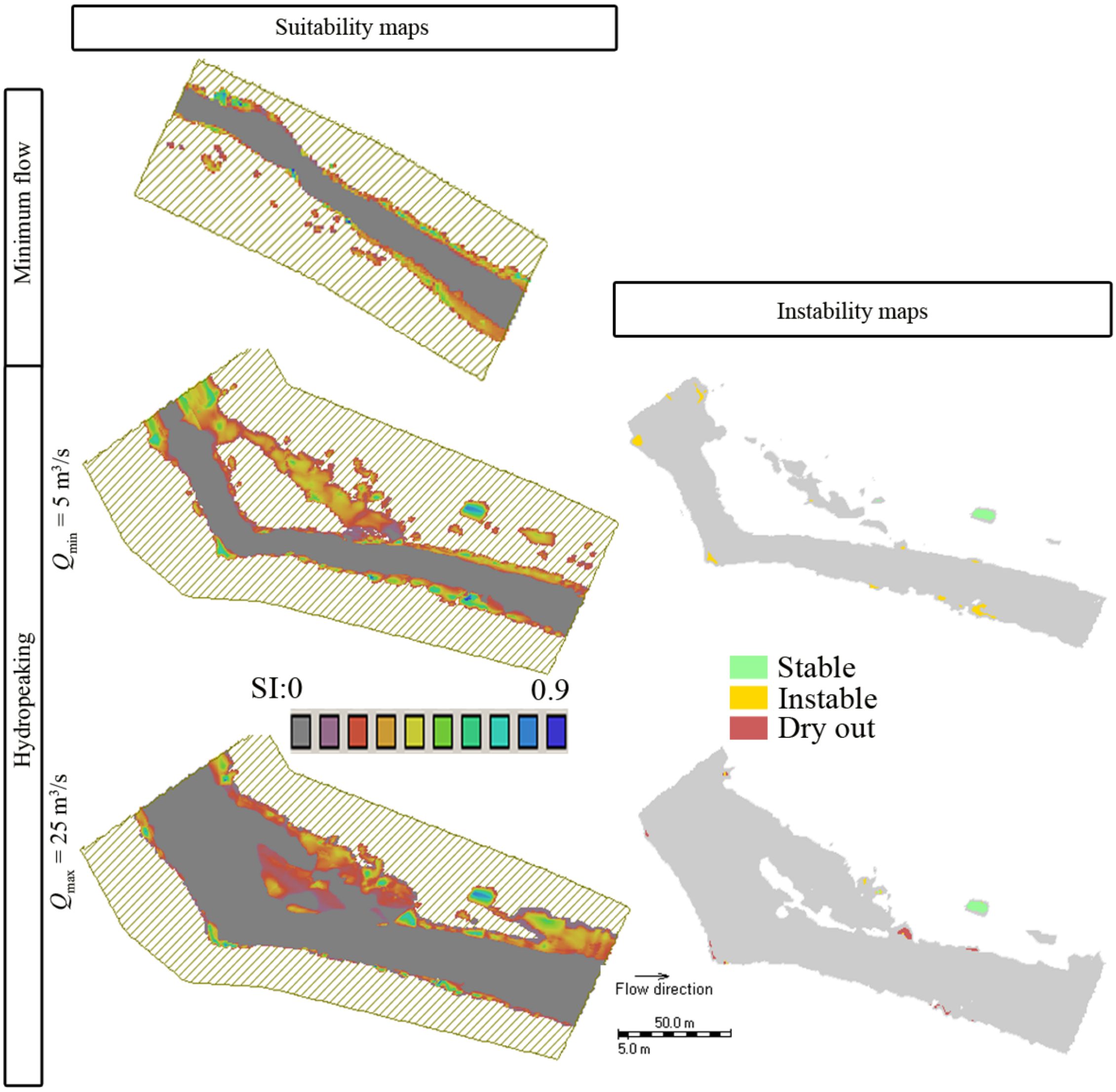


Figure 4.10 : Habitat suitability (SI) maps and habitat instability maps for young-of-the-year (YOY) brown trout resulting from habitat modeling for residual flow, hydropeaking at off-peak ($Q = 5$ m^3/s) and hydropeaking at peak ($Q = 25$ m^3/s) river reaches for October. Left panels show habitat suitability (SI) maps where grey stands for low habitat quality, whereas blue for high habitat quality. SHR is respectively 12, 14 and 21% of the total wetted area for residual flow, hydropeaking at off-peak ($Q = 5$ m^3/s) and hydropeaking at peak ($Q = 25$ m^3/s) river reaches. Right panels show habitat instability maps where grey shows the effective wetted area (where water depth > 10cm), green shows the areas where habitat conditions stays stable between the two steady states Q_{min} and Q_{max}, yellow where habitat conditions change from suitable to unsuitable and redd where habitat conditions change from suitable to dewatered. The arrow indicates the flow direction (from left to right).

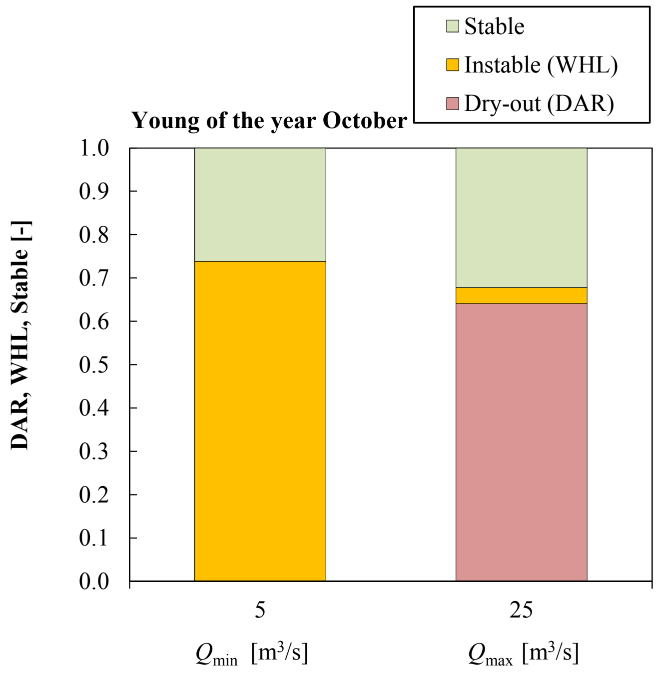


Figure 4.11 : Fate of the suitable habitat (SI > 0.5) when discharge changes from off-peak Q_{min} to peak Q_{max} and from peak to off-peak for young-of-the-year (YOY) in October 2009. For discharge changes from Q_{min} to Q_{max} (left box) and Q_{min} to Q_{max} (right box) respectively, percentage of stable (green), instable (yellow) and dewatering (red) habitat is indicated.

Natural reproduction success

Figure 4.12 shows the results of the egg in-situ incubation experiment. Average standard mortality (lab control) was 19 % and was lower than in-situ mortality recorded in the Vorderrhein River. Mortality ranged from 30% in the residual flow section to 36% in the hydropeaking section. Besides, a rather high amount of missing individuals was recorded due to the permeability (large mesh size) of the Vibert box to the alevin stage. No strong difference was found in alevin survival between upstream and downstream HPP release reaches. Moreover the uncertainty in survival counts due to missing individuals is comparable in both reaches (Figure 4.12).

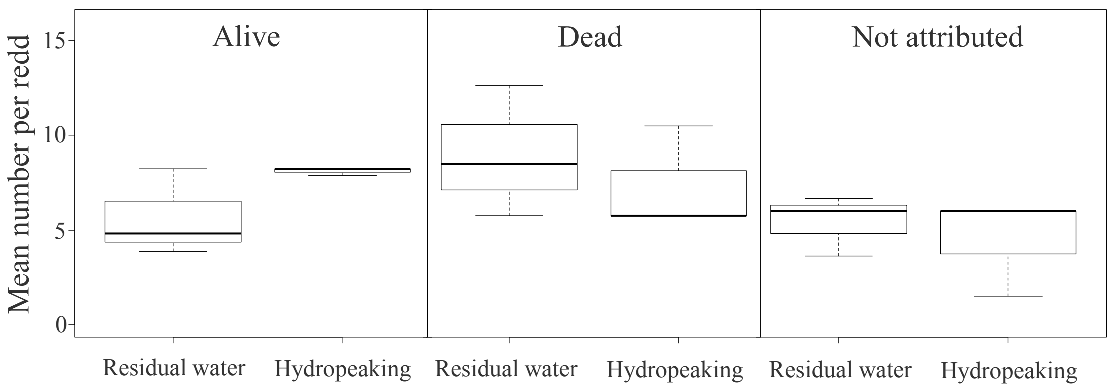


Figure 4.12: Boxplot of the mean of alive until alevin stage (alive), dead before alevin stage (dead) and missing (not attribute) individuals counted per Vibert box per redd was calculated for residual and hydropeaking reaches. Each reach contains three redds replicates. Analysis of the results was based on a descriptive approach due to the low number of replicates. No difference of survival was shown between residual flow and hydropeaking reaches.

Shore-line electrofishing results are presented in Figure 4.13a. Results show that YOY density is slightly higher in constant flow reaches. If related to total surface of the reach, the density is about four times higher in the residual flow (RF) reach than in the hydropeaking (HP) reach. However, this difference in fish density between upstream and downstream of HPP water release reaches is not significant (p-value = 0.1). This result is consistent with habitat modeling outcomes showing that suitable shore habitats are present in the reaches influenced by hydropeaking (Figure 4.10). In addition, YOY body length was not statistically different (p-value = 0.312) between fish sampled upstream and downstream of HPP water release (Figure 4.13b).

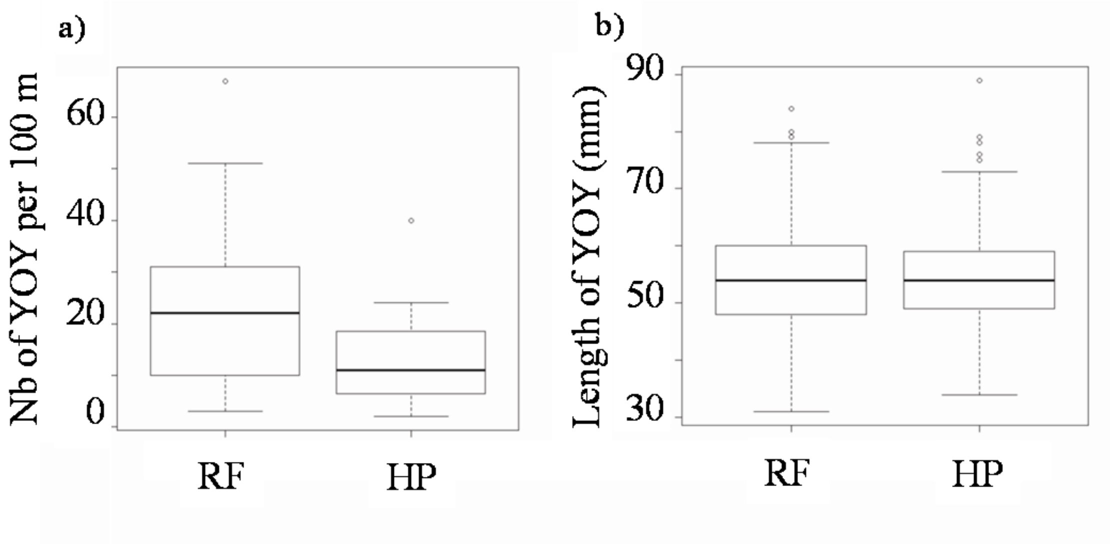


Figure 4.13: Boxplot of density per 100 m shore and body length data for residual and hydropeaking sections. RF stands for residual flow reach and HP for hydropeaking reach. (a) YOY number caught per 100 m. There was no significant difference in YOY density between residual and hydropeaking sections (non-parametric permutation test; p-value = 0.1). (b) body length of brown trout caught either in residual or hydropeaking section. Data did not show statistical difference (wilcoxon test; p-value 0.312).

4.6 Discussion & Conclusion

Prior work has documented the effects of HPP operation on fish populations (Young *et al.* 2011) and habitat models were used to assess the effect of hydropeaking on fish habitats and to plan future mitigation efforts (Valentin *et al.* 1994; Valentin *et al.* 1996; Garcia *et al.* 2010). However, current discussion on mitigating hydropeaking are limited to hydrological parameters (Meile *et al.* 2011) and do not emphasize the combined role of flow pattern and morphology. When assessing river habitat suitability for fish, both hydrology and morphology need to be considered. Moreover, most modeling studies are limited to the adult stages of the investigated species. But hydrological extremes can cause a bottleneck in the ontogeny of fish species. For the present study, the effect of sub-daily discharge changes on habitat distribution and availability was investigated in a river with natural morphology. Hydrodynamic conditions under hydropower operation have been modeled for brown trout, focusing thereby on the effects on the early life stages. Reproduction success was evaluated by monitoring egg to hatching survival in an in-situ experiment and sampling YOY density in a hydropeaking and residual flow reach. The results demonstrate that natural reproduction is possible but impaired in rivers influenced by hydropeaking. Habitat for both spawning and YOY was present at peak and off peak flow and in approximately similar quantities in the constant and in the hydropeaking influenced reach. Even if slightly lower in the hydropeaking reach, no statistically significant difference was found in egg to hatching survival as well as in the density and length of YOY between natural reaches upstream and downstream of HPP water release.

HSCs from River Vorderrhein for velocity, depth and substrate were similar to the HSCs described in literature. This supports that spawning female are very selective for depth, substrate and velocity, only showing slight differences between rivers. YOY preference were consistent with the majority of HSCs found in the literature regarding velocity and depth. However, no trend in substrate preference was observed. This suggests that depth and velocity may be more crucial in YOY habitat choice than substrate. The variability observed in fish habitat preference provides evidence that regional differences in HSCs can influence modeling outcomes. There are many reasons for HSCs regional divergence. Microhabitat selection by fish can be influenced by behavioral plasticity of different brown trout populations or specific environmental factors such as predation risk, presence of competitors or thermal regime of the stream (Orth 1987). In this work, the sensitivity of fish habitat models to fish preference was assessed relying on a large panel of HSCs describing worldwide spawning and YOY brown trout preference. The analysis showed that spawning HSCs from alpine regions give similar model output. However, model outputs were in general very sensitive to HSCs origin for both life stages. Thus, input habitat preference should be adapted to the investigated river and the use of regional data is expected to increase the accuracy of predictions of habitat modeling tools. Further work should include comparison of preference for contrasting rivers to validate this hypothesis.

The characteristics and availability of the hydraulic habitat have a crucial impact on fish populations (Armstrong *et al.* 2003; Gouraud *et al.* 2004). This habitat is determined by velocity, depth and substrate profiles and is strongly affected by discharge instability downstream HPPs (Person & Peter 2012) (see chapter 3). Results from the habitat model as well as field studies suggest that reproduction success is not precluded under peak operation in a natural morphology, albeit lowered by the strong instability of the habitat. During discharge increase, a relatively low amount of habitat, which is used by spawning or by YOY, is lost (7% and 5%, respectively). However, habitat for both life stages is strongly shifted during flow change and at least 60 % of the habitat present at peak flow is dewatered during off-peak flow. Several studies demonstrate that salmonid egg survival is not affected, when redds become dewatered but stay moist for a couple of weeks (Becker *et al.* 1982; Becker & Neitzel 1985). However, spawning behavior might be impaired by habitat instability. In fact, previous studies reported redds being abandoned before spawning is completed as a result of sudden flow change. However, some females were observed returning to continue redd construction at peak flow (Hamilton & Buell 1976; Chapman *et al.* 1986). Disturbance due to sudden changes in flow might result in females choosing less suited habitats for spawning and spawning into poorly constructed redds, increasing scouring risk (Hunter 1992). Juvenile salmonid behavior in relation to habitat displacement was previously studied by several authors. Different behaviors were reported ranging from high site fidelity to considerable movement under unstable flow conditions (Scruton *et al.* 2003; Scruton *et al.* 2005; Scruton *et al.* 2008). It was reported that growth and growth efficiency in juvenile brown trout was reduced under fluctuating flow (Flodmark *et al.*

2004; Korman & Campana 2009) and that increased movement could affect fish overwintering survival (Scruton *et al.* 2008). Extra fish movement could be due to individuals forced to change locations from suitable habitat areas at peak flow and off-peak flow to meet their habitat requirement under changing conditions. This hypothesis is supported by the strong habitat displacement between peak and off-peak flow shown by habitat model results in the current and in previous works (Person & Peter 2012) (see chapter 3).

Yet, in this work, some discrepancy is present between habitat modeling and river monitoring results. Even if egg survival and YOY density was slightly lower in the hydropeaking reach, the field experiments did not clearly show the consequences of habitat displacement and dewatering on the fish population. No significant difference in YOY body length was found between upstream and downstream HPP water release. However, body length may not be suitable to detect differences in growth. Further tests should involve body fat and otolith analysis. Other parameters such as predation risk, territoriality and competition may aggravate the impact of habitat displacement (Heland *et al.* 1995). Moreover, impact of habitat instability on juvenile fishes is still controversial. Some authors argue that fish are able to adapt to sub-daily flow fluctuation (Flodmark *et al.* 2002) and that hydropeaking effects on juveniles are relatively small, if stranding can be avoided (Flodmark *et al.* 2006). The large area, that gets dewatered during off-peak, indicates, that stranding is a potential risk for YOY in rivers having a natural morphology. Stranding depends on different parameters as the wetted history, ramping rate, season, night or day timing of event (Saltveit *et al.* 2001; Halleraker *et al.* 2003; Irvine *et al.* 2009; Tuhtan *et al.* 2012). Further investigation could provide insight on how stranding affects survival in braided rivers influenced by hydropeaking.

This study implies consequences for future research, which are outlined in the following. The data show that tools for quantifying habitat displacement and dewatering are essential to assess the impact of dynamic flow conditions on fish populations. The use of the newly developed habitat indicators Suitable Habitat Ratio (SHR), Weighted Habitat Loss (WHL) and Drained Habitat ratio (DAR) allow a more accurate and better qualitative description of fish habitat, first in overlooking poor habitats ($SI > SI_{lim}$) and second in quantifying habitats dynamic. The results provide evidence that natural braided river morphology, act as an intrinsic factor to buffer negative effects of flow changes. The diversity of abiotic and spatial organization of natural river, compared to narrower and channelized morphologies, may help fishes to find habitat that meet their requirements at varying discharges. However, this implies a dynamic and instability of the spatial habitat which is detrimental to fish. The spatial distribution of abiotic parameters under different morphologies and flow conditions should be further investigated. The results state that natural morphology might act as a mitigator to hydropeaking. Thus, further ecological improvements might get achieved when instream measures buffering hydrological variation are established.

Some constraints and limitations have to be considered in this work. Parameters affecting fish populations such as water quality, temperature, and flood episodes are not analyzed here as this study concentrates on the hydraulic characteristics associated with hydropeaking. As for all PHABSIM derived models, the assumption was made that fish habitat preference is independent of discharge. However, work from Holm *et al.* (2001)

on Atlantic salmon (*Salmo salar*) emphasized that this assumption may not be valid. Therefore, brown trout habitat preference under varying discharge should be tested in future hydropeaking related research. In this work, variation in habitat was investigated between peak and off-peak conditions and intermediate discharge change or habitat duration curves were not considered. Further study should include variation of the habitat over time and integrate speed of habitat displacement and habitat dewatering, which are important indicators in assessing stranding risks and fish movement. It is important to note that this work presents the same limitations as other PHABSIM model approaches, interaction between univariate preference for abiotic parameters are not taken into account (Heggenes 1996). Applying logistic regression to the microhabitat data may be a solution to integrate the interaction between velocity, depth and substrate in fish habitat preference (Parasiewicz & Walker 2007). In this study, the residual flow section was defined as the control due to the absence of an hydrological intact reach. The residual flow reach is not comparable to a natural reach, as it provides less habitat diversity and reduced fish biomass (Baran *et al.* 1995). Thus the residual flow reach cannot represent natural conditions for fish populations and must be interpreted accordingly. Nevertheless, in the absence of a natural reach, it represents a constant flow control allowing investigation of the effects of flow instability on habitat patterns. Egg incubation in Vibert boxes resulted in a rather high amount of missing individuals due to the permeability of the box to the alevin stage. Other incubation system preventing alevin to escape could reduce uncertainties in survival rates (see chapter 5). The life stage of post-emerged fry was not investigated due to sampling difficulties and time constrains. However, emergence and the first months of the fry are particularly sensitive and vulnerable stages (Gaudin *et al.* 1995; Heland *et al.* 1995) and thus should be included in further studies.

Joint effect of river channelization and flow regulation on brown trout population

Mitigating the adverse impacts of human activities is a crucial step in restoring aquatic ecosystems. However, treating hydropeaking or geomorphological deficits independently might not guarantee successful mitigation. In this chapter, the effect of hydropeaking on brown trout reproduction is studied in the Hasliaare River, which experienced river channelization. The channelization influenced strongly the abiotic habitat conditions. Three morphologically different types of reaches were studied, groynes, gravel bars and monotonous channel reaches. Spawning habitat of lake (LR) and stream (SR) resident and young-of-the-year trout (YOY) brown trout was evaluated by means of a CASiMiR habitat model and dynamic habitat indices (habitat loss and dewatering) (see chapter 4 and 6). Specific preference curves were calculated for each of the three cohorts. Egg to hatching survival experiments and post emergent fry density surveys were conducted. Results show that the complex equilibrium between hydrological, morphological and ecological conditions needed to sustain viable fish populations is strongly disrupted by the joint effect of channelization and hydropeaking. Fish habitat instability resulting from hydropeaking was aggravated by reduction of river width and habitat heterogeneity due to channelization. Results showed that the absence of rearing habitat constituted an important deficit in rivers where embankments replaced shallow water areas on the channel margins usually colonized by YOY. Habitat simulation showed that lack of fish habitat was slightly decreased in the less monotonous channelized reach types, including groynes and gravel bars. Finally, the results emphasize that rehabilitation strategies should be undertaken on an integrative scale due to the complex interaction between morphology and hydraulics. Environmental flow should be defined by concomitantly establishing river engineering and hydraulic mitigation measures.

5.1 Introduction

Rivers under multiple pressure

In industrialized, densely populated areas such as Western Europe, the freshwater environment has been strongly modified for centuries (Vischer 2003; Hering *et al.* 2013). Natural floodplains were straightened into monotonous and fragmented river courses to meet different human goals such as flood protection, increase land for agricultural use or hydropower production (Ward & Stanford 1995; Poppe *et al.* 2003; Nilsson *et al.* 2005; Bernhardt & Palmer 2011). As a consequence, about 90% of the natural floodplains have been lost (Müller-Wenk *et al.* 2004). These modifications have resulted in strong deficits in hydrological, morphological and ecological processes, such as impairment of the interaction between the riparian zone and the ground water (Hancock 2002), bed load transport and sedimentation (Surian & Cisotto 2007).

In Switzerland, one third of the river network has significant morphological deficits and is classified as heavily impacted, unnatural or artificial (Woolsey *et al.* 2005). Morphological deficit is mainly the consequence of river channelization and flow regulation, through hydropower exploitation. Channelization increases flow velocity in the river as a result of slope, and roughness modification (Elosegi & Sabater 2012). High-head storage hydropower plants (HPP) affect the natural flow regime of rivers (Poff *et al.* 1997; Jones 2013) by producing sub-daily flow fluctuations (Baumann & Klaus 2003). This phenomenon is called hydropeaking and defines the release of water from a storage basin to generate energy depending on the energy demand (Moog 1993; Charmasson & Zinke 2011). In the receiving river, the impacts on the ecosystem are significant, including a modification of velocity and depth distributions (Hu *et al.* 2008) as well as temperature and sediment characteristics (Bunn & Arthington 2002; Bruno & Siviglia 2012). The impact on temperature is defined as the thermopeaking phenomenon and strongly modifies daily and seasonal temperature regimes (Zolezzi *et al.* 2011; Dickson *et al.* 2012). Alteration of sediment transport is characterized by two phases resulting from the variation between peak to off-peak flow. During the off-peak phase, sediment is deposited, which results in bed clogging, whereas during the peak phase, the sediment is re-suspended, which causes higher erosion and water turbidity (Anselmetti *et al.* 2007; Wang *et al.* 2013). In addition, other important processes such as water exchange with the hyphorreic zone are also altered (Gailiuis & Kriauciuniene 2009; Sawyer *et al.* 2009).

Effect of hydropeaking on the river fauna

Distribution of species within rivers is strongly dependent on the hydrological and geomorphological processes. Thus, aquatic organisms are strongly affected by sub-daily flow fluctuation resulting from a hydropeaking regime (Sanz 2012). The macrophyte community composition is modified (Bernez & Ferreira 2007), and the riparian fauna, macroinvertebrate and fish distribution and abundance is affected (van Looy *et al.* 2007; Bruno *et al.* 2009; Smokorowski *et al.* 2011). Macroinvertebrate and juvenile fishes drift or are stranded during peak flow periods (Halleraker *et al.* 2003). Even if a large variety of organisms were studied, most research use fish as a target species, for being good indicators of anthropogenic pressure on ecosystems and easy to sample (Harris 1995). Moreover, fish species allow researchers to treat several aspects of the hydropeaking problem through their migratory behavior, complex life cycle and specific habitat requirements. This is particularly true for salmonids species, which occur in the upper part of catchments where storage hydropower schemes are mostly built. Under hydropeaking, fish habitat is strongly displaced or dewatered due to the variation between peak and off-peak flow. The effect is particularly strong on spawning and juvenile life stages (Person & Peter 2012; Person & Peter submitted) (see chapter 3 and 4). Furthemore, observations of the fish behavioral response to flow change showed that movements are significantly increased (Taylor *et al.* 2012; Taylor & Cooke 2012) and juvenile growth reduced (Scruton *et al.* 2005; Flodmark *et al.* 2006; Scruton *et al.* 2008). During spawning, which occurs in winter when the hydropeaking regime is the most severe (Person & Peter 2012; Person & Peter submitted) (see chapter 3 and 4), the risk for females to abandon the spawning site or spawn in poorly constructed redds is increased (Chapman *et al.* 1986). Redds are exposed to scouring risk (at peak flow) and dewatering (at off-peak flow) which might impair egg development (McMichael *et al.* 2005). In addition, salmonid eggs are very sensitive to high particles and low oxygen conditions in the intragravel space; a situation which is aggravated under hydropeaking (Greig *et al.* 2005a; Greig *et al.* 2005b; Sear *et al.* 2008; Jensen *et al.* 2009; Yamada & Nakamura 2009). Preliminary studies on brown trout egg development in rivers influenced by hydropeaking showed that survival was reduced (Eberstaller & Pinka 2001; Person & Peter submitted) (see chapter 4). However, studies did not include survival after the eyed egg stage or could not show a statistically significant difference.

Channelization and hydropeaking

River degradation by human impact results in hydromorphological pressures that influence the habitat of the river fauna. Most studies concentrate on the isolated impact of one pressure, such as of river channelization, or of hydropeaking. Even if these effects are often separately studied, they often occur in the same system. River channelization is responsible for the uniformity in sediments and hydraulic characteristics resulting in the loss of flow refugia and backwaters (Negishi *et al.* 2002; Garcia *et al.* 2012; Dzialowski *et al.* 2013). This creates unfavorable habitat conditions for fish juveniles and impairs habitat heterogeneity (Millidine *et al.* 2012). Such physical habitat deficit can constitute landscape "filters" limiting the distribution and abundance of species or specific life stages (Poff 1997). The hydraulic characteristics resulting from the hydropeaking regime and local reach morphology and roughness could act as such landscape filters (Hauer *et al.* 2012). In fact it was shown previously that the diversity of fish and other aquatic organisms as well as riparian arthropod is strongly reduced when the two effects are associated (Fette *et al.* 2007; Weber *et al.* 2007; Paetzold *et al.* 2008). Besides, fish stranding risk is determined by river morphological and hydropeaking characteristics such as shore slope, peak amplitude and ramping rates.

Restoring river habitat

River widening is a common restoration approach for formerly braided rivers that have been strongly spatially constrained (Rohde *et al.* 2005). This type of morphological improvement allows channel movement within a spatially limited area, increasing instream habitat heterogeneity (Rohde *et al.* 2004). However, in hydropeaking rivers, widening might increase fish habitat instability and stranding risks (Tuhtan *et al.* 2012; Person *et al.* 2013) (see chapter 6). Flow refugia can be constructed through river engineering measures to provide habitat shelters (Vehanen *et al.* 2003; Ribi 2011). However, several studies showed that morphological improvement was not successful if the flow deficits due to hydropower operations were not concomitantly mitigated (Pellaud *et al.* 2006; Weber *et al.* 2007). Similarly, mitigation strategies that focus solely on flow mitigation often have their effectiveness constrained by existing morphological deficits (Brown & Pasternack 2008). To solve this dilemma, management strategies should be focused on ecosystem-centered approaches in which watercourses are considered as heterogeneous systems where morphological, hydrological and biological processes are interconnected (Ward *et al.* 2001; Peter 2010).

Habitat models are useful tools to assess hydrological and morphologic impacts of human river management, on the habitat of aquatic biota (Bovee *et al.* 1988). CASiMiR is a micro-habitat model as the Physical Habitat Model (PHABSIM) family developed for the assessment of minimum flow (Bovee *et al.* 1988; Munoz-Mas *et al.* 2012) and later used in hydropeaking impact assessment on fish habitat (Garcia *et al.* 2010). Recently, the fish module of the CASiMiR model was enhanced with new indicators especially developed for modeling habitat instability in hydropeaking rivers (Person & Peter submitted) (see chapter 4). The new indicators are able to quantify habitat loss and dewatering due to variation between peak and off-peak flow.

Understanding the interaction between different human-induced stressors is fundamental to orienting future mitigation strategies. Nevertheless, the joint effect of river channelization and hydropeaking on fish habitat is still poorly understood. In response, several projects – such as the CTI project “Sustainable use of hydropower” in Switzerland (Person & Peter 2012) (see chapter 1 and 3), the “Future Alpenrhein River” platform by the International Governmental Commission for the Alpenrhein (IRKA) (Zarn 2008; Kindle *et al.* 2012) or the EnviPEAK project in Norway (Bakken 2009) - were initiated in Europe to build science-based concepts for hydropeaking mitigation (Zarn 2008; Person & Peter 2012; Schneider *et al.* 2012) (see chapter 3, 4 and 6).

This chapter is part of the Swiss CTI project “Sustainable use of hydropower” and focuses on the effect of hydropeaking on brown trout natural reproduction in a river which exhibits morphological deficits. Through a combination of modeling and field monitoring approaches, potential landscape filters limiting population renewal were characterized. Therefore, lake (LR) and stream (SR) spawners and late summer YOY habitat was simulated using the fish module of the CASiMiR model and the habitat indices developed by Person & Peter (submitted) (see chapter 4). The habitat was modeled in three reaches of the Hasliaare River in Switzerland with different river engineered morphologies. Specific preference curves for LR and SR spawners as well as YOY brown trout were developed. In addition, reproductive success was monitored by egg to hatching survival experiments and post-emergent fry density surveys carried out in May. Egg survival under hydropeaking conditions was evaluated using an enhanced experimental design based on a preliminary study (Person & Peter submitted) (see chapter 4).

5.2 Study area

The Hasliaare River rises to a mean catchment elevation of 2150 m a.s.l. and has a length of 30 km. The drainage basin is mainly composed of sedimentary, crystalline and granite rocks and is 554 km^2 in area. Approximately 20% of the catchment is glaciated with 6 main glaciers. The river flows from its source, the glaciers of Oberaar and Unteraar under the Finsteraarhorn peak (4274 m a.s.l.), to Lake Brienz (564 m a.s.l.).

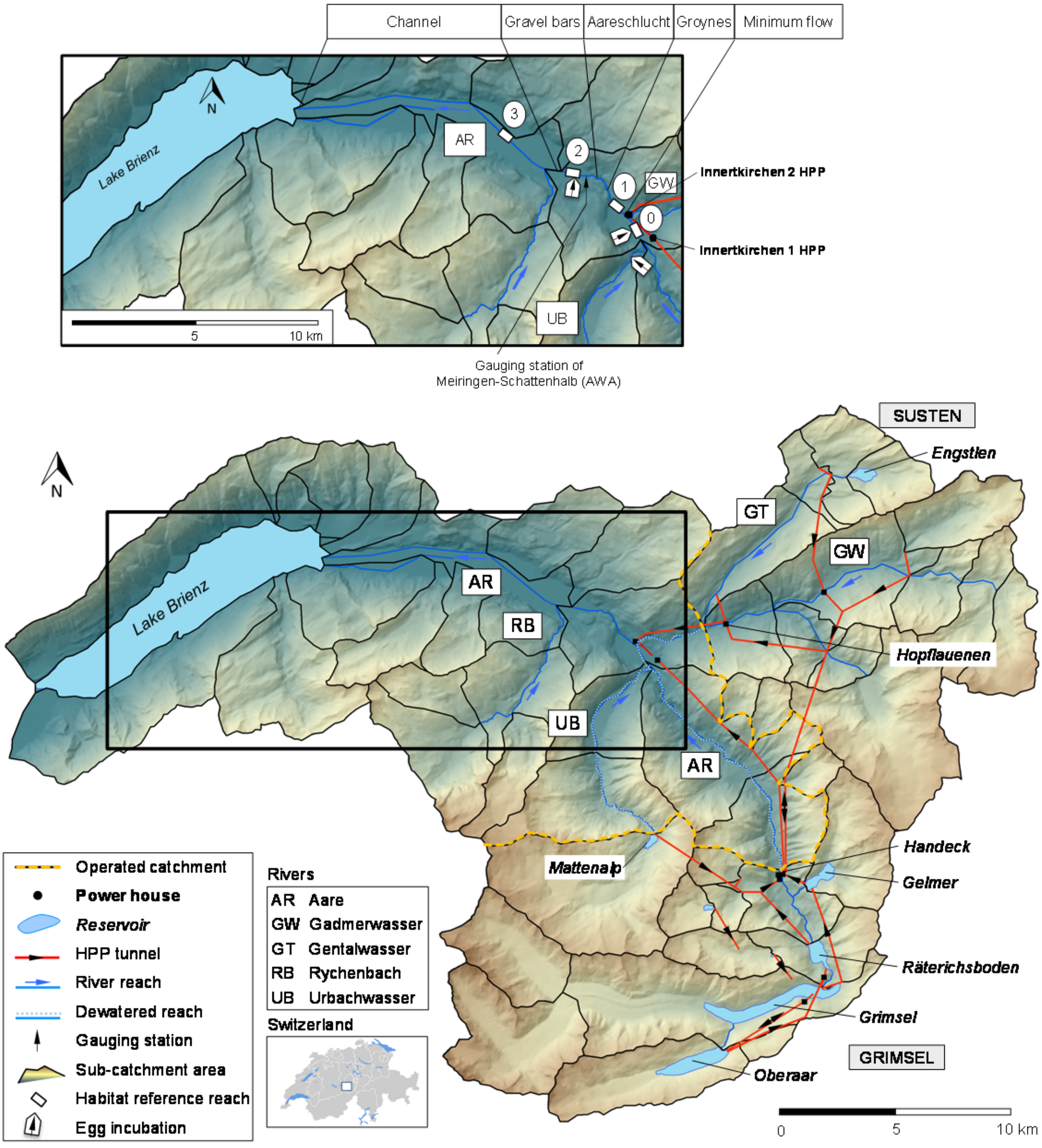


Figure 5.1: Map of the upper Aare catchment area in Switzerland with the Oberhasli hydropower scheme (reservoirs, HPP tunnels and powerhouses), the limit of the utilized catchment area, the sub-catchment areas and the river network. The zoom view in the upper frame displays the study area of the Hasliaare River, with the regulated reach, the minimum flow reach and the Urbachwasser tributary and the two gauging stations. White boxes indicate the modeled reference reaches with minimum flow (0), groynes (1), gravel bars (2) and channel (3) reaches. White boxes with arrows indicate the egg incubation areas.

The Hasliaare River is gravel-bed dominated and defined as being in the trout or upper grayling zone (Huet, 1949). The flow regime is glacio-nival (Weingartner & Aschwanden 1986). Recent fishery records describe eight fish species for the Hasliaare: brown trout (Salmo trutta), bullhead (Cottus gobio), rainbow trout (Oncorhynchus mykiss), brook trout (Salvelinus fontinalis), arctic char (Salvelinus alpinus), grayling (Thymallus thymallus), burbot (Lota lota), and perch (Perca fluviatilis). Rainbow trout and brook trout are introduced species and are scarce in the river. Arctic char, grayling, burbot, and perch are rare immigrants from Lake Brienz and found only in the vicinity of the river mouth. The only widely distributed species in the Hasliaare is the brown trout (Haas & Peter 2009). The river carries populations of lake (LR) and stream (SR) resident brown trout cohorts. LR spawners migrate from the lake upstream during winter to spawn in the Hasliaare River.

The major issues in the Hasliaare River are directly related to flood protection and hydropower production. Historical records show that since the early 20th century, the river course has been stabilized to gain land over the pristine floodplain and to protect settlements against floods. The river was successively straightened and constrained (Haas & Peter 2009). River engineering measures involved river-bed deepening and bank protection works. Beginning in 1925, Kraftwerke Oberhasli (KWO) has built a complex hydropower scheme of nine powerhouses and several artificial reservoirs in the Hasliaare catchment (Figure 5.1). The High-Head Powerplant (HPP) utilizes 60% of the Hasliaare catchment area, which represents 700 mio m^3 of water runoff per year in the form of rain and snow. The HPPs generated approximately 1750 GWh in 2010,, corresponding to 10% of the electricity produced by Swiss HPPs and covering the energy consumption of approximately 1 million inhabitants. In Innertkirchen, the powerhouse outflow resulting from electricity production is restituated into the Hasliaare River by two powerhouses. One of the powerhouses (Innertkirchen 1) releases the water directly into the Hasliaare. The other powerhouse (Innertkirchen 2) is situated at the mouth of the Gadmerwasser River, which flows into the Hasliaare and drains the eastern part of the basin. Both powerhouses produce significant hydropeaking. The turbine capacities of the Innertkirchen 1 and 2 HPPs are 39 and 29 m^3/s, respectively. Upstream from Innertkirchen, the Hasliaare carries residual flow. This minimum flow reach (16 km) is a natural stream flowing until Innertkirchen where the powerhouse outflow is released back to the river. The main tributary of the minimum flow reach is the Urbachwasser River. The headwater of the Hasliaare and the Urbachwasser rivers are known as important spawning grounds for LR and SR brown trout. The hydropeaking reach downstream of Innertkirchen can be divided into four morphologically distinct types; 1) a groynes reach (650 m) with streambank protection structures perpendicular to the riverbank limiting lateral bank erosion, followed by 2) a short natural and steep canyon (1.4 km) called Aareschlucht, 3) a gravel bar reach (1.3 km): stands for a channelized stream bed with gravel bars increasing velocity and depth variability. The riverbed in the gravel bar reach is confined with rip rap protection at its banks and 4) the channel reach (11 km) is a long monotonous trapezoidal cross section, confined by train tracks and road. This channel reach enters into Lake Brienz. According to the ecomorphology module concept (Hütte & Niederhauser 1988), which classifies streams by their physical characteristics, the minimum flow and regulated reaches of the Hasliaare river where assessed as minimally and heavily impacted, respectively (Haas & Peter 2009). A major environmental issue in the catchment area focuses on the conservation of the lake resident trout population and the protection of its spawning grounds (Meyer 2010).

5.3 Method

The Hasliaare River system was used as study case to perform a quantitative and qualitative analysis of combined effects of degraded river bed morphology and hydropeaking on brown trout habitat. To achieve this, both modeling of habitat suitability and in-situ monitoring of the success of brown trout reproduction were conducted.

5.3.1 Habitat suitability

Univariate habitat suitability curves for LR and SR spawners as well as late summer YOY were calculated according to sampling design of Bovee *et al.* (1988) and based on habitat use and availiability as detailed in Person & Peter (submitted) (see chapter 4).

Univariate habitat suitability curves were based on site-specific measurements of the use and availability of habitat for spawning and YOY brown trout in the Hasliaare river and two of its tributaries; the Gadmerwasser and Urbachwasser. In winter 2011 (November – December), spawning activity was surveyed and mapped along 1 km of the Hasliaare river dewatered reach, which carries residual flow and along 600 m of the Urbachwasser. Redds were assigned to either LR or SR cohorts based on the direct observation of fish during spawning activity. In the hydropeaking reach, spawning activity could not be mapped as the high turbidity did not allow direct redd observation. In the residual flow reach, 28 and 38 redds of LR and SR spawners were surveyed and habitat use data collected. Velocity, depth and dominant substrate was measured as described in Riedl & Peter (2013), at five points on each redd (front, back, left, right and middle of the redd). YOY habitat use was sampled in late summer 2011 in the lowermost 50 m and 100 m of the Urbachwasser and the Gadmerwasser reaches respectively. Habitat use was analyzed using point sampling electrofishing while moving upstream and keeping a distance of 2 m between each point to avoid fright bias. 307 YOY individuals were collected and their exact position recorded. Position was determined at the very first moment of the anodic reaction. Colored metal plates were dropped at each fish location for later measurement of habitat variables.

For both life stages, habitat availability was determined using river transects distributed every 10 m. Mean velocity, depth and dominant substrate were recorded every 1 m along transects. For spawning conditions, transects were distributed along 600 m of river within the mapped spawning grounds. They were distributed to be representative of the types and frequencies of microhabitats present within the Hasliaare and Urbachwasser surveyed reaches. For YOY, transects were placed on the whole electrofished section.

5.3.2 Fish habitat modeling

A representative section of approximately 250 m for each of the four reach types was chosen. For each of the four representative reaches, a 3D digital elevation model (DEM) was computed based on reach measurements using a tachymeter terrestrial system (Leica TC1102) with a GPS echo sounder (DESO14). The grid size was set to 0.5 m, producing a detailed map of the riverbed elevation and topographic composition. Dominant substrate was mapped according to the modified Wentworth scale (Krumbein and Sloss, 1963) on the entire modeled reach. For model calibration, flow velocity was measured in situ using a SEBA mini current meter (type M1).

Mean velocity, depth and substrate distributions were simulated using a 2D hydrodynamic model HYDRO_AS-2D (Tolossa *et al.* 2009) for 30 discharges ranging from 3 to 100 m^3/s. This discharge series is representative of the yearly discharge fluctuation calculated for the years 2006 to 2011 in Schattenhalb gauging station, excluding the flood events. To describe flow conditions for YOY during late summer and for spawning trout during winter, hydrographs from August and November 2009 from the Schattenhalb gauging station were used. The off-peak (Q_{min}) and peak (Q_{max}) flow was determined using the 10% and 90% percentiles derived from the monthly hydrographs. The percentiles indicate mean sub-daily flow change. For time series analysis, 9th August and 25th November were used as representative days of their month. Both days display a characteristic hydropeaking pattern for late summer and winter situations.

Hydropeaking effects on fish habitat were modeled in a two-step approach. First, the Univariate Habitat Suitability Curves developed with the site-specific measurements for the Hasliaare system were integrated in the fish module of the CASiMiR habitat model. The model computed the distribution of the Suitability Index (SI) in the four modeled reaches for YOY and spawners. Second, the three habitat indices, developed in Person & Peter (submitted) (see chapter 4), were inferred from the SI values: i. the Suitable Habitat Ratio (SHR), ii. the Wetted Habitat Loss (WHL) and iii. the Drained Area Ratio (DAR). SHR quantifies the percentage of the total wetted area with a SI value higher than 0.5, WHL stands for the percentage of the area with a high SI (SI > 0.5) becoming unsuitable after flow change (SI < 0.5) and DAR stands for the percentage of high SI area (SI > 0.5) dewatered after flow decrease. Formulas are detailed in Person *et al*. (2013) (see chapter 6). WHL can be calculated for habitat loss when discharge changes from off-peak to peak flow and vice versa. DAR calculates habitat dewatering when discharge changes from peak to off-peak flow.

5.3.3 Natural reproduction success

Survival until eyed egg and hatching

Egg incubation experiments were conducted in November 2011. In situ incubation was performed using a capsule system (Dumas & Marty 2006). This method is an interesting alternative to Vibert boxes, which do not allow to sample hatched alevins due to their large mesh size. Eggs were obtained from a pool of mature SR spawners caught in the Gadmerwasser. 3000 pooled eggs from 20 SR females were fertilized with a sperm mix from 20 SR males. Male and female length ranged from 20 to 50 cm. One hour after fertilization, dead and unfertilized eggs were removed. 10 fertilized eggs were placed in each capsule.

Artificial redds were constructed in three sites: gravel bars and residual flow reaches in the Hasliaare and a control reach in the Urbachwasser. In the regulated (gravel bars site), minimum (minimum flow site) and control (Urbachwasser site) flow treatments, 20, 10 and 10 artificial redds were built respectively. The redds were built at the riffle-pool interface as described in Riedl & Peter (2013). Artificial redds enclosed six capsules. A control pool of 800 eggs divided in eight batches of 100 eggs was incubated in the lab to assess mortality rates in lab-reared clutches. For some artificial redds, frequent dewatering was documented at off-peak by direct visual observation during the experiment period. Water temperature was recorded every minute in each study site using temperature loggers. Based on degree-day calculations, three capsules from each artificial redd were removed at the "eyed egg" stage (250 degree-days) and at hatching time (430 degree days) in each artificial redd. At the eyed egg stage, dead and living eggs per capsule were counted. At the hatching stage, dead eggs and dead and living hatched individuals were counted. At this stage, all living individuals had hatched and no living egg was found. For statistical analysis, dead and living fry were counted as "survived until hatching". Difference in survival until eyed egg and hatching stages between sites was tested statistically (Kruskal–Wallis one-way analysis of variance and a one way ANOVA, respectively). For the regulated site treatment, statistical difference in survival until eyed egg and hatching stages between the dewatered and constantly wet redds at off-peak flow was assessed (one way ANOVA).

Young-of-the-year density survey

YOY density was compared among the four reach types. Electrofishing surveys were conducted every spring during the years 2009 to 2012. Several sections of 100 m shore were electrofished in each reach type. In each section, the number of YOY captured was counted. Difference in YOY number among reach types and years was analyzed by means of a Generalized Linear Model, using a Poisson probability distribution.

5.4 Results

5.4.1 Habitat suitability

Spawning activity took place from the 2 November to the 19 December 2011. Sixty-six spawning events were observed in the residual flow reach of the Hasliaare and the Urbachwasser. SR and LR cohorts spawned at the same time and no superimposition of redds was observed. Redds were visible still 3 weeks after construction, on average. Fishes spent 2-3 days on the redd.

Figure 5.2 shows Habitat Suitability Curves (HSC) for SR and LR spawners as well as YOY trout. HSCs for both spawning cohorts are similar. The preference for velocity and depth ranges between 0.2-1 ms^{-1} (Figure 5.2a) and 200-400 mm (Figure 5.2c) respectively. Preference for substrate differs slightly between SR and LR spawners. SR spawners prefer smaller substrate ranging from fine to coarse gravel (2-32 mm) while LR spawners choose coarser substrate ranging from middle size gravel to small stones (8-128 mm) (Figure 5.2e). In late summer, YOY were found in shore or gravel bars with shallow habitat and were strongly associated with cover. YOY preferred low velocities between 0.05-0.2 ms^{-1} (Figure 5.2b), shallow depths (100-300 mm) (Figure 5.2d) and fine substrate from sand to middle size gravel (> 16 mm) with a higher preference for sand (Figure 5.2f)

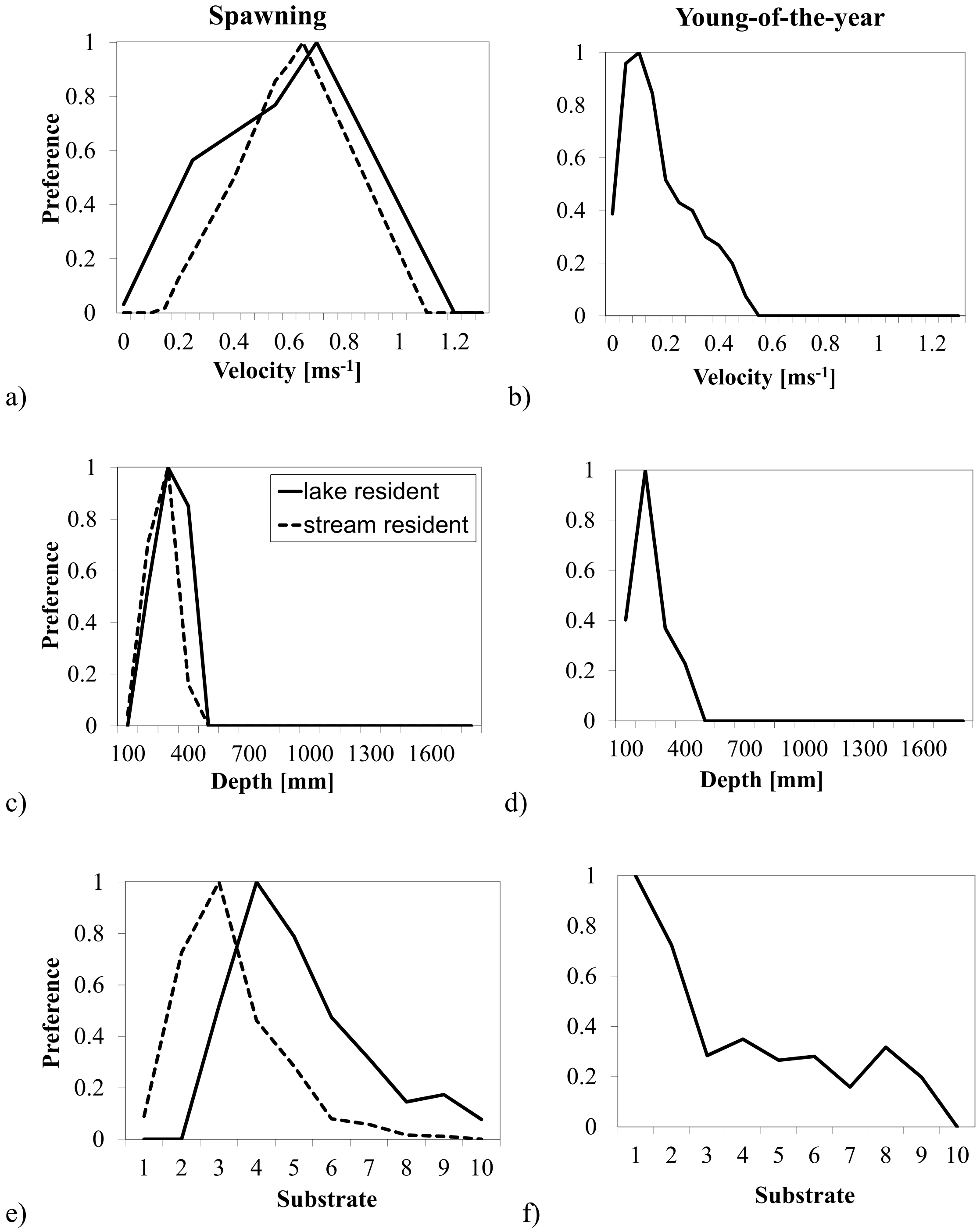


Figure 5.2: Habitat suitability curves for (a)(c)(e) SR (dashed line) and LR (solid line) spawners and (b)(d)(f) young-of-the-year (YOY) brown trout in the Hasliaare river system. (a-b) Mean water velocity, (c-d) Mean water depth, (e-f) Substrate is classified according to modified Wentworth scale (1. Sand, clay < 2 mm, 2. Fine gravel 2-8 mm, 3. Middle size gravel 8-16 mm, 4. Coarse gravel 16-32 mm, 5. Very coarse gravel 32-64 mm, 6. Small stones 64-128 mm, 7. Stones 128-256 mm, 8. Big stones 256-384 mm, 9. Small boulders 384-512 mm, 10. Big boulders >512 mm).

5.4.2 Fish habitat modeling

Suitability Index (SI) habitat maps were superposed on observed spawning grounds for SR and LR cohorts. Model predictions fitted well with the observed data (Figure 5.3). All observed spawning grounds were included in areas were the predicted SI value was higher than 0.5.

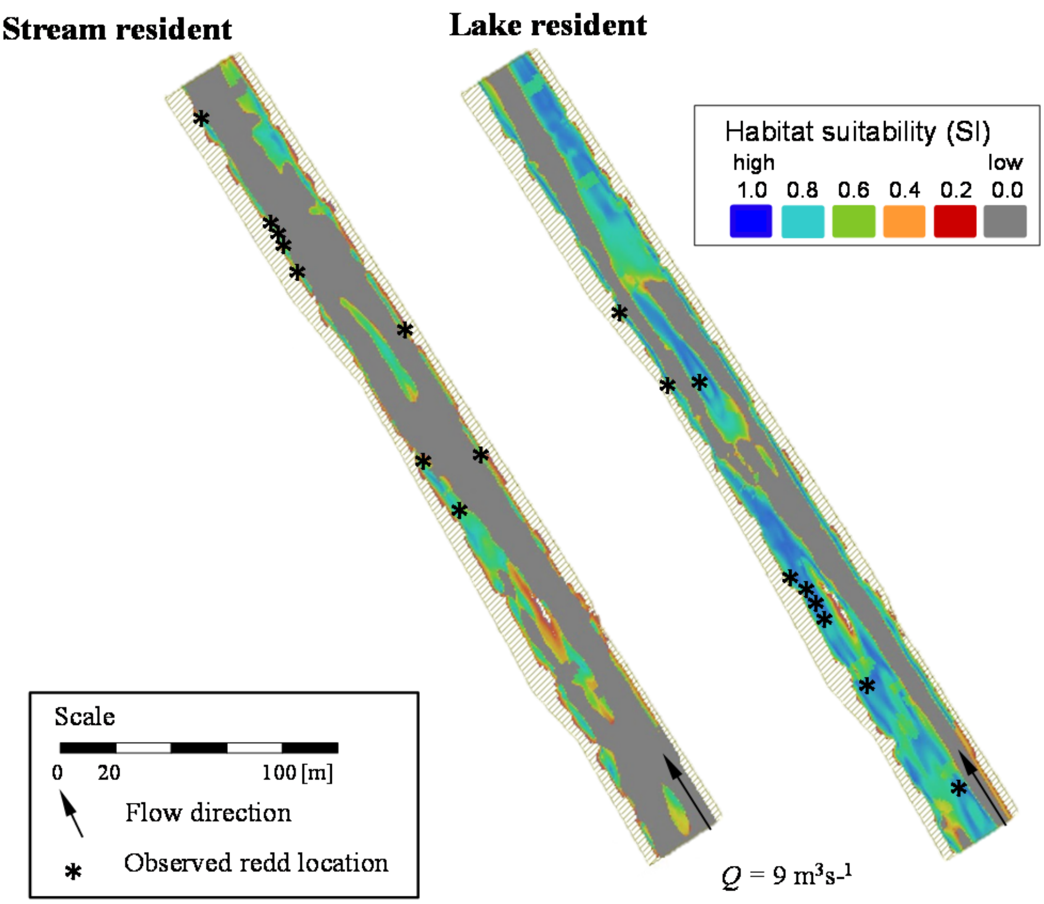


Figure 5.3: Predicted and observed spawning areas for stream resident (SR) and lake resident (LR) cohorts. The section modelled represents the dewatered reach, which carries residual flow in Innertkirchen. Habitat suitability ranges from grey (low suitability) to blue (high suitability). The stars represent location of the redds observed during the spawning cartography survey.

Figure 5.4 shows the Suitable Habitat Ratio (SHR) as a function of discharge for LR and SR spawners and YOY brown trout for the three hydropeaking reaches. In all reaches, habitat-discharge series show a similar pattern; the wetted area showing a SI value higher than 0.5 rapidly decreases with discharge increase. For all life stages, suitable habitat is only present at low flow. However, the pattern of SHR change with discharge is slightly different between reach types. In the groynes and channel reach, SHR decreases rapidly with discharge and no habitat remains for discharge higher than 20 m^3/s for all life stages (Figure 5.4a and c). In the gravel bars reach, the area of suitable habitat (SI > 0.5) decreases slower with discharge increase than in the groynes and channel reaches (Figure 5.4b). The quantity of suitable habitat area for YOY is generally lower than for both spawning cohorts for the three modeled reaches, only the gravel bar reach shows a slightly higher amount of suitable habitat at low discharge values compared to the other reaches.

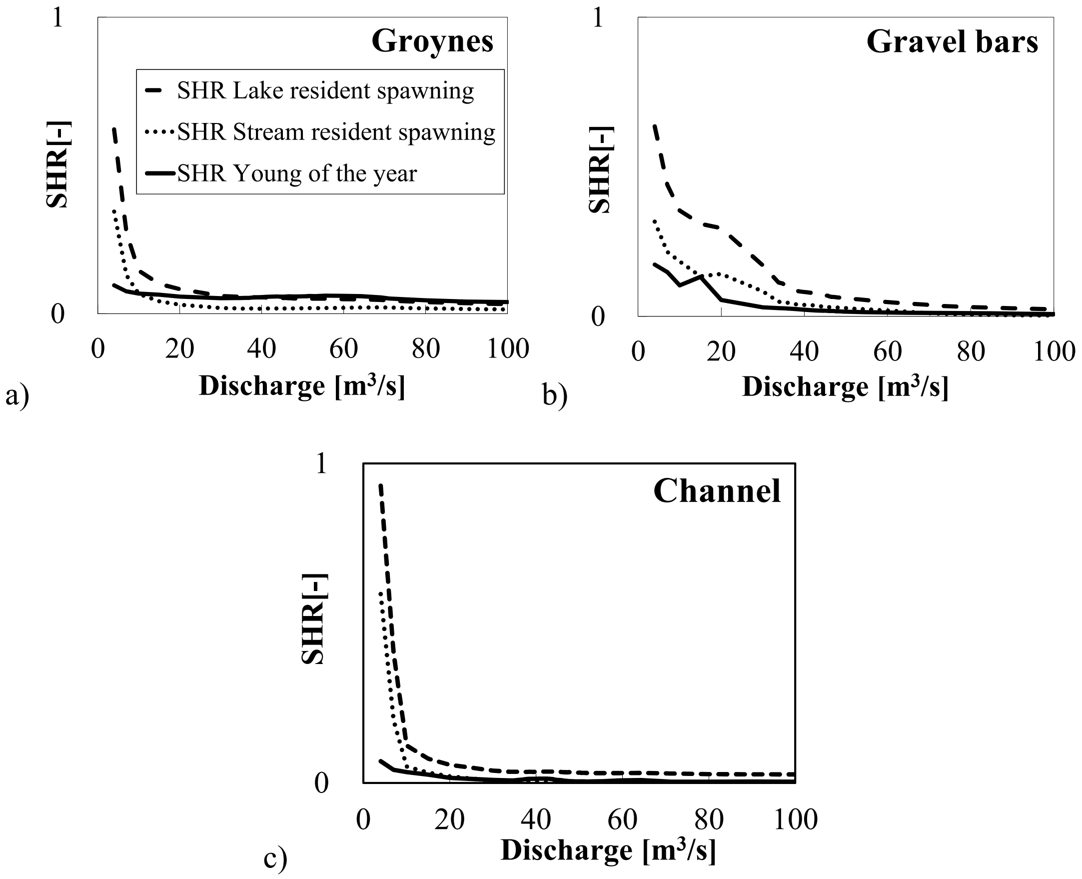
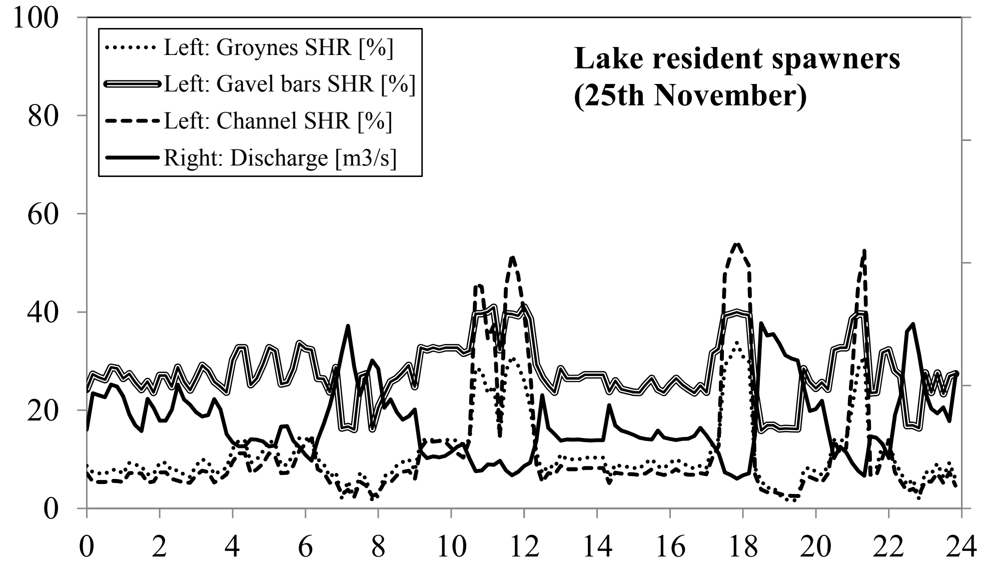


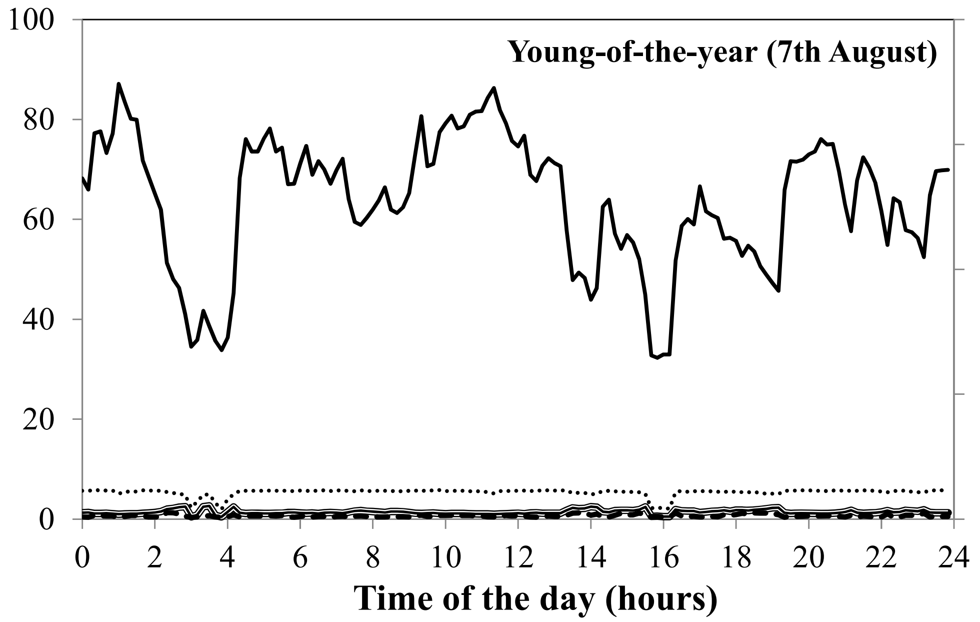
Figure 5.4 : Suitable Habitat Ratio (SHR) for the three hydropeaking reaches (a) groynes, (b) gravel bars and (c) channel as a function of discharge. For lake (LR) (dashed line) and stream (SR) (dotted line) resident spawners and young-of-the-year (YOY) (solid line) brown trout.

Monthly hydrograph analysis for November and August 2009 revealed that the pattern of sub-daily flow fluctuation is rather constant within a month (Figure 5.5). In November, off-peak flow and peak flow frequently oscillate around 9 m^3/s and around 27 m^3/s, respectively. In August, off-peak flow averages 37 m^3/s and peak flow is around 70 m^3/s. The drawdown range (Q_{max}/Q_{min} ratio) (Bieri & Schleiss 2011) is 3:1 in November and 2:1 in August.

Figure 5.5 shows the hourly variation in SHR for a representative November (LR cohorts habitat) and August (YOY habitat) day, describing daily typical habitat conditions under hydropower production in the three different reach types. Spawning habitat for the SR cohort had a very similar pattern of sub-daily habitat change for all reaches, compared to the LR cohort. To avoid redundancy, the results for the SR cohort are not shown here. The gravel bars reach shows a higher amount of suitable habitat than the two other reaches. However, for all reaches, the areas of suitable habitat are higher under off-peak flow and decreases with discharge increase. All areas of suitable habitat disappear when discharge increases above 30 m^3/s (Figure 5.5a). For YOY, sub-daily change in habitat is similar among the three reaches. The groynes reach shows a higher amount of suitable habitat than the two other reaches. Nevertheless, the variation in habitat amount is low compared to spawning habitat results. Moreover, the areas of suitable habitat, are higher under peak flow and decrease with discharge decrease (Figure 5.5b).



a)



b)

Figure 5.5 : Discharge and Suitable Habitat ratio (SHR, left y-axis) as a function of time. Discharge (solid line, right y-axis) was measured by Schattenhalb gauging station for a representative day for (a) lake resident (LR) spawners (25th of November 2009) and (b) young-of-the-year (YOY) (7th of August 2009) brown trout. For both life stages, hourly change in SHR is predicted for the three regulated flow reaches; the groynes (dashed line), the gravel bars (triple line) and the channel (dotted line) reaches. SHR is expressed in % of the wetted area.

Figure 5.6 shows the habitat suitability (SI) maps and the instability maps for stream resident (SR) spawners in the four modeled reaches. In the residual flow reach, flow is constant and SHR represents 18% of the total wetted area (Figure 5.6a). In the three hydropeaking reaches habitat is highly instable. At off-peak flow ($Q = 9$ m^3/s), SHR is 4, 12 and 3 % of the total wetted area for the groynes, the gravel bars and the channel reaches. At peak flow ($Q = 27$ m^3/s), SHR is respectively 0.6, 1.8 and 0 % of the total wetted area for the groynes, the gravel bars and the channel.

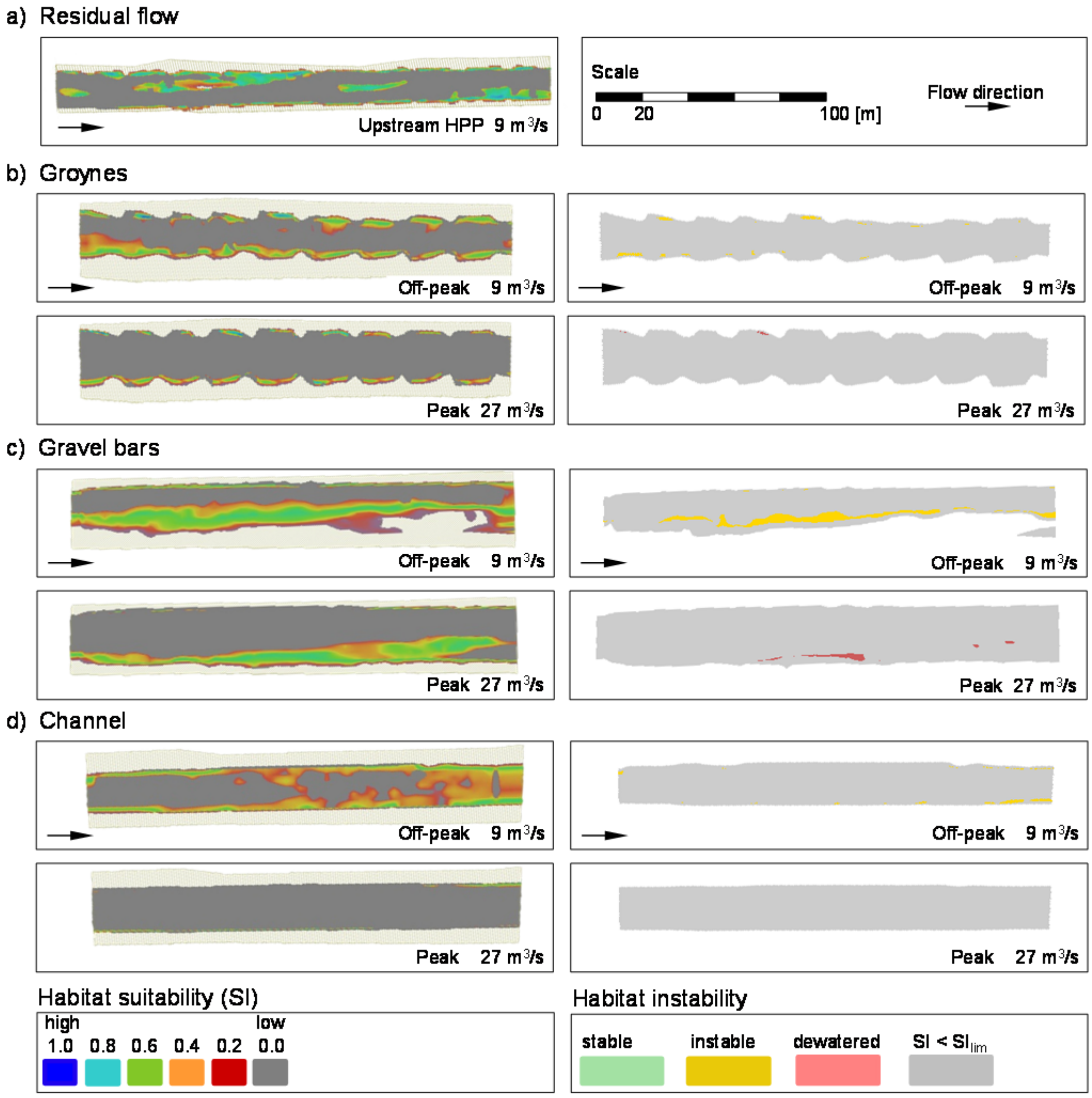


Figure 5.6 : Habitat suitability (SI) maps and habitat instability maps for stream resident (SR) spawners resulting from habitat modeling for (a) the residual flow, (b) the groynes, (c) the gravel bars and (d) the channel reaches. In the flow regulated reaches, discharge at off-peak ($Q = 9$ m^3/s) and peak ($Q = 27$ m^3/s) was inferred from the 10% and 90% percentiles of the Schattenhalb gauging station hydrographs for November 2009. Left panels show habitat suitability (SI) maps where SI ranges from grey (low SI value) to blue (high SI value). Right panels show habitat instability maps where grey stands for the effective wetted area (water depth H>10 cm), green for the areas where habitat conditions stays stable between the two steady states Q_{min} and Q_{max}, yellow for habitat conditions changing from suitable to unsuitable and red for habitat conditions changing from suitable to dewatered. The arrow indicates flow direction.

Figure 5.7 shows the habitat suitability (SI) maps and instability maps for LR spawners in the four modeled reaches. In the residual flow reach, the SHR represents 32% of the total wetted area (Figure 5.7a). In the three reaches operated by hydropower, habitat is highly unstable. At off-peak flow ($Q = 9$ m^3/s), SHR is respectively 3, 16 and 3 % of the total wetted area for the groynes, the gravel bars and the channel reaches. At peak flow ($Q = 27$ m^3/s), SHR is respectively 14, 35 and 13 % of the total wetted area for the groynes, the gravel bars and the channel reaches.

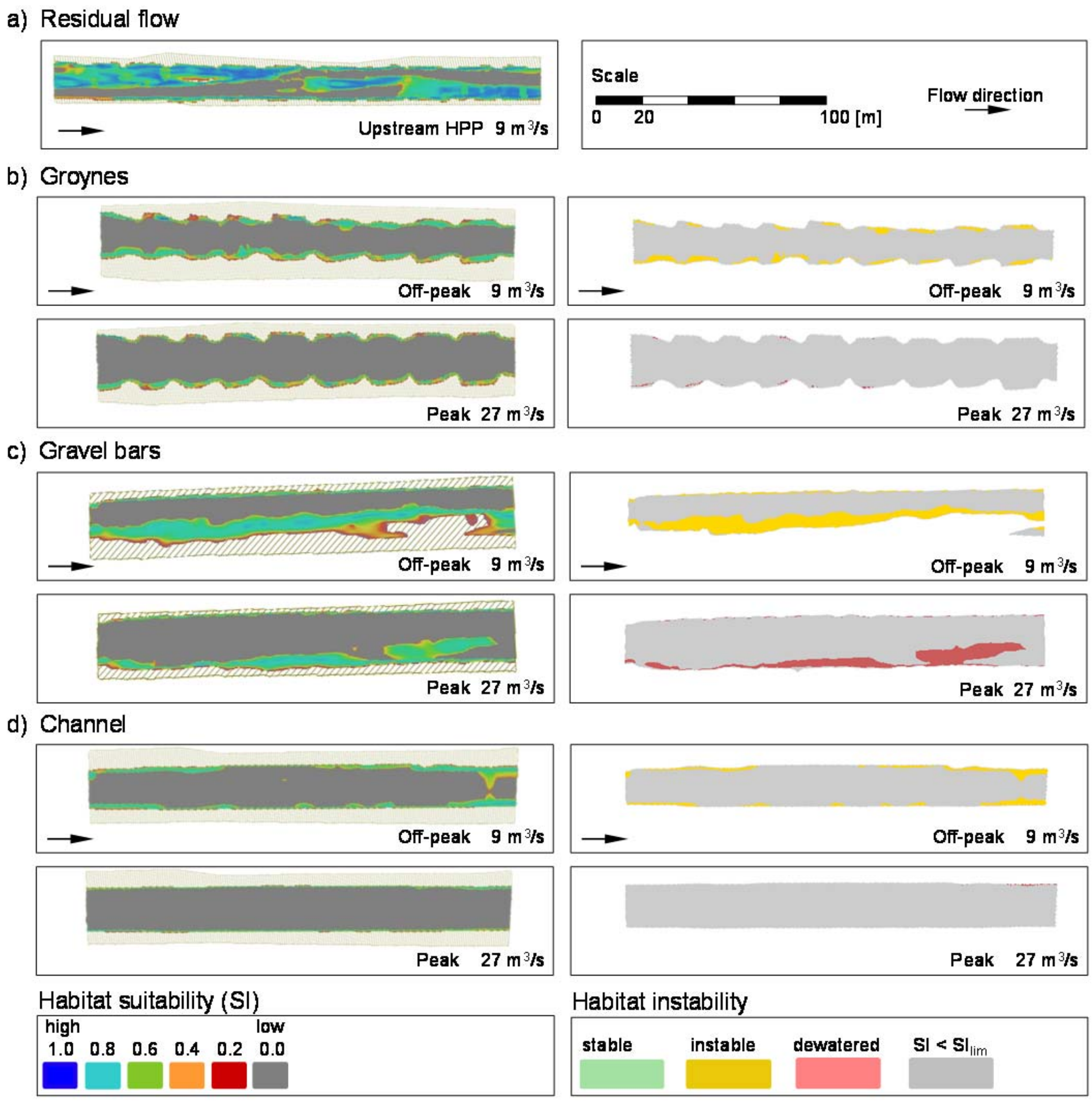


Figure 5.7: Habitat suitability (SI) maps and habitat instability maps for lake resident (LR) spawners resulting from habitat modeling for (a) the residual flow, (b) the groynes, (c) the gravel bars and (d) the channel reaches. In the flow regulated reaches, discharge at off-peak ($Q = 9$ m^3/s) and peak ($Q = 27$ m^3/s) was inferred from the 10% and 90% percentiles of the Schattenhalb gauging station hydrographs for November 2009. Left panels show habitat suitability (SI) maps where SI ranges from grey (low SI value) to blue (high SI value). Right panels show habitat instability maps where grey stands for the effective wetted area (water depth H>10 cm), green for the areas where habitat conditions stays stable between the two steady states Q_{min} and Q_{max}, yellow for habitat conditions changing from suitable to unsuitable and red for habitat conditions changing from suitable to dewatered. The arrow indicates flow direction.

Figure 5.8 shows the habitat suitability (SI) maps and instability maps for YOY brown trout in the four modeled reaches. In the residual flow reach, SHR represents only 1% of the total wetted area (Figure 5.8a). In the three reaches operated by hydropower, habitat is highly instable. At off-peak flow ($Q = 37$ m^3/s), SHR is respectively 5, 2 and 1 % of the total wetted area for the groynes, the gravel bars and the channel reaches. At peak flow ($Q = 70$ m^3/s), SHR is respectively 5, 1 and 0.3 % of the total wetted area for the groynes, the gravel bars and the channel reaches.

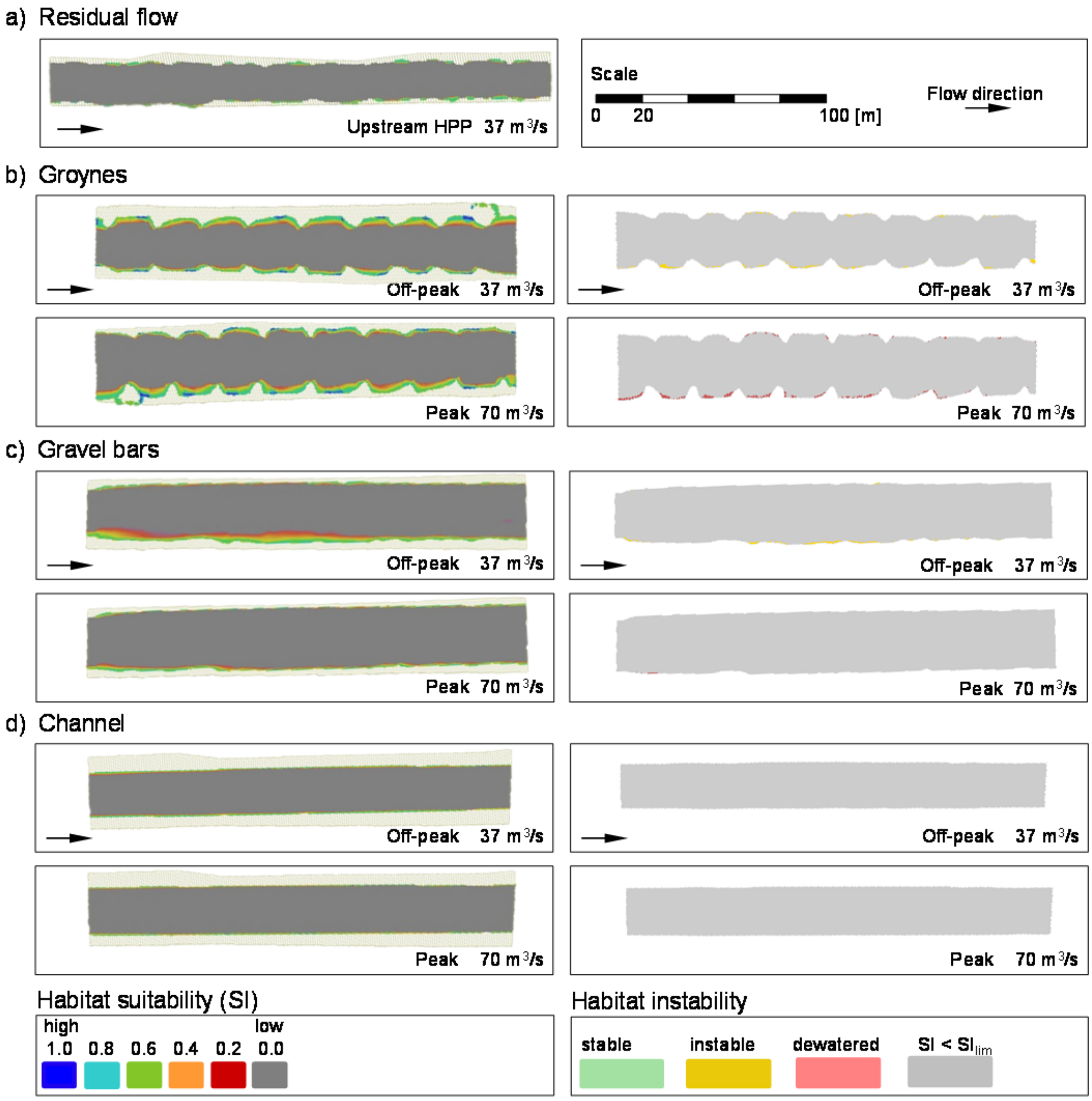


Figure 5.8: Habitat suitability (SI) maps and habitat instability maps for YOY brown trout resulting from habitat modeling for (a) the residual flow, (b) the groynes, (c) the gravel bars and (d) the channel reaches. In the flow regulated reaches, discharge at off-peak ($Q = 37$ m^3/s) and peak ($Q = 70$ m^3/s) was inferred from the 10% and 90% percentiles of the Schattenhalb gauging station hydrographs for August 2009. Left panels show habitat suitability (SI) maps where SI ranges from grey (low SI value) to blue (high SI value). Right panels show habitat instability maps where grey stands for the effective wetted area (water depth H>10 cm), green for the areas where habitat conditions stays stable between the two steady states Q_{min} and Q_{max}, yellow for habitat conditions changing from suitable to unsuitable and red for habitat conditions changing from suitable to dewatered. The arrow indicates flow direction.

Figure 5.9 shows the percentage of the SHR which is lost or dewatered when flow changes between off-peak to peak and vice versa for the two spawner cohorts and the YOY. In the three hydropeaking reaches, habitat was completely lost or displaced during hydropower operation and entirely dewatered when flow decreased. There is no stable habitat in the regulated reaches.

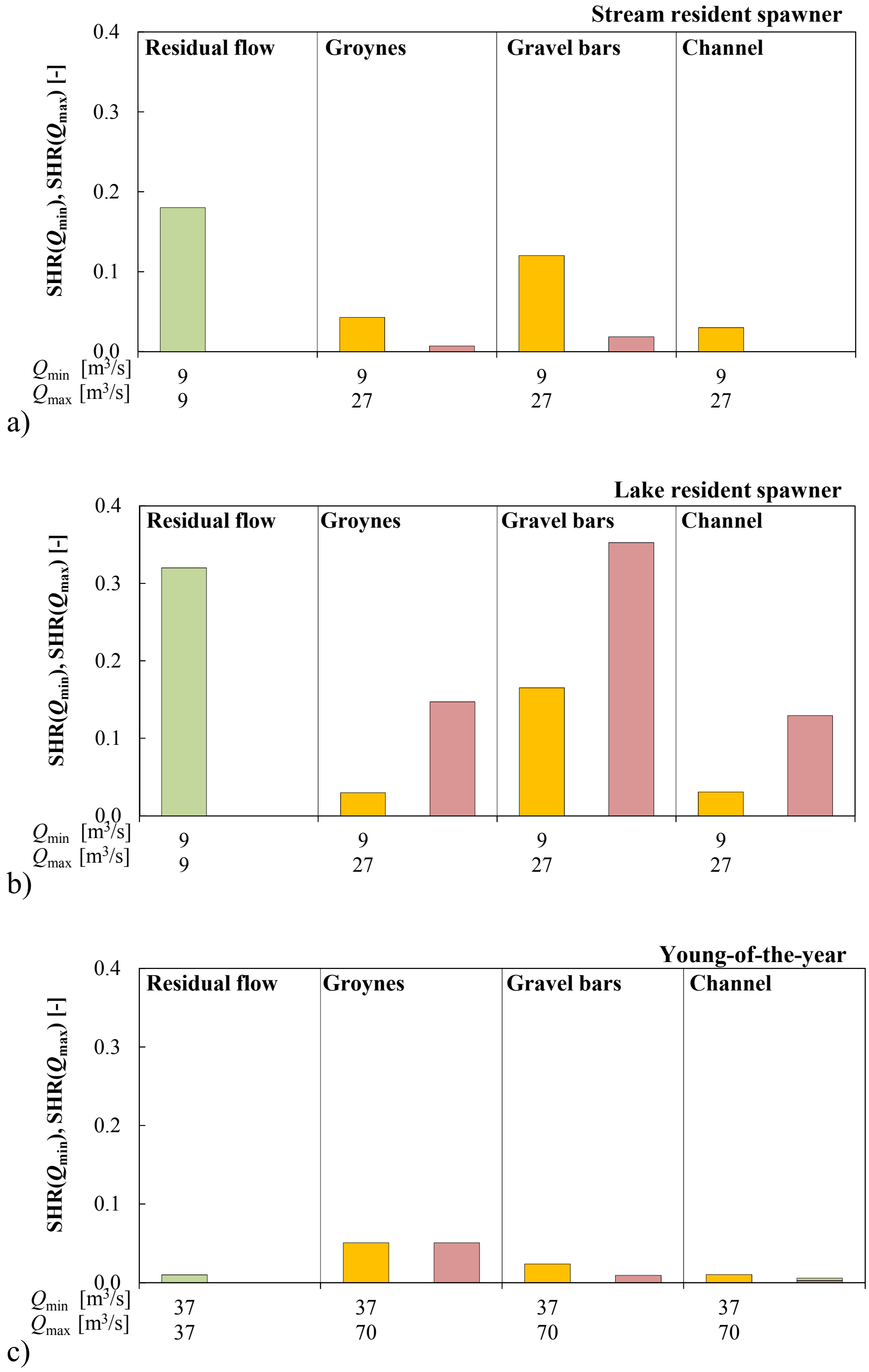


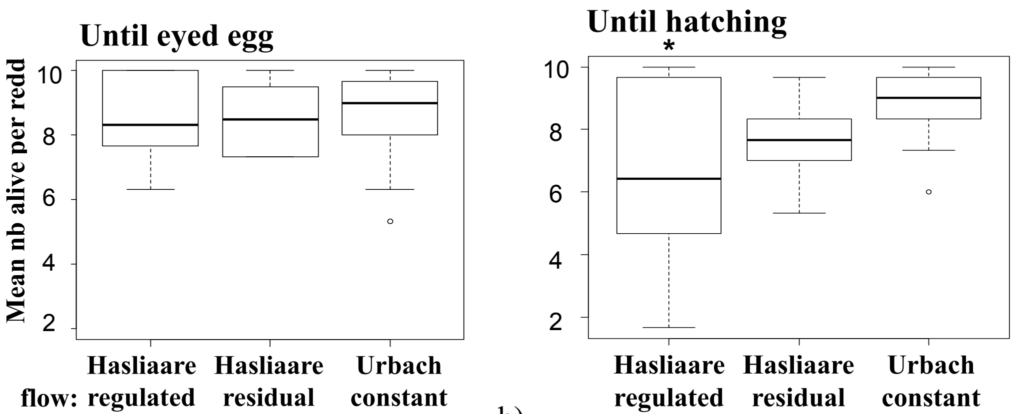
Figure 5.9 : Suitability Habitat Ratio (SHR) for (a) stream resident (SR) spawners (b) lake resident (LR) spawners and (c) young-of-the-year (YOY) brown trout for the off-peak Q_{min} and the peak Q_{max} discharge of November and August conditions respectively. SHR values are computed for the residual flow, the groynes, the gravel bars and the channel reaches. The percentage of stable (green), instable (yellow) and dewatering (red) habitat is given for discharge changes from Q_{min} to Q_{max} and Q_{max} to Q_{min}, respectively.

5.4.3 Natural reproduction success

Survival until eyed egg and hatching

Survival rates in the control lab incubation were very high, ranging to 98% and 93% of survival in average until eyed egg stage and hatching, respectively. In the in situ experiment, survival is slightly decreased in the regulated flow reach compared to the constant flow reaches (Urbachwasser and residual flow reach of the Hasliaare River). Mean survival until eyed egg was 88% for the constant flow (Urbachwasser) reach, 83% for the residual flow reach and 80% in the hydropeaking reach (gravel bars). However, the difference in survival was not significant between treatments (Figure 5.10a). The same pattern was observed for survival until hatching. Mean survival until hatching was 85%, 73% and 60% respectively for the constant flow (Urbachwasser), the residual flow and the hydropeaking (gravel bars) reaches. Variance in survival was much higher in the regulated than the two other flow treatments and the survival rate was significantly different between the regulated and the constant flow treatments (Figure 5.10b).

In the regulated flow treatment (gravel bars reach), six out of 20 artificial redds were dewatered, when discharge fell below 11 m^3/s. All the other redds were constantly wet. Based on the frequency hydrograph from the Schattenhalb gauging station data for November 2011 to March 2012, discharge was 17 % of the time below 11 m^3/s (Q_{min}) during the incubation period. However, no difference in survival until eyed egg stage (p-value=0.4) or hatching (p-value=0.9) was observed between the redds which were dewatered and the redds which were constantly underwater at off-peak discharge.



a) b)

Figure 5.10 : Boxplot of the mean number of alive individuals until (a) eyed egg stage and (b) hatching stage counted per capsule per redd for the three incubation sites; regulated and residual flow sites in the Hasliaare and the constant flow site in the Urbachwasser. No difference in survival until eyed egg was shown between sites (p-value = 0.96). There was a significant difference in survival until hatching between the Hasliaare regulated flow and the Urbachwasser contant flow treatments (p-value = 0.03).

Young-of-the-year density survey

In May, when post-emergent fry were sampled, the mean body length was 31 mm. Over the four years, the number of YOY caught in the residual flow reach was significantly higher than in the three regulated flow reaches (p-value = < 0.001) (Figure 5.11).

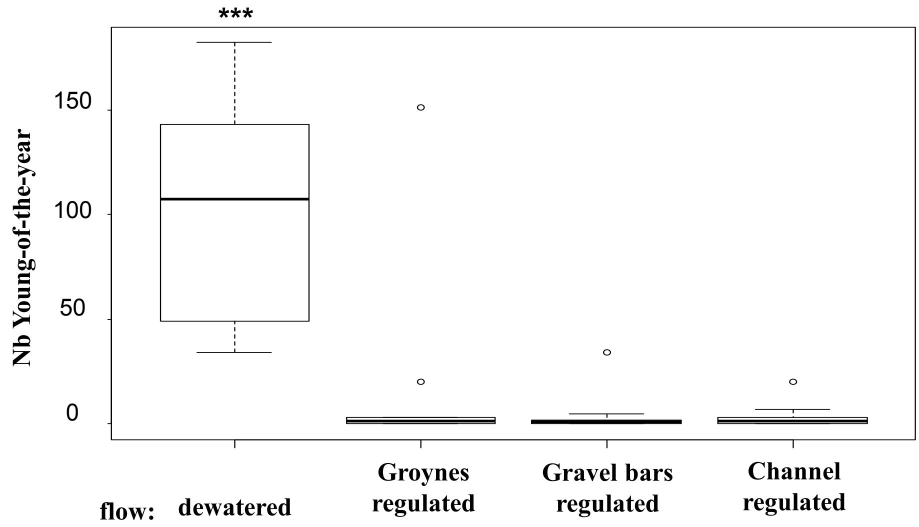


Figure 5.11 : Boxplot of young-of-the-year (YOY) density per 100 m shore electrofished for the dewatered reach, which carries residual flow, and the three types of hydropeaking reaches; the groynes, the gravel bars and the channel reaches. Difference in YOY density among residual flow and flow regulated reaches was significant (p-value = < 0.001***)

5.5 Discussion & Conclusion

In most of the alpine rivers, regulated flow is often associated with river channelization. In the Hasliaare River, the joint effect of hydropeaking and river channelization was studied on three sensitive life stages of brown trout, young-of-the-year (YOY), lake (LR) and stream (SR) resident spawners. Habitat preference for each studied life stage was determined with specific preference curves. HSC results for the both spawning cohorts were very similar to preference calculated in other Swiss alpine rivers (Caviezel 2006; Riedl & Peter 2013; Person & Peter submitted) (see chapter 4).

Late summer YOY preferred shallow habitat with low depth and velocity. Preference for fine substrate and sand was observed as for other Swiss alpine rivers (Person & Peter submitted) (see chapter 4). Here, in addition to SR spawners, LR spawners habitat preference was calculated. HSCs for both spawner cohorts was very similar except that LR spawner habitat preference for substrate was slightly higher than those observed for SR spawners. This can be explained by the fact that the size of the selected substrate is positively correlated to the body length of the female (Crisp 2000; Morbey & Hendry 2008) and LR females are bigger than SR females (Elliot 1994). Cartography of spawning grounds showed that both cohorts spawned at the same time but in distinct areas of the reach due to the difference in substrate preference.

Preference curves calculated in the Haslisaare River were used to simulate habitat suitability with the CASiMiR fish module in the hydropeaking section. However, the model assumptions imply that preference does not change with discharge, a postulate which is currently under debate (Holm *et al.* 2001; Ibbotson & Dunbar 2002; Fukuda *et al.* 2012). The residual flow section was defined as the control due to the absence of an intact comparable hydrological reach. Nevertheless, in the absence of a natural reach, it allows identification of the effects of flow instability on habitat patterns in comparison to a constant flow situation. Accordingly, the same limitations must be applied in the interpretation of the results as described in the previous chapter (see chapter 4).

In the regulated reach, habitat simulation and field surveys showed that flow regulation and channelization might be jointly responsible for deficits in the brown trout population. Suitable habitat for the three life stages investigated was present at off-peak discharge but was severely reduced at peak flow in the three reach types. Slightly better habitat conditions were found in the groynes reach for YOY and in the gravel bars reach for spawners. However, habitat areas were strongly instable and dewatered under peak flow, whereat YOY were stronger impacted than spawners due to the overall low quantity of YOY suitable habitat.

Egg incubation results showed that survival was significantly lower in the regulated reach compared to the reaches without hydropeaking. The same results were obtained by Zarn *et al*. (2008) which showed that mortality was mainly due to bed clogging and high level of sand which impaired egg development and entrapped the hatched fry (Eberstaller & Pinka 2001). Thus, reducing bed clogging through active rehabilitation measures could significantly increase spawning habitat and YOY recruitment (Pulg *et al.* 2013).

However, in the Hasliaare River the strongest deficit in population renewal resulted from the unusual absence of post-emergent fry in all the regulated reaches. In alpine rivers, YOY abundance is correlated with river width and substrate size (Schager *et al.* 2007). In this study, predicted habitat quantity (SHR values) for YOY was very low even in the flow control conditions (residual flow reach) representing only 1% of the total wetted area. In natural conditions, habitat values might be normally low as YOY only occurred in shore habitats representing a restrained area of the total riverbed. Indeed during post-emergent fry electrofishing surveys (conducted in May) or YOY habitat sampling (late summer) no deficit in density was observed in the residual flow reach. These results are confirmed by YOY habitat predictions from other alpine systems (Person & Peter submitted) (see chapter 4).

Habitat simulations showed that spawning and late summer YOY habitat conditions were aggravated in the channel reach compared to the groynes and gravel bars reaches. However, none of the three regulated morphologies are able to provide suitable habitat areas at peak and off-peak discharge. The lack of instream heterogeneity, flow refugia and backwater resulting from channelization might be directly responsible for the observed habitat deficit. According to previous work, the following conditions are needed to sustain YOY and spawning suitable habitat in reaches influenced by hydropeaking: higher instream heterogeneity, a good connectivity with tributaries as well as constantly submerged anabranch sections (defined as sections of the river diverted from the main channel) (Eberstaller & Pinka 2001; Kindle *et al.*

2012; Person & Peter submitted) (see chapter 4). Thus, the results provide evidence that in the Hasliaare River under the joint pressure of river channelization and hydropeaking, brown trout reproductive success is strongly undermined. Egg development is reduced, spawning grounds are instable and lost with a stronger impact on SR spawners. These findings extend those of Schneider *et al.* (2012) confirming that the effective habitat for spawning is strongly reduced when the mortality associated with redd dewatering is included in the model calculation. The present study therefore supports the concept that hydropeaking rivers must be seen as two rivers in one (resulting from the variation between peak to off-peak flow), as suggested in Jones (2013). Therefore, habitat models should be adapted to integrate the two rivers habitat templates and the risk associated to the change between them. Such modeling approaches, as developed with the dynamic indices WHL and DAR (Person & Peter submitted)(see Chapter 4), are very useful to study this new dynamic conception of hydropeaking rivers.

Hydropeaking mitigation have been predominantly focused on hydrological parameters such as the reduction of the Q_{min}/Q_{max} ratio (Bieri & Schleiss 2011; Meile *et al.* 2011), independent of the geomorphological characteristics of the river system. The findings presented in this study emphasize that river morphology and flow mitigation should be considered as inseparable and equally important (Person *et al.* 2013) (see chapter 6). Nevertheless, defining a threshold for a Q_{min}/Q_{max} ratio (drawdown range) to provide adequate water for the aquatic ecosystem is difficult. According to the results, the definition of the appropriate drawdown range is strongly dependent on the width of the downstream river absorbing the peak flows. In the case of the Hasliaare River, the reduced width of the riverbed is a limiting factor for an acceptable maximum peak flow. However, it is still unknown which minimum width could guarantees suitable velocity and depth distribution able to sustain fish habitat at peak flow. Moreover, river widening might not be sufficient to rehabilitate good ecological conditions for brown trout natural reproduction. The presence of underwater heterogeneous mesohabitat elements and good connectivity to the tributaries is crucial (Charmasson & Zinke 2011; Kindle *et al.* 2012).

However, in areas where land use and settlements are dense, such river widening is often not possible. Further research should investigate the relationship between river width and fish habitat improvement to determine the minimum widening required in rehabilitation projects of formerly braided rivers to support self-sustainable fish populations. The effectiveness, along with the cost, of such river engineering measures should be assessed. Currently, there is no method to compare costs and effectiveness of mitigation scenarios. Jorde (1996) developed an interesting tool for comparison of economic and ecological benefits in making decisions regarding minimum flows. However, further work is needed to develop a method which allows decision makers to choose the best mitigation scenarios including appropriate river restoration and flow mitigation strategies in rivers impacted by hydropeaking.

A tool to evaluate the cost-effectiveness of mitigation measures to improve fish habitat.

In mountainous areas, high-head-storage hydropower plants (HPPs) produce peak load energy. The resulting unsteady water release to rivers, called hydropeaking, alters the natural flow regime. Mitigating the adverse impacts of hydropeaking on aquatic ecosystems has become a crucial step in recent water policies. A novel economic-ecological diagnostic and intervention method to assess hydropeaking mitigation measures for fish habitat improvement was developed. This method was applied to an alpine river downstream of a complex storage hydropower scheme. The approach comprises (1) a hydropower operation model of flow regime generation and cost estimates for different mitigation measures, (2) a 2D hydrodynamic model to simulate the flow conditions in representative river reaches, and (3) a dynamic fish habitat simulation tool to assess the sub-daily changes in habitat conditions of three brown trout (*Salmo trutta fario*) life stages (adult, spawning, and young-of-the-year (YOY)). Simulations showed that operational measures such as limiting maximum turbine discharge, increasing residual flow, and limiting drawdown range incur high costs in relation to their ecological effectiveness. Compensation basins and powerhouse outflow deviation achieved the best cost-benefit ratio. Hydropeaking impact was strongly dependent on river morphology. Monotonous river reaches exhibited low habitat suitability for peak discharge, whereas a braided morphology provided high instream structure and thus suitable habitat for unsteady flow conditions. The interdisciplinary approach to economic and habitat rating informs decision makers regarding the effectiveness of measures implemented to mitigate the environmental impacts associated with fluctuating hydropower operations.

This chapter is the result of an interdisciplinary project with Dr. Martin Bieri, Civil engineer at EPFL and responsible for Project D of the CTI research project. He provided Routing System modeling, flow series and mitigation costs data. The habitat assessment tool was commonly developed and applied.

6.1 Introduction

Since 1950, a large number of high-head-storage hydropower plants (HPPs) in the Alps have supplied peak load energy to the European power grid (Schleiss 2007). In Switzerland, for example, 32% of the total electricity in 2010 was produced by storage hydropower plants. Water retention in large reservoirs and concentrated turbine operations allow electricity to be produced on demand. The sudden opening and closing of the turbines produces highly unsteady flow in the river downstream of the powerhouse (Moog 1993). This so-called hydropeaking is the major hydrological alteration in alpine regions (Petts 1984; Poff *et al.* 1997). Due to the unpredictability and intensity of flow change, sub-daily hydropeaking events disturb the natural discharge regime, a key factor in ecological quality and the natural abiotic structure of ecosystems (Parasiewicz *et al.* 1998; Bunn & Arthington 2002). These disturbances directly affect riverine biological communities (Young *et al.* 2011). Frequent and rapid fluctuations change hydraulic parameters, such as flow depth, velocity, and bed shear stress (Petts & Amoros 1996), and thus influence fish habitat availability, stability, and quality. Salmonid populations are less abundant and have reduced population sizes in rivers with hydropeaking (Moog 1993). In headwaters of alpine rivers, brown trout (*Salmo trutta fario*) is one of the species most impacted by dam operations. Without appropriate flow refugia, the hydropeaking-impacted flow regime becomes energetically costly for fish and affects their over-wintering survival (Scruton *et al.* 2003; Scruton *et al.* 2008). Spawning areas are faced with the risk of dewatering, and young-of-the-year (YOY) shore habitat is displaced or lost (Liebig *et al.* 1998; Saltveit *et al.* 2001). Success in natural reproduction and YOY survival are key factors for the natural renewal of fish populations.

As part of the "Green Hydropower" assessment procedure for river management, hydropeaking has been identified as a future research priority due to the lack of knowledge of its interaction with riparian ecology (Bratrich *et al.* 2004). For impact assessment, individual investigations are recommended, as riverbed morphologies and the layout as well as the operating characteristics of hydropower facilities differ locally (Baumann & Klaus 2003).

After decades of the extensive use of water resources, with severe consequences for aquatic and riverine biota, governments have begun to recognise the need for a water protection policy, e.g., the European Union Water Framework Directive. In Switzerland, Parliament adopted the Law on Water Protection in 2009 to improve the quality of Swiss waters, including hydropeaking mitigation.

To support decision makers in defining optimum restoration measures, tools are needed to define, assess, and compare the associated costs and habitat improvements associated with these measures (Palmer & Bernhardt 2006; Heller *et al.* 2010). Various modelling approaches are commonly used to simulate the impact of hydropower plants. Several methods of qualitative decision support exist, such as participatory methods

(Leach & Pelkey 2001; Luyet 2005), expert judgment (Landeta 2006), system dynamics (Maani & Maharaj 2004; Park *et al.* 2004), and mixed methods such as fuzzy (Zadeh 1965) and multi-criterion analysis (Mena 2000).

Pfaundler & Keusen (2007a) and Meile *et al.* (2011) discuss several methods for flow regime analysis. Sub-daily flow variations can be expressed by the ratio between maximum (Q_{max}) and minimum (Q_{min}) daily discharge, called the drawdown range. The gradient in flow change is described by the flow ramping rate HP_2. These and other parameters based on hydraulic data (Richter *et al.* 1997; Black *et al.* 2005) are useful for comparison and preliminary analysis. However, the interaction between hydropeaking and river ecology is complex (Poff *et al.* 1997; Bunn & Arthington 2002), and the current metrics are still rudimentary (Meile *et al.* 2011).

River habitat modelling has become a powerful tool for evaluating altered flow conditions in aquatic ecosystems (Armour & Taylor 1991; Maddock 1999). A common microhabitat model contains three components: (i) the hydrodynamic model, (ii) the biological input data, e.g., fish habitat preference; and (iii) the habitat model. The results of the hydraulic model and biological sampling are combined to determine habitat suitability for one or several target species. The microhabitat habitat model CASiMiR includes a module for fish habitat suitability under steady flow conditions (Jorde *et al.* 2000; Schneider *et al.* 2010; Tuhtan *et al.* 2012). Garcia *et al* (2010) applied this model in a conservation study to predict the habitat evolution of eight fish species under hydropeaking conditions in the Biobío River in Chile.

In common habitat modelling approaches, Weighted Usable Area (WUA) and Hydraulic Habitat Suitability (HHS) were developed within the instream flow incremental methodology (Bovee 1982) to determine the minimum flow requirement for the target species. These flow requirements are calculated using the dimensionless Suitability Index (SI) and the simulated flow patterns. WUA is commonly defined as the sum of stream surface area weighted by SI for a given discharge Q. HHS is the ratio between WUA and the total wetted area for Q, representing the percentage of suitable areas over the total wetted area for the species considered. WUA and HHS integrate the overall habitat suitability on a reach for a steady state. The same WUA or HHS value can represent several low-quality or a few high-quality habitat areas. The WUA and HHS values do not quantify habitat instability or the dynamic changes in habitat distribution when discharge is not constant, such as the instability induced by hydropeaking.

Hydropower operation models, metrics for flow regime analysis, and habitat models are too often developed and applied independently. In the framework of minimum flow regulation, Jorde (1996) linked macrozoobenthic habitat to the energy production of a run-of-river HPP, including in CASiMiR a hydropower module simulating HPP operation. However, most approaches do not consider the relevant interdependency between economic and ecological concerns (Palmer & Bernhardt 2006). Here, a novel economic-ecological diagnostic and intervention method with integrated river basin and HPP modelling as well as a habitat assessment is proposed to evaluate the effect of operational and structural hydropeaking mitigation projects. In other words, the impact of sub-daily flow fluctuation on a target species is assessed. A set of mitigation measures, such as peak discharge limitations, increase of residual flow, limited drawdown range, compensation basins, and river engineering projects, has been implemented and tested in the hydropower operation model using a semi-distributed conceptual approach for flow regime generation and economic rating. The 2D hydrodynamic model of reference river reaches defines the flow depth and velocity of the simulated flow regimes. The dynamic habitat simulation tool allows fish habitat suitability to be assessed. This method has been applied to the upper River Aare catchment, which comprises a complex HPP and a downstream river system with various river morphologies. Suitability and stability indices have been developed for habitat rating and applied to adult, spawning, and YOY brown trout (*Salmo trutta fario*). For each mitigation strategy examined, the costs generated by the hydropower operation model and the biological benefits quantified by the dynamic habitat simulation tool were correlated for comparison and assessment of their effectiveness.

6.2 Case study

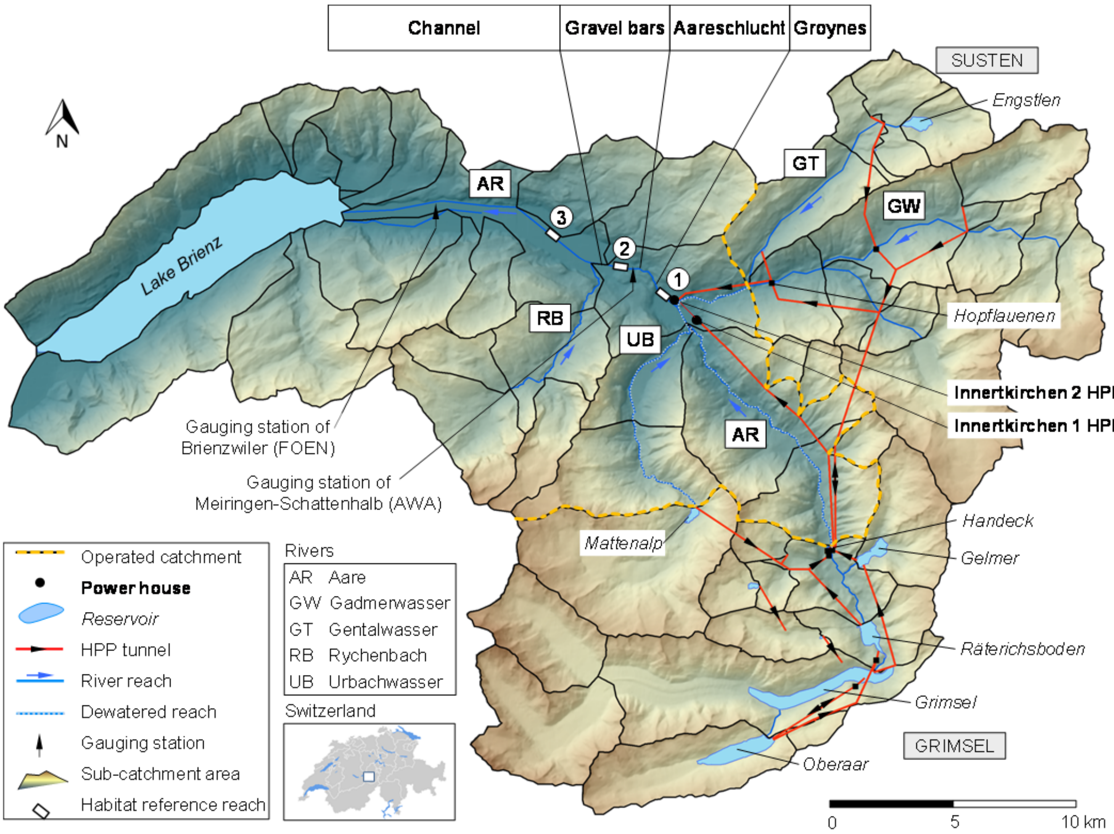


Figure 6.1: Map of the upper Aare catchment area in Switzerland with today's layout of the Oberhasli hydropower scheme (reservoirs, HPP tunnels and powerhouses), the limit of the utilized catchment area, the sub-catchment areas, the two river gauging stations, and the river network. The Hasliaare downstream of the turbine release in Innertkirchen shows four main morphologies: groynes, Aareschlucht canyon, gravel bars and channel river reaches. White boxes indicate the modelled reference reaches with groynes (1), gravel bars (2) and channel (3).

Figure 6.1 shows the upper River Aare basin located upstream of Lake Brienz in the centre of the Swiss Alps. This river basin comprises a very complex hydropower scheme and three types of degraded morphologies in a very short distance (>15 km) downstream from the powerhouse release. Therefore, the catchment is suitable for a pilot study, incorporating various scenarios of hydropower production and mitigation measures and allowing for the evaluation of the effect of reach morphology on fish habitat. The surface area of the Hasliaare Catchment in Brienzwiler is 554 km^2, of which 21% was glaciated in 2003. The hydrological regime of the River Aare, with a mean annual discharge of 35 m^3/s, is glacial, with low discharge in winter and high runoff in summer due to snow and glacier melt (Weingartner & Aschwanden 1986). The mean catchment altitude is 2150 m a.s.l. The River Aare, also called the Hasliaare at its headwaters, has its source in the Unteraar and Oberaar glaciers (Schweizer *et al.* 2008). The River Aare is an oligotrophic alpine stream with good water quality. The river has high oxygen content and low amounts of phosphate, nitrate, and organic matter (with an oxygen saturation of almost 100%, orthophosphate > 0.005 mg P/l, DOC > 0.5 mg C/l, and nitrite > 0.5 mg N/l; data from the Brienzwiler gauging station, Canton Bern, AWA).

Due to settlement in the artificial storage reservoirs of the hydropower scheme, the mean annual sediment concentration in the Halsiaare has been decreased by approximately 70% (Finger *et al.* 2006).

Oberhasli hydropower scheme

Since the early 20th century, a hydropower scheme of nine powerhouses and several reservoirs and intakes has been constructed. The Kraftwerke Oberhasli (KWO) Company utilises 60% of the catchment area for a complex high-head-storage hydropower scheme. KWO has a total installed capacity of 650 MW and, in 2010, generated approximately 1750 GWh, corresponding to approximately 10% of the Swiss hydropower output. The water from the partially glacierized catchment of Lake Grimsel flows through the artificial reservoirs of Oberaar, Grimsel, Räterichsboden, and Handeck. In Innertkirchen, the water is returned to the River Hasliaare by the Innertkirchen 1 HPP. The River Gadmerwasser drains the eastern part of the basin (Susten). After driving the turbines, the water is released from the tailrace of Innertkirchen 2 HPP to the Hasliaare. The substantial turbine capacities of the Innertkirchen 1 and 2 HPPs of 39 and 29 m^3/s, respectively, produce severe hydropeaking in the downstream river reaches (Figure 6.1).

An upgrading programme for the entire scheme, called *KWOplus*, comprises a large number of technical, economic, and ecological improvements to the scheme, such as the increase of the installed capacity of several powerhouses as well as the retention volume of Lake Grimsel. To compensate for the turbine capacity increase of Innertkirchen 1 HPP by 25 m^3/s, a basin of 50,000 m^3 downstream of the powerhouse outflow is planned to facilitate lower flow ramping.

River morphology

In the 19th century, the dynamic braided river network of the Hasliaare was drained for agricultural use and flood control. A mainly straight channel resulted from the pristine braided network because of the successive river channelization. Based on the three parameters of variability of water surface width, bank slope, and mesohabitat, the reach downstream of the powerhouse outlets can be divided into four reference morphologies: a reach with artificial groynes (650 m), the Aareschlucht Canyon (1.4 km), a reach with alternating gravel bars (1.3 km), and a monotonous and straight channel reach (11 km). The dewatered reach upstream of Innertkirchen, which carries residual flow, has a natural morphology. The river is of the rhithral type, with cold water in summer, high flow velocities, and a riverbed composed mainly of gravel and boulders.

Runoff and hydropeaking

River Hasliaare discharge series are available for 1925–1929 (pre-HPP) and 1974–2010 (with HPP) from the Brienzwiler gauging station (Federal Office for the Environment, FOEN) and since September 2006 from the Meiringen-Schattenhalb gauging station (Canton Bern, AWA) (Figure 6.1). Comparing the 75% non-exceedance probability of the daily drawdown ranges Q_{max}/Q_{min} in Brienzwiler in the pristine condition before construction of the power plants with the current condition, an increase from 1.1:1 to 5:1 is observed (Meile *et al.* 2006). On 5% of the days in a year, values higher than 8:1 occur. The gauging station of Meiringen-Schattenhalb is closer to the powerhouse outlet; thus, modification of the discharge series due to flow routing is negligible. This discharge series therefore exhibits higher fluctuations than the discharge series at the Brienzwiler gauging station situated a few kilometers downstream.

Fish community

According to the Huet longitudinal zonation of 1949, the Hasliaare catchment is defined as a trout or upper grayling zone. Eight fish species are known in River Hasliaare: brown trout (*Salmo trutta*), bullhead (*Cottus gobio*), rainbow trout (*Oncorhynchus mykiss*), brook trout (*Salvelinus fontinalis*), arctic char (*Salvelinus alpinus*), grayling (*Thymallus thymallus*), burbot (*Lota lota*), and perch (*Perca fluviatilis*). Rainbow trout and brook trout are introduced species and are not indigenous to Switzerland. Arctic char, grayling, burbot, and perch are Lake Brienz immigrants and found only in the vicinity of the river mouth. The only widely distributed species in River Hasliaare is the brown trout (Haas & Peter 2009).

6.3 Methods

A three-step approach to the economic and habitat rating of hydropeaking mitigation measures was developed. The approach works as follows: 1) The hydropower operation model receives mitigation measures as input. This model generates the cost of the measure and the flow series in the downstream river reaches. 2) Based on peak and off-peak discharge retrieved from the flow series, the 2D hydrodynamic model generates flow depth and velocity distributions in the reference reach for Q_{min} and Q_{max}. 3) The dynamic habitat simulation tool produces habitat indices based on fish habitat preferences for the two discharge states. Figure 6.2 presents a flowchart of the economic-ecological diagnostic and intervention method.

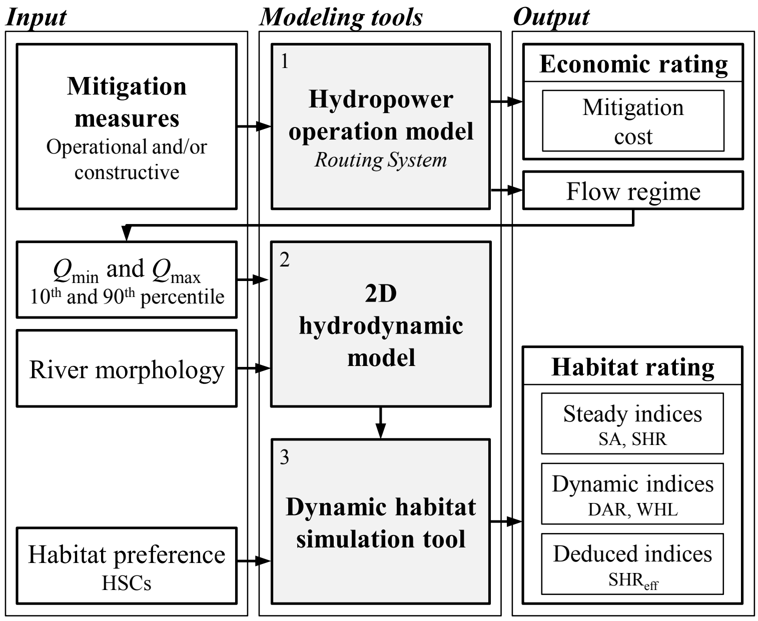


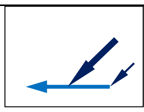
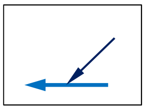
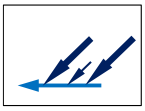
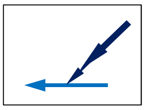
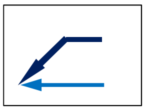
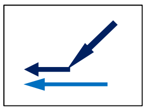
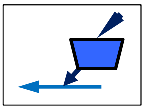
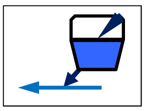
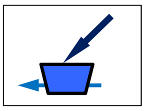
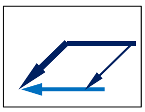
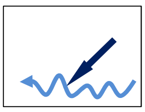
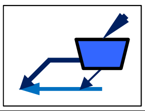
Figure 6.2: Flowchart of the economic-ecological diagnostic and intervention method for assessing the hydropeaking mitigation measures. The approach contains three modelling tools (1, 2, 3) for simulating the flow regime and its economic and habitat rating.

Mitigation measures

Table 6.1 lists 12 possible measures to mitigate the negative effects of hydropeaking:

- *Operational measures*, such as restrictions in the turbine operation mode, are effective measures in modifying the downstream flow regime.
- *Structural measures,* such as regulated compensation basins downstream of the powerhouse, can be located beside or on the river (Meile 2006). Compensation basins with significant storage volumes can decrease the maximum and increase the minimum daily discharge of the downstream river reach (Meile *et al.* 2006). Multipurpose schemes can compensate construction costs (Heller *et al.* 2010). Underground spaces such as tunnels or caverns reduce visual impact and land use. Ecological issues, such as a powerhouse outflow in a deviation tunnel channel or directly into a lake, can be addressed in the framework of HPP enhancement projects.
- *Morphological measures* such as river engineering may improve the morphology and restore the river to a more natural state. Widening the riverbed increases the flow resistance and the natural retention capacity of rivers. One goal of today's river restoration projects is to widen the riverbeds to improve both flood evacuation capacity and morphology (Willi 2002). Such projects are ecologically effective only if the flow regime is within an acceptable range (Peter 2004).

Table 6.1: Operational (O) and structual (C) hydropeaking mitigation measures. The powerhouse outflow of a HPP (➚) affects the flow regime of the downstream river (←). Detailed descriptions are given in addition to related costs and concerns.

	Measure	Type		Details	Related costs and concerns
1	Increase of residual flow	O		Higher base flow to increase minimum flow Q_{min} and thus to reduce drawdown range	– Legal constraints – Decline in earnings – Loss of flexibility
2	Power or discharge limitation	O		Lower peak flow to decrease daily maximum flow Q_{max} and thus to reduce drawdown range	– Legal constraints – Decline in earnings – Loss of flexibility
3	Anti-cyclical operation of the different plants	O		Reduce peak and increase base flow for a more constant flow regime in the whole river system	– Legal constraints – Decline in earnings due to production during low demand – Loss of flexibility
4	Successive increase/decrease of discharge	O		Lower flow ramping rate HP_2 to avoid flushing of riparian species	– Legal constraints – Decline in earnings – Loss of flexibility
5	Powerhouse outflow directly into the lake	C		Turbine outlet directly connected to a lake to avoid hydropeaking in the river reach	– Lake too far away – Construction costs – Impact on lake ecosystem
6	Powerhouse outflow into a side channel or tunnel	C		Parallel side channel or tunnel to evacuates the turbine water without impacting the river reach	– Land availability – Construction cost – Groundwater
7	Compensation basin	C		Powerhouse outflow realised to basin of volume V_{basin} with controlled outflow to the river	– Land availability – Construction cost – Fluctuating level (recreation) – Volume depending on $Q_{turbine}$
8	Compensation cavern	C		Powerhouse outflow linked with underground retention space of V_{cavern} controlling outflow	– High construction cost – Volume depending on $Q_{turbine}$
9	Powerhouse outflow into basin (of a run-of-river plant)	C		Basin of V_{res} located on the river controlling flow by turbines or weirs	– Legal constraints – Land availability – Construction cost – Fish migration, sediment
10	Powerhouse outflow into lake and residual run-of-river release	C		Existing plant used in run-of-river mode and new parallel system for peak production	– Construction cost – Decline in earnings due to operations during low demand
11	Morphological improvements of the river	C		Macro-roughness or river widening to reduce Q_{max} of short turbine sequences and HP_2	– Legal and environmental constraints – Construction cost – Improve habitat conditions
12	Combination of measures	O, C		Combinations of different mitigation measures	– See above

By analysing the feasibility of the measures for the study site in Table 6.1, several operational and structural measures have been applied to reduce the sub-daily flow fluctuations of the River Hasliaare (Table 6.2):

- *Limitation of maximum turbine discharge*: To reduce peak flow Q_{max}, the maximum turbine releases of Innertkirchen 1 and 2 HPPs of 39 m^3/s and 29 m^3/s, respectively, were limited to 90%, 80%, and 70% of their present-day capacity (Table 6.2, D). More severe restrictions influence the operating mode of the plants up to Lake Grimsel and thus prevent on-demand production.

- *Increase of residual flow*: The constant outflow from the Handeck compensation basin was set to 1, 2, and 3 m^3/s (Table 6.2, E). These values are considerably higher than the values required by law and therefore correspond to important energy losses.
- *Limited drawdown range*: Turbine operations of Innertkirchen 1 and 2 HPPs had to maintain drawdown ranges Q_{max}/Q_{min} of 12:1, 8:1, and 5:1 (Table 6.2, F). Lower ranges were not considered, as it is not possible to apply the lower ranges without changing the operating rules of the plants located upstream.
- *Powerhouse outflow directly into the lake*: Through a tunnel or open channel between Innertkirchen and Lake Brienz of approximately 15 km in length and a capacity corresponding to the total turbine discharge, the flow in the Hasliaare was reduced to the released residual flow and the inflow from the river basin not utilised for hydropower production (Table 6.2, G).
- *Scheme enhancements*: Currently, the turbine capacity of the Innertkirchen I HPP is increased by 25 m^3/s (*KWOplus*), leading to a maximum peak discharge of 64 m^3/s. The impact of this enhanced scheme was simulated without mitigation (Table 6.2, H). In a second step, further (not yet under construction) enhancement was taken into account. The enhancement consisted of the new Brienzwersee pumped-storage plant, moving the water between Lake Räterichsboden and Lake Brienz. This movement of water may allow for a reduction of hydropeaking in River Hasliaare, as peak load production would be achieved by the new plant and the production of the existing Innertkirchen I HPP could be restricted according to ecologically defined HPP operating rules, e.g., $Q_{max}/Q_{min} < 2:1$ (Table 6.2, I).
- *Compensation basins and caverns*: Retention volumes could be installed downstream of the turbine outlets in Innertkirchen. In this approach, the water is temporarily stored in a basin and then released to the river by a guided system, respecting ecologically defined operating rules. Limited space availability would be the major problem for the construction of these compensation basins. The present parameter study did not take these practical constraints into account. A cavern could be implemented as an alternative to compensation basins with a significant environmental and visual impact. In this study, retention volumes, V_{basin}, of between 50,000 and 1,000,000 m^3 and V_{cavern} of between 20,000 and 300,000 m^3 were implemented in the model and economically rated (Table 6.2, J). Water release to the river increased with the higher water level in the reservoir or cavern, from 20 m^3/s at low level up to the maximum turbine release.

The measures detailed above were implemented in the three-step approach for economic and habitat rating of hydropeaking mitigation measures.

Table 6.2: Flow regime characteristics of real data series and simulations with and without operational restrictions, as well as for different HPP layouts and structural mitigation measures. Production losses due to operational measures as well as capital and maintenance costs for the basins are given as the mean annual mitigation cost over the 5-year period.

	Conditions and/or measure type	Details		Q_{max}*[1] November	Q_{min}*[2] November	Q_{max}*[1] August	Q_{min}*[2] August	Mean annual mitigation	
				[m³/s]	[m³/s]	[m³/s]	[m³/s]	[€10⁶]	
A	Flow regime **before HPP operation** based on Brienzwiler 1926–29		A	14	14	80	60	-	
B	Measured **real data** at Meiringen-Schattenhalb for 2009		B	27	9	70	37	-	
C	Simulation under market-based conditions **without restrictions** of 2009		C	68	5	73	25	0.0	
D	Simulation of 2005–2009 with **discharge limitations** for powerhouses Inn 1/2 by …	90%	D1	62	5	66	29	2.9	
		80%	D2	58	5	61	30	5.8	
		70%	D3	62	5	61	30	8.5	
E	Simulation of 2005–2009 with **increase of residual flow** at Handeck by Q = … [m³/s]	1	E1	69	6	74	26	1.8	
		2	E2	70	7	72	27	3.5	
		3	E3	67	8	75	28	5.4	
F	Simulation of 2005–2009 with **limited drawdown range** of Q_{max}/Q_{min} = … [-]	12:1	F1	61	6	69	25	0.8	
		8:1	F2	60	9	70	27	2.0	
		5:1	F3	56	10	69	27	3.9	
G	Simulation of 2009 with **only residual flow** in River Hasliaare	Residual flow	G	6	6	6	6	not known	
H	Simulation of 2005–2009 by **KWOplus** without restrictions	KWO+	H	93	5	94	20	0.0	
I	Simulation of 2005–2009 by KWOplus and **Brienzersee** pumped-storage **HPP** (2:1)	KWO++	I	40	10	48	22	not known	
J	Simulation of 2005–2009 with implementation of **compensation basin** immediately downstream of the turbine outlets of Inn 1/2 of volume V_{basin} = … [10³ m³]	1,000	J1	41	9	64	38	4.4[wt]	4.5
		700	J2	43	7	68	34	3.3[wt]	3.4
		400	J3	48	6	71	34	2.1[wt]	2.2
		100	J4	68	5	73	31	0.9[wt]	1.1
		50	J5	68	5	73	27	0.6[wt]	0.8

*[1] 90th and *[2] 10th percentiles of 1 h flow series for November and August of the hydrological year (series of November 2008 and August 2009 are taken for the 2005–2009 period discharge).
[wt] with individually optimised micro-turbines at the outlet of the basin (electricity price of €0.10/kWh)

Hydropower operation model

The Routing System model is a semi-distributed conceptual hydrological-hydraulic model (Bieri & Schleiss 2012). In a first step, the Routing System simulates the hydrological processes in Alpine river basins by a reservoir-based precipitation runoff model, including flow routing by the kinematic wave assumption. The output can be linked to the HPP operation model. By defining the main characteristics of the hydropower scheme (reservoirs, power houses, and their interconnection) as well as an electricity price scenario, optimal operation is simulated by a heuristic approach. Inflow, reservoir water level, operated and released flow, and thus power generation and revenue are computed at every time step. Despite the complexity of high-head-storage schemes, the influence of climate change, electricity market issues, plant enhancements, and hydropeaking constraints can be simulated. The released water from the power plants to the river system, as well as runoff from the non-operated catchment area, are used as inputs for further flow regime analysis. As climate change will impact the future daily flow regime only marginally (Bieri & Schleiss 2011), the simulation period was limited to five hydrological years, from 2005 to 2009, assuming a slightly volatile electricity price scenario with a mix of renewable energy suppliers. The simulations were performed with a ten-minute time step. The results were saved as hourly mean values.

The optimised operation of today's Oberhasli hydropower scheme without any restrictions or mitigation measures was defined as the reference scenario (Table 6. 2, C). Simulations with the implemented operational restrictions give the resulting mean annual mitigation cost in terms of production losses [€], where the economic efficiency of a structural measure depends on the investment cost. Basins are formed by dykes built by excavated material from reservoir construction. The cavern is created by drilling and blasting. The annual capital costs are defined by multiplying the present investment by the annuity, with an interest rate of 4% and a constant redemption time of 50 years. The applied method is sufficiently precise for a parameter study comparing different measures. For further evaluation, specific design and detailed economic analysis would be required.

Flow routing and the 2D hydrodynamic model

The 2D hydrodynamic model, used to simulate the distribution of velocities and depths in the reach, is based on an elevation model and generates the distribution of hydraulic conditions for an input discharge. These hydraulic conditions determine the abiotic habitat conditions on which the fish habitat assessment will be based.

Flow series in the river reaches were generated by the hydropower operation model Routing System. Off-peak (minimum: $Q_{\min}$) and peak (maximum: $Q_{\max}$) discharges are inferred from the simulated monthly hydrographs generated by the Routing System, corresponding to the 10^{th} and 90^{th} percentiles, respectively. The two percentages indicate steady flow conditions that are achieved with regularity. The simulated flow regime was compared to the measured discharge series before 1926–29 and with 2009 hydropower exploitation of the upper Aare catchment.

For habitat modelling of the river system, four morphologies were investigated. Three of these morphologies represent real habitat conditions in the Hasliaare downstream of powerhouse outlets in Innertkirchen. The groynes, gravel bars, and channel reaches (Figure 6.5a, b, and c) had been selected due to their morphological characteristics. Mean water column velocity, depth, and substrate distributions vary considerably among the three reference morphologies and thus influence the suitability of the habitat for fish differently. A fourth morphology was tested to assess potential future river restoration, consisting of a transformation of parts of the channel into a braided reach. For this purpose, a naturally shaped section of River Vorderrhein (Person & Peter 2012) (see chapter 3) was chosen as the braided reach (Figure 6.5d). The Vorderrhein is a Swiss alpine river with a nivo-glacial regime, a mean annual discharge of 30.5 m^3/s, and a mean catchment altitude of 2020 m a.s.l., characteristics similar to those of the Hasliaare. This naturally braided river is part of the trout region (Huet longitudinal zonation, 1949). The four reference morphologies were tested with the same simulated flow regimes, corresponding to a location close to the powerhouse outlets in Innertkirchen (Meiringen-Schattenhalb), to compare the influence of the bed form on fish habitat conditions.

For each test reach, the riverbed bathymetry was measured, and a digital elevation model was developed as input for the 2D hydrodynamic model. Riverbed elevation and drainage area topography were measured, combining a tachymeter terrestrial system (LEICA TC1102) with a GPS echo sounder (DESO 14). The grid size had to be defined in terms of the instream structure of the river. Values were sampled every 0.5 seconds, producing a grid size of 0.5 m and therefore a very detailed representation of the riverbed. A 3D digital elevation model (DEM) was then computed. Flow velocity was measured in situ by a SEBA mini current meter (type M1) for model calibration. The substrate was classified according to granulometry.

The flow depth and mean vertical velocity for every grid cell were simulated by the 2D hydrodynamic model HYDRO_AS-2D (Tolossa *et al.* 2009) for a range of 30 discharges evenly distributed between 3 and 100 m^3/s. This discharge spectrum covers the normal flow regime of 2009 for Meiringen-Schattenhalb, disregarding flood events, and embeds the flow series generated by the Routing System. The boundary conditions were defined by measured stage-discharge relationships.

Dynamic fish habitat simulation tool

To evaluate the habitat response to hydropeaking, the fish module of the CASiMiR habitat model was combined with regional univariate preference curves for adult, YOY, and spawning brown trout. The preference curves from field investigations in the Hasliaare (see chapter 5) were used to define the habitat suitability of YOY and spawning brown trout. For adult fish, no specific suitability curves for the Hasliaare are available, and adult suitability curves from (Souchon *et al.* 1989) were used, as they show habitat preferences similar to Hasliaare data for YOY and spawning brown trout. This indicates that the two populations have similar habitat preferences. The suitability curves were implemented in the CASiMiR model for the four river reaches (groynes, gravel bars, channel, and braided reaches). For the 30 simulated discharges, the Suitability Index (SI), ranging between 0 (unsuitable) and 1 (suitable), was computed for every grid cell using flow depth, water velocity, and substrate preferences.

Several mathematical methods are known to define the overall SI based on the different preference values, including the product equation, the arithmetic mean, and the geometrical mean. Different assumptions are associated with the mathematical methods used to define of the overall suitability. Applying the arithmetic mean assumes that a high preference for one parameter, such as velocity, can compensate for poor preferences for another, such as depth, while applying the geometrical mean assumes that each abiotic parameter is equally important (Layher & Maughan 1985). In the calculation of the overall SI, the geometric mean was chosen because the product and the arithmetic mean tend to overestimate overall suitability when one of the preferences for an abiotic parameter is very high.

To evaluate the dynamic impact of sub-daily flow fluctuation on the target species, five indices have been developed based on SI maps:

Suitable Area (SA) [m^2] considers an area or a cell only if the associated SI reaches or exceeds a defined threshold value SI_{lim}. The SA for discharge Q corresponds to the total surface area where SI is greater than or equal to SI_{lim}. SI_{lim} was set to 0.5, including middle- to high-SI areas. Only water levels H achieving H_{lim}, the threshold water depth at which flow is too shallow to sustain the species of interest, were taken into account and are described as the Effective Wetted Area (WA_{eff}) [m^2] for discharge Q. According to the habitat preference curves and field observations of the habitat use of brown trout in Hasliaare(see chapter 5), H_{lim} was set to 5 cm for YOY and 10 cm for adult and spawning individuals.

$$\mathrm{SA}(Q) = \sum_{i=1}^{n} A_i \Big|_{\mathrm{SI}_i(Q) \geq \mathrm{SI}_{\mathrm{lim}} \text{ and } H_i(Q) \geq H_{\mathrm{lim}}} \tag{1}$$

where A_i [m^2] represents the area of the ith cell, $SI_i(Q)$ [-] stands for the SI of the ith cell for discharge Q, SI_{lim} is the threshold SI, $H_i(Q)$ is the flow depth for discharge Q, and H_{lim} is the threshold water depth.

Suitable Habitat Ratio (SHR) [-] is the ratio of SA and the Effective Wetted Area (WA_{eff}) [m^2] for Q.

$$\mathrm{SHR}(Q) = \frac{\mathrm{SA}(Q)}{\mathrm{WA}_{\mathrm{eff}}(Q)} \tag{2}$$

Wetted Habitat Loss (WHL) [-] indicates the unstable habitat which is lost between two steady flows. This unstable habitat represents the area where habitat conditions change from suitable ($SI \geq SI_{lim}$) at discharge Q_1 to unsuitable ($SI < SI_{lim}$) at discharge Q_2 over the Effective Wetted Area (WA_{eff}) [m^2] for Q_1. Habitats becoming dry are not considered in this index:

$$\mathrm{WHL}(Q_1, Q_2) = \frac{\sum_{i=1}^{n} A_i \Big|_{\mathrm{SI}_i(Q_1) \geq \mathrm{SI}_{\mathrm{lim}} \text{ and } \mathrm{SI}_i(Q_2) < \mathrm{SI}_{\mathrm{lim}} \text{ and } H_i(Q_2) \geq H_{\mathrm{lim}}}}{\mathrm{SA}(Q_1)} \tag{3}$$

The Drained Area Ratio (DAR) [-] also describes changing habitat conditions, indicating the relative loss of suitable habitat due to dewatering when discharge switches from Q_1 to Q_2. The DAR represents the relative area where habitat conditions change from suitable ($SI \geq SI_{lim}$) at Q_1 to drained ($H < H_{lim}$) at Q_2.

$$\mathrm{DAR}(Q_1, Q_2) = \frac{\sum_{i=1}^{n} A_i \Big|_{\mathrm{SI}_i(Q_1) \geq \mathrm{SI}_{\mathrm{lim}} \text{ and } H_i(Q_2) < H_{\mathrm{lim}}}}{\mathrm{SA}(Q_1)} \tag{4}$$

The Effective Suitable Habitat Ratio (SHR_{eff}) [-] is a deduced index based on DAR and SHR, defining the relative suitable habitat ($SI \geq SI_{lim}$) remaining wetted when discharge is reduced from Q_2 to Q_1. The SHR_{eff} is useful for assessing suitable spawning conditions.

$$\mathrm{SHR}_{\mathrm{eff}}(Q_1, Q_2) = \left(1 - \mathrm{DAR}(Q_2, Q_1)\right) \cdot \mathrm{SHR}(Q_2) \tag{5}$$

The sum of unstable (WHL) and dewatered (DAR) habitat defines the total loss of high-quality habitat between Q_1 and Q_2. Consequently, the remaining suitable habitat is defined as stable. On one hand, SA and SHR are related to a specific discharge state and present habitat suitability for steady flow conditions. On the other hand, WHL and DAR indicate the change of habitat conditions between two flow states and are therefore considered dynamic indices.

November and August were chosen for habitat simulations. Spawning activity takes place in November. The drawdown range is greater in winter, when discharge is naturally low. Previous studies on hydropeaking showed that its impact on adult brown trout is greater during the winter period (Person & Peter 2012) (see chapter 3). YOY were sampled in August, as they are large enough to be caught by electrofishing and the period of density-dependent mortality has passed (Crisp 2000). For each mitigation scenario, habitat indices for the three life stages and the four reference morphologies were computed for the corresponding Q_{min} and Q_{max}.

6.4 Results

6.4.1 Flow regime

Measured discharge series of the Hasliaare at the Brienzwiler gauging station before the construction of the Oberhasli hydropower scheme (1926–1929) showed sub-daily fluctuations in August between 80 (Q_{max}) and 60 m^3/s (Q_{min}) due to the alpine hydrological regime. For November, no major sub-daily flow fluctuations were observed, and the monthly average of 14 m^3/s was therefore chosen (Table 6.2, A). For the discharge series at Meiringen-Schattenhalb, the runoff of the Hasliaare in November was between 27 and 9 m^3/s for 2009, whereas in August, values of between 70 and 37 m^3/s were measured (Table 6.2, B).

Comparing the simulated and measured flow regimes of the Hasliaare at Meiringen-Schattenhalb (Table 6.2, B and C), both of the reference months November and August showed higher sub-daily fluctuations for the Routing System results. This difference was caused by the different HPP operating driving parameters. Fully market-dependent production undertakes on-off operations even for short periods, whereas the present contract-based production causes smaller fluctuations. Turbine sequences with maximum discharge are also conducted in reality but occur less frequently than simulated. The two flow regimes cannot be directly compared. The simulated scenarios therefore represent a future behaviour that corresponds to an open and electricity-price-driven market. The reference scenario of optimised operation without restrictions for the period 2005–2009 gives a Q_{max} between 63 and 68 m^3/s and Q_{min} of approximately 5 m^3/s in November. The peak discharge between 73 and 96 m^3/s in August is influenced mostly by flood events. The hydrological year of 2009, with only a minor flood event in August, was applied as the reference year for the flow regime analysis, with a Q_{max} of 73 m^3/s and Q_{min} of 25 m^3/s (Table 6.2, C).

Limiting the discharge from the turbines of Innertkirchen 1 HPP (39 m^3/s) and Innertkirchen 2 HPP (29 m^3/s) by 90%, 80%, and 70% (Table 6.2, D) can reduce the flow downstream of the turbine outlet Q_{max} from 68 to 58 m^3/s in November and from 73 to 61 m^3/s in August. Q_{min} in winter remains at 5 m^3/s. Strongly limiting the outlet capacity of the HPP complex by up to 70% affects the operation of the plants located upstream, i.e., Handeck and Hopflauenen. In the case of large storage volumes, such as Lake Räterichsboden, water can be utilised later for electricity production. Only small compensation basins are located in the eastern catchment. Strong inflow produces overflow, which increases flow in dewatered reaches that carry only residual flow, and therefore compensates for the achieved peak reduction by limited turbine release, as shown for the 70% limitation.

Increasing the outflow from the Handeck compensation basin by 1, 2, and 3 m^3/s (Table 6.2, E) raises the Q_{min} for winter and summer. The Q_{max} generally also increases. Due to water losses, turbine operations are shorter and the 90th percentile can be lowered.

The impact of the limited drawdown range Q_{max}/Q_{min} of 12:1, 8:1, and 5:1 was simulated (Table 6.2, F). In winter, with low residual flow in the upstream river reach, there is a decrease of 7 to 12 m^3/s for Q_{max} and an increase in Q_{min} by 1 to 5 m^3/s in November. The drawdown range is guaranteed for at least 75% of all winter days. Annual values are less affected due to summer months achieving a satisfactory flow regime, even without intervention. In consequence, mean summer daily drawdown ranges are generally lower than the set values.

For a powerhouse outflow directly into Lake Brienz through a tunnel or open channel, the monthly average discharge in the Hasliaare would be 6 m^3/s for both November and August (Table 6.2, G). The minor natural flow fluctuations in August were neglected due to runoff retention in the reservoirs of the HPP, whereas scenario A (Table 6.2, A) included the natural sub-daily variations of high-mountain catchment areas.

The upgrading programme called KWOplus will increase the turbine capacity of Innertkirchen 1 HPP from 39 m^3/s to 64 m^3/s. Simulation of the optimised operation of the HPP without restrictions resulted in a Q_{max} of 93 and 94 m^3/s in November and August, respectively. Low flow in winter was not affected, but Q_{min} in summer was reduced to 20 m^3/s (Table 6.2, H). The Brienzersee pumped-storage plant would increase operation flexibility. In addition, hydropeaking in the River Aare can be limited to a drawdown range of 2:1 (Table 6.2, I). November discharge fluctuates between 40 and 10 m^3/s, irrespective of the indicated drawdown range, due to a lack of storage capacity in the Susten Catchment, whereas August flow is between 48 and 22 m^3/s.

For compensation basins or caverns downstream of the powerhouses in Innertkirchen, the simulations showed that a minimum storage volume of 100,000 m^3 is required to achieve a reduction of Q_{max} and/or an increase of Q_{min} (Table 6.2, J). Larger compensation basins can reduce peak flow to values of 41 m^3/s in winter and 64 m^3/s in summer, and low flow is increased to values of 9 and 38 m^3/s, respectively. Nearly all volumes higher than 100,000 m^3 generated lower Q_{max} and higher Q_{min} than the operational measures.

6.4.2 Economic rating

An average annual revenue of €118 M/yr for optimised turbine and pump operations of the Oberhasli hydropower scheme resulted from the applied electricity price scenario and runoff from the catchment area for 2005–2009.

Table 6.2 shows that the highest production losses (between 2.4% and 7.2% (€2.9 M and €8.5 M)) were generated for discharge limitations due to the important head of Innertkirchen 1 HPP and the impact on the power plants upstream (Table 6.2, D). Increased residual flow leads to water losses and therefore energy losses. The corresponding annual production loss was 1.4% and 4.6% (€1.8 M and €5.4 M) for 1 and 3 m^3/s, respectively (Table 6.2, E). A drawdown range Q_{max}/Q_{min} of 12:1 caused 0.7% (€0.8 M) less revenue, whereas 5:1 reduced revenue by 3.3% (€3.9 M) (Table 6.2, F). Future extensions of hydropower schemes such as the Brienzersee pumped-storage plant combined with ecologically defined HPP operating rules reduced the annual revenue by 8% from €316 M to €290 M/yr for the current inflow (Table 6.2, I).

Comparing the annual costs for the compensation basins among the different basin volumes without the individually optimised micro-turbines (Figure 6.3a), the mean annual cost can be reduced slightly from €0.8 M to 0.6 M/yr for a 50,000 m^3 reservoir and from €4.5 M to €4.4 M/yr for a 1,000,000 m^3 reservoir (Table 6.2, J). The costs for caverns (Figure 6.3b) showed a nearly linear relationship between retention volume V_{cavern} and cost. The larger the cavern, the less competitive the cavern will be compared to the reservoir. Construction costs are more than double for a storage volume of 150,000 m^3, and the cavern is therefore not discussed further.

Figure 6.4 presents the comparison of drawdown ranges Q_{max}/Q_{min} and the corresponding production losses for the different scenarios. For a mitigation type, the minimum drawdown range normally generated the highest mitigation cost.

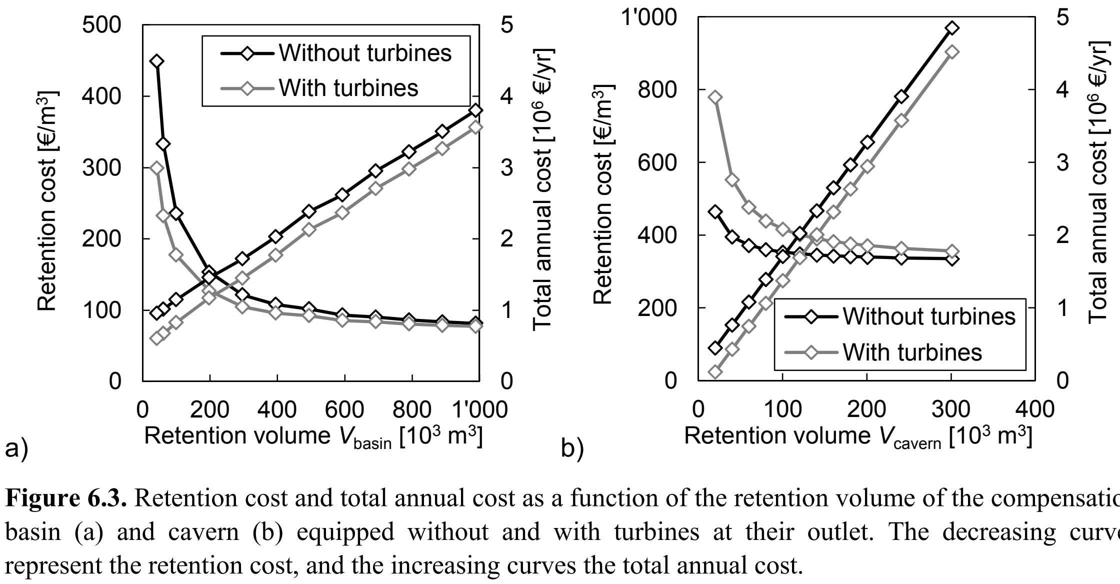


Figure 6.3. Retention cost and total annual cost as a function of the retention volume of the compensation basin (a) and cavern (b) equipped without and with turbines at their outlet. The decreasing curves represent the retention cost, and the increasing curves the total annual cost.

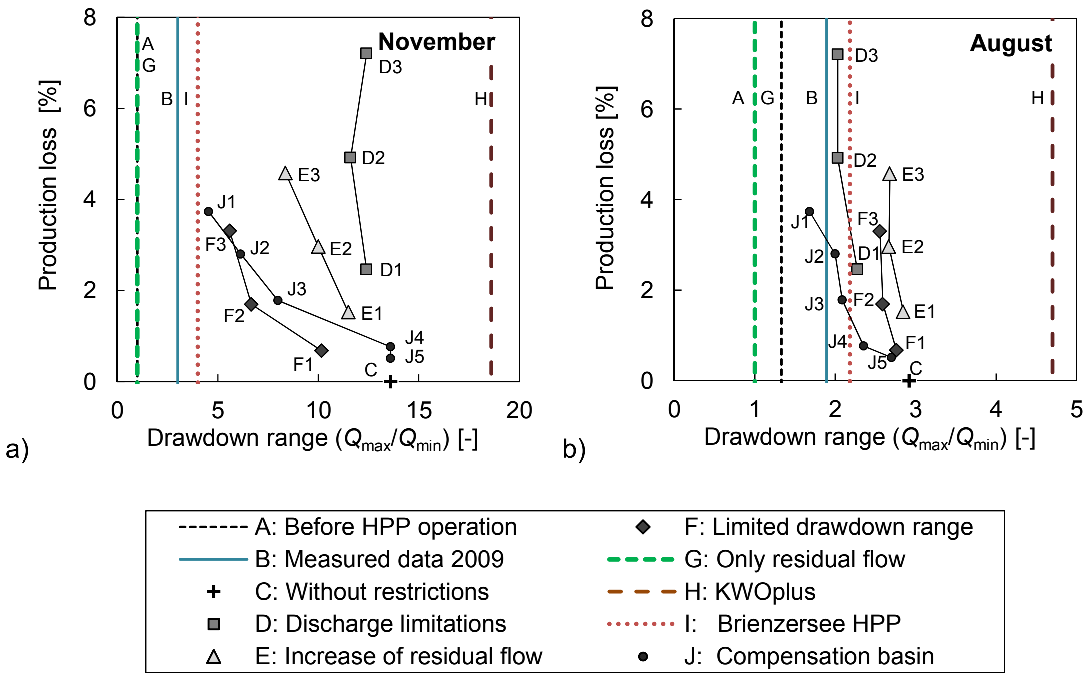


Figure 6.4. Drawdown range and mitigation cost (production loss from annual revenue without restrictions of €118 M/yr) from measured and simulated flow regimes (with and without mitigation measures) for November (a) and August (b). The vertical lines stand for the scenarios which do not have mitigation costs (e.g. A: Before HPP operation, B: Measured data) or for which no mitigation costs could be calculated (e.g. H: KWOplus, I: Brienzersee HPP).

6.4.3 Habitat rating

Habitat maps

Figure 6.5 shows habitat suitability maps for spawning brown trout for the four morphologies and for a common November off-peak (5 m^3/s) and peak (68 m^3/s) discharge as well as the mean monthly discharge of 14 m^3/s without HPP operation. For the groynes reach (Figure 6.5a), the main flow with relatively high water depth and velocity is concentrated in the inner part of the riverbed, whereas recirculation cells are generated between the groynes. The gravel bars reach (Figure 6.5b) is characterised by a wider morphology and allows for the presence of shallow flow conditions along the right riverbank. The channel reach (Figure 6.5c) has a monotonous morphology with no major instream structure and thus little habitat for nearly the whole range of discharges. The braided reach (Figure 6.5d) generates different habitat conditions compared to the three existing Hasliaare reaches. Lower discharges allow the braided structure to disappear and concentrate flow in the main riverbed, whereas higher discharges increase flow velocities in the inner part of the curve, reducing habitat quality in the normally shallow zone. However, the rich instream structure generates varying conditions, and fluctuating flow may generate habitat instability. Habitat suitability decreases with increasing discharge for groynes, gravel bars, and channel reaches. In these three cases, habitat suitability is high for very low flow and drops rapidly when discharge is increased beyond 8 m^3/s. For the braided reach, habitat suitability remains relatively constant for the different discharges.

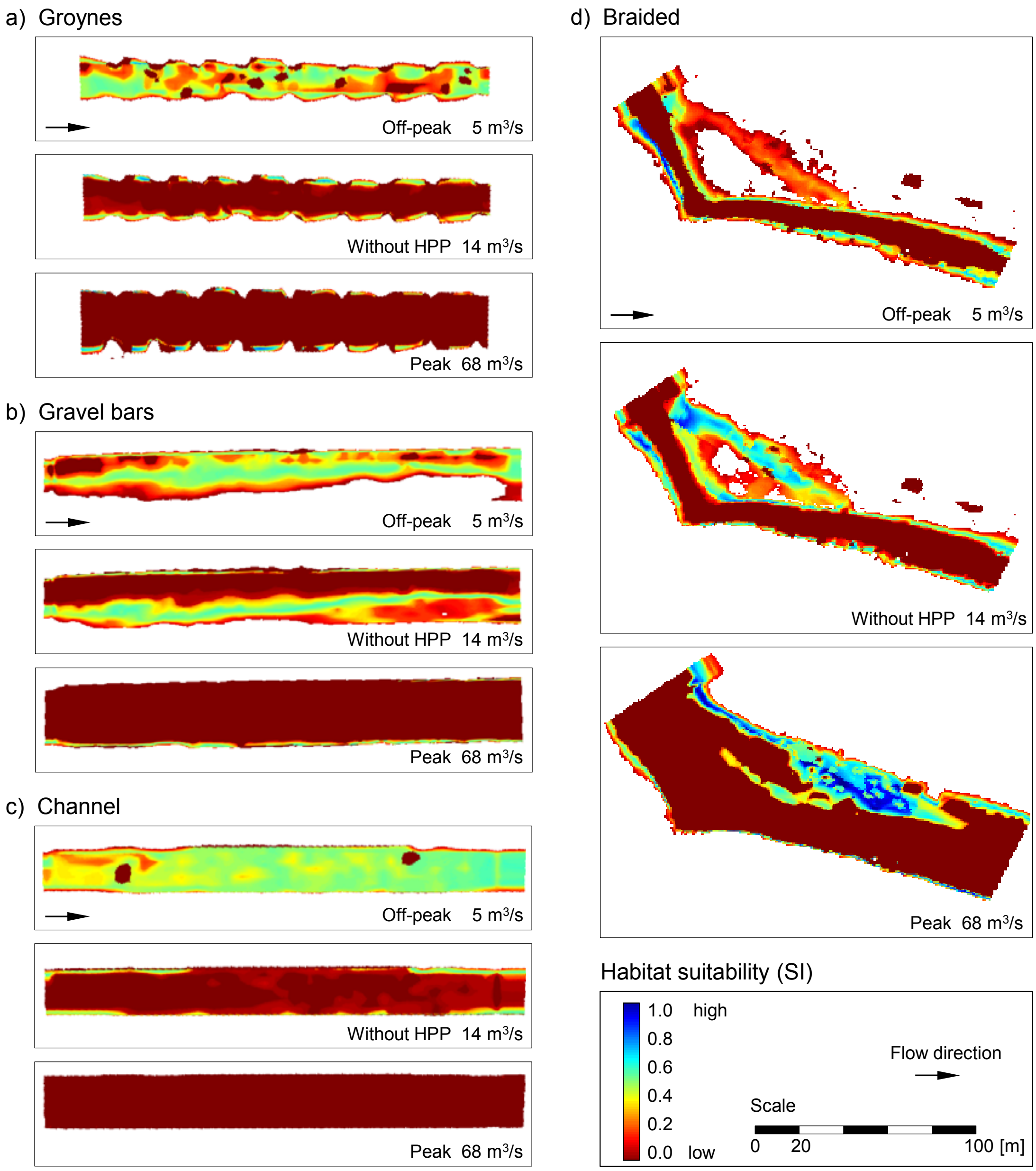


Figure 6.5: Habitat quality in terms of Suitability Index (SI) for spawning of brown trout resulting from habitat modelling for the groynes (a), gravel bars (b), channel (c) and braided (d) reaches for November off-peak ($Q = 5$ m^3/s) and peak ($Q = 68$ m^3/s) of the scenario without restrictions (C), as well as the mean discharge without HPP operation ($Q = 14$ m^3/s). Red represents low habitat quality, and blue high habitat quality.

Habitat as a function of discharge

Figure 6.6 shows the SHR, with a threshold habitat SI of 0.5, for the three life stages and the four morphologies for the whole range of 2D simulated discharges. In the habitat model for the adult life stage, the relationship between the SHR index and discharge is similar for gravel bars and channel reaches. The SHR is high for very low discharge but drops drastically to poor conditions for higher discharges. The reach with groynes shows similar habitat pattern, with suitable habitat stabilising at approximately 20% for discharges of more than 20 m^3/s. The SHR of the braided reach decreases only slightly with discharge. The highest habitat suitability for spawning is achieved in the braided reach at approximately 40 m^3/s, corresponding to 30% of the Effective Wetted

Area (WA_{eff}). For high flow, only a few shore habitats remain in the three existing Hasliaare reaches, whereas in the braided reach, the percentage of suitable habitat remains higher than 10% for up to 80 m^3/s. However, habitat is displaced when discharge changes. For groynes, gravel bars, and channel reaches, the SHR for spawning and YOY (Figure 6.6b and c) rapidly decreases for discharges higher than 20 m^3/s. For adult and spawning life stages, the habitat suitability for YOY in the braided reach is more resilient to increasing discharge. At least 20% of WA_{eff} has high habitat suitability at up to 50 m^3/s.

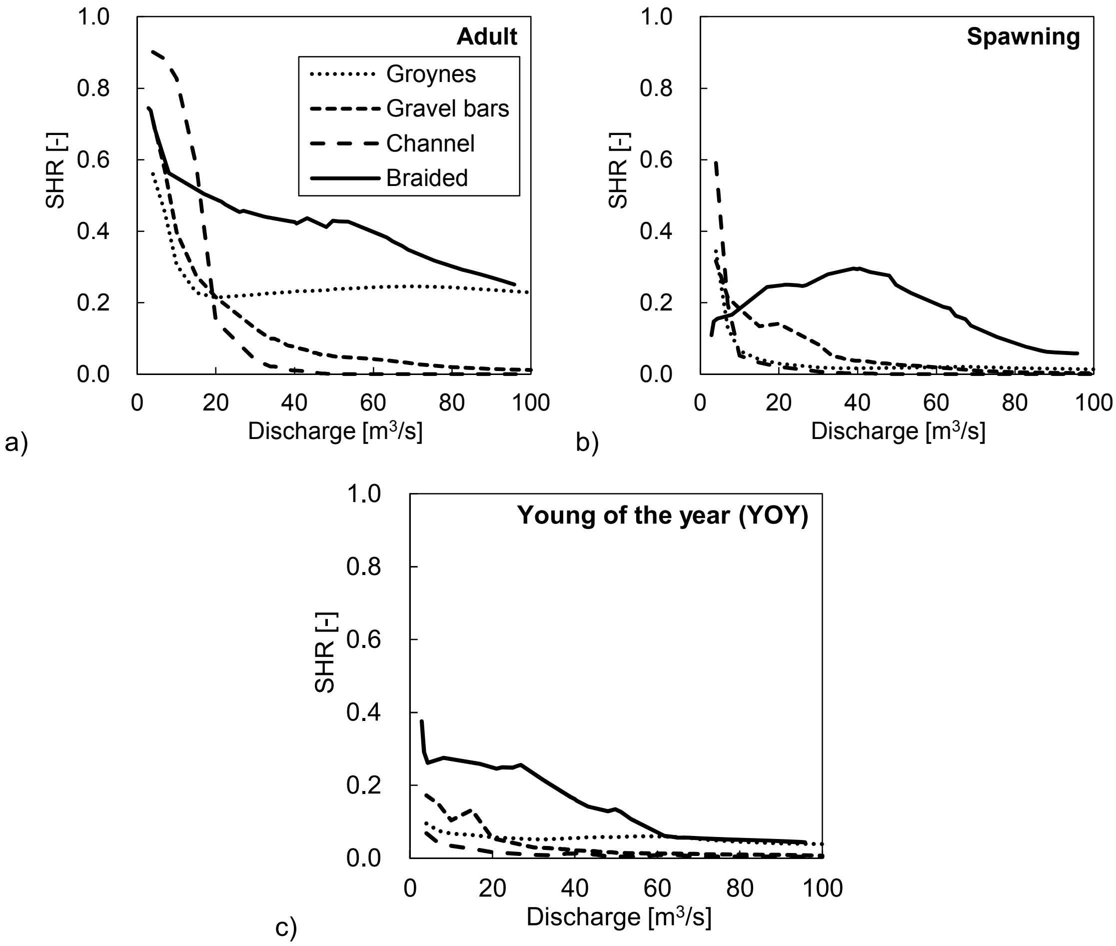


Figure 6.6. Suitability Habitat Ratio (SHR) for adult (a), spawning (b) and young-of-the-year (YOY) (c) of stream resident brown trout for the Hasliaare as a function of discharge for the groynes (round dotted line), gravel bars (dashed line), channel (long dashed line) and braided reaches (solid line).

Comparison of habitat between scenarios

Figures 6.7, 6.8, and 6.9 show habitat suitability and stability between off-peak (Q_{min}) and peak (Q_{max}) situations for the applied scenarios with and without mitigation measures (Table 6.2) and the three brown trout life stages. Each scenario shows the percentage of SHR being lost (unstable), becoming dry (dewatering), or remaining stable (stable) when discharge changes from Q_{min} to Q_{max} and vice versa.

Adult brown trout

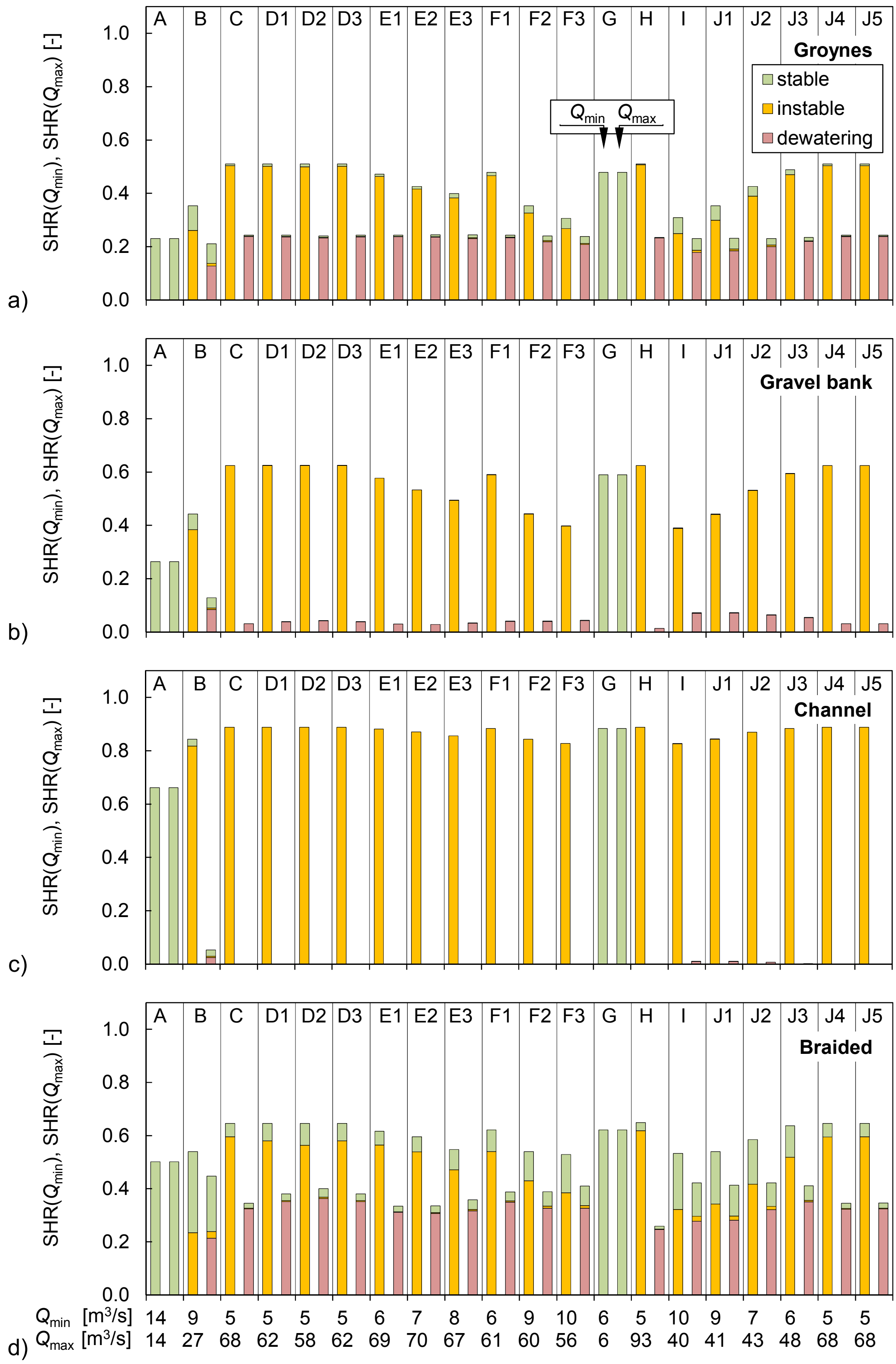


Figure 6.7: Suitability Habitat Ratio (SHR) for adult brown trout for the off-peak Q_{min} and the peak Q_{max} discharge of the measured and simulated November conditions (Table 6.2), computed for the groynes (a), gravel bars (b), channel (c) and braided (d) reaches. The percentage of stable (green), instable (yellow) and dewatering (red) habitat is given for discharge changes from Q_{min} to Q_{max} and Q_{max} to Q_{min}, respectively.

The results for adults are given in Figure 6.7. For the four morphologies, scenario A, without HPP operation, and scenario G, with only residual flow, are the only ones with a noticeable amount of stable suitable habitat. Both scenarios have a constant flow regime without hydropeaking and low discharges of up to 14 m^3/s. For all the other scenarios, a considerable habitat loss is defined for discharge increase from Q_{min} to Q_{max}, and a high dewatering rate for discharge decrease from Q_{max} to Q_{min}. The market-driven operation in scenario C leads to poorer conditions due to higher fluctuations than the existing contract-based operation of scenario B.

The channel reach (Figure 6.7c) exhibits the best habitat conditions for constant flow (scenarios A and G). For all other scenarios, the high SHR for Q_{min} disappears completely when discharge increases to Q_{max}. Almost no suitable habitat is available for Q_{max}. The gravel bars reach (Figure 6.7b) produces similar results except that SHR for Q_{min} is different for each scenario. Suitable habitat for Q_{min} is entirely unstable in changing flow conditions. A very small amount of high-quality habitat is present for Q_{max}. However, this small amount entirely dewaters when discharge decreases to Q_{min}. The groynes (Figure 6.7a) and braided reach (Figure 6.7d) have a similar SHR. For both morphologies, a low amount of SHR remains spatially stable under hydropeaking conditions. However, the fraction of stable SHR is slightly higher for the braided reach.

The analysis for adult fish shows highly unstable habitat for all scenarios with hydropeaking, independent of morphology. Only groynes and braided reaches have low ratios of SHR that remain stable under fluctuating flow conditions. No major difference for SHR is found among the different scenarios for channel reach (Figure 6.7c). For groynes (Figure 6.7a), gravel bars (Figure 6.7b), and braided reach (Figure 6.7d), SHR for Q_{min} does not change with discharge limitation scenarios (D1 to D3), whereas increased residual flow (E1 to E3), limited drawdown ranges (F1 to F3), and compensation basins (J1 to J5) reduce suitable habitat slightly for Q_{min}. However, habitat stability is increased for the braided reach (Figure 6.7d), although SHR is slightly decreased with increasing volumes of the compensation basins (J1 to J5). For all morphologies, discharge limitations (D1 to D3) do not affect SHR.

Spawning brown trout

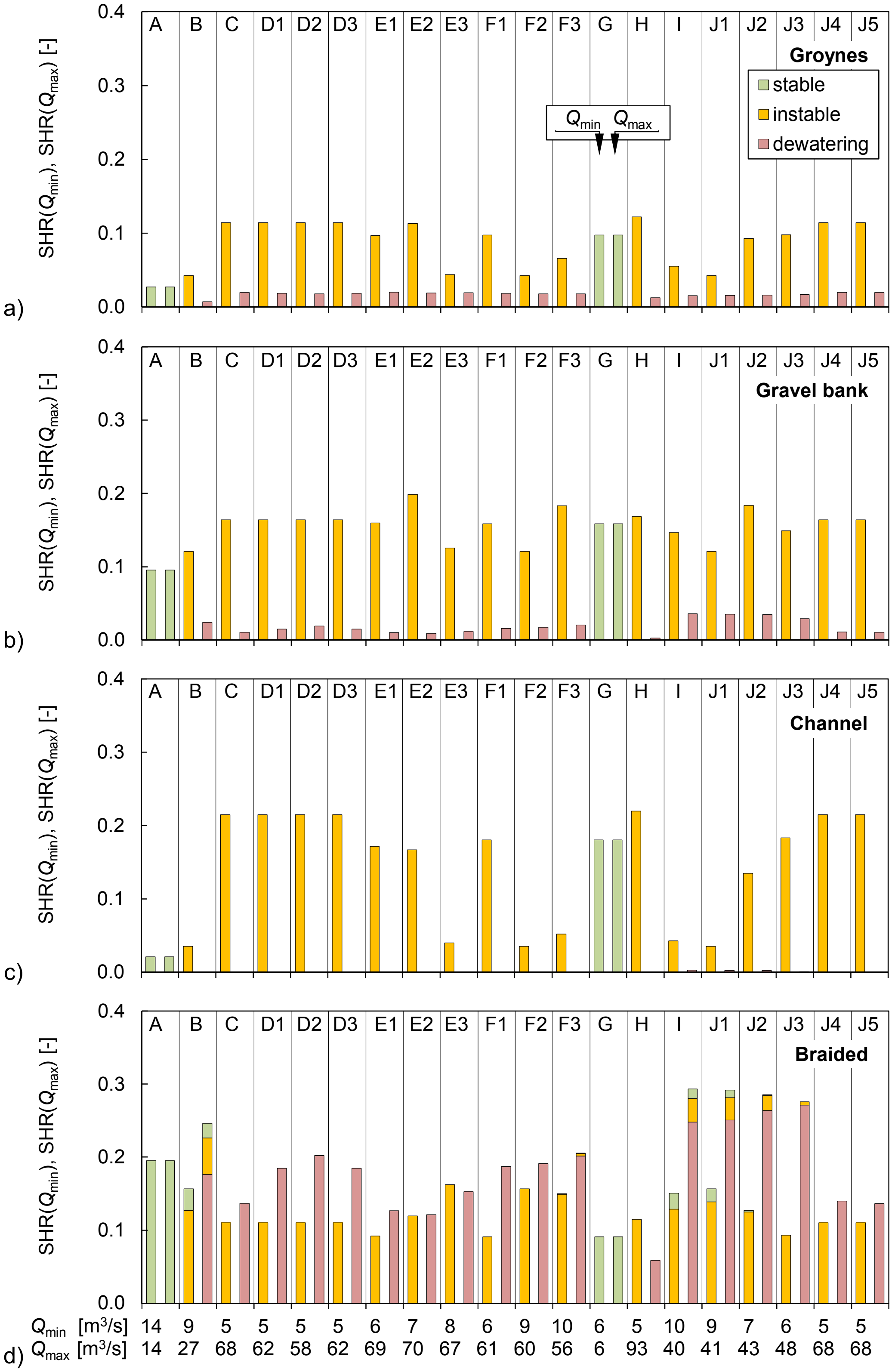


Figure 6.8: Suitability Habitat Ratio (SHR) for spawning brown trout for the off-peak Q_{min} and the peak Q_{max} discharge of the measured and simulated November conditions (Table 6.2), computed for the groynes (a), gravel bars (b), channel (c) and braided (d) reaches. The percentage of stable (green), instable (yellow) and dewatering (red) habitat is given for discharge changes from Q_{min} to Q_{max} and Q_{max} to Q_{min}, respectively.

Habitat conditions for spawning brown trout for the different scenarios listed in Table 6.2 are shown in Figure 6.8. SHRs for all morphologies and scenarios are lower than for the adult life stage. SHRs do not range above 30% of WA_{eff}. The braided reach (Figure 6.8d) is the only morphology with a small amount of stable SHR for simulated scenarios with hydropeaking, such as the measured real data for 2009 (B), the powerhouse outflow into the lake by HPP Brienzwiler (I), and the 1,000,000 m^3 compensation basin (J1). Groynes (Figure 6.8a), gravel bars (Figure 6.8b), and channel (Figure 6.8c) reaches show similar results. SHR is higher for Q_{min} than for Q_{max}, where suitable habitat is rare or, in the case of the channel reach, non-existent. The small amount of SHR available for Q_{max} for the groynes and gravel bars reaches becomes entirely dry when discharge drops for Q_{min}. Suitable habitat at Q_{min} is lost entirely or displaced when discharge increases to Q_{max}. The braided reach (Figure 6.8d) shows a completely different situation. SHR is slightly higher for Q_{max} than for Q_{min} except for KWOplus (H) with the highest peak discharge of 93 m^3/s. In all scenarios with hydropeaking, a high percentage of SHR is lost or displaced during peak independent of the size of the peak flow or the drawdown range ratio.

Young-of-the-year brown trout

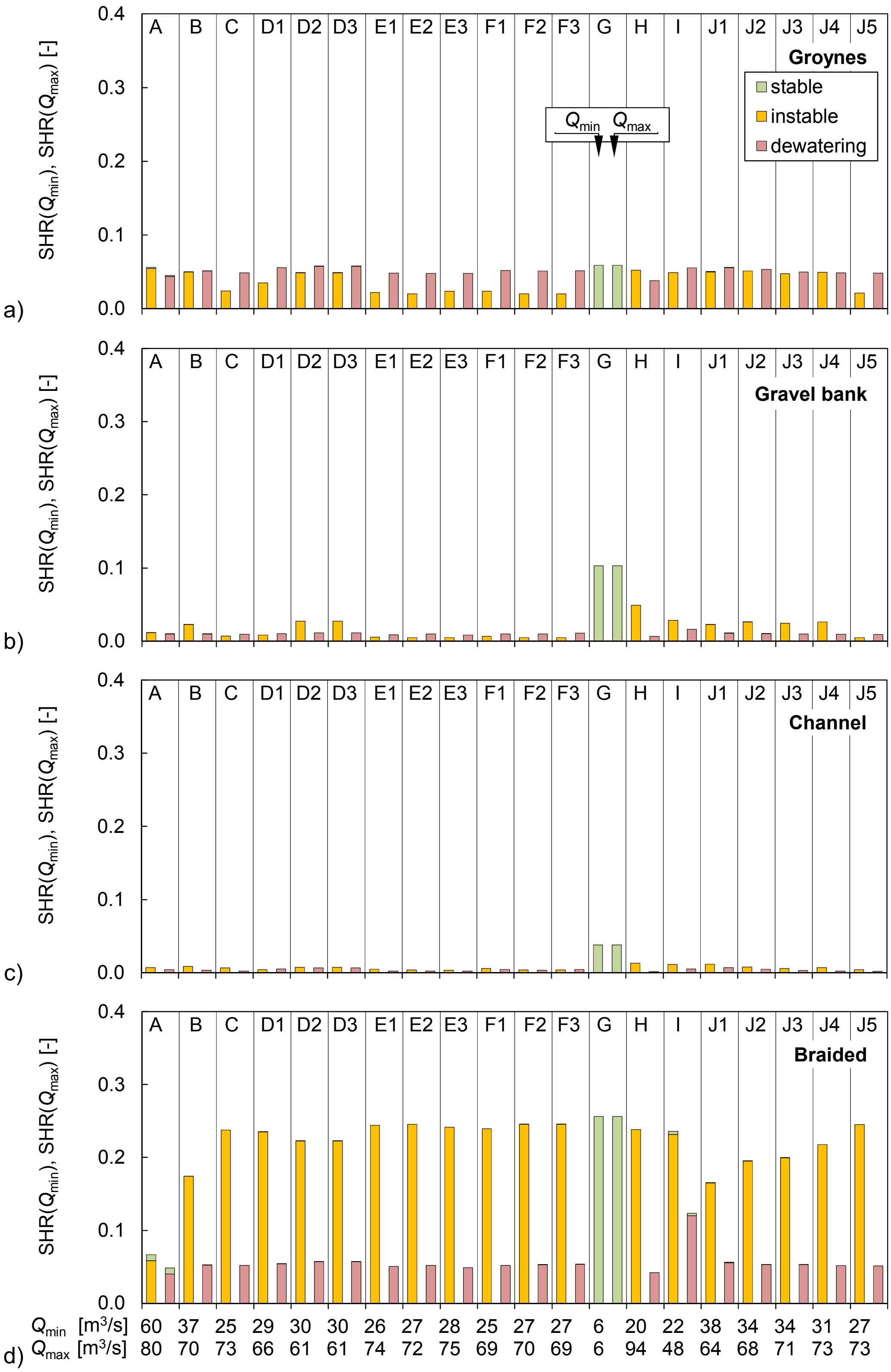


Figure 6.9: Suitability Habitat Ratio (SHR) for young-of-the-year (YOY) brown trout for the off-peak Q_{min} and the peak Q_{max} discharge of the measured and simulated August conditions (Table 6.2), computed for the groynes (a), gravel bars (b), channel (c) and braided (d) reaches. The percentage of stable (green), instable (yellow) and dewatering (red) habitat is given for for discharge changes from Q_{min} to Q_{max} and Q_{max} to Q_{min}, respectively.

Habitat suitability and stability for YOY brown trout are shown in Figure 6.9 for all scenarios of Table 6.2. August hydrographs were used for YOY. Scenario G is the only scenario without sub-daily discharge fluctuations in August. SHR is very low to almost negligible for the groynes (Figure 6.9 a), gravel bars (Figure 6.9 b), and channel (Figure 6.9 c) reaches. Gravel bars and channel reaches show very low and constant SHR for all scenarios except scenario G. For the reach with groynes, SHR is relatively constant at 2 to 4%. The braided reach (Figure 6.9 d) differs greatly from the other morphologies. Scenario G has very high and stable SHR. A low amount of stable habitat can also be found before HPP operation (A) and for the Brienzersee HPP with a limited drawdown range of 2:1 (I). In general, the SHR in all the scenarios except G is either lost or displaced at Q_{max} and becomes dry at Q_{min}. The SHR is higher for Q_{min} than for Q_{max} in the braided reach.

Cost-benefit analysis

The developed and applied steady and dynamic fish habitat suitability indices can be compared to the annual costs of the hydropeaking mitigation measures. Figure 6.10 presents such a cost-benefit evaluation for spawning brown trout in the Hasliaare for the channel and braided reaches. Fish habitat is assessed in terms of SHR at the two steady states Q_{min} (Figure 6.10a1 and a2) and Q_{max} (Figure 6.10b1 and b2). In addition, dewatering risk is taken into account in the Effective Suitable Habitat Ratio $SHR_{eff}(Q_{max}, Q_{min})$ (Figure 6.10c1 and c2).

For the channel reach under low flow conditions (Figure 6.10a1), the most expensive mitigation measures are not always the ecologically most effective measures. Discharge limitation (D1 to D3) as well as compensation basins of 100,000 and 50,000 m3 (J4 and J5) show highest SHR for Qmin for very different costs. For increased residual flow (E1 to E3), limited drawdown range (F1 to F3), and larger compensation basins (J1 to J3), the higher the cost of the measure, the smaller the ecological improvement. Compared to the flow regime without restrictions (C), no mitigation potential remains. Peak conditions (Figure 6.10b1) due to the narrow and monotonous riverbed result in velocity distributions that are much higher than the spawning abilities of the brown trout. SHR for Qmax thus drops to zero for almost all scenarios. Independent of cost, no scenario can generate suitable spawning habitat. As shown in Figure 6.10c1, SHReff(Qmax, Qmin) is zero as a consequence of the SHR(Qmax) zero values, except for the residual flow scenario G, where sub-daily fluctuations are low and almost negligible.

The cost-benefit analysis for the braided reach shows rather different results than for the channel reach. Considering SHR for Q_{min} (Figure 6.10a2) and for Q_{max} (Figure 6.10b2), for increased residual flow (E1 to E3), limited drawdown range (F1 to F3), and compensation basins (J1 to J5), ecological improvements increase with increasing mitigation costs. Maximal ecological benefit is achieved for the highest residual flow (E3), the lowest drawdown range (F3), and the largest compensation basin (J1). Similar fish-spawning habitat improvement can be achieved by the Brienzersee HPP (I), where evaluation of costs takes into account the amortisation costs as well as the revenue from pumped-storage operation. Regarding $SHR_{eff}(Q_{max},Q_{min})$ (Figure 6.10c2), the increased residual flow (E1 to E3) and limited drawdown range (F1 to F3) lose their value in terms of improving suitable habitat for spawning. Brienzersee HPP (I) and the

1,000,000 m^3 compensation basin (J1) can maintain almost 5% of WA_{eff} as high-quality habitat for spawning under hydropeaking conditions.

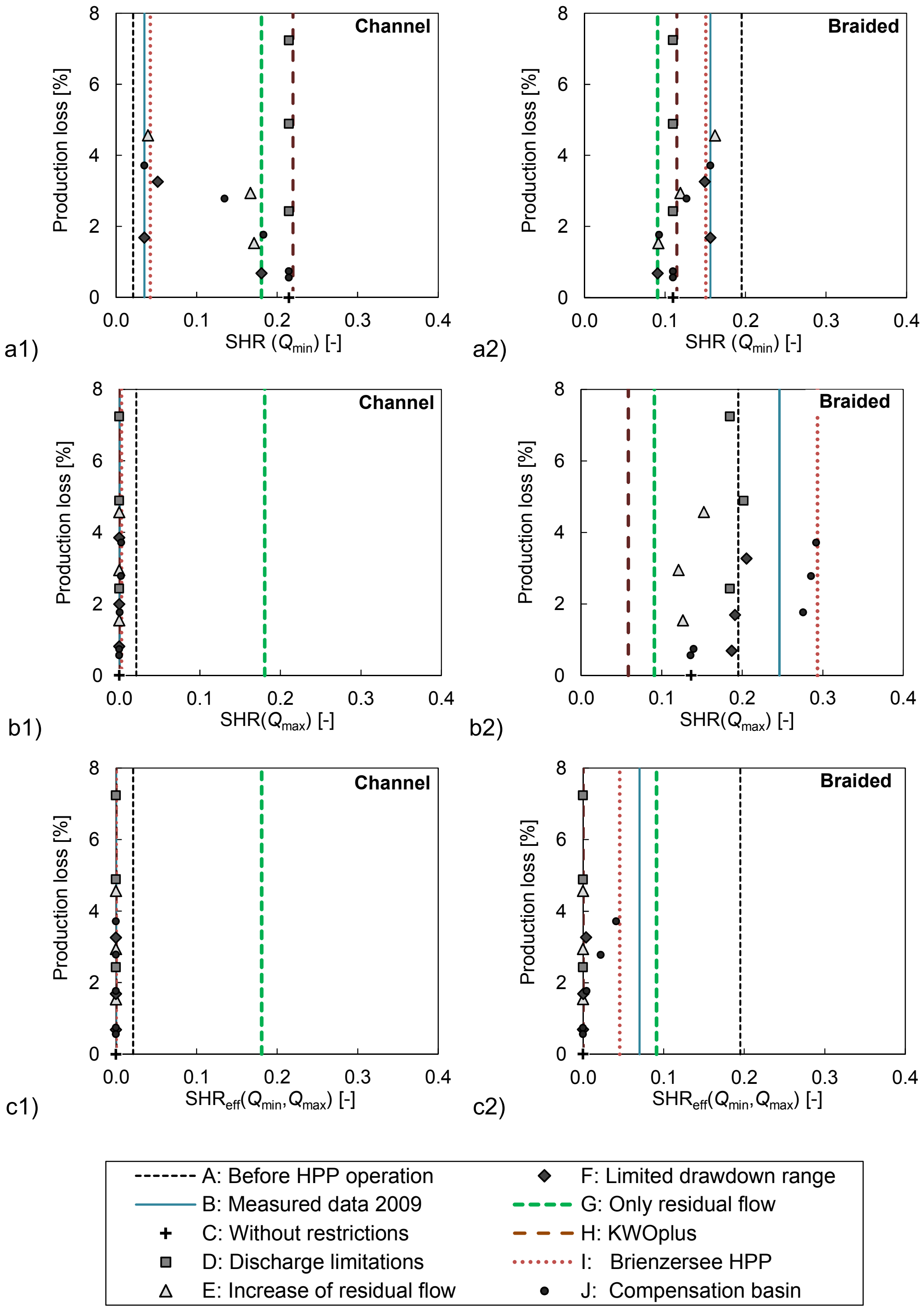


Figure 6.10: SHR indices and mitigation cost (production loss from annual revenue without restrictions of 118 M€/yr) for spawning brown trout resulting from measured and simulated flow regimes (with and without mitigation measures) for the channel (1) and braided (2) reaches. X-axis: (a) Suitable Habitat Ratio for discharge Q_{min} SHR(Q_{min}); (b) Suitable Habitat Ratio for discharge Q_{max} SHR(Q_{max}); (c) Effective Suitable Habitat Ratio $SHR_{eff}(Q_{min}, Q_{max})$. Y-axis: Annual production loss of the related scenarios. The vertical lines stand for the scenarios which do not have mitigation costs (e.g. A: Before HPP operation, B: Measured data) or for which no mitigation costs could be calculated (e.g. H: KWOplus, I: Brienzersee HPP).

6.5 Discussion

This chapter presents a method to evaluate fish habitat improvement and the economic impact of hydropeaking mitigation measures for alpine rivers. For complex high-head-storage hydropower schemes, sophisticated hydrological-hydraulic modelling such as the Routing System (Bieri and Schleiss, 2012) is needed to evaluate the financial consequences for economic rating as well as to generate the resulting flow regime. To evaluate the ecological impact, the current hydraulic-based metrics (Meile *et al.* 2011) are not sufficiently specific for a reliable assessment, as shown by the drawdown ranges of the simulated scenarios in this study. The developed simulation tool is therefore based on local biological data (Smokorowski *et al.* 2011). The hydraulic habitat model CASiMiR (Jorde *et al.* 2000; Schneider *et al.* 2010; Tuhtan *et al.* 2012) estimates the aquatic habitat quality as a function of discharge and therefore provides a better understanding of the complex aquatic conditions. In previous published work (Valentin *et al.* 1996; Garcia *et al.* 2010), only the steady indices WUA and HHS assess the impact of hydropeaking. For the present study, the results of habitat modelling were post-processed by specifically developed steady and dynamic fish habitat indices. These new indices provide more appropriate assessment of hydropeaking impact on fish habitat. Suitable Habitat Ratio (SHR) quantifies the amount of high-quality habitat available at a steady state. In contrast to the Hydraulic Habitat Suitability (HHS), SHR considers habitat only above a defined threshold value. The developed dynamic habitat indices quantify habitat instability (WHL), dewatering risk (DAR), and effective suitable spawning conditions (SHR_{eff}).

The developed methodology was applied to the upper River Aare catchment. The reference scenario consists of an HPP operation with no constraints or mitigation measures. Operational restrictions, such as a limitation of maximum and minimum turbine discharge, affect the ability to produce peak energy. These scenarios thus remain more expensive than other measures, such as compensation basins. Moreover, the effectiveness of the tested operational restrictions is low. More beneficial ecological effects can be achieved by structural measures. Compensation basins or caverns (J1 to J3) can be installed downstream of the turbine outlets in Innertkirchen. Nearly all volumes greater than 100,000 m^3 generate lower peak discharge and higher residual flow than the operational measures. Compensation basins reduce the sub-daily flow fluctuations for reasonable costs. If basins are built as multipurpose schemes, they could generate synergies in terms of recreational zones or flood retention (Heller *et al.* 2010). Hydropeaking can be completely eliminated in certain cases by bypass tunnels as a component of plant-enhancement projects (G). The simulations proved the ability of the Routing System to address complex schemes and to generate realistic results. Mitigation measures were defined to positively impact the current operations. This pragmatic and practically relevant approach could be extended to less common mitigation measures, e.g., the removal of dams and intakes, a reorganisation of the whole cascade, or a run-of-river operating mode. In addition to the types of measures, the magnitude could also be increased for a sensitivity analysis of a given parameter, e.g., the drawdown range.

The fish habitat simulations show that hydropeaking impact is strongly dependent on river morphology, and the ecological mitigation effect can be increased by upgrading the altered river morphology, as discussed in previous studies (Willi 2002; Baumann &

Meile 2004). Moreover, spawning and YOY SHR values are lower than SHR values for adults for all morphologies and simulated scenarios. These results confirm previous work establishing that spawning and YOY life stages are particularly affected (Person & Peter 2012; Person & Peter submitted) (see chapter 3 and 4). To cover the relevant life stages, post-emergent fry should be included in further assessments of the impact on natural reproduction. However, for sampling reasons, post-emergence stadia were not considered in this study. For all mitigation scenarios with a hydropeaking regime, fish habitat is highly unstable. Stable suitable habitat can be achieved only without hydropeaking, as in the simulated scenarios before HPP operation, or with a powerhouse outflow in a side channel or directly into the lake. The groynes, gravel bars, and channel reaches showed poor habitat values when discharge increased over 20 m^3/s. This discharge limit is unrealistic in current energy production patterns. The braided reach provides the richest instream structure because the riverbed is wider. The braided reach is the only morphology able to absorb HPP-influenced discharges and to produce varying velocity conditions suitable at the fish scale. Such velocity conditions that meet the fish requirements cannot be achieved under peak flow in the narrow streambeds of the three current Hasliaare morphologies resulting from successive river channelization. Considering the four morphologies and the three brown trout life stages, the braided reach offers the best habitat conditions in terms of quantity and stability for most of the scenarios. Stranding of juveniles was not quantified in this study. However, a high risk for YOY might exist considering the substantial amount of dewatered habitat in the braided morphology.

The present approach concentrated on three life stages of brown trout, a salmonid species of high economic value in alpine streams and thus defined as an appropriate target species. Much less is known about cyprinids and other freshwater fish species, macro-invertebrates (Baumann & Klaus 2003; Pellaud 2007), riparian arthropods (Paetzold *et al.* 2008), or riparian vegetation (Merritt *et al.* 2010). Hydromorphological conditions suitable for one salmonid species may be inappropriate for other aquatic biota (Bratrich *et al.* 2004). In addition to further research and integration of other biological communities, extensions in terms of lateral and longitudinal (hotspots) connectivity and landscape as well as physical (water temperature, sediment load) and chemical conditions could be taken into account (Flodmark *et al.* 2004; Olden & Naiman 2010). The habitat-rating indices should be adapted to the target species. The evaluation of the hydropeaking magnitude could then be extended to include frequency and duration as well as flow-ramping analysis. Further development of the method should include up- and down-ramping analyses, defining areas of high stranding or redd-dewatering risks. In this case, the Drained Area Ratio (DAR) could be calculated over small time steps during a decreasing flow phase. Some methodologies include temporal variation in water depth, flow velocity, and substrate to assess stranding risk (Tuhtan *et al.* 2012) or redd dewatering (Schneider *et al.* 2012). However, there is a lack of biological data on the effect of habitat dewatering on spawning and stranding risk. More experiments are needed to accurately integrate these data in a modelling tool.

The hydropower operation tool is based on inflow and electricity price scenarios and does not precisely generate the real contract-based production behaviour. The resulting on/off turbine operations produce a more highly fluctuating flow regime, which is ecologically more problematic than the observed flow regime. Thus, flow regime mitigation should be rated based on a simulated reference scenario. Flow propagation in the river network could be improved by using 1D or even 2D flow propagation models. The costs of construction and the purchase of land for basins or channels require knowledge of local conditions, which is not easily available without detailed investigations. Conservative cost estimation with high security margins is thus recommended. Biological rating can also be affected by uncertainties regarding data sampling and expert knowledge. In addition to the commonly known problems of habitat modelling, defining a reference case for natural or initial conditions remains difficult. Natural hydro-morphological conditions do not always produce maximum habitat suitability. Some of important findings in this paper can be described as general rules: 1) River revitalisation is a prerequisite for mitigating the impact of hydropeaking on the aquatic ecosystem. 2) Hydropeaking, even at a reduced magnitude, always results in high habitat instability. 3) The economic-ecological diagnostic and intervention method itself can be used for any hydropower plant downstream impact assessment. Nevertheless, some results are specific to the Hasliaare case study. The most efficient mitigation scenario depends on the power plant outline and its operating rules as well as the downstream river morphology and the habitat requirement of the target species.

6.6 Conclusion

An economic-ecological diagnostic and intervention method for mitigating fish habitat conditions in alpine streams affected by hydropeaking was developed and applied. The approach contains a hydropower operation model for flow regime generation and the definition of mitigation costs, a 2D hydrodynamic model of representative river reaches, and a dynamic fish habitat simulation tool. The new parameters assessing habitat instability are very promising for the assessment of the impact of hydropeaking on downstream fish habitat.

Operational and structural measures to mitigate hydropeaking produce a change in the flow regime. As shown for the River Hasliaare, metrics based only on hydrological data are unsuitable for defining the ecological effectiveness of an intervention. Habitat suitability for brown trout greatly depends on river morphology and life stage. Flow assessment using the dynamic habitat indices that have been developed showed that the best ecological rating is achieved by large compensation basins for the braided reach or by eliminating hydropeaking with a powerhouse outflow directly into the lake. For effective flow regime mitigation, restoration of the altered morphology is essential. The method developed will facilitate science-based decision making. The method can be integrated into an overall assessment tool for sustainable river management. The study may help to support the application of the Law on Water Protection to river restoration projects at existing and newly developed hydropower facilities in alpine areas.

7 Synthesis

This chapter provides a summary of the main achievements of this thesis. An outline of the main conclusions is presented for the four research objectives covered in chapter 3 to 6. Each research objective is presented as a subsection entitled by representative key words. The outlook and future research objectives section provides a discussion of the limitations of this work as well as specific areas to be addressed in future research.

7.1 Achievements

To understand the effect of hydropeaking on fish and their habitat, various approaches and tools have been tested in this work. Modeling as well as experimental approaches were used. Brown trout (*Salmo trutta*) was chosen as a target species and different aspects of the fish life cycle were studied. The effect of seasons and instream river characteristics from near natural to strongly channelized morphologies were investigated. Current approaches in habitat modeling were challenged and improvements in the form of additional tools and indices were proposed. The work carried out here, gave the following scientific insights:

- Characterization of the type of effects induced by hydropeaking on fish habitat.
- Identification of landscape filters (Poff 1997) and target life stages of the European brown trout limiting population renewal.
- Construction of specific preference curves for spawning and young-of-the-year brown trout in Swiss alpine rivers.
- Assessment of the influence of variable Habitat Suitability Curves on the CASiMiR fish model results.
- Extension of habitat models in order to account for habitat instability: Development of dynamic habitat indicators.
- Clarification of the synergies between flow mitigation and morphological improvement.

- Development of an economic-ecological diagnostic and intervention method linking decision making to its actual economic and ecological outcomes.
- Proposition of mitigation strategies for the future management of hydropeaking.

The knowledge and tools presented in this work help to better understand the impact of hydropower plant operations on the river habitat and to find the adapted mitigation strategies. In the context of sustainable use of hydropower, such approaches are essential to build science-based management strategies.

The following sub-sections review the major conclusions for each of the four research objectives (chapter 3 to 6).

Determining the seasonal impact of hydropeaking (chapter 3)

The seasonal impact of hydropeaking on physical habitat conditions for adult brown trout was investigated using the fish module of the CASiMiR habitat model. The Vorderrhein River, a natural braided river subjected to hydropower operation was chosen. The goals achieved were: 1) understanding how hydropeaking affects adult brown trout habitat, 2) identification of possible critical seasons, 3) clarification of the limitations of the current habitat models in assessing irregular discharge associated to hydropeaking and 4) identification of the adaptation potential of habitat models. The habitat simulations revealed that hydropeaking has negative impacts on the adult brown trout habitat. Moreover, results showed that the impacts were not constant all year long. The situation was worse during winter due to natural low discharge conditions, which intensify the effects of the hydropeaking regime. The ratio between off-peak and peak flow varied from 1/10 to 1/15 during the winter months compared to 1/1.5 during the summer months. For adult brown trout, hydropeaking did not only affect the quantity but also the quality of the habitat. The habitat was strongly displaced between high and low flow during winter, forcing the individuals to move between suitable areas, which constantly changed location. Adult brown trout are strong swimmers, thus the consequences of daily habitat displacement might be worse on less mobile life stages. This can include juveniles or spawners. Juveniles have lower swimming capacities and need shallow shore habitat with a low flow velocity. Spawners stay in a fixed location to build the redd. In addition, spawning occurs during winter months when the effect of hydropeaking is highest.

The impact of hydropeaking on brown trout habitat is seasonal and magnified in winter. For adults, mainly the quality of the habitat is impaired (in term of habitat instability).

Natural reproduction of fish in a regulated braided river (chapter 4)

A focus was put on the sensitive life stages of brown trout: the reproduction and the early life stages of brown trout (young-of-the-year (YOY)). Habitat suitability was modeled and for this purpose, regional preference curves were developed for the study river: the Vorderrhein River. This specific HSCs were compared to available data from literature, which provides evidence that regional variation in preference influences the model outcome. In addition to the current habitat indices used in PHABSIM models, Weighted Usable Area (WUA) and Hydraulic Habitat Suitability (HHS), three new steady and dynamic fish habitat indices were developed and tested. These indices were developed to quantify the instability of the habitat resulting from hydropeaking. The first new index, the Suitable Habitat Ratio (SHR) quantifies the amount of high-quality habitat for a given discharge. In contrast to the existing Hydraulic Habitat Suitability (HHS), SHR considered habitat only above a defined threshold value ($SI \geq SI_{lim}$): thus focusing on highly suitable habitat areas. The two other developed habitat indices quantified habitat instability (WHL) and dewatering risk (DAR). These new indicators allowed a more accurate and better quantitative and qualitative description of fish habitat, first in overlooking poor habitats ($SI < SI_{lim}$) and second in quantifying habitat dynamics between peak and off-peak flow. If hydropeaking rivers are viewed as two rivers in one (e.g. peak flow conditions and off-peak flow conditions) (Jones 2013), these new indices are able to quantify the associated risks for fish habitat according to alternation between these conditions. In situ observations and field experiments were combined to the theoretical habitat model approach. Reproduction success was evaluated by monitoring egg to hatching survival with a Vibert box in-situ incubation system. YOY density was compared between hydropeaking and residual flow reaches with electrofishing surveys. Results showed that brown trout natural reproduction was impaired by the hydropeaking regime. Habitat for both spawning and YOY was present at peak and off peak flow. However, the habitat was substantially shifted or dewatered, as previously shown for the adult life stage. The instability was accurately quantified with the help of the newly developed indices. For spawning and YOY, 50 % of the suitable habitat (SI > 0.5) was exposed to dewatering while the other 50 % was strongly displaced. Spawning and YOY preference curves for the study river were similar to the reviewed literature data. However, regional differences strongly influenced the CASiMiR model output predicting differences from 5- to 8-fold increase in HHS and SHR values depending on the HSCs data used. Field surveys demonstrated that YOY density was slightly higher in the control sections where the habitat was not displaced (Median of the number of YOY per 100m: control = 23; hydropeaking = 13). However, no statistical evidence was found that hydropeaking impaired YOY density or egg survival. Despite hydropeaking and the resulting habitat instability, the braided morphology did sustain the renewal of brown trout population. Abiotic conditions that meet fish habitat requirements were found at all tested flow conditions. Therefore, rivers with a natural morphology may be more resilient to hydropeaking, compared to channelized systems.

Young-of-the-year and spawners are sensitive and useful indicators. The natural river morphology provides suitable habitat conditions for all tested discharges. The suitable habitat areas are almost entirely dewatered or displaced due to hydropower operations. The new instability indices are useful tools to quantify the magnitude of habitat loss.

Hydropeaking and channelization (chapter 5)

Fish reproduction and habitat availability was characterized in a river displaying river channelization and hydropower operations. Therefore, the upper Aare catchment was chosen. The river has undergone successive channelization, which resulted in three types of degraded morphologies: groynes, gravel bars and channel reaches. The method developed previously in this work was applied (see Chapter 4). Sensitive life stages (spawning and YOY) of the European brown trout were investigated. Specific preference curves for the Hasliaare River were developed and the habitat was modeled for the three types of degraded morphologies. Results showed that the habitat model predictions using regional preference curves were accurate. All the observed spawning grounds were mapped in areas where the model predicted a high Suitability Index ($SI > 0.6$). In the hydropeaking reaches, fish habitat was present under low flow conditions for spawners and YOY. Nevertheless, for both life stages, the habitat totally disappears at peak flow. SHR values for YOY and spawners were reduced to almost zero when discharge increased above 10, 15 and 40 m^3/s for channel, groynes and gravel bars reach, respectively. The reproduction success was compared between hydropeaking and near natural reaches with a constant daily in situ discharge regime. The egg to hatching incubation experiment design was improved due to the limitations experienced with the Vibert boxes approach in the Vorderrhein River. First, Vibert boxes were replaced by egg capsules (Dumas & Marty 2006). The number of replicates was significantly increased and a tributary (Urbach River) of the Hasliaare River was used as a flow control site. Survival until hatching was significantly lower in the hydropeaking section compared to the Urbachwasser, a near natural tributary with constant flow (median survival until hatching was decreased from a third in the hydropeaking reach compared to the Urbachwasser). Electrofishing surveys showed that YOY individuals were almost absent in the hydropeaking reaches (Median of the number of YOY per 100 m: control reach = 110; hydropeaking reach ≈ 0). In the Hasliaare River characterized by both morphological and flow deficits, brown trout population renewal is strongly impaired. The results confirm the assumption enunciated with the Vorderrhein River results. Morphology helps mitigate the effect of hydropeaking by providing habitat at all discharge conditions. However natural morphology cannot hinder the high habitat instability and dewatering risk created by the hydropeaking regime. The presence of constantly underwater habitats and a good connectivity to tributaries must be restored (Kindle *et al.* 2012). Rehabilitation measures focusing solely on flow mitigation (e.g. with the reduction of the Q_{min}/Q_{max} ratio) independently of the geomorphological characteristics of the receiving river system might not be successful. Defining an acceptable threshold for a Q_{min}/Q_{max} ratio providing adequate water for the aquatic ecosystem is difficult. According to the results presented in this chapter , it appears that setting such a ratio is strongly dependent on the width and the morphology of the downstream river. These findings support the current development of concepts including hydropeaking mitigation as part of integrated and global catchment restoration projects (Peter 2010; Charmasson & Zinke 2011; Kindle *et al.* 2012).

Channelization aggravates the impact of hydropeaking. Little to no habitat is sustained at peak flow conditions. Egg development is impaired. Young-of-the year are absent. These factors lead natural populations to collapse. The river width is a limiting factor for acceptable maximum peak flow because it determines the depth and velocity distribution and therefore the physical habitat.

Mitigation measures for fish habitat improvement (chapter 6)

A tool to assess the effectiveness of hydropeaking mitigation measures to improve fish habitat was developed. The approach was called "economic-ecological diagnostic and intervention method" and comprises (1) a hydropower operation model which generates flow regimes downstream of the powerhouse outflow and estimates the cost for given mitigation measures; (2) a 2D hydrodynamic model to simulate the flow conditions in representative river reaches; (3) a dynamic fish habitat simulation tool to assess the sub-daily changes in habitat conditions of three brown trout life stages (adult, spawners, and YOY).

The developed methodology was applied to the upper River Aare catchment. In the model, the reference scenario consists of hydropower plant (HPP) operation with no constraints or mitigation measures. Then, different types of mitigation scenarios were implemented in the economic-ecological diagnostic and intervention method. The measures tested belong to the following three categories: 1) operational measures, such as restrictions in the turbine operation mode, 2) structural measures, such as regulated compensation basins downstream of the powerhouse, 3) morphological measures, such as river restoration works. The first two types of measures are existing measures developed in current hydropeaking mitigation strategies and categorized as flow mitigation measures. The third type of measure does not belong directly to flow mitigation measures and consisted in widening the river and improving instream structure. The goal was to create areas of suitable fish habitat at higher discharge as suggested by the results from the Vorderrhein and Hasliaare River (see chapter 3 to 5). However, only one widening scenario was tested; the rehabilitation of the strongly channelized reach into a braided one. Habitat modeling results showed that habitat quantity and quality for spawning and YOY is always lower than for adult life stage. This confirms the results obtained previously from the Vorderrhein and Hasliaare River (chapter 3 to 5). Model output for the operational restrictions scenarios, such as a limitation of maximum and minimum turbine discharge, did affect the ability of peak energy production and had little effect on fish physical habitat improvement. In addition, these scenarios remained more expensive than structural measures, e.g. compensation basins. Higher ecological effect was not achieved by operation or structural measures in the existing degraded reaches from the Hasliaare River. In the three degraded morphologies: groynes, gravel bars and channel reaches, the peak discharge limit (Q_{max}) which should be set to sustain a small amount of fish habitat (20 m^3/s) is unrealistic in current energy production patterns. Only the combination of the compensation basin with a braided reach was able to sustain brown trout habitat at higher discharge. This combination of measures provided the heterogeneous instream structure and a reduced hydropeaking regime able to create fish habitat. The wider riverbed allowed operators to set a higher upper acceptable limit for environmental flow, which can meet current electricity production constrains. However, even if fish habitat was created by the combination of morphological and flow mitigation measures, habitat instability was very high (> 80% of habitat dewatering by off-peak flow for all life stages). Currently, alternative river engineering measures to improve the ecomorphological structure of regulated alpine rivers are tested on the Hasliaare study case with the help of physical models (Speerli & Schneider 2012).

The study and method applied here provide evidence that for effective hydropeaking mitigation, restoration of both the altered morphology and flow regime is essential. The developed method will help setting the best combination of flow/morphology mitigation scenario.

River restoration is a necessary condition for the success of flow mitigation on the aquatic ecosystem. The economic-ecological diagnostic and intervention method is a useful tool for hydropower plant downstream impact assessment.

7.2 Outlook & future research objectives

To understand the impact of hydropower plant operations on the downstream aquatic ecosystem, a complex and interdisciplinary study was conducted. This thesis presents a variety of tools and experiments to understand and identify the interaction between river morphology, discharge regime and fish ecology in a hydropeaking influenced river. The insights and current limitations of this work suggest specific research areas to be investigated in future works:

- The analysis of fish habitat dynamics between off-peak and peak flow states should be extended to include frequency, duration of peak flow as well as up and down- and up-ramping rates. Additional time steps between the two steady states ($Q_{\min}$,$Q_{\max}$) should increase accuracy in the spatial identification of high stranding or redd dewatering areas. Several modeling approaches are being developed in this direction (Leo *et al.* 2012; Schmidt *et al.* 2012; Schneider *et al.* 2012).
- In current microhabitat models, sediment dynamics are not taken into account. Further development of existing models should include sediment transport such as particles erosion and re-deposition. Indeed, scouring of redds and bed clogging of spawning grounds and intragravel refugia could be quantified and predicted with such models developments. Nevertheless, this integration is still difficult as 2D/3D sediment transport models are not yet fully validated.
- To understand the mechanisms responsible for lower egg survival in rivers influenced by hydropeaking, the possible influence of sediment and thermopeaking need to be further investigated.
- For a global assessment of the effects of hydropeaking on the aquatic ecosystem, the early life stages of brown trout (e.g. post-emergent fry) and more generally other target species (e.g. grayling, macroinvertebrates) must be further considered.
- Physical habitat models based on univariate preference curves are useful to define environmental flow for the target species. However, the biotic habitat conditions (e.g. the impact of predation or age class structure) are not considered and the interdependency between depth, substrate and velocity preference is not take into account. Several authors tried to solve this problematic using other descriptors of habitat preference such as fuzzy-rules (Lane *et al*. 2006), stepwise linear regression (Lamouroux & Capra 2002; Leathwick *et al*. 2005), random forest models (Vezza *et al*. 2012), evolutionary polynomial regression (EPR) methods (Giustolisi *et al*. 2007; Giustolisi & Savic 2009) or non-equilibrium thermodynamics approach (Tuhtan 2011, 2012). The implementation of such approaches in microhabitat models could increase the ability to predict the interaction between habitat characteristics and allow a better integration of fish

habitat choice complexity. However, when using current univariate approaches, habitat suitability curves should be elaborated for low flow and for peak conditions (Holm *et al.* 2001; Ibbotson & Dunbar 2002; Fukuda *et al.* 2012).

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List of symbols and acronyms

Roman capitals

A_i	Area of cell *i* of the river morphology	[m^2]
DAR	Drained Area Ratio	[-]
H_i	Flow depth of cell *i* of the river morphology	[m]
H_{lim}	Threshold water depth	[m]
HHS	Hydraulic Habitat Suitability	[-]
HP2	Flow ramping rate	[-]
Q	Discharge	[m^3/s]
Q_{max}	Maximum *or* peak discharge	[m^3/s]
Q_{min}	Minimum *or* off-peak discharge	[m^3/s]
SA	Suitable Area	[m^2]
SHR	Suitable Habitat Ratio	[-]
SI	Suitability Index	[-]
SI_{lim}	Threshold Suitability Index	[-]
Vbasin	Storage volume of compensation basin	[m^3]
Vcavern	Storage volume of cavern	[m^3]
WAeff	Effective Wetted Area	[m^2]
WA_{tot}	Total Wetted Area	[m^2]
WHL	Wetted Habitat Loss	[-]
WUA	Weighted Usable Area	[m^2]

Acronyms

AWA	Amt für Wasser und Abfall of Bern Canton
CA	Catchment area
CTI	Commission for Technology and Innovation
DEM	Digital elevation model
EAWAG	Swiss Federal Institute of Aquatic Science and Technology
EPFL	Ecole Polytechnique Fédérale de Lausanne
ETHZ	Swiss Federal Institute of Technology Zurich
FOEN	Federal Office for the Environment
IEA	International Energy Agency
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
KWO	Kraftwerke Oberhasli AG
HPP	Hydropower plant
HSC	Habitat Suitability Curve
LCH	Laboratoire de Constructions Hydrauliques
SFOE	Swiss Federal Office for Energy
SGHL	Schweizerische Gesellschaft für Hydrologie und Limnologie
UNIL	Université de Lausanne
WEC	World Energy Council
WFD	Water Framework Directive
YOY	Young of the year

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